SPECIAL FEATURE

The material footprint of nations

Thomas O. Wiedmann[a,b,c,1], Heinz Schandl[b,d], Manfred Lenzen[c], Daniel Moran[c,e], Sangwon Suh[f], James West[b], and Keiichiro Kanemoto[c,g]

[a]School of Civil and Environmental Engineering, The University of New South Wales, Sydney, NSW 2052, Australia; [b]Commonwealth Scientific and Industrial Research Organisation (CSIRO) Ecosystem Sciences, Canberra, ACT 2601, Australia; [c]Integrated Sustainability Analysis (ISA), School of Physics A28, The University of Sydney, Sydney, NSW 2006, Australia; [d]Australian National University, School of Sociology, Canberra, ACT 2601, Australia; [e]Programme for Industrial Ecology, Norwegian University of Science and Technology (NTNU), 7013 Trondheim, Norway; [f]Bren School of Environmental Science and Management, University of California, Santa Barbara, CA 93106-5131; and [g]Graduate School of Environmental Studies, Tohoku University, Sendai 980-8579, Japan

Edited by Joan Martínez Alier, Autonomous University of Barcelona, Barcelona, Spain, and accepted by the Editorial Board August 1, 2013 (received for review November 30, 2012)

Metrics on resource productivity currently used by governments suggest that some developed countries have increased the use of natural resources at a slower rate than economic growth (relative decoupling) or have even managed to use fewer resources over time (absolute decoupling). Using the material footprint (MF), a consumption-based indicator of resource use, we find the contrary: Achievements in decoupling in advanced economies are smaller than reported or even nonexistent. We present a time series analysis of the MF of 186 countries and identify material flows associated with global production and consumption networks in unprecedented specificity. By calculating raw material equivalents of international trade, we demonstrate that countries' use of nondomestic resources is, on average, about threefold larger than the physical quantity of traded goods. As wealth grows, countries tend to reduce their domestic portion of materials extraction through international trade, whereas the overall mass of material consumption generally increases. With every 10% increase in gross domestic product, the average national MF increases by 6%. Our findings call into question the sole use of current resource productivity indicators in policy making and suggest the necessity of an additional focus on consumption-based accounting for natural resource use.

raw material consumption | multiregion input–output analysis | sustainable resource management

SUSTAINABILITY SCIENCE

Policy attention on natural resource security is growing worldwide amid the recognition of an increasing dependence on international trade in acquiring raw materials, an emerging scarcity of particular key resources, and rising prices for primary materials (1, 2). To gauge the sustainability of resource use and to support decision making, metrics of economy-wide material flow accounting, such as domestic material consumption (DMC), have been adopted as sustainability indicators by governments and authorities. For example, the European Commission proposes "resource productivity," defined as gross domestic product (GDP) divided by DMC, as the headline indicator of its "resource efficiency roadmap," one of the main building blocks of Europe's resource efficiency flagship initiative as part of the Europe 2020 strategy (1). Eurostat monitors GDP/DMC as one of the headline indicators of the European Union (EU) sustainable development strategy (3), and the Organization for Economic Cooperation and Development (OECD) (4) and the United Nations Environment Program (5) also use GDP/DMC as an indicator of their green growth strategies. [Another indicator suggested in the literature is total resource (or material) productivity, which includes hidden flows and ecological rucksacks, as reported by Bringezu and Bleischwitz (6) and discussed in *SI Text*.] Trends show that resource productivity measured in this way has increased in most European (7) and OECD (8) countries in the past decade, suggesting that a relative, and even absolute in some cases, decoupling of economic growth and resource use has been achieved. However, the scope of DMC is limited to the amount of materials directly used by an economy (raw materials extracted from the domestic territory plus all physical imports minus all physical exports). It does not include the upstream raw materials related to imports and exports originating from outside of the focal economy.

This truncation might mislead assessments of national resource productivity and supply security of natural resources as the increasing spatial separation of production and consumption in global supply chains leads to a shift of resource use and associated environmental pressures among countries. This has been demonstrated well for greenhouse gas emissions (9–11), land use (12, 13), water use (14–17), and threats to species (18). The "carbon footprint" indicator has especially been used to quantify and monitor carbon leakage among countries (19). Although the direct and indirect flow of materials across nations has been studied well (20–27), a consumption-based material flow indicator equivalent to the carbon footprint has only recently been investigated more closely using the notion of raw material consumption (RMC) (28–35).

Because of its analogy to other footprint indicators (14, 17, 36), we suggest using the term "material footprint" (MF) for this indicator and define it as the global allocation of used raw material extraction to the final demand of an economy. In contrast to indicators of standard economy-wide material flow accounting, which are based on apparent physical consumption (35, 37–39), the MF does not record the actual physical movement of materials within and among countries but, instead, enumerates the link between the beginning of a production chain (where raw materials are extracted from the natural environment) and its end (where a product or service is consumed). (For a discussion of different approaches to international material flow accounting,

Significance

This original research paper addresses a key issue in sustainability science: How many and which natural resources are needed to sustain modern economies? Simple as it may seem, this question is far from trivial to answer and has indeed not been addressed satisfactorily in the scholarly literature. We use the most comprehensive and most highly resolved economic input–output framework of the world economy together with a detailed database of global material flows to calculate the full material requirements of all countries covering a period of two decades. Called the "material footprint," this indicator provides a consumption perspective of resource use and new insights into the actual resource productivity of nations.

