Contributions of socio-metabolic research to sustainability science

Invited review article for *Nature Sustainability*

Helmut Haberl,[1,*] Dominik Wiedenhofer,[1,**] Stefan Pauliuk,[2,**] Fridolin Krausmann,[1]
Daniel B. Müller,[3] Marina Fischer-Kowalski[1,**]

[1] Institute of Social Ecology, University of Natural Resources and Life Sciences, Vienna (BOKU), 1070 Vienna, Austria.
[2] Industrial Ecology Group, Faculty of Environment and Natural Resources, University of Freiburg, D-79085 Freiburg, Germany
[3] Industrial Ecology Programme, Department of Energy and Process Engineering, Norwegian University of Science and Technology (NTNU), 7491 Trondheim, Norway

* Corresponding author helmut.haberl@boku.ac.at
** These authors contributed equally to this article

2nd revision, submitted 2 January 2019

Accepted final version of:

Haberl, H., Wiedenhofer, D., Pauliuk, S., Krausmann, F., Müller, D.B., Fischer-Kowalski, M., 2019. Sustainable society-nature interactions? Contributions from socio-metabolic research, Nature Sustainability 2, 173–184

Abstract

Recent high-level agreements such as the Paris climate accord or the Sustainable Development Goals aim at mitigating climate change, ecological degradation and biodiversity loss while pursuing social goals such as reducing hunger or poverty. Systemic approaches bridging natural and social sciences are required to support these agendas. The surging human use of biophysical resources (materials, energy) results from the pursuit of social and economic goals, while it also drives global environmental change. Socio-metabolic research links the study of socioeconomic processes with biophysical processes and thus plays a pivotal role for understanding society-nature interactions. It includes a broad range of systems science approaches for measuring, analyzing and modelling of biophysical stocks and flows as well as the services they provide to society. Here we outline and systematize major socio-metabolic research traditions that study the biophysical basis of economic activity: urban metabolism, the multi-scale integrated assessment of societal and ecosystem metabolism, biophysical economics, material and energy flow analysis, and environmentally extended input-output analysis. Examples from recent research demonstrate strengths and weaknesses of socio-metabolic research. We discuss future research directions that could also help to enrich related fields.

1. A primer on socio-metabolic research

Transformations toward a sustainable future, as manifested in the Sustainable Development Goals (SDGs), require substantial development efforts in many parts of the world. Human use of the Earth's biophysical resources such as energy, materials or land, needs to be strongly reduced or altered to avoid severe ecological degradation and mitigate climate change[1–3]. Too often, these challenges are tackled independently or even at the expense of one another, while they are indeed strongly interlinked. Examples include the expected economic damages resulting from global warming[4], the economic affordability, resource requirements and environmental impacts of low-carbon technologies[5,6], or the manifold interdependencies between sustainability and energy use[7]. Quantitative, comprehensive research capable of linking social, economic and environmental domains is hence required to guide and monitor progress towards sustainability[8,9]. Systemic interdisciplinary research frameworks help to integrate scientific knowledge from different disciplines, across the great divides between natural and social sciences as well as the humanities. They provide common definitions and system boundaries, and guide indicator, database and model development. Application of too narrow or ambiguous system boundaries as well as oversimplification of complex interactions may result in misleading research outcomes if fundamental conflicts among SDGs, synergies and other systemic effects are neglected[10].

1.1 Overview and definitions

Socio-metabolic research (SMR) is a systems approach to studying society-nature interactions at different spatio-temporal scales. It is based on the assumption that social systems and ecosystems are complex systems that reproduce themselves, interact with each other, and co-evolve over time[11–13]. Social metabolism encompasses biophysical flows exchanged between societies and their natural environment as well as the flows within and between social systems (Fig 1). Socio-metabolic flows operate and maintain biophysical structures of society, such as buildings, infrastructures or machinery, usually denoted as "artefacts"[11], "manufactured capital"[14,15], "in-use stocks of materials"[16] or "material stocks"[17]; we here use the latter notion. Systematically observing societies' use of biophysical resources is a core goal of SMR[18]. SMR helps to overcome the widespread conceptual disregard of biophysical processes in many economic and social science approaches[19] and to demonstrate the "size" or "scale" of human activities compared to the biosphere[20,21].

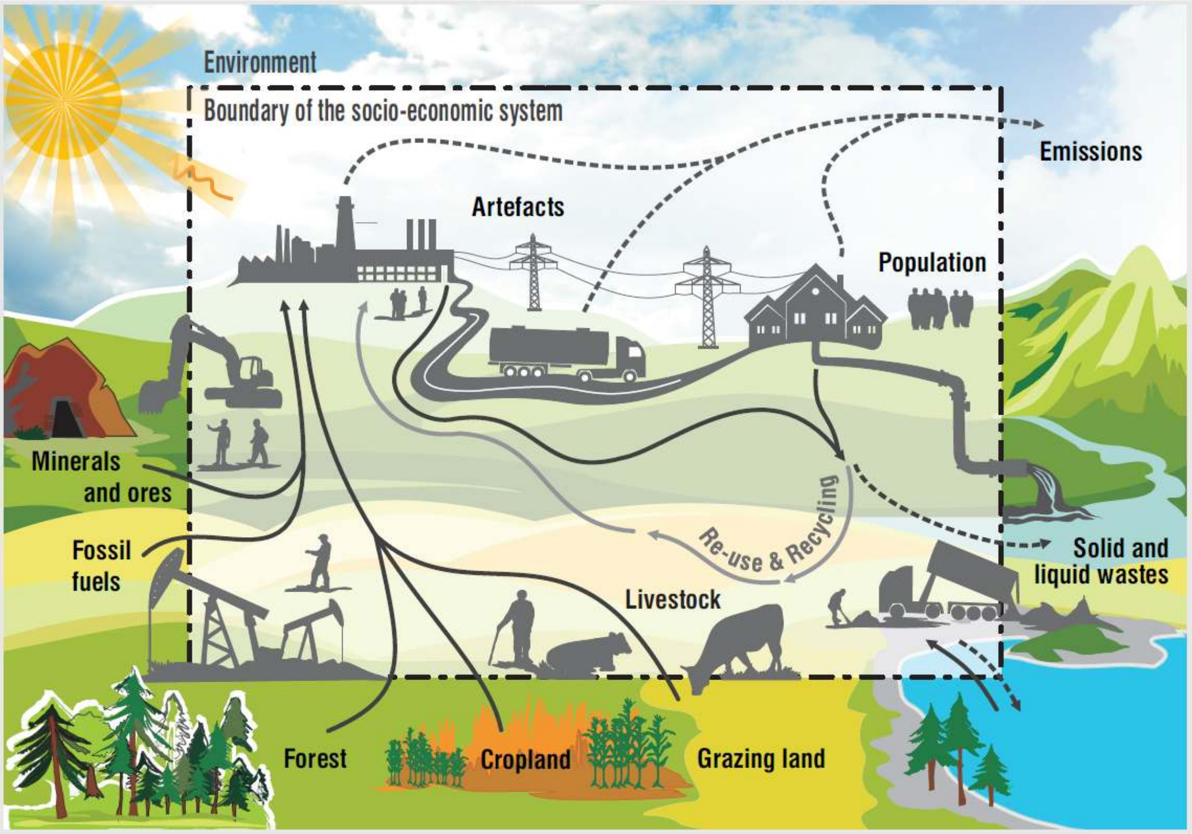


Fig. 1. Socio-metabolic research (SMR) systematically quantifies flows of biophysical resources associated with defined social systems or their components. SMR investigates the socioeconomic transformations of natural resources and traces outputs of waste and emissions to the environment. This graph highlights major biophysical stocks and flows considered in SMR. It shows the system boundaries used in Material and Energy Flow Analysis (MEFA, section 1.3), which traces extraction of materials and energy from the natural environment, their use for feeding people and livestock or expanding, maintaining and operating artefacts such as buildings, factories, machinery or infrastructures. Materials and energy are eventually released into the environment as wastes and emissions. Traded raw materials or products are important, often dominant, components of social metabolism on all levels below the global total. Source: own graph.

Explicitly or implicitly, socio-metabolic research builds upon the following assumptions[11,18]: (1) The functioning of social systems, including the economy, rests upon successfully organizing energy and material flows to expand, maintain and operate its biophysical basis: human population, livestock, and artefacts such as buildings, infrastructures or durable commodities. These stocks generate important flows, such as physical, intellectual or emotional labor, products such as bread, clothes or electricity, and services such as living space or mobility. (2) The composition, magnitude and patterns of social metabolism determine society's environmental pressures and impacts. Sustainability requires socio-metabolic flows to be compatible with the supply and sink capacity of the biosphere. (3) First principles of the natural sciences (e.g. the laws of thermodynamics) apply to the metabolism of socioeconomic systems and are fundamental to their understanding.

In that sense, social systems (like humans themselves) constitute hybrids of biophysical and symbolic systems shaped by discourses, power relations or monetary flows, and are subject to intentional organization[11]. At what point in social metabolism natural elements cross the system boundary of society (Fig 1) requires theoretically grounded, consistent, and pragmatic decisions depending on the respective research goals. A criterion used to define the boundary between nature and society is the intensity of society's interventions into natural systems[18]. The boundaries shown in Fig 1 were defined for economy-wide material flow accounting[22] and comprise all flows required to reproduce society's material stocks[11]. Different socio-metabolic approaches (section 1.3) deviate in their specific operationalization of these boundaries, but share a focus on the biophysical reproduction of specific functionally integrated socioeconomic systems. Regarding social metabolism as a systems phenomenon leads to the expectation that nexus features resulting from systemic interdependencies such as synergies, trade-offs, problem shifting, lock-in or non-linearity may be relevant (discussed below).

1.2 A family tree of socio-metabolic research

SMR presupposes a common ground between social and natural sciences[23]. Such a common ground had existed among early political economists and social theorists who acknowledged the role of natural factors such as land, labor and energy on the social sciences side, and natural scientists who extended their disciplinary knowledge on nutrient flows, energy and thermodynamics to economies and societies (Fig 2)[24,25]. Increasing academic differentiation in the course of the late 19th and early 20th century discouraged shared paradigms between social and natural sciences. On the social sciences side, few scholars discussed, for example, the role of energy for societal development[26], whereas the mainstream focused on culture, discourses and decision-making. Economics became a science of markets, prices and flows of money. In the 1960s and 1970s, the intellectual separation of social and natural phenomena was criticized by researches who revived and created mind models and knowledge relinking both scientific realms[27,28]. These approaches relied on emerging new epistemologies derived, among others, from the theory of complex systems[29,30] and theoretical ecology[31,32].

