The material footprint of nations

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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

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.

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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

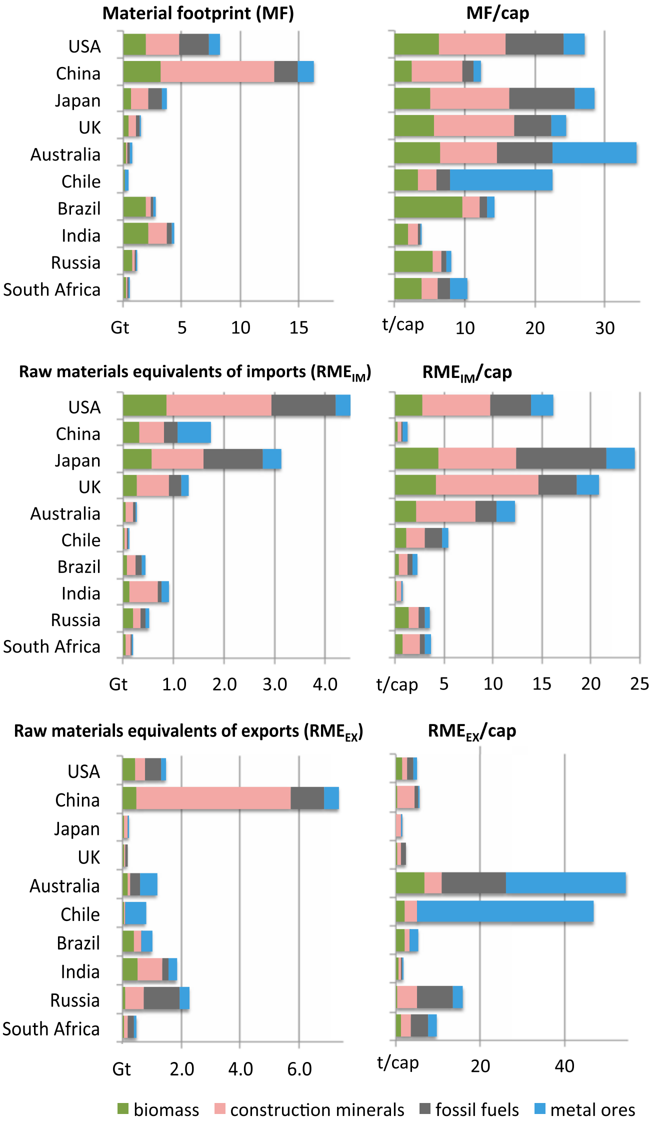

Fig. 1. MF of national final demand and RMEs of imports (RME_{IM}) and exports (RME_{EX}) of selected countries in 2008 (totals and per capita).

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).

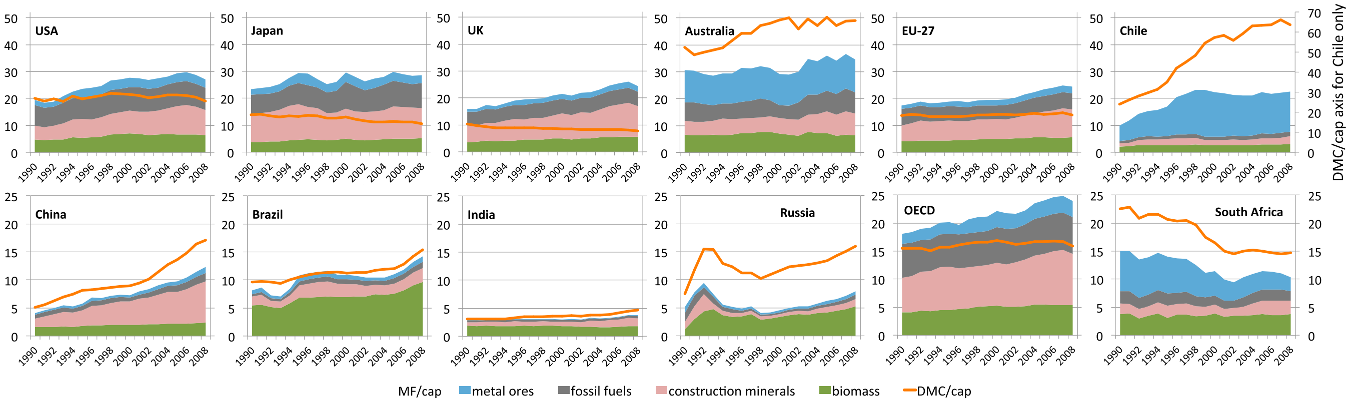

Fig. 2. MF/cap (by four categories) and DMC/cap (total) of selected countries and regions in 1990–2008 (different scales for upper and lower rows, with the DMC/cap scale different for Chile only).