Author contributions: T.O.W., H.S., and M.L. designed research; D.M. and K.K. performed research; T.O.W., M.L., D.M., and J.W. analyzed data; and T.O.W., H.S., M.L., and S.S. wrote the paper.

The authors declare no conflict of interest.

This article is a PNAS Direct Submission. J.M.A. is a guest editor invited by the Editorial Board.

[1]To whom correspondence should be addressed. E-mail: t.wiedmann@unsw.edu.au.

This article contains supporting information online at www.pnas.org/lookup/suppl/doi:10.1073/pnas.1220362110/-/DCSupplemental.

the reader is referred to *SI Text*.) This link may span multiple countries and economic sectors.

In this empirical study, we demonstrate the additional insights to be gained by using the MF as a basis for assessing resource productivity. Countries depend increasingly on international trade for acquiring their natural resource base; global physical trade in materials has increased by a factor of 2.5 over the past 30 y (20, 21). With this research, we show that the real dependence on nondomestic resources far exceeds the actual physical quantity of traded goods. Using the MF as a measuring rod results in reduced resource productivity for import-dependent countries. It opens up a new perspective on global material supply chains and on the shared responsibility for impacts of extraction, processing, and consumption of environmental resources.

We calculated the raw material equivalents (RMEs) of economic trade flows between 186 countries by linking national material flow accounts with a global multiregion input–output (MRIO) model. Adding the RME of imports to the domestic extraction (DE) of the raw material of a country and subtracting the RME of exports results in the country's MF. Establishing the trade balance in this way is characteristic of the consumption perspective adopted by any footprint indicator (10, 17).

Improving on previous studies (28–34), this work presents the MF for most countries in the world as annual time series for two decades. We also used a substantially more comprehensive and detailed MRIO account (40) than any previously available, thus mapping material flows in the structure of the world economy with unprecedented specificity. With all-but-complete country coverage and no gaps in the time series, our calculation framework avoids the use of surrogate data and interpolation used in previous studies and improves the representation of trade flows among individual countries, making the analysis more robust and reliable.

To understand driving forces of national MFs, we compare the results of a number of key countries and carry out a multivariate regression analysis. We essentially redefine resource productivity based on the MF and compare it with the conventional indicator based on DMC to assess the veracity of resource productivity indicators currently used to inform policies for sustainable resource and materials management. Viewed from a consumption perspective, the meaning of resource productivity thus changes to one that truly captures all upstream material movements along global supply chains.

1. Results

1.1. MF of Nations and International Trade in 2008. The total global MF, which is equal to the total used DE of raw materials, amounted to 70 billion metric tons (Gt) in 2008. Forty-one percent of this amount (29 Gt) was indirectly associated with trade flows between the 186 countries studied in this research. [These numbers do not include unused extraction of raw materials, as incorporated in the total material requirement (TMR) and total material consumption (TMC) indicators (35, 39, 41). When adding unused extraction, the total indirect material flow of traded goods was estimated at 41 Gt in 2005 (27).] For comparison, 26% of global CO_2 emissions (42), 30% of the world's threatened species (18), and 32% of the world's scarce water consumption (16) can be linked to internationally traded commodities.

In other words, two-fifths of all global raw materials were extracted and used just to enable exports of goods and services to other countries. This is far more than the 10 Gt of direct physical trade of materials and products (20, 21), reflecting the fact that the physical flow of traded commodities is less than the tonnages of raw materials required to produce the export commodities. The consumption-based MF includes raw material extractions in the trade balance even if some of the materials never actually leave the country of origin (particularly process wastes and auxiliary material flows).

Results for 12 selected countries at different stages of their socioeconomic development and with broad geographical coverage are presented in Fig. 1. MF results for 2008 for all countries studied are presented in *SI Text* and Dataset S1.

In 2008, the Chinese economy had by far the largest MF in absolute values (16.3 Gt), twofold as large as that of the United States and fourfold that of Japan and India. Sixty percent of China's MF consists of construction materials, testament of the fast industrial transformation and urbanization China has undergone over the past two decades. China also has by far the largest amount of raw materials associated with exports (7.3 Gt). Again, the majority of this (5.2 Gt) is construction materials, meaning that a substantial part of the country's infrastructure (more than one-third of the DE of this material group) is related to consumption in other countries.

Although Australia has the highest per-capita MF [MF/cap; 35 tons per capita (t/cap)], other developed economies show similar levels at around 25 t/cap (e.g., United States, Japan, United Kingdom, Chile). A lower material standard of living and a lower average level of consumption in many developing countries are