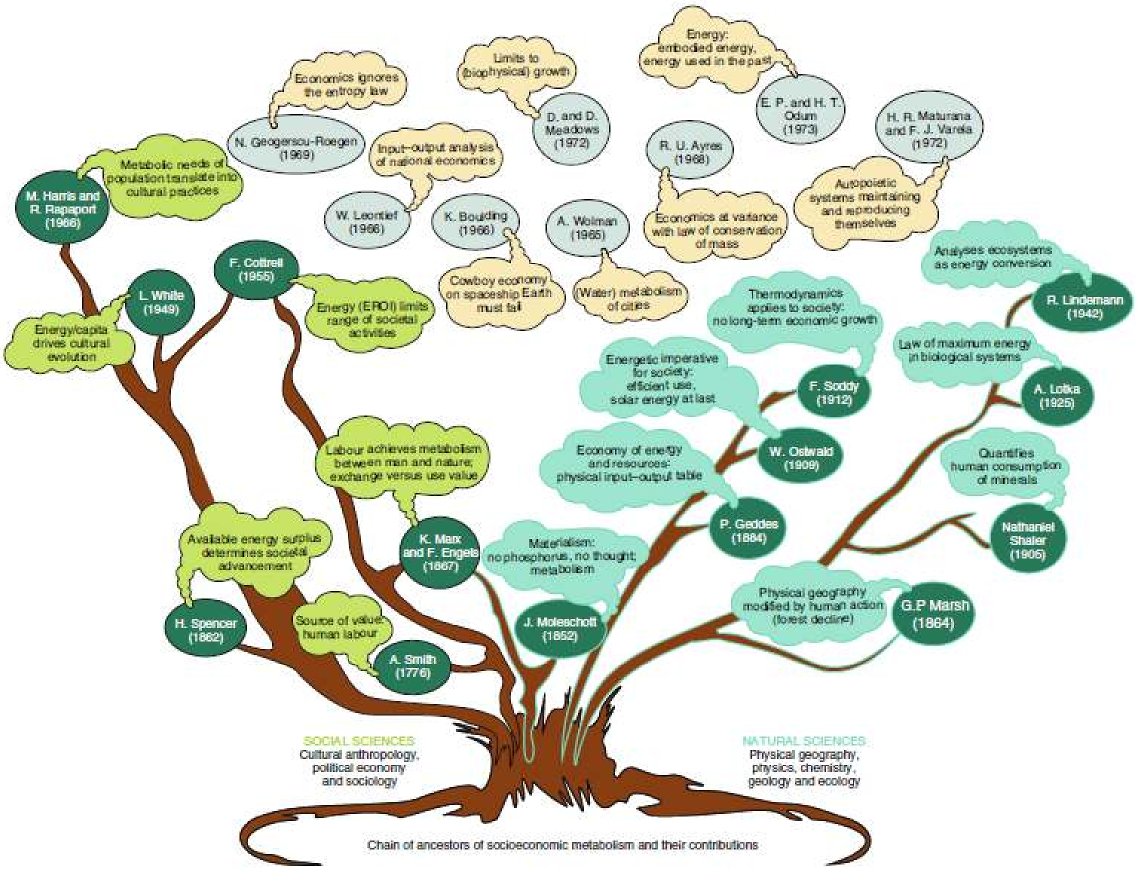


Fig 2. Family tree of research traditions from social sciences (left side) and natural sciences (right side) that inspire current socio-metabolic research. Own graph, developed on data in[26,33]. Color legend: Pale green: roots from the social sciences. Dark green: roots from the natural sciences. Grey: ancestors and founders of current SMR traditions discussed in section 1.3.

Increasing environmental concerns motivated researchers from different backgrounds to develop various research strands of SMR. Despite efforts at harmonization[34], several variants of SMR with differing scopes and methods exist (section 1.3). A recent bibliographical analysis found that the number of references to the term "social metabolism" has risen from 400 in the period 1991-2000 to over 3000 in the following decade, and another 6000 in the period 2011-2015[35].

1.3 Socio-metabolic research traditions

We here discuss five selected research traditions by summarizing their respective conceptual backgrounds, the social systems studied, key empirical tools and indicators, the temporal scale of their analytical perspectives and main regulatory and policy applications. The focus is on traditions explicitly investigating the biophysical basis of society and identifying themselves as part of SMR. Given space constraints, we do not aim to be comprehensive.

Urban metabolism studies focus on material and energy flows within urban systems, accumulation of material stocks, and the exchange processes of urban areas with their hinterlands. This tradition was pioneered among others by Abel Wolman and Stephen Boyden (Fig 2)[36,37], and indeed *avant la lettre* by Heinrich von Thünen[38]. A long-standing concern of this research strand are the relationships between urbanization, density, urban form and the resource requirements and waste outputs of cities. Recent research analyzed whether dense urban areas require less energy and materials use than scattered settlements providing the same standard of living[39]. Other studies focused on resource flows outside cities resulting from consumption of urban dwellers, reckoning that resources saved within dense urban settings may be overcompensated by "upstream" resource use in supply chains supporting city dwellers[40]. Another topic is how to plan and organize new urban areas with lower resource use[41,42]. Urban metabolism research uses MEFA to directly investigate cities using similar system boundaries as in Fig 1, and EE-IOA to analyze (inter)national supply chains to quantify footprints of urban areas (both discussed below)[43–45]. Another strand of research uses the term urban metabolism rather metaphorically. These studies employ concepts and methods from political science, sociology, social geography or ethnography but usually do not aim at quantifying the biophysical processes at the core of SMR[46,47]; for a recent review see[48].

Multi-scale integrated analysis of societal and ecosystem metabolism, abbreviated MuSIASEM. This approach was developed by researchers around Mario Giampietro and Kozo Mayumi based on the work of Nicholas Georgescu-Roegen[49]. Its proponents argue that since socio-ecological systems are self-organized, their proper analysis requires considering their hierarchically organized structural and functional compartments operating at different space-time scales[50,51]. MuSIASEM applies the theory of complex hierarchical systems to SMR by integrating information on social, economic and socio-metabolic dimensions at multiple scales. It uses Georgescu-Roegens concept of "funds" which refers to entities such as labor, land or technological capital that provide services to the social system. Funds have to be maintained but are not consumed[51,52]. MuSIASEM studies typically account for energy use, human activity, and value added for the system as a whole and its compartments. Variables are often used in a context-dependent manner to fit the purpose of each specific study[50]; data are derived from census statistics, MEFA (see below) or other models. MuSIASEM has been applied to rural systems[53], mining[54], and urban waste management[55]. The nexus between resources such as food, water or energy[56] and the links to ecosystem metabolism[57] are increasingly studied. A recent review is[51].

Biophysical economics focuses on the central role of energy for the economy, which is often ignored in mainstream economics. Its founders include Kenneth Boulding[58] and Robert U.

Ayres[59]. This tradition can be traced back well into the 19th century (Fig 2) and was inspired by Eugene and Howard Odum[60] as well as others working on ecological energy analysis[25,29,61]. One of its central tenets is that net energy gained is more important to society than the total amount of primary energy used, hence its core interest on energy return on energy investment (EROI)[62,63]. EROI can be applied at a variety of scales, from technologies or supply chains[64] to system-wide analyses that aim to integrate social and biophysical approaches[65–67]. This tradition often uses other system boundaries than those shown in Fig 1 because it traces energy flows from extraction through processing to final uses, thereby not emphasizing territorial boundaries. One typical finding is that fossil fuels have a relatively high EROI which gradually declines over time, while renewable technologies usually have lower EROIs[68]. This poses substantial challenges for a low-carbon transition because it implies reductions in useful energy[69]. Biophysical economics also uses methods such as emergy and exergy accounting. Emergy is a measure of energy embodied in resources traced back to a common denominator, e.g. solar energy[70–72]. Exergy is the share of an energy flow that can actually perform work, depending on conversion technologies, and has been related to the rate of economic growth[67,73,74]. A recent review is[75].

Material and energy flow analysis (MEFA) focuses on the role of resources for social and economic development and aims to inform sustainable resource management. One of its founders is Robert U. Ayres[59,76], who advocated the mass-balanced analysis of economic systems as a counterpart to monetary-economic perspectives (Fig 2). MEFA studies range from investigations of specific substances[77] to comprehensive assessments of many materials[78]. They trace biophysical flows through socioeconomic systems, their accumulation as stocks and the ensuing waste or recycling flows (Fig 1). MEFA covers national and global scales as well as regions, households, industries or other units and uses stationary or dynamic approaches[79]. Substance flow analysis tracks individual chemical elements linked with services such as shelter and transport[77]. Economy-wide material flow accounting comprehensively monitors material flows through economies (Fig 4) and is applied in environmental reporting (section 2.2)[2,80]. Studies of long-term trends in resource use as well as comparative cross-country datasets[81,82] investigate the potentials for decoupling the use of materials and energy from economic growth and wellbeing[83]. Material flow accounting and substance flow analysis can be combined to provide detailed assessment of flows of specific materials and substances. Such data support environmental, resource, circular economy, and waste management policies and can help to improve supply chains[84]. Recent MEFA research emphasizes dynamic modelling of the relation between in-use stocks of products and the associated resource flows required to deliver physical services such as shelter and transport[16]. For reviews see[80,85].

Environmentally extended input-output analysis (EE-IOA) focuses on the biophysical and monetary interrelations between economic sectors. It links production, consumption and environmental stressors within and across countries. EE-IOA goes back to the work of Wassily Leontief (Fig 2)[86] and has been proposed early on as a means to "integrate the world of commodities into the larger economy of nature"[87]. It is used to study flows through economic sectors within a socioeconomic system (boundaries as in Fig 1), but also to assess international supply chains. EE-IO tables report supply and use flows between economic sectors in a specific year, usually in monetary values. They extend this sectoral information with biophysical or social information, such as materials, energy, greenhouse gas emissions, water or human labor. Several detailed, high quality global Multi-Regional Input-Output models exist that integrate national tables with global trade data and extend them with a large array of environmental and social indicators[88,89]. Aggregated monetary IO tables and detailed physical process descriptions were combined to so-called hybrid models[90,91]. These approaches have tremendously increased the potential of EE-IOA for studying sustainability concerns "embodied" in consumption and displaced across supply chains. Such studies reveal structural changes in the supply chains of commodities over time and shed light on the interplay between growing consumption, international burden-shifting due to expanding supply chains and increasing industrial efficiency[92–94]. A recent review is[95].