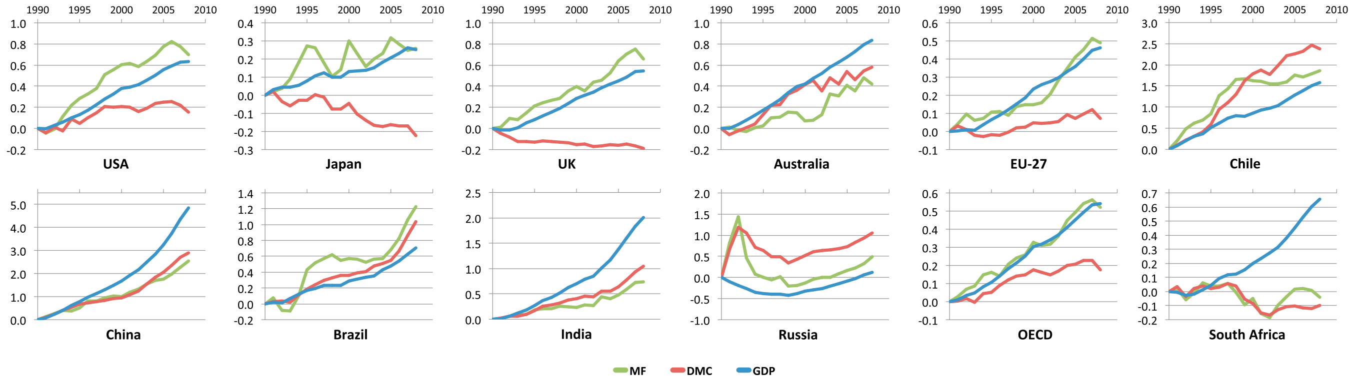

Fig. 3. Relative changes in total resource use (MF and DMC) and GDP-PPP-2005 between 1990 and 2008 [values are plotted as $\Delta X = (X_{t2} - X_{t1})/X_{t1}$; $t_1 = 1990$].

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*.

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Supporting Information

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SI Text

S1. Additional Results and Analysis

Detailed results for 2008 are available in spreadsheet format in Dataset S1. Results from the Eora model are also accessible via www.worldmrio.com. The following figures provide additional visualization of results and context to the analysis presented in the main text. The 2008 per-capita material footprint (MF) of nations is shown on a world map (Fig. S1) and by main material category (Fig. S2). The world average MF in 2008 was 10.5 tons per capita.

The "flows" of raw materials within and among nations are depicted in Fig. S3. The lines between resource-extracting countries on the left side and consuming countries on the right side are kept in the color of the country of origin. About 40% of raw materials produced worldwide are associated with international trade and serve the consumption of products and services in countries other than that of extraction. A dynamic version of this graphic, which allows adjusting a threshold for domestic extraction (DE) data, can be viewed at www.truthstudio.com/code/code_2012_csiro.html.

Domestic material consumption (DMC) represents the apparent physical consumption of an economy and does not distinguish between the intermediate demand and final demand for materials, whereas the MF is a measure of the total amount of primary materials required to satisfy a country's own final demand. Differences between the two indicators are expected, depending on the level of resource extraction, processing, and trading in a country. We find these differences to be remarkably large; in fact, for most countries, DMC is closer to DE than to the MF. Fig. S4 shows the average relative distance between the three indicators for all countries for which sufficient data on DE were available.

Fig. S5 is a detailed version of Fig. S4 and shows the position of DMC in relation to DE and the MF. Note that negative numbers in the graph occur when either DMC or the MF is larger than DE. Countries have been sorted by increasing per-capita gross domestic product (GDP/cap) from left to right.

S2. Details on Methodology and Data

S2.1. Conceptual Framework. The global multiregion input–output (MRIO) analysis used in this work is based on monetary interrelationships between economic sectors and countries, considering intermediate demand by industries and final demand by consumers and governments. To this highly disaggregated framework of the global economy, we linked country-specific extraction data for primary materials to those industries that produce or extract these materials in the first place. Raw material equivalents (RMEs) associated with final demand and imports in each country were then calculated according to Kanemoto et al. (1) [also Lenzen et al. (2)]:

$$\mathrm{MF} = \sum_{r} f_i^r \sum_{it} L_{ij}^{rt} y_j^{ts} \qquad \textbf{[S1]}$$

$$\mathrm{RME}_{\mathrm{IM}} = \sum_{r} f_i^r \sum_{it \neq s} L_{ij}^{rt} y_j^{ts}, \qquad \textbf{[S2]}$$

where:

r, t, s = country of origin (r), last seller (t), and destination (s)

i, j = sector of origin (i) and destination (j)

f_i^r = material intensity of sector i