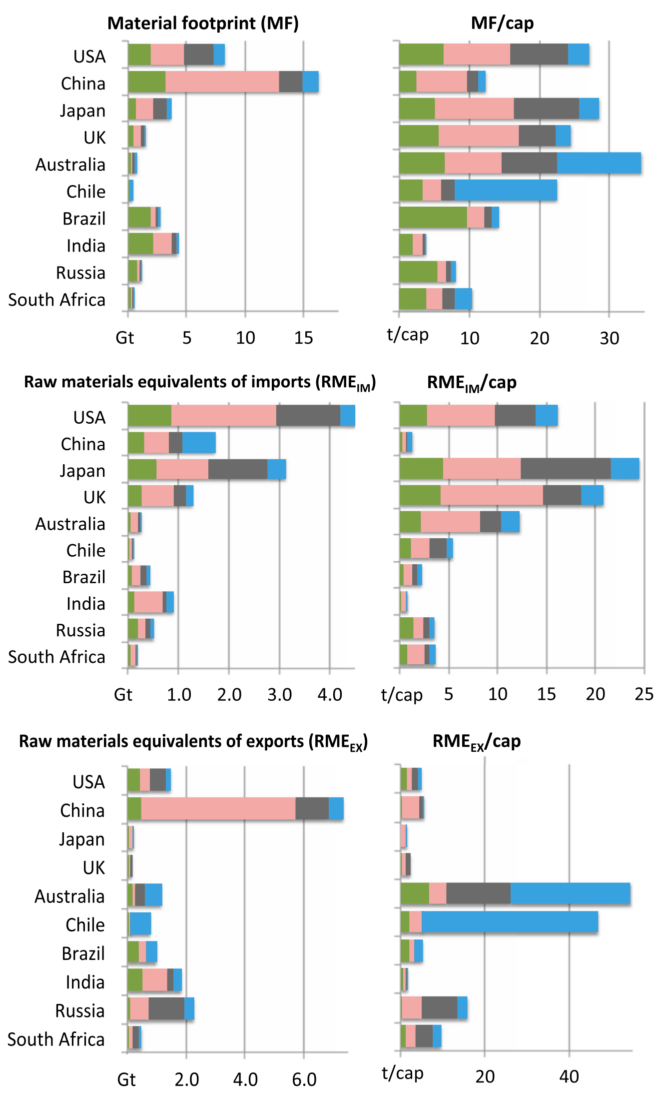

Fig. 1. MF of national final demand and RMEs of imports (RME_{IM}) and exports (RME_{EX}) of selected countries in 2008 (totals and per capita).

reflected in a footprint below 15 t/cap, with India at the lower end of 3.7 t/cap.

In absolute values, the United States is by far the largest importer of primary resources embodied in trade and China is the largest exporter of primary resources embodied in trade. Per-capita RMEs of imports is largest for developed nations and is smallest (although growing) for China and India. The largest per-capita exporters of embodied primary materials, particularly metal ores, are Australia and Chile.

A comparison of indicators over time (Fig. 2) shows that as economies mature, their MF/cap becomes considerably larger than their DMC/cap, with the United Kingdom and Japan at the extreme end of the spectrum due to their postindustrial economic structure and their dependence on imports for final consumption. For Brazil, India, and China, the MF/cap levels are very similar to those of the DMC/cap, but large resource exporters, such as Australia, Russia, or South Africa, show a DMC/cap much larger than their MF/cap. The DMC/cap has declined in Japan and the United Kingdom, but the MF/cap has increased markedly.

The difference between DMC and the MF can be explained by the fact that traded goods require much more material than what is physically incorporated in them. Wealthier countries' imports of finished and semifinished products are linked to a larger amount of raw materials compared with the physical quantity traded. This also applies to metals, which are traded in the form of concentrates rather than ores (34 and ref. 43, p. 357). Nonexported mine tailings are included in DMC of the exporting country, whereas the MF allocates them to the importing (final demand) countries. DMC will therefore overestimate consumption for exporters of metals and biomass and underestimate it for importers of metals and biomass.

Growing specialization, with some countries increasingly supplying primary resources for industrial development in other countries (44), means the burden of raw material extraction is shifting (20, 27). The DMC indicator shifts with it, as reflected in increasing DMC values for exporting countries and decreasing values for importing, mostly developed, countries. The MF indicator, on the other hand, reallocates the burden back to the ultimate point of consumption, and is therefore less affected by specialization trends.

1.2. Reassessing Resource Productivity. Decoupling the use of natural resources (and associated environmental impacts from economic growth) is the main goal of achieving sustainable development and "green economies" (5). Over the past century, global average resource intensity (DMC/GDP) is reported to have almost continuously decreased from 3.6 kg/dollar in 1900 to 1.3 kg/dollar in 2005 (7, 22–26, 35, 45–50). According to the OECD (8), G8 countries halved their resource intensity between 1980 and 2008, and Canada, Germany, Italy, and Japan have succeeded in decoupling DMC from economic growth in absolute terms.

How do these reported trends compare with trajectories measured on an MF basis (GDP/MF)? We plotted relative changes in the MF, DMC, and GDP [expressed in purchasing power parity (PPP) at 2005 constant prices] between 1990 and 2008 for the 10 selected countries (Fig. 3). We added the EU-27 and OECD as regions where official resource productivity data based on DMC have been published (7, 8). Relative changes in resource productivity can be derived from Fig. 3: Increasing resource productivity and decoupling are indicated by material indicator lines running below the blue line (GDP-PPP-2005) (i.e., when the MF or DMC has grown slower than the GDP).

Again, the process of externalization of resource-intensive processes of mature economies becomes apparent. The EU-27, the OECD, the United States, Japan, and the United Kingdom have grown economically while keeping DMC at bay or even reducing it, leading to large apparent gains in GDP/DMC resource productivity. In all cases, however, the MF has kept pace with increases in GDP and no improvements in resource productivity at all are observed when measured as the GDP/MF. This means that no decoupling has taken place over the past two decades for this group of developed countries. The main reason in most cases was increased indirect use of (dependency on) construction materials (Fig. 1).