Related approaches with their own large, partially overlapping, scientific communities include the Ecological Footprint, Life-Cycle Assessment (LCA) and Integrated Assessment Models (IAMs). The Ecological Footprint translates resource use into a measure of bio-productive land required for its sustenance ('footprint') and compares it with the availability of such land ('biocapacity') to determine the extent to which humans live beyond planetary limits[96]. LCA is used to evaluate product life cycles, compare products or identify potentials for reducing environmental impacts[97–100]. Consequential LCA considers systemic feedbacks[6], which could also profit from SMR methods discussed here. IAMs are comprehensive and detailed tools to analyze feedbacks between socioeconomic and earth systems, but mostly do not include an explicit representation of society's biophysical basis and its underlying thermodynamic principles[101]. Whether one pigeonholes these traditions within or outside SMR may be a matter of taste; discussing them in detail is out of scope for this review.

2. Recent insights from socio-metabolic research

We here exemplify how SMR can bridge natural and social sciences in addressing sustainability and providing useful information for monitoring and policy-making. Due to space limitations, we focus on the global level and do not include examples from all SMR traditions.

2.1 The great acceleration to the Anthropocene

Proposals to introduce a new geological epoch, the Anthropocene[102], reflect how profoundly the planet is being transformed by human activities, as planetary boundaries have been transgressed[103]. Socioeconomic flows of reactive nitrogen and carbon affect global biogeochemical cycles, with severe consequences for climate[104] and biodiversity[105]. The notion of a "great acceleration"[103] highlights the increasing speed of these transformations.

SMR corroborates these concepts by providing long-term trajectories of social metabolism and its relations to socioeconomic and political factors (Fig 3). Over the last century, humanity's use of materials and energy has reached a comparable magnitude as flows within the biosphere (e.g. energy, nitrogen and phosphorous), representing a step change in earth history[106]. Over the last 115 years, extraction of materials, energy and water increased eight to twelve-fold (Fig 3a), while material stocks, global GDP and useful physical work surged (Fig 3b). Global population increased five-fold, and average life expectancy doubled, indicating that the increasing availability of resources and material stocks resulted in improved living conditions for substantial parts of the world population. Solid waste generation and dissipative uses increased 15-fold, while emissions of carbon, nitrogen, sulphur and methane increased ten-fold (Fig 3c). CO_2 emissions from fossil fuel combustion increased 19-fold, constituting a major driver of human-induced climate change[104].

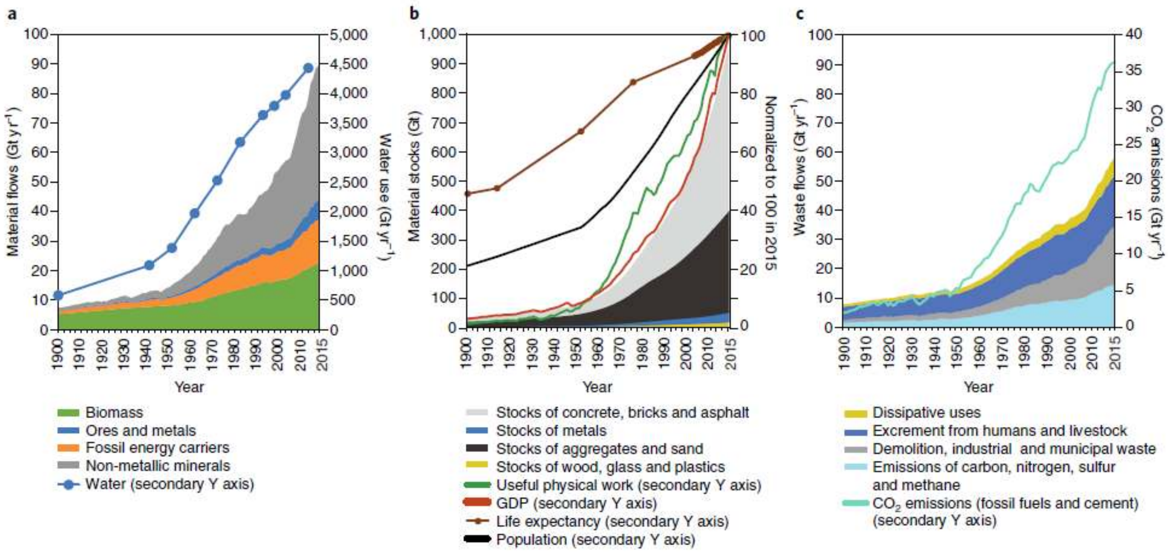


Fig. 3. Scale and dynamics of global social metabolism in the Anthropocene, illustrating the systemic interlinkages between resource use, socioeconomic dynamics and ensuing waste and emissions. (a) Resource extraction and inputs into social metabolism. (b) Key socioeconomic dynamics such as population, GDP, life expectancy, useful physical work/useful exergy, as well as material stocks (here the mass of manufactured capital). (c) A comprehensive mass-balanced (i.e. output = input – net change of stocks) estimate of all outputs of wastes and emissions to the environment as well as fossil-fuel related CO_2 emissions. System boundaries as in Fig 1. Data sources: Global extraction of materials, primary energy and freshwater[107–109]. Global GDP in intl. Geary-Khamis $, population and life-expectancy[110–112], material stocks[15], and useful physical work or useful exergy[113]. Outputs of waste and emissions to the environment[109]; CO_2 emissions from fossil fuel use and cement production[114].

Fig 3 shows no signs of a global stabilization of societal resource use; rather, it suggests a new acceleration period since the early 2000's, mainly due to rapidly progressing industrialization and urbanization in many emerging economies, as well as steadily high consumption in many high-income economies[115]. It supports the view that world population growth has contributed to rising environmental pressures[116], while the growth of resource use per capita associated with rising economic activity and affluence played an even larger role[117].

Asking how economic (GDP) growth drives resource use[118–120], and conversely, to what extent resources such as energy contribute to economic growth[121,122], has occupied SMR researchers for decades. Patterns found vary between different studies, but mostly suggest that resource use and emissions per unit of GDP decline over time due to gains in resource efficiency, which is defined as the ratio of resources used per inflation-corrected GDP[83,123]. Improvements of resource efficiency are denoted as "decoupling" of economic growth and resource use. "Relative decoupling" means that resource use grows at a slower pace than GDP, while "absolute decoupling" refers to absolute reductions in resource use coinciding with economic growth[124]. Fig 3 as well as country-level studies[83,125] suggest that relative decoupling is frequent, but absolute decoupling is rare and mainly observed during recessions or periods of low or absent economic growth[83,126]. Globally, resource use rises along with economic growth, although mostly at a slower pace. An exception is the accumulation of material stocks, which matched GDP almost perfectly (Fig 3b)[15]. The use of GDP in such studies is controversial because GDP only measures economic activity, not social wellbeing, and neglects inequality and services delivered by existing capital stocks[127] (see also section 2.4).

2.2 Monitoring resource use at the country level

As the surging human use of resources drives the earth system into unchartered territory, the question arises how to consistently monitor it. This is especially useful at levels where political competencies for resource management exist, e.g. for countries. SMR has developed country-level indicators applied in sustainable resource use policies across the world, including the monitoring of progress towards the SDGs[115,128]. The International Resource Panel of the United Nations Environment Programme maintains a comprehensive international database covering most countries worldwide available at http://www.resourcepanel.org/global-material-flows-database. It provides data on extraction, trade, processing and consumption of resources and provides indicators from both production- and consumption-based perspectives (Figure 4). The production-based perspective relates to MEFA focused on the national territory (Fig 1), while the consumption-based perspective allocates resources used along international supply chains to a country's final consumption, utilizing EE-IOA.

Within a production-based perspective, country-level resource use is measured as "domestic material consumption" (Fig 4a) or DMC (explained in caption of Fig 4). DMC differs between countries by more than one order of magnitude, largely following their development status and pathway, population density and resource endowments[83,115,129,130]. According to the UNEP database, the average DMC of low-income countries was 3.2±1.1 t/cap/yr in 2012, while it was approximately six times higher (18±10.1 t/cap/yr) in high-income countries. Inequality is even larger from a consumption-based perspective, i.e. measured as the "material footprint" (MF; explanation in caption of Fig 4) of goods consumed in each country. The MF is 2.3±1 t/cap/yr in low-income countries compared to over ten times more (26.7±15.5 t/cap/yr) in high-income countries that rely on the import of resource-intensive products[115,131]. A map of the difference between DMC and MF (Fig 4b) shows that MF exceeds DMC in most high-income countries in Europe and North America. The reason is that resource-intensive production steps increasingly take place in other, largely poorer and less resource-efficient, economies[93], partially due to 'outsourcing' of environmental pressures from rich to poor regions[132], but also due to export-oriented growth in many developing economies.