The fast-growing economies of China and India achieved a relative decoupling on both accounts (DMC and MF), whereas the resource-exporting nations of Chile, Brazil, and Russia had a decline in resource productivity observed with both metrics. The most remarkable case is South Africa, where both DMC and the MF have decreased in absolute terms (i.e., both indicators testify absolute decoupling and a large increase in resource productivity).

1.3. What Drives the MF of Nations? Using regression or structural decomposition techniques, a number of studies have identified affluence, along with other factors, as a key driver for consumption-based indicators, such as land (13), carbon (10, 51), energy (52), ecological footprints(53), and water footprints (54), as well as resource use (47, 55).

Weinzettel et al. (13), for example, show that the global displacement of land use, expressed as the import component of per-capita national land use footprints, is strongly correlated (in fact, exactly proportional) to per-capita national income. The influence of variables other than the GDP on material productivity was investigated by Steger and Bleischwitz (25).

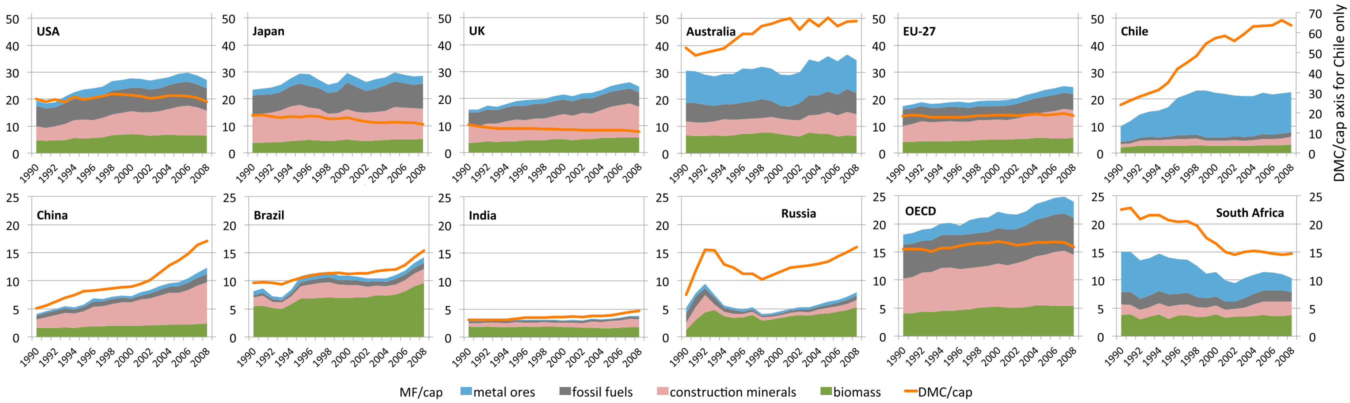

Fig. 2. MF/cap (by four categories) and DMC/cap (total) of selected countries and regions in 1990–2008 (different scales for upper and lower rows, with the DMC/cap scale different for Chile only).

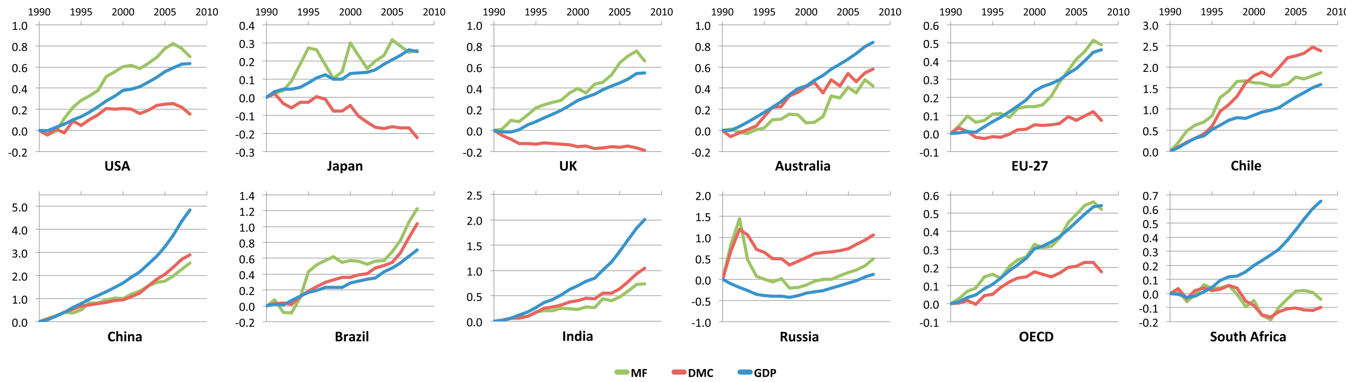

Fig. 3. Relative changes in total resource use (MF and DMC) and GDP-PPP-2005 between 1990 and 2008 [values are plotted as $\Delta X = (X_{t2} - X_{t1})/X_{t1}$; $t_1 = 1990$].

We carried out a cross-country, multivariate regression analysis for the year 2008 to test how changes in MF and DMC indicators can be explained by changes in three independent explanatory variables that potentially influence the consumption of materials. These three variables were as follows (details are provided in *SI Text*):

i) GDP-PPP-2005/cap as a proxy for the wealth (individual income) of nations.

ii) DE/cap as a measure for the actual production of raw materials. DE is related (although not equivalent) to the availability of natural resources and the ability for raw material production. The main reason for choosing this variable was to test the hypothesis that DMC is more strongly influenced by DE than by the MF.

iii) Population density (population per area) as a proxy for the need to import materials from abroad, with the reasoning being that the ability to produce land-based raw materials (crops, fodder, and wood, as well as open-cast mining of minerals to some extent) might be dependent on the availability of unpopulated land (22).

Elasticities α, β, and γ for explanatory variables were calculated as the regression coefficients of the relationship $F = k \cdot A^{\alpha} \cdot B^{\beta} \cdot C^{\gamma}$, with F being the MF/cap or DMC/cap and k being a constant. The elasticities represent the relative change in per-capita resource use corresponding to a relative change in the explanatory variable (details are provided in *SI Text*). To gain additional insight into the use of biomass, we chose to break down this component into two main subcategories [crops for human consumption (category A.1.1) and fodder crops, crop residues, and grazed biomass (A.1.2)]. The third subcategory of wood (A.1.3) was omitted in this analysis due to its relatively small size.

Table 1 shows that variations in the total MF/cap are mostly explained by variations in the GDP/cap; for a 10% increase in wealth, the MF would increase by 6% ($\alpha = 0.60$). Changes in the DMC/cap, on the other hand, are mostly explained by variations in the DE/cap ($\beta = 0.75$) and, to a much lesser extent, by variations in the GDP/cap ($\alpha = 0.15$).

This result broadly confirms that products subsequently manufactured out of raw materials are traded with their material embodiment "in tow," thus adding to the MF of consuming (importing) countries but not to their DMC. This holds especially for traded animal and dairy products, which embody a large amount of upstream biomass (56). The trade in such biomass embodiments is an order of magnitude higher than the trade in biomass itself, clearly showing that whereas DMC attributes the grazed biomass and fodder crops to the country where the animal was raised, the MF attributes these inputs to the country where meat or dairy products are consumed. Similarly, the ability of rich countries to buy products is indirectly dependent on construction materials from abroad; the construction component of the MF/cap is clearly explained by the GDP/cap ($\alpha = 0.86$) and not at all by the DE/cap ($\beta = 0.01$). The DMC/cap of construction materials, on the other hand, is mainly explained by the DE/cap ($\beta = 0.80$).

Interestingly, the use of metal ores and fossil fuels is well explained by the GDP/cap in both indicators ($\alpha \geq 0.9$). The elasticities for fossil fuels are even higher than found in other studies [e.g., Lenzen et al. (52) found an elasticity of 0.9 for the dependence of embodied energy on the GDP]. This confirms the very strong link found previously (24) between growth in building materials, ores, and fossil fuels use and economic growth in most of developing Asia, most notably in China.

Population density seems to have a lesser and mixed influence on resource use indicators. Negative elasticities for metal ores ($\gamma = -0.16$ for the MF and -0.20 for DMC) suggest that more densely populated areas require fewer materials in this category, possibly through the more efficient use of products. Steger and Bleischwitz (25) also report mixed findings with a univariate regression analysis showing a negative influence of population density on DMC material intensity and a multivariate analysis showing the opposite.

What do these findings mean for resource productivity? Expressing the regression coefficients of resource productivity with income as $1 - \alpha$ (*SI Text*), we find that total resource productivity increases less with income when measured on a GDP/MF basis ($1 - \alpha = 0.40$) compared with a GDP/DMC basis ($1 - \alpha = 0.85$). Mostly responsible for this difference are the biomass and construction material components. It is thought that high-income countries can achieve higher resource productivity because their GDP is relatively more decoupled from biomass consumption than from other materials (23, 46), and possibly because demand for construction materials may reach a certain level of saturation [the case of steel is reported in ref. (57)]. However, the MF does not attest to such decoupling. As nations become richer, the change in their socioeconomic metabolism (from agricultural to industrial production) helps less to improve resource productivity than previously thought. In an additional regression analysis of country ensembles with varying GDP/cap averages (presented in *SI Text*), we show that the elasticity of the MF of fodder particularly increases with an increase in wealth, highlighting the role of meat-based diets in richer societies. Our findings confirm a previous analysis of drivers of global land use that also provided "...strong support for the hypothesis that biomass use increases with affluence" (ref. 13, p. 436).

2. Discussion

Humanity is using natural resources at a level never seen before. The total amount of 70 billion t of raw material extraction is

Table 1. Elasticities and adjusted regression coefficients for a multivariate regression of five material categories for the MF and DMC as explained variables and GDP-PPP-2005/cap, DE/cap of the same material category, and population density as explanatory variables (137 countries, year 2008)

	Explained variables (EW-MFA material categories)											
	MF total	MF crops	MF fodder	MF ores	MF construction materials	MF fossil fuels	DMC total	DMC crops	DMC fodder	DMC ores	DMC construction materials	DMC fossil fuels
Explanatory variables	(A.1–4)	(A.1.1)	(A.1.2)	(A.2)	(A.3)	(A.4)	(A.1–4)	(A.1.1)	(A.1.2)	(A.2)	(A.3)	(A.4)
i) GDP/cap (elasticity, α)	0.60***	0.57***	0.46***	0.90***	0.86***	1.23***	0.15***	0.17***	0.04	0.99***	0.45***	1.7***
ii) DE_i/cap* (elasticity, β)	0.30***	0.25***	0.11*	0.02**	0.01	−0.01	0.75***	0.60***	0.95***	0.25***	0.80***	0.55***
iii) PopDens (elasticity, γ)	0.03	0.07*	−0.05	−0.16**	0.09*	−0.02	0.05***	0.06**	0.01	−0.20	0.17	0.11
Log (*k*)	0.13	−0.63***	−0.13	−0.47***	−0.35***	−1.03***	0.03	−0.2***	−0.06	−0.48	−0.60**	−1.55*
Adjusted $R^{2\dagger}$	0.74	0.65	0.46	0.62	0.71	0.77	0.88	0.65	0.79	0.37	0.84	0.61

EW-MFA, economy-wide material flow accounting classification; PopDens, population density. Significance: ***>99% level of confidence; **95–99%; *90–95%; no asterisk, <90%.