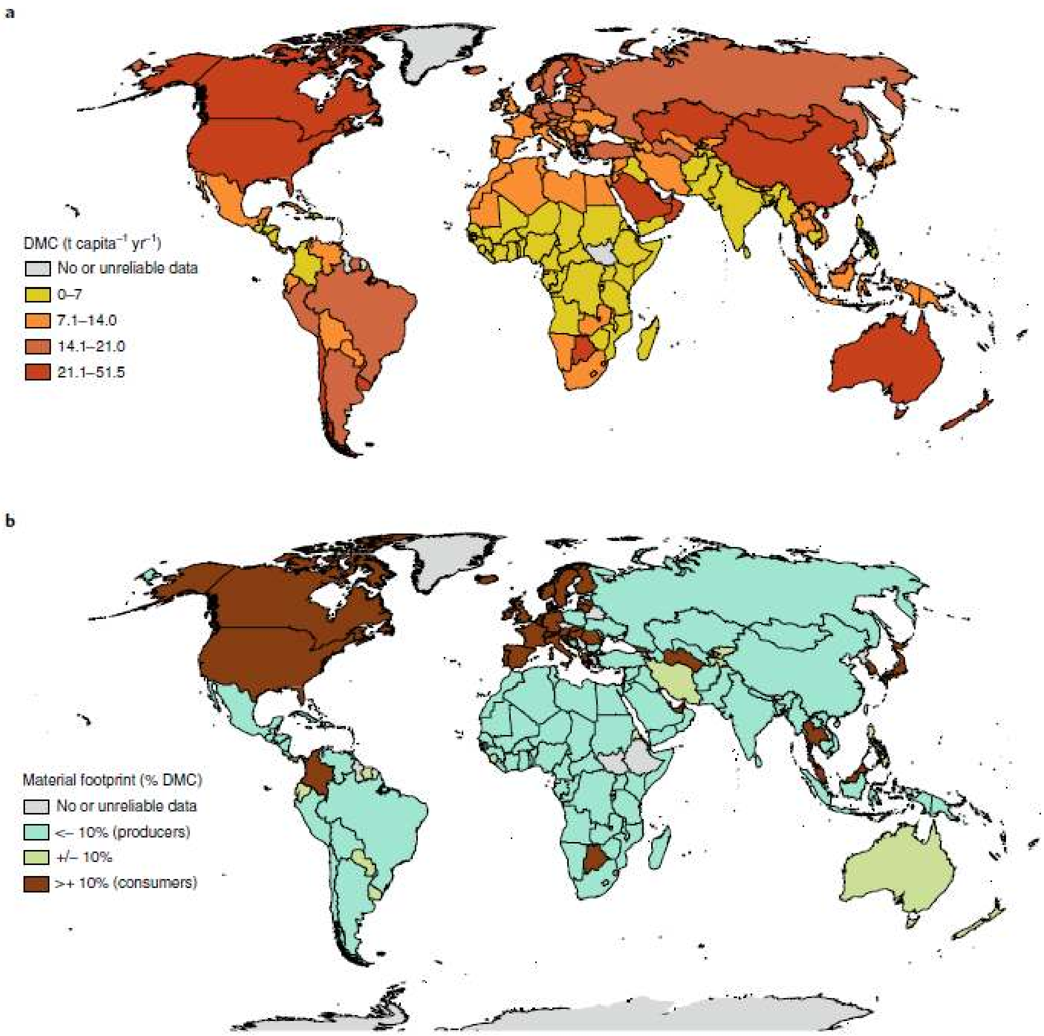
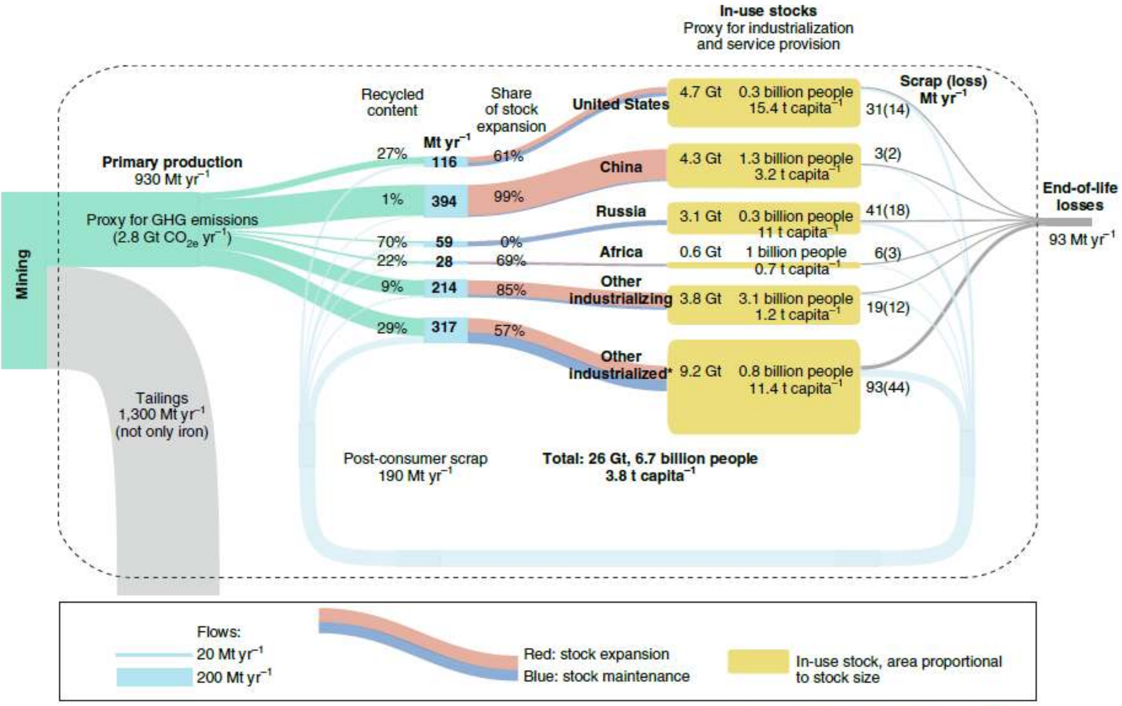


Fig. 4: Biophysical resource use within national-political boundaries. (a) Domestic material consumption (DMC), i.e. the mass of domestic extraction plus the mass of actual import minus export (MEFA methods, system boundaries as in Fig 1). (b) The material footprint (MF), a consumption-based perspective, which attributes resource use along supply chains to national final demand. It is calculated by extending MEFA with data from EE-IOA. Both indicators are proxies for environmental pressures (a) within national boundaries (DMC) and (b) and along global supply chains linking all extraction to final consumption (MF). Countries in the "green" category (MF differs from DMC by less than 10%) extract approximately the same mass of resources on their own territory as is embodied in the goods they consume; "producers" extract more domestically, "consumers" less. The global sum total of yearly resource use is the same for DMC and MF (mass balance principle). Sources: own mapping based on[2,115]. http://www.resourcepanel.org/global-material-flows-database

Although the link between material flows and environmental impacts differs by types of materials and impacts, indicators from MEFA can serve as useful proxies for aggregate environmental pressures, both on national territory (DMC) and along supply chains (MF). The material footprint is highly correlated with the carbon footprint and the ecological footprint[83,133] and indicates how much environmental pressure is related globally to national consumption. SMR studies so far found no evidence for successful continued absolute decoupling between resource use and economic growth (section 2.1)[134]. Reducing material flows to sustainable levels within planetary boundaries will require far-reaching transformations of social metabolism[17,135–137], and probably also of socioeconomic systems.

2.3 Social metabolism and the circular economy

Early statements from biophysical economics and MEFA traditions of SMR[58] already advocated closing of material cycles, later denoted as 'circular economy'. In the last decades, the circular economy concept has gained substantial traction in China and Japan and increasingly in the European Union and the USA[138,139]. Developing sector-, material-, and product-specific strategies and policies to foster circularity requires disaggregated information. SMR can provide such data, as shown in Fig 5, which gives an overview of the global steel cycle in 2008. MEFA tools allow for taking a closer look at the flows within the socioeconomic system boundaries delineated in Fig 1. The material cycle perspective allows to consistently depict material stocks and flows. Results support hypotheses formulated in section 1.1 on temporal dynamics of stock-flow-relations: they show how fast material stocks grow, when and how materials become available for recycling, and how much recycling contributes to maintaining stocks.



*Europe, Japan, Canada, Australia, Korea and Israel

Fig 5. Depiction of the global steel cycle in 2008 showing the link between material stocks, their maintenance and expansion, and primary metal production, the latter being a major driver of greenhouse gas emissions. Steel remelted from postconsumer scrap accounts for less than 20% of global steel production. Rapidly expanding in-use stocks demand high levels of primary production, as secondary production can only maintain existing stocks. Own graph, data sources[15,140,141].

The rapid growth of global steel stocks limits the potential of supplying a large fraction of steel inputs from recycled material (Fig 5). Globally, 75% of all steel inputs go into new stocks; hence, the steel cycle is a combination of a linear with a circular system. Hypothetically avoiding all end-of-life losses (impossible for thermodynamic reasons) would reduce the need for primary production of steel by only ~10%. Material stocks, which are closely correlated with economic activity (Fig 3b), are growing in all world regions (Fig 5). In the US, 60% of final steel consumption goes into the net expansion (i.e. inflows minus outflows) of stocks; in China, this figure is at a staggering 99%. Steel stocks in China and the US are of similar size in absolute numbers, but per-capita values are much lower in China, suggesting a huge potential for further stock growth in China in a catch-up scenario.

Recycling rates of end-of-life steel outflows are substantial, and while there may still be potentials to raise them further, the energetic and monetary costs of doing so must not be underestimated[142,143]. Moreover, modern technologies not only require steel but increasingly rely on most of the elements in the periodic table, thereby corroborating hypotheses formulated in section 1.1 regarding systemic feedbacks between different parts of social metabolism. For example, mixtures of metals in products results in barriers to their recyclability and substitutability[143,144]. Knowledge about the full life cycle of metal stocks, including losses by design[145], and when and where stocks reach the end of their service lifetime and subsequently become available for re-use and recycling into secondary resources, can help to improve circularity[140,146]. When taking all resource inputs into the global economy into account, however, socio-metabolic circularity is only at ~6% of inflows, due to the high relevance of stock expansion and energy throughputs for total resource use, as well as the low end-of-life recovery rates of most minor metals[147] and materials other than metals[148].

2.4 The biophysical basis of social progress

Reducing resource use would be a less daunting challenge if it were possible with little detriment to social wellbeing. Recent SMR suggests that social progress rests not only on annual flows of resources, a high EROI[63], or creation of value-added (GDP), but also on the services from material stocks such as buildings, infrastructure and machinery[14,16,17,141,144,149]. This warrants a broader approach toward eco-efficiency considering aspects of social progress beyond economic activity. Toward that end, we here analyze relations between social metabolism and the recently established Social Progress Index (SPI). The SPI is a composite index based on a dashboard of outcome-oriented indicators of fulfilment of basic human needs and foundations of wellbeing and opportunities. It considers nutrition, shelter, water, sanitation, safety, access to knowledge and information, health, education, freedom, rights, and environmental quality but not monetary measures such as investments or GDP[150]. Social progress in terms of SPI is related to social metabolism; for example, it is correlated with a sustained history of high resource use[149].