*Subindex *i* in DE_i refers to the part of the MF and DMC that is being explained (e.g., MF crops is explained by DE crops).

†Adjusted R^2 values take into account the number of explanatory variables.

unprecedented, and per-capita levels of resource consumption are at their highest level in history (10.5 t/cap in 2008). These numbers are predicted to rise unless stringent reduction targets and policies are put in place (5, 6, 21, 58). Few countries would be able to satisfy their material needs with domestic resources, and the current level of national material consumption has only been made possible through a record increase in international trade. Our results show that 41% (29 Gt) of total global resource extraction was associated with international trade flows in 2008. Only one-third of these materials actually crossed national borders, but all enabled consumption in countries other than the extracting countries. With respect to environmental impacts associated with resource extraction, however, it is the net-exporting countries that are at the receiving end.

On the one hand, there is the actual process of extracting resources from the natural environment and subsequent processing and transporting. Many environmental impacts, such as water resource depletion; soil erosion; biodiversity loss; or pollution through agrochemicals, mine tailings, or oil spillages, occur at these stages. On the other hand, consumption has been a driving force, resulting from a general increase in economic growth and prosperity for most of the time since World War II. The MF of nations reflects the increasing complexity and multicountry nature of global supply chains and is the appropriate indicator if the aim is to pinpoint the ultimate consumer responsibility of a country for impacts associated with raw material extractions worldwide. In contrast to DMC, the MF allocates higher upstream material extractions to the ultimate receiving country, and therefore establishes a direct connection between production (extraction) and consumption.

The MF can be seen as a "mirror indicator" of DE, which reflects producer responsibility for impacts related to material extraction. DMC can be regarded as an "intermediate" indicator that correlates well with actual physical trade flows but also often returns values closer to DE than to the MF and tends to be relatively higher if resource extracting and processing activities are strong.

The measure of resource productivity based on DMC alone does not reveal the true extent of resource dependence and burden shifting and can limit decision making. Our analysis does not support the observation of resource productivity increases in developed countries over the past decades (7, 8, 59). A less steep increase in the GDP/MF with income (compared with GDP/DMC) demonstrates that countries might find it more difficult than previously thought to increase resource productivity as their economies mature. Even absolute decoupling measured by DMC, at the individual country level, may not indicate that resource use is actually decreasing with increasing income. It may just indicate that more material extraction has been off-shored. Developed nations experience an increase in imports of semifinished and finished products and a change in economic structure toward service economies, which add high value to the GDP. These trends make developed countries look more resource-efficient, but they actually remain deeply anchored to a material foundation underneath.

Shortcomings of GDP/DMC have been acknowledged in the *Roadmap to a Resource Efficient Europe* (1), and as stated in ref. 34 (p. 8904), "…Eurostat plans to supplement or replace the DMC indicator by publishing the RMC [MF] indicator on a regular basis." The OECD's recent report on *Resource Productivity in the G8 and the OECD* acknowledges that "…further progress can only be achieved through more integrated policy approaches that take account of the full life-cycle of materials..." (ref. 8, p. 5).

This underpins the need for sustainable resource and materials policies to be informed by consumption-based indicators such as the MF, in addition to accurate data on resource extraction and physical trade. The MF is particularly suited to pinpointing the driving force behind global resource use and consumption as well as to initiate and facilitate political discourse aimed at reducing associated environmental impacts (6, 59).

Importantly, our research confirms that pressure on natural resources does not relent as most of the human population becomes wealthier. Rather than a mere decline in intensities of use and impact (60), true dematerialization has to mean an absolute decoupling of impacts if a growing world population is to make ends meet on a finite planet. The MF indicates that this goal might be harder to achieve than previously thought as global affluence grows.

3. Materials and Methods

We calculated the MF of nations by multiplying the final demand of a country for goods and services with multipliers representing all upstream global material requirements associated with one unit (dollar) of product. These multipliers were derived from environmentally extended global input–output analysis following Leontief's standard input–output calculus (61). The high-resolution global MRIO database used in this work, Eora, contains domestic and international monetary transactions between 14,787 industry sectors across 186 countries (40). To this database, we added physical unit data on the DE of raw materials from a global reference database of material flows. Using a binary concordance matrix, we attributed 35 material subcategories to matching product categories at a four-digit level in the OECD Harmonized System, which, in turn, has been used to establish concordances among industry sectors in each country. To be consistent across our analyses, we used GDP-PPP in a constant international unit (dollar) for the year 2005 (denoted as "GDP-PPP-2005") both for comparing among countries and over time. Details and limitations of the methodology, as well as MF results for 2008, are provided in *SI Text*.