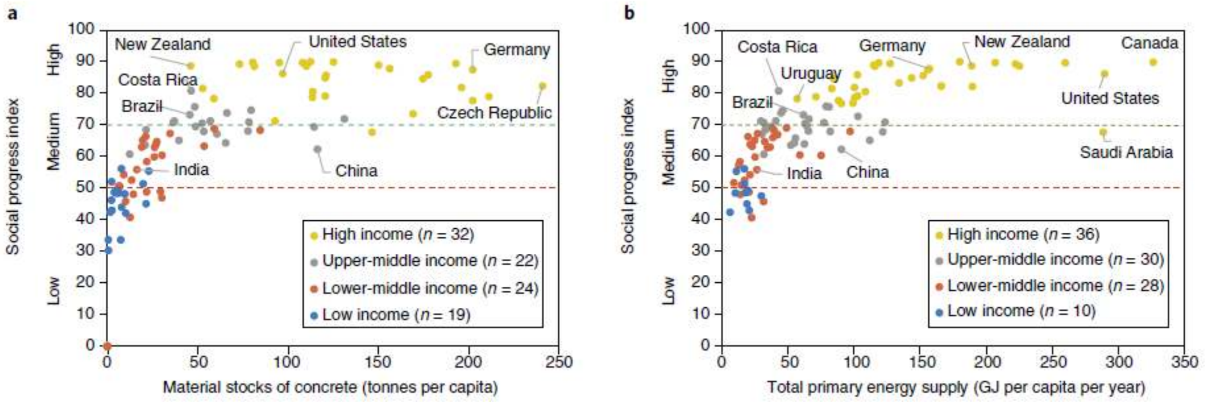


Fig 6. The socio-metabolic basis of human well-being and social progress, as measured through the Social Progress Index (SPI). (a) Concrete stocks versus SPI in 97 countries. (b) Total primary energy supply (TPES, GJ/cap/yr) versus SPI in 104 countries. The green and red dashed lines show the ranges defined as high respectively medium social progress[150]. Concrete amounts to ~45% of total global material stocks[15,151]. Material stocks of buildings, infrastructure and machinery and the energy required to operate and maintain these stocks jointly provide services to society. Sources: Concrete[151], TPES and SPI[150], income classes[111]. TPES and concrete stocks are available for different subsets of countries, which explains the different numbers of countries in income classes in graph (a) and (b).

Fig 6 documents the number of countries achieving a certain SPI for any level of (a) material stocks of concrete, a good proxy of overall material stocks[15], and (b) total primary energy supply (TPES) per capita and year. It reveals that very high levels of SPI are reached at a level of ~50 tons of concrete stocks per capita and below ~100 GJ/cap/y of total primary energy use. No clear trend in SPI prevails above those levels. Income is represented by a color code, demonstrating that there are deviations between the material stocks and energy flows, economic activity and the SPI worthy of further analysis. Results corroborate findings from recent work on the resource requirements of social wellbeing and development employing the human development index (HDI). The HDI integrates indicators of life expectancy, education, as well as GDP and its distribution[152]. Recent SMR typically found saturation functions indicating that a high HDI can be reached at intermediate levels of resources use with no clear trend above certain thresholds[83,153]. While resource requirements for achieving a decent HDI decreased in the last decades due to rising resource efficiency[119,141], most countries still either transgress planetary boundaries and/or fail on social goals[136]. Similar insights have been generated using indicators for energy and carbon footprints as well as EROI[63,119]. These results support the hypotheses formulated in section 1.1 regarding non-linearities in socio-ecological systems and the relevance of going beyond monetary perspectives.

3. Outlook and conclusions

Social metabolism is a thriving research framework guiding empirical analysis and modelling of society-nature interactions. Different SMR traditions reviewed in section 1.3 essentially study the same underlying process, i.e. society's use of biophysical material and energy resources. They provide insights on patterns, drivers, systemic feedbacks, and sustainability implications of resource use from different angles. SMR provides perspectives missing from dominant approaches based primarily on monetary or social data. When coupled with information on the ability of the environment to generate resources or absorb wastes, results from SMR indicate transgressions of planetary[103] or regional boundaries[154]. SMR can also help to integrate social science approaches into the analysis of the great acceleration towards the Anthropocene (section 2.1) and provides a robust, internationally accepted basis for the monitoring of resource use in various contexts of national and international policy-making (section 2.2.)[155], based on the laws of thermodynamics[156].

The reviewed literature and examples corroborate expectations that systemic interactions in resource use are crucially important (section 1.1). Interactions between and among different resources, e.g. between materials and energy[144,145,157,158], are a case in point (section 2.3). The patterns shown in Fig 3 reveal only the tip of the iceberg of leakage or burden-shifting phenomena analyzed with EE-IOA methods (section 1.3)[159,160]. SMR revealed many examples for non-linear society-nature interactions. For example, the research reviewed in section 2.4 suggests saturation functions between indicators of social progress and resource flows respectively material stocks (section 2.1).

SMR suggests existence of important lock-in effects and legacies related to the build-up of material stocks. Future GHG emissions (from 2010-2060) expected to result from fossil fuels required for the operation of existing infrastructures until the end of their lifetime amount to roughly one-half of the remaining emission budget consistent with the 2°C target[161,162]. Over one-half of all socio-metabolic material flows is currently used to build up infrastructure and artefacts (section 2.1)[15], indicating that these lock-ins may worsen. These results point to the central role of urban and infrastructure development for reducing future resource requirements[39,163]. Such considerations have motivated proposals for a "stock-flow-service nexus" framework[14,16,17,144], which recognizes that specific combinations of stocks and flows provide essential services such as nutrition, shelter or mobility, and hence are crucial for understanding resource requirements associated with development trajectories or sustainability transformations[135]. The absence of continued absolute decoupling between GDP and resource use (section 2.2) indicates how large this challenge is.

SMR, however, also has weaknesses. In interdisciplinary research, it is often hard to clearly identify research boundaries and label research approaches (section 1.3). The construction of SMR may seem artificial to scholars not familiar with the approach. Areas requiring more attention in the future include approaches to link social metabolism with the behavior of individual agents, e.g. via microeconomics, agent-based modelling, or costs. The use of statistical methods, including proper uncertainty analysis or data reconciliation based on statistical inference, and the reporting of uncertainties in publications is underdeveloped in current SMR[164,165]. Efforts to gather high-quality data on biophysical resources remain high on the agenda of SMR. A central concern is the consistent integration of system-wide assessments with approaches aiming at better process and product resolution. A high level of detail in evaluating technologies and production processes or identifying potentially critical materials, though, is often at odds with capturing system-wide effects such as resource availability, rebound effects or problem shifting related with substitution, lock-in (legacies), leakage or rebound effects[166].

SMR has become a core element in communities such as Ecological Economics[28], Industrial Ecology[167,168], and Integrated Land-Change Science[169,170]. SMR explicitly addresses economic theory and aims at broadening economic thought[51,65] by providing a biophysical perspective on growth theory[121], efficiency and rebound effects[166,171] or the decoupling debate[172]. Incorporating SMR principles into the macroeconomic modules of integrated assessment models would strengthen their ability to comply with thermodynamic principles and more systematically take feedbacks between different resources into account[101]. Links between social sciences and SMR include analyses of issues such as inequality or social conflict[173–176]. SMR is used in Political Ecology to investigate environmental conflicts[177,178], labor[179,180], or ecologically unequal exchange[181–183]. Efforts to explicitly link SMR to other social science efforts, e.g. practice theory or socio-technical systems approaches, could be strengthened, in particular in the emerging fields of sustainability transformation research[132,135,184,185]. While decoupling and resource-efficiency will be an important part of strategies for more sustainable resource use, many SMR researchers now believe that ecological modernization will not suffice and far-reaching social and economic transformations are required[12,136,186]. SMR can form a backbone of sustainability science by delivering consistent analyses of social metabolism that help to better understand the interdependencies between societal well-being and the physical services provided by society's metabolism.

Author for correspondence: Helmut Haberl, helmut.haberl@boku.ac.at

Acknowledgements: This project has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (MAT_STOCKS No [741950]). Further we acknowledge research funding from the Austrian Science Fund FWF (projects MISO P27590 and GELUC P29130-G27). We thank Manja Podovac for help with Figs 1&2 and Dr. Maria Niedertscheider for help with the maps in Fig 3.

Author contributions: All authors contributed to reviewing and discussing literature and writing the article. H.H. and D.W. conceived Fig 1. M.F.K. conceived Fig 2. F.K. and DW compiled data and drafted Fig 3. D.W. compiled data and drafted Fig 4. S.P. compiled data and drafted Fig 5. D.W. and S.P. compiled data and drafted Fig 6. H.H. structured the paper and discussions. All authors contributed to writing the text.

Competing financial interests: The authors declare no competing financial interests.

Data availability statement: The analyses shown in Figs. 3-6 rely on publicly available data from the cited references.

References

1. IPCC. *Climate Change 2014: Mitigation of Climate Change, Working Group III contribution to the IPCC Fifth Assessment Report (AR5), Summary for Policy Makers*. (Intergovernmental Panel for Climate Change, 2014).
2. UNEP. *Global Material Flows and Resource Productivity*. (United Nations Environment Programme, 2016).
3. UNEP, M. A. *Policy Coherence of the Sustainable Development Goals, A Natural Resources Perspective*. (United Nations Environment Programme, 2015).
4. Stern, N. The Economics of Climate Change. *American Economic Review: Papers and Proceedings* **98**, 1–37 (2008).
5. Foxon, T. J. Transition pathways for a UK low carbon electricity future. *Energy Policy* **52**, 10–24 (2013).
6. Hertwich, E. G. *et al.* Integrated life-cycle assessment of electricity-supply scenarios confirms global environmental benefit of low-carbon technologies. *Proceedings of the National Academy of Sciences* **112**, 6277–6282 (2015).
7. McCollum, D. L. *et al.* Connecting the sustainable development goals by their energy inter-linkages. *Environment Research Letters* **13**, 033006 (2018).
8. Liu, J. *et al.* Systems integration for global sustainability. *Science* **347**, 1258832 (2015).
9. Hoekstra, A. Y. & Wiedmann, T. O. Humanity’s unsustainable environmental footprint. *Science* **344**, 1114–1117 (2014).
10. Plevin, R. J., Delucchi, M. A. & Creutzig, F. Using Attributional Life Cycle Assessment to Estimate Climate-Change Mitigation Benefits Misleads Policy Makers. *Journal of Industrial Ecology* **18**, 73–83 (2014).
11. Fischer-Kowalski, M. & Weisz, H. Society as hybrid between material and symbolic realms. *Advances in Human Ecology* **8**, 215–251 (1999).
12. González de Molina, M. & Toledo, V. M. *The Social Metabolism. A Socio-Ecological Theory of Historical Change*. (Springer, 2014).
13. Weisz, H. The Probability of the Improbable: Society–nature Coevolution. *Geografiska Annaler: Series B, Human Geography* **93**, 325–336 (2011).
14. Weisz, H., Suh, S. & Graedel, T. E. Industrial Ecology: The role of manufactured capital in sustainability. *Proceedings of the National Academy of Sciences* **112**, 6260–6264 (2015).
15. Krausmann, F. *et al.* Global socioeconomic material stocks rise 23-fold over the 20th century and require half of annual resource use. *Proceedings of the National Academy of Sciences* **114**, 1880–1885 (2017).
16. Pauliuk, S. & Müller, D. B. The role of in-use stocks in the social metabolism and in climate change mitigation. *Global Environmental Change* **24**, 132–142 (2014).
17. Haberl, H., Wiedenhofer, D., Erb, K.-H., Görg, C. & Krausmann, F. The Material Stock–Flow–Service Nexus: A New Approach for Tackling the Decoupling Conundrum. *Sustainability* **9**, 1049 (2017).
18. Pauliuk, S. & Hertwich, E. G. Socioeconomic metabolism as paradigm for studying the biophysical basis of human societies. *Ecological Economics* **119**, 83–93 (2015).
19. Lejano, R. P. & Stokols, D. Social ecology, sustainability, and economics. *Ecological Economics* **89**, 1–6 (2013).
20. Goodland, R. & Daly, H. Environmental Sustainability: Universal and Non-Negotiable. *Ecological Applications* **6**, 1002–1017 (1996).
21. Daly, H. E. Economics in a Full World. *Scientific American* **293**, 78–85 (2005).
22. Fischer-Kowalski, M. *et al.* Methodology and Indicators of Economy-wide Material Flow Accounting - State of the Art and Reliability Across Sources. *Journal of Industrial Ecology* **15**, 855–876 (2011).
23. Fischer-Kowalski, M. Society’s Metabolism: The Intellectual History of Materials Flow Analysis, Part I, 1860– 1970. *Journal of Industrial Ecology* **2**, 107–136 (1998).