ACKNOWLEDGMENTS. We thank David Fleming, Karin Hosking, and Art Langston for technical help. D.M., M.L., and K.K. thank Sebastian Juraszek, Charlotte Jarabak, and Leonardo Souza for support. Thomas Dunne and three anonymous reviewers provided very helpful comments. T.O.W., H.S., and J.W. acknowledge financial support from the Commonwealth Scientific and Industrial Research Organisation's Climate Adaptation Flagship and Integrated Carbon Pathways Initiative and the United Nations Environment Program (UNEP). D.M., M.L., and K.K. acknowledge financial support from the Australian Research Council through Discovery Projects DP0985522 and DP130101293.

1. European Commission (2011) *Roadmap to a Resource Efficient Europe. COM(2011)571 Final* (European Commission, Brussels).
2. National Research Council (2008) *Minerals, Critical Minerals, and the U.S. Economy* (National Academy Press, Washington, DC).
3. Eurostat (2012) *Sustainable Development Indicators* (Statistical Office of the European Communities, Luxembourg).
4. OECD (2011) *Towards Green Growth: Monitoring Progress (OECD Indicators)* (Organisation for Economic Co-operation and Development, Paris).
5. UNEP (2011) *Decoupling Natural Resource Use and Environmental Impacts from Economic Growth* (United Nations Environment Programme, Nairobi).
6. Bringezu S, Bleischwitz R (2009) *Sustainable Resource Management—Global Trends, Visions and Policies* (Greenleaf Publishing, Sheffield, U.K).
7. Eurostat (2012) *Eurostat Material Flow Accounts Dataset: Resource Productivity.* (Statistical Office of the European Communities, Luxembourg).
8. OECD (2011) *Resource Productivity in the G8 and the OECD—A Report in the Framework of the Kobe 3R Action Plan* (Organisation for Economic Co-operation and Development, Paris).
9. Davis SJ, Caldeira K (2010) Consumption-based accounting of CO_2 emissions. *Proc Natl Acad Sci USA* 107(12):5687–5692.
10. Hertwich EG, Peters GP (2009) Carbon footprint of nations: A global, trade-linked analysis. *Environ Sci Technol* 43(16):6414–6420.
11. Wiedmann T, et al. (2010) A carbon footprint time series of the UK: Results from a multiregion input-output model. *Economic Systems Research* 22(1):19–42.
12. Yu Y, Feng K, Hubacek K (2013) Tele-connecting local consumption to global land use. *Global Environ Change*, 10.1016/j.gloenvcha.2013.04.006.
13. Weinzettel J, Hertwich EG, Peters GP, Steen-Olsen K, Galli A (2013) Affluence drives the global displacement of land use. *Glob Environ Change* 23(2):433–438.
14. Steen-Olsen K, Weinzettel J, Cranston G, Ercin AE, Hertwich EG (2012) Carbon, land, and water footprint accounts for the European Union: Consumption, production, and displacements through international trade. *Environ Sci Technol* 46(20):10883–10891.
15. Feng K, Chapagain A, Suh S, Pfister S, Hubacek K (2011) Comparison of bottom-up and top-down approaches to calculating the water footprints of nations. *Econ Syst Res* 23(4):371–385.
16. Lenzen M, et al. (2013) International trade of scarce water. *Ecol Econ* 94:78–85.
17. Galli A, et al. (2012) Integrating ecological, carbon and water footprint into a "footprint family" of indicators: Definition and role in tracking human pressure on the planet. *Ecol Indic* 16:100–112.
18. Lenzen M, et al. (2012) International trade drives biodiversity threats in developing nations. *Nature* 486(7401):109–112.
19. Peters GP (2010) Policy update: Managing carbon leakage. *Carbon Management* 1(1): 35–37.
20. Dittrich M, Bringezu S (2010) The physical dimension of international trade, part 1: Direct global flows between 1962 and 2005. *Ecol Econ* 69(9):1838–1847.
21. Dittrich M, Giljum S, Lutter S, Polzin C (2012) *Green Economies Around the World? Implications of Resource Use for Development and the Environment.* (Sustainable Europe Research Institute, Vienna).
22. Krausmann F, Fischer-Kowalski M, Schandl H, Eisenmenger N (2008) The global sociometabolic transition. *J Ind Ecol* 12(5-6):637–656.
23. Krausmann F, et al. (2009) Growth in global materials use, GDP and population during the 20th century. *Ecol Econ* 68(10):2696–2705.
24. Schandl H, West J (2010) Resource use and resource efficiency in the Asia-Pacific region. *Glob Environ Change* 20(4):636–647.
25. Steger S, Bleischwitz R (2011) Drivers for the use of materials across countries. *J Clean Prod* 19(8):816–826.
26. Steinberger JK, Krausmann F, Eisenmenger N (2010) Global patterns of materials use: A socioeconomic and geophysical analysis. *Ecol Econ* 69(5):1148–1158.
27. Dittrich M, Bringezu S, Schütz H (2012) The physical dimension of international trade, part 2: Indirect global resource flows between 1962 and 2005. *Ecol Econ* 79:32–43.
28. Muñoz P, Giljum S, Roca J (2009) The raw material equivalents of international trade. *J Ind Ecol* 13(6):881–897.
29. Weinzettel J, Kovanda J (2009) Assessing socioeconomic metabolism through hybrid life cycle assessment—The case of the Czech Republic. *J Ind Ecol* 13(4):607–621.