24. Christensen, P. Classical roots for a modern materials-energy analysis. *Ecological Modelling* **38**, 75–89 (1987).
25. Cleveland, C. J. Biophysical economics: historical perspective and current research trends. *Ecological Modelling* **38**, 47–73 (1987).
26. Martinez-Alier, J. *Ecological Economics. Energy, Environment and Society*. (Blackwell, 1987).
27. Dunlap, R. E. & Catton, W. R. Struggling with human exemptionalism: The rise, decline and revitalization of environmental sociology. *American Sociologist* **25**, 5–30 (1994).
28. Røpke, I. Trends in the development of ecological economics from the late 1980s to the early 2000s. *Ecological Economics* **55**, 262–290 (2005).
29. Martinez-Alier, J., Munda, G. & O'Neill, J. Theories and methods in ecological economics: a tentative classification. in *The Economics of Nature and the Nature of Economics* (eds. Cleveland, C. J., Stern, D. I. & Costanza, R.) (Edward Elgar, 2001).
30. Varela, F. G., Maturana, H. R. & Uribe, R. Autopoiesis: The organization of living systems, its characterization and a model. *Biosystems* **5**, 187–196 (1974).
31. Ulanowicz, R. E. *Ecology, the ascendent perspective*. (Columbia University Press, 1997).
32. Holling, C. S. Resilience and Stability of Ecological Systems. *Annual Review of Ecology, Evolution, and Systematics* **4**, 1–23 (1973).
33. Fischer-Kowalski, M. & Hüttler, W. Society's Metabolism.: The Intellectual History of Materials Flow Analysis, Part II, 1970-1998. *Journal of Industrial Ecology* **2**, 107–136 (1998).
34. Bringezu, S., Fischer-Kowalski, M., Kleijn, R. & Palm, V. *Regional and National Material Flow Accounting: From Paradigm to Practice of Sustainability. Proceedings of the ConAccount workshop 21-23 January, 1997 Leiden*. (Wuppertal Institute, 1997).
35. Amate, J., Molina, M. G. de & Toledo, V. M. El metabolismo social. Historias, métodos y principales aportationes. *Revista Iberoamericana de Economia Ecológica* **27**, 30–152 (2017).
36. Wolman, A. The metabolism of Cities. *Scientific American* **213**, 179–190 (1965).
37. Boyden, S., Millar, S., Newcombe, K. & O'Neill, B. *Ecology of a city and its people: the case of Hong Kong*. (Austrian National University, 1981).
38. von Thünen, J. H. *Der isolierte Staat in Beziehung auf Landwirtschaft und Nationalökonomie*. (Historisches Wirtschaftsarchiv, 2013).
39. Kennedy, C. A. *et al.* Energy and material flows of megacities. *Proceedings of the National Academy of Sciences* **112**, 5985–5990 (2015).
40. Lenzen, M. & Peters, G. M. How City Dwellers Affect Their Resource Hinterland. *Journal of Industrial Ecology* **14**, 73–90 (2010).
41. Schäffler, A. & Swilling, M. Valuing green infrastructure in an urban environment under pressure — The Johannesburg case. *Ecological Economics* **86**, 246–257 (2013).
42. Ramaswami, A., Russell, A. G., Culligan, P. J., Sharma, K. R. & Kumar, E. Meta-principles for developing smart, sustainable, and healthy cities. *Science* **352**, 940–943 (2016).
43. Athanassiadis, A. *et al.* Comparing a territorial-based and a consumption-based approach to assess the local and global environmental performance of cities. *Journal of Cleaner Production* **173**, 112-123 (2018).
44. Kennedy, C., Pincetl, S. & Bunje, P. The study of urban metabolism and its applications to urban planning and design. *Environmental Pollution* **159**, 1965–1973 (2011).
45. Zhang, Y., Yang, Z. & Yu, X. Urban Metabolism: A Review of Current Knowledge and Directions for Future Study. *Environmental Science & Technology* **49**, 11247–11263 (2015).
46. Gandy, M. Rethinking urban metabolism: water, space and the modern city. *City* **8**, 363–379 (2004).
47. Newell, J. P. & Cousins, J. J. The boundaries of urban metabolism: Towards a political-industrial ecology. *Progress in Human Geography* **39**, 702–728 (2015).
48. Beloin-Saint-Pierre, D. *et al.* A review of urban metabolism studies to identify key methodological choices for future harmonization and implementation. *Journal of Cleaner Production* **163**, S223–S240 (2017).
49. Georgescu-Roegen, N. *The Entropy Law and the Economic Process*. (Harvard University Press, 1971).
50. Giampietro, M., Mayumi, K. & Sorman, A. H. *The Metabolic Pattern of Societies. Where economists fall short*. (Routledge, 2012).
51. Gerber, J.-F. & Scheidel, A. In Search of Substantive Economics: Comparing Today's Two Major Socio-metabolic Approaches to the Economy – MEFA and MuSIASEM. *Ecological Economics* **144**, 186–194 (2018).
52. Giampietro, M., Mayumi, K. & Ramos-Martin, J. Multi-scale integrated analysis of societal and ecosystem metabolism (MuSIASEM): Theoretical concepts and basic rationale. *Energy* **34**, 313–322 (2009).
53. Ravera, F. *et al.* Pathways of rural change: an integrated assessment of metabolic patterns in emerging ruralities. *Environment, Development and Sustainability* **16**, 811–820 (2014).
54. Silva-Macher, J. C. A Metabolic Profile of Peru: An Application of Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM) to the Mining Sector's Exosomatic Energy Flows: A Metabolic Profile of Peru. *Journal of Industrial Ecology* **20**, 1072–1082 (2016).

55. Chifari, R., Lo Piano, S., Bukkens, S. G. F. & Giampietro, M. A holistic framework for the integrated assessment of urban waste management systems. *Ecological Indicators* **94**, 24-36 (2016).
56. Giampietro, M., Aspinall, R. J., Ramos-Martin, J. & Bukkens, S. G. F. *Resource Accounting for Sustainability Assessment. The Nexus between Energy, Food, Water and Land Use*. (Routledge, 2014).
57. Lomas, P. L. & Giampietro, M. Environmental accounting for ecosystem conservation: Linking societal and ecosystem metabolisms. *Ecological Modelling* **346**, 10–19 (2017).
58. Boulding, K. The Economics of the Coming Spaceship Earth. in *Steady State Economics* (ed. Daly, H. E.) 121–132 (W.H. Freeman, 1972).
59. Ayres, R. U. & Kneese, A. V. Production, Consumption, and Externalities. *American Economic Review* **59**, 282–297 (1969).
60. Odum, H. T. *Environment, Power and Society*. (Wiley-Interscience, 1971).
61. Dale, M., Krumdieck, S. & Bodger, P. Global energy modelling — A biophysical approach (GEMBA) part 1: An overview of biophysical economics. *Ecological Economics* **73**, 152–157 (2012).
62. Cleveland, C. J., Costanza, R., Hall, C. A. S. & Kaufmann, R. Energy and the U.S. Economy: A Biophysical Perspective. *Science* **225**, 890–897 (1984).
63. Lambert, J. G., Hall, C. A. S., Balogh, S., Gupta, A. & Arnold, M. Energy, EROI and quality of life. *Energy Policy* **64**, 153–167 (2014).
64. Gupta, A. K. & Hall, C. A. S. A Review of the Past and Current State of EROI Data. *Sustainability* **3**, 1796–1809 (2011).
65. Hall, C. A. S. & Klitgaard, K. A. *Energy and the Wealth of Nations. An Introduction to Biophysical Economics*. (Springer, 2017).
66. Kümmel, R. *The Second Law of Economics, Energy, Entropy and the Origins of Wealth*. (Springer, 2011).
67. Hall, C., Lindenberger, D., Kümmel, R., Kroeger, T. & Eichhorn, W. The Need to Reintegrate the Natural Sciences with Economics. *BioScience* **51**, 663–673 (2001).
68. Hall, C. A. S., Balogh, S. & Murphy, D. J. R. What is the Minimum EROI that a Sustainable Society Must Have? *Energies* **2**, 25–47 (2009).
69. King, L. C. & van den Bergh, J. C. J. M. Implications of net energy-return-on-investment for a low-carbon energy transition. *Nature Energy* **3**, 334–340 (2018).
70. Odum, H. T. *Environmental Accounting, EMERGY and Environmental Decision Making*. (Wiley, 1996).
71. Geng, Y., Sarkis, J., Ulgiati, S. & Zhang, P. Measuring China's Circular Economy. *Science* **339**, 1526–1527 (2013).
72. Yang, Z. F. *et al.* Solar emergy evaluation for Chinese economy. *Energy Policy* **38**, 875–886 (2010).
73. Ayres, R. U., Ayres, L. W. & Warr, B. Exergy, power and work in the US economy, 1900–1998. *Energy* **28**, 219–273 (2003).
74. Sousa, T. *et al.* The Need for Robust, Consistent Methods in Societal Exergy Accounting. *Ecological Economics* **141**, 11–21 (2017).
75. Romero, J. C. & Linares, P. Exergy as a global energy sustainability indicator. A review of the state of the art. *Renewable and Sustainable Energy Reviews* **33**, 427–442 (2014).
76. Ayres, R. U. & Ayres, L. W. *Accounting for Resources, 1, Economy-Wide Applications of Mass-Balance Principles to Materials and Waste*. (Edward Elgar, 1998).
77. Baccini, P. & Brunner, P. H. *Metabolism of the anthroposphere*. (Springer-Verlag, 1991).
78. Moriguchi, Y. Material flow indicators to measure progress toward a sound material-cycle society. *Journal of Material Cycles & Waste Management* **9**, 112–120 (2007).
79. Baccini, P. & Bader, H.-P. *Regionaler Stoffhaushalt*. (Spektrum Akademischer Verlag, 1986).
80. Krausmann, F., Schandl, H., Eisenmenger, N., Giljum, S. & Jackson, T. Material Flow Accounting: Measuring Global Material Use for Sustainable Development. *Annual Review of Environment and Resources* **42**, (2017).
81. Giljum, S., Dittrich, M., Lieber, M. & Lutter, S. Global Patterns of Material Flows and their Socio-Economic and Environmental Implications: A MFA Study on All Countries World-Wide from 1980 to 2009. *Resources* **3**, 319–339 (2014).
82. Dong, L. *et al.* Material flows and resource productivity in China, South Korea and Japan from 1970 to 2008: A transitional perspective. *Journal of Cleaner Production* **141**, 1164–1177 (2017).
83. Steinberger, J. K., Krausmann, F., Getzner, M., Schandl, H. & West, J. Development and Dematerialization: An International Study. *PLoS ONE* **8**, e70385 (2013).
84. Chen, M. & Graedel, T. E. A half-century of global phosphorus flows, stocks, production, consumption, recycling, and environmental impacts. *Global Environmental Change* **36**, 139–152 (2016).
85. Huang, C.-L., Vause, J., Ma, H.-W. & Yu, C.-P. Using material/substance flow analysis to support sustainable development assessment: A literature review and outlook. *Resources, Conservation and Recycling* **68**, 104–116 (2012).
86. Leontief, W. Environmental Repercussions and the Economic Structure: An Input-Output Approach. *The Review of Economics and Statistics* **52**, 262 (1970).

87. Daly, H. E. On Economics as a Life Science. *Journal of Political Economy* **76**, 392–406 (1968).
88. Tukker, A. *et al.* Towards Robust, Authoritative Assessments of Environmental Impacts Embodied in Trade: Current State and Recommendations. *Journal of Industrial Ecology* **22**, 585-598 (2018).
89. Malik, A., McBain, D., Wiedmann, T. O., Lenzen, M. & Murray, J. Advancements in Input-Output Models and Indicators for Consumption-Based Accounting: MRIO Models for Consumption-Based Accounting. *Journal of Industrial Ecology*, in press, doi:10.1111/jiec.12771 (2018).
90. Bullard, I. & Herendeen, R. A. The energy cost of goods and services. *Energy Policy* **3**, 268–278 (1975).
91. Bullard, C. W., Penner, P. S. & Pilati, D. A. Net energy analysis: Handbook for combining process and input-output analysis. *Resources and Energy* **1**, 267–313 (1978).
92. Wood, R., Stadler, K., Bulavskaya, T., Giljum, S. & Lutter, S. Growth in Environmental Footprints and Environmental Impacts Embodied in Trade: Resource Efficiency Indicators from EXIOBASE3. *Journal of Industrial Ecology* **22**, 553-564 (2018).
93. Plank, B., Eisenmenger, N., Schaffartzik, A. & Wiedenhofer, D. International Trade Drives Global Resource Use: A Structural Decomposition Analysis of Raw Material Consumption from 1990–2010. *Environmental Science & Technology* **52**, 4190–4198 (2018).
94. Meng, J. *et al.* The rise of South–South trade and its effect on global CO2 emissions. *Nature Communications* **9**, 1871 (2018).
95. Wiedmann, T. & Lenzen, M. Environmental and social footprints of international trade. *Nature Geoscience* **11**, 314–321 (2018).
96. Wackernagel, M. *et al.* Tracking the ecological overshoot of the human economy. *Proceedings of the National Academy of Sciences* **99**, 9266–9271 (2002).
97. Guinée, J. B. & Heijungs, R. Life Cycle Assessment. in *Kirk-Othmer Encyclopedia of Chemical Technology* doi: 10.1002/0471238961.lifeguin.a01 (Wiley, 2015).
98. Hellweg, S. & Canals, L. M. i. Emerging approaches, challenges and opportunities in life cycle assessment. *Science* **344**, 1109–1113 (2014).
99. Zamagni, A., Guinée, J., Heijungs, R., Masoni, P. & Raggi, A. Lights and shadows in consequential LCA. *International Journal of Life Cycle Assessment* **17**, 904–918 (2012).
100. Earles, J. M. & Halog, A. Consequential life cycle assessment: A review. *International Journal of Life Cycle Assessment* **16**, 445–453 (2011).
101. Pauliuk, S., Arvesen, A., Stadler, K. & Hertwich, E. G. Industrial ecology in integrated assessment models. *Nature Climate Change* **7**, 13–20 (2017).
102. Crutzen, P. J. Geology of mankind. *Nature* **415**, 23–23 (2002).
103. Steffen, W. *et al.* Planetary boundaries: Guiding human development on a changing planet. *Science* **347**, 1259855–1259855 (2015).
104. IPCC. *Climate Change 2013: The Physical Science Basis. Summary for Policymakers*. (Intergovernmental Panel on Climate Change, 2013).
105. Johnson, C. N. *et al.* Biodiversity losses and conservation responses in the Anthropocene. *Science* **356**, 270–275 (2017).
106. Lenton, T. M., Pichler, P.-P. & Weisz, H. Revolutions in energy input and material cycling in Earth history and human history. *Earth System Dynamics* **7**, 353–370 (2016).
107. Shiklomanov, I. A. Appraisal and Assessment of World Water Resources. *Water International* **25**, 11–32 (2000).
108. Krausmann, F. *et al.* Growth in global materials use, GDP and population during the 20th century. *Ecological Economics* **68**, 2696–2705 (2009).
109. Krausmann, F., Lauk, C., Haas, W. & Wiedenhofer, D. From resource extraction to outflows of wastes and emissions: The socioeconomic metabolism of the global economy, 1900-2015. *Global Environmental Change* **52**, 131-140 (2018).
110. Riley, J. C. Estimates of regional and global life expectancy, 1800–2001. *Population and Development Review* **31**, 537–543 (2005).
111. The World Bank. *World Development Indicators*. [available online, last accessed: 8.22.2017]. URL http://data.worldbank.org/data-catalog/world-development-indicators, (2017).
112. Maddison, A. *Maddison Project Database: estimates of economic growth in the world economy between AD 1 and 2010*. (The Maddison Project, 2013).
113. De Stercke, S. *Dynamics of Energy Systems: a Useful Perspective (IIASA Interim Report No. IR-14-013)*. (International Institute for Applied Systems Analysis, 2014).
114. Marland, G., Boden, T. A. & Andres, R. J. *Global, Regional, and National Fossil-Fuel CO2 Emissions*. (Carbon Dioxide Information Analysis Center, Environmental Sciences Division, Oak Ridge National Laboratory, 2016).
115. Schandl, H. *et al.* Global Material Flows and Resource Productivity: Forty Years of Evidence. *Journal of Industrial Ecology* **22**, 827-838 (2017).

116. Ehrlich, P. R. *The population bomb - population control or race to oblivion?* (Sierra Club - Ballantine Books, 1968).
117. York, R., Rosa, E. A. & Dietz, T. STIRPAT, IPAT and ImPACT: analytic tools for unpacking the driving forces of environmental impacts. *Ecological Economics* **46**, 351–365 (2003).
118. Moran, D. D., Wackernagel, M., Kitzes, J. A., Goldfinger, S. H. & Boutaud, A. Measuring sustainable development — Nation by nation. *Ecological Economics* **64**, 470–474 (2008).
119. Steinberger, J. K., Timmons Roberts, J., Peters, G. P. & Baiocchi, G. Pathways of human development and carbon emissions embodied in trade. *Nature Climate Change* **2**, 81–85 (2012).
120. Dietz, T., Rosa, E. A. & York, R. Environmentally efficient well-being: Is there a Kuznets curve? *Applied Geography* **32**, 21–28 (2012).
121. Ayres, R. U. & Warr, B. *The Economic Growth Engine: How Energy And Work Drive Material Prosperity*. (Edward Elgar, 2009).
122. Warr, B. & Ayres, R. U. Useful work and information as drivers of economic growth. *Ecological Economics* **73**, 93–102 (2012).
123. Zhang, C., Chen, W.-Q. & Ruth, M. Measuring material efficiency: A review of the historical evolution of indicators, methodologies and findings. *Resources, Conservation and Recycling* **132**, 79–92 (2018).
124. UNEP. *Decoupling Natural Resource Use And Environmental Impacts From Economic Growth*. (United Nations Environment Programme, 2011).
125. Pothen, F. & Schymura, M. Bigger cakes with fewer ingredients? A comparison of material use of the world economy. *Ecological Economics* **109**, 109–121 (2015).
126. Shao, Q., Schaffartzik, A., Mayer, A. & Krausmann, F. The high 'price' of dematerialization: A dynamic panel data analysis of material use and economic recession. *Journal of Cleaner Production* **167**, 120–132 (2017).
127. Costanza, R. *et al.* Development: Time to leave GDP behind. *Nature* **505**, 283–285 (2014).
128. Bringezu, S. *et al.* Multi-Scale Governance of Sustainable Natural Resource Use—Challenges and Opportunities for Monitoring and Institutional Development at the National and Global Level. *Sustainability* **8**, 778 (2016).
129. Krausmann, F., Fischer-Kowalski, M., Schandl, H. & Eisenmenger, N. The Global Sociometabolic Transition. *Journal of Industrial Ecology* **12**, 637–656 (2008).
130. Steinberger, J. K., Krausmann, F. & Eisenmenger, N. Global patterns of materials use: A socioeconomic and geophysical analysis. *Ecological Economics* **69**, 1148–1158 (2010).
131. Wiedmann, T. O. *et al.* The material footprint of nations. *Proceedings of the National Academy of Sciences* **112**, 6271–6276 (2015).
132. Muradian, R., Walter, M. & Martinez-Alier, J. *Global transformations, social metabolism and the dynamics of socio-environmental conflicts*. (Special Issue of *Global Environmental Change*, **22**, 559-794, 2012).
133. Simas, M., Pauliuk, S., Wood, R., Hertwich, E. G. & Stadler, K. Correlation between production and consumption-based environmental indicators. *Ecological Indicators* **76**, 317–323 (2017).
134. Steinberger, J. K. & Krausmann, F. Material and Energy Productivity. *Environmental Science & Technology* **45**, 1169–1176 (2011).
135. Görg, C. *et al.* Challenges for Social-Ecological Transformations: Contributions from Social and Political Ecology. *Sustainability* **9**, 1045 (2017).
136. O'Neill, D. W., Fanning, A. L., Lamb, W. F. & Steinberger, J. K. A good life for all within planetary boundaries. *Nature Sustainability* **1**, 88–95 (2018).
137. Bringezu, S. Possible Target Corridor for Sustainable Use of Global Material Resources. *Resources* **4**, 25–54 (2015).
138. Ghisellini, P., Cialani, C. & Ulgiati, S. A review on circular economy: the expected transition to a balanced interplay of environmental and economic systems. *Journal of Cleaner Production* **114**, 11–32 (2016).
139. McDowall, W. *et al.* Circular Economy Policies in China and Europe: Circular Economy Policies in China and Europe. *Journal of Industrial Ecology* **21**, 651–661 (2017).
140. Pauliuk, S., Milford, R. L., Müller, D. B. & Allwood, J. M. The Steel Scrap Age. *Environmental Science & Technology* **47**, 3448–3454 (2013).
141. Pauliuk, S. Critical appraisal of the circular economy standard BS 8001:2017 and a dashboard of quantitative system indicators for its implementation in organizations. *Resources, Conservation and Recycling* **129**, 81–92 (2018).
142. Björklund, A. & Finnveden, G. Recycling revisited—life cycle comparisons of global warming impact and total energy use of waste management strategies. *Resources, Conservation and Recycling* **44**, 309–317 (2005).
143. Reck, B. K. & Graedel, T. E. Challenges in Metal Recycling. *Science* **337**, 690–695 (2012).
144. Graedel, T. E., Harper, E. M., Nassar, N. T. & Reck, B. K. On the materials basis of modern society. *Proceedings of the National Academy of Sciences* **112**, 6295–6300 (2015).