30. Weinzettel J, Kovanda J (2011) Structural decomposition analysis of raw material consumption—The case of the Czech Republic. *J Ind Ecol* 15(6):893–907.
31. Bruckner M, Giljum S, Lutz C, Wiebe KS (2012) Materials embodied in international trade—Global material extraction and consumption between 1995 and 2005. *Glob Environ Change* 22(3):568–576.
32. Wiebe KS, Bruckner M, Giljum S, Lutz C, Polzin C (2012) Carbon and materials embodied in the international trade of emerging economies. *J Ind Ecol* 16(4):636–646.
33. Kovanda J, Weinzettel J (2013) The importance of raw material equivalents in economy-wide material flow accounting and its policy dimension. *Environ Sci Policy* 29:71–80.
34. Schoer K, Weinzettel J, Kovanda J, Giegrich J, Lauwigi C (2012) Raw material consumption of the European Union—Concept, calculation method, and results. *Environ Sci Technol* 46(16):8903–8909.
35. Kovanda J, van de Sand I, Schütz H, Bringezu S (2012) Economy-wide material flow indicators: Overall framework, purposes and uses and comparison of material use and resource intensity of the Czech Republic, Germany and the EU-15. *Ecol Indic* 17:88–98.
36. Moran DD, Lenzen M, Kanemoto K, Geschke A (2013) Does ecologically unequal exchange occur? *Ecol Econ* 89:177–186.
37. Eurostat (2001) *Economy-Wide Material Flow Accounts and Derived Indicators. A Methodological Guide* (Statistical Office of the European Communities, Luxembourg).
38. Eurostat (2011) *Economy-Wide Material Flow Accounts (EW-MFA): Compilation Guidelines for Eurostat's 2011 EW-MFA Questionnaire* (Statistical Office of the European Communities, Luxembourg).
39. Fischer-Kowalski M, et al. (2011) Methodology and indicators of economy-wide material flow accounting. *J Ind Ecol* 15(6):855–876.
40. Lenzen M, Kanemoto K, Moran D, Geschke A (2012) Mapping the structure of the world economy. *Environ Sci Technol* 46(15):8374–8381.
41. Bringezu S, Schütz H, Steger S, Baudisch J (2004) International comparison of resource use and its relation to economic growth. *Ecol Econ* 51(1-2):97–124.
42. Peters GP, Minx JC, Weber CL, Edenhofer O (2011) Growth in emission transfers via international trade from 1990 to 2008. *Proc Natl Acad Sci USA* 108(21):8903–8908.
43. Schandl H, West J (2012) Material flows and material productivity in China, Australia, and Japan. *J Ind Ecol* 16(3):352–364.
44. Muradian R, Walter M, Martinez-Alier J (2012) Hegemonic transitions and global shifts in social metabolism: Implications for resource-rich countries. Introduction to the special section. *Glob Environ Change* 22(3):559–567.
45. Gierlinger S, Krausmann F (2012) The physical economy of the United States of America. *J Ind Ecol* 16(3):365–377.
46. Steinberger JK, Krausmann F (2011) Material and energy productivity. *Environ Sci Technol* 45(4):1169–1176.
47. Schandl H, Turner GM (2009) The dematerialization potential of the Australian economy. *J Ind Ecol* 13(6):863–880.
48. Hashimoto S, et al. (2008) What factors have changed Japanese resource productivity? *J Ind Ecol* 12(5-6):657–668.
49. Kovanda J, Hak T (2008) Changes in materials use in transition economies. *J Ind Ecol* 12(5-6):721–738.
50. Weisz H, Schandl H (2008) Materials use across world regions—Inevitable pasts and possible futures. *J Ind Ecol* 12(5-6):629–636.
51. Wood R (2009) Structural decomposition analysis of Australia's greenhouse gas emissions. *Energy Policy* 37(11):4943–4948.
52. Lenzen M, et al. (2006) A comparative multivariate analysis of household energy requirements in Australia, Brazil, Denmark, India and Japan. *Energy* 31(2-3):181–207.
53. Wiedmann T, Minx J, Barrett J, Wackernagel M (2006) Allocating ecological footprints to final consumption categories with input-output analysis. *Ecol Econ* 56(1):28–48.
54. Lenzen M, Foran B (2001) An input–output analysis of Australian water usage. *Water Policy* 3:321–340.
55. Wood R, Lenzen M, Foran B (2009) A material history of Australia—Evolution of material intensity and drivers of change. *J Ind Ecol* 13(6):847–862.
56. Krausmann F, Erb K-H, Gingrich S, Lauk C, Haberl H (2008) Global patterns of socioeconomic biomass flows in the year 2000: A comprehensive assessment of supply, consumption and constraints. *Ecol Econ* 65(3):471–487.
57. Müller DB, Wang T, Duval B (2011) Patterns of iron use in societal evolution. *Environ Sci Technol* 45(1):182–188.
58. Giljum S, Behrens A, Hinterberger F, Lutz C, Meyer B (2008) Modelling scenarios towards a sustainable use of natural resources in Europe. *Environ Sci Policy* 11(3):204–216.
59. Bleischwitz R (2010) International economics of resource productivity—Relevance, measurement, empirical trends, innovation, resource policies. *Int Econ Econ Policy* 7(2-3):227–244.
60. Ausubel JH, Waggoner PE (2008) Dematerialization: Variety, caution, and persistence. *Proc Natl Acad Sci USA* 105(35):12774–12779.
61. Leontief W (1970) Environmental repercussions and the economic structure: An input-output approach. *Rev Econ Stat* 52(3):262–271.