145. Ciacci, L., Reck, B. K., Nassar, N. T. & Graedel, T. E. Lost by Design. *Environmental Science & Technology* **49**, 9443–9451 (2015).
146. Wang, P., Li, W. & Kara, S. Dynamic life cycle quantification of metallic elements and their circularity, efficiency, and leakages. *Journal of Cleaner Production* **174**, 1492–1502 (2018).
147. Graedel, T. E. *et al.* What Do We Know About Metal Recycling Rates? *Journal of Industrial Ecology* **15**, 355–366 (2011).
148. Haas, W., Krausmann, F., Wiedenhofer, D. & Heinz, M. How Circular is the Global Economy? An Assessment of Material Flows, Waste Production, and Recycling in the European Union and the World in 2005. *Journal of Industrial Ecology* **19**, 765–777 (2015).
149. Mayer, A., Haas, W. & Wiedenhofer, D. How Countries' Resource Use History Matters for Human Well-being – An Investigation of Global Patterns in Cumulative Material Flows from 1950 to 2010. *Ecological Economics* **134**, 1–10 (2017).
150. Porter, M., Stern, S. & Green, M. *Social Progress Index 2017*. (Social Progress Imperative, 2017).
151. Cao, Z., Shen, L., Løvik, A. N., Müller, D. B. & Liu, G. Elaborating the history of our cementing societies: an in-use stock perspective. *Environmental Science & Technology* **51**, 11468–11475 (2017).
152. Costa, L., Rybski, D. & Kropp, J. P. A Human Development Framework for CO2 Reductions. *PLoS ONE* **6**, e29262 (2011).
153. Lamb, W. F. *et al.* Transitions in pathways of human development and carbon emissions. *Environmental Research Letters* **9**, 014011 (2014).
154. Dearing, J. A. *et al.* Safe and just operating spaces for regional social-ecological systems. *Global Environmental Change* **28**, 227–238 (2014).
155. OECD. *Measuring Material Flows and Resource Productivity. Volume I. The OECD Guide*. (Organisation for Economic Co-Operation and Development, 2008).
156. Liao, W., Heijungs, R. & Huppes, G. Thermodynamic analysis of human–environment systems: A review focused on industrial ecology. *Ecological Modelling* **228**, 76–88 (2012).
157. Liu, G., Bangs, C. E. & Müller, D. B. Stock dynamics and emission pathways of the global aluminium cycle. *Nature Climate Change* **3**, 338–342 (2012).
158. Sandberg, N. H. *et al.* Dynamic building stock modelling: Application to 11 European countries to support the energy efficiency and retrofit ambitions of the EU. *Energy and Buildings* **132**, 26–38 (2016).
159. Hertwich, E. G. & Peters, G. P. Carbon Footprint of Nations: A Global, Trade-Linked Analysis. *Environ. Sci. Technol.* **43**, 6414–6420 (2009).
160. Peters, G. P., Minx, J. C., Weber, C. L. & Edenhofer, O. Growth in emission transfers via international trade from 1990 to 2008. *Proceedings of the National Academy of Sciences* **108**, 8903–8908 (2011).
161. Davis, S. J., Caldeira, K. & Matthews, H. D. Future CO2 Emissions and Climate Change from Existing Energy Infrastructure. *Science* **329**, 1330–1333 (2010).
162. Raupach, M. R. *et al.* Sharing a quota on cumulative carbon emissions. *Nature Climate Change* **4**, 873–879 (2014).
163. Seto, K. C., Golden, J. S., Alberti, M. & Turner, B. L. Sustainability in an urbanizing planet. *Proceedings of the National Academy of Sciences* **114**, 8935–8938 (2017).
164. Bretschger, L. & Smulders, S. Challenges for a sustainable resource use: Uncertainty, trade, and climate policies. *Journal of Environmental Economics and Management* **64**, 279–287 (2012).
165. Laner, D., Rechberger, H. & Astrup, T. Systematic Evaluation of Uncertainty in Material Flow Analysis. *Journal of Industrial Ecology* **18**, 859–870 (2014).
166. Hertwich, E. G. Consumption and the Rebound Effect: An Industrial Ecology Perspective. *Journal of Industrial Ecology* **9**, 85–98 (2005).
167. Ayres, R. U. & Simonis, U. E. *Industrial Metabolism: Restructuring for Sustainable Development*. (United Nations University Press, 1994).
168. Chertow, M., Lifset, R. & Yang, T. Industrial Ecology. *Oxford Bibliographies in Ecology* [online, last accessed 1.1.2019] (DOI: 10.1093/obo/9780199830060-0200, 2018).
169. Erb, K.-H. How a socio-ecological metabolism approach can help to advance our understanding of changes in land-use intensity. *Ecological Economics* **76**, 8–14 (2012).
170. Turner, B. L., Lambin, E. F. & Reenberg, A. The emergence of land change science for global environmental change and sustainability. *Proceedings of the National Academy of Sciences* **104**, 20666–20671 (2007).
171. Allwood, J. M., Ashby, M. F., Gutowski, T. G. & Worrell, E. Material efficiency: A white paper. *Resources, Conservation and Recycling* **55**, 362–381 (2011).
172. Schandl, H. *et al.* Decoupling global environmental pressure and economic growth: Scenarios for energy use, materials use and carbon emissions. *Journal of Cleaner Production* **132**, 45–56 (2016).
173. Duro, J. A., Schaffartzik, A. & Krausmann, F. Metabolic Inequality and Its Impact on Efficient Contraction and Convergence of International Material Resource Use. *Ecological Economics* **145**, 430–440 (2018).

174. Pichler, M., Schaffartzik, A., Haberl, H. & Görg, C. Drivers of society-nature relations in the Anthropocene and their implications for sustainability transformations. *Current Opinion in Environmental Sustainability* **26**–**27**, 32–36 (2017).
175. López, L. A., Arce, G., Morenate, M. & Zafrilla, J. E. How does income redistribution affect households' material footprint? *Journal of Cleaner Production* **153**, 515–527 (2017).
176. Ahmed, N. M. *Failing States, Collapsing Systems. Biophysical Triggers of Political Violence*. (Springer Nature, 2017).
177. Martinez-Alier, J. *The Environmentalism of the Poor. A Study of Ecological Conflicts and Valuation*. (Edward Elgar, 2002).
178. Pérez-Rincón, M., Vargas-Morales, J. & Crespo-Marín, Z. Trends in social metabolism and environmental conflicts in four Andean countries from 1970 to 2013. *Sustainability Science* **13**, 635–648 (2018).
179. Simas, M., Goldsteijn, L., Huijbregts, M. a. J., Wood, R. & Hertwich, E. The "Bad Labor" Footprint: Quantifying the Social Impacts of Globalization. *Sustainability* **6**, 7514–7540 (2014).
180. Simas, M., Wood, R. & Hertwich, E. Labor Embodied in Trade. *Journal of Industrial Ecology* **19**, 343–356 (2015).
181. Giljum, S. & Eisenmenger, N. North-South Trade and the Distribution of Environmental Goods and Burdens: A Biophysical Perspective. *Journal of Environment and Development* **13**, 73–100 (2004).
182. Hornborg, A. & Jorgensen, A. K. *International Trade and Environmental Justice: Toward a Global Political Ecology*. (Nova Science Pub Inc, 2010).
183. Hornborg, A. & Martinez-Alier, J. Ecologically unequal exchange and ecological debt. *Journal of Political Ecology* **23**, 328–333 (2016).
184. Rotmans, J. & Fischer-Kowalski, M. Conceptualizing, observing and influencing socio-ecological transitions. *Ecology and Society* **14**, 3 (2009).
185. Geels, F. W., Schwanen, T., Sorrell, S., Jenkins, K. & Sovacool, B. K. Reducing energy demand through low carbon innovation: A sociotechnical transitions perspective and thirteen research debates. *Energy Research & Social Science* **40**, 23–35 (2018).
186. Haberl, H., Fischer-Kowalski, M., Krausmann, F., Martinez-Alier, J. & Winiwarter, V. A socio-metabolic transition towards sustainability? Challenges for another Great Transformation. *Sustainable Development* **19**, 1–14 (2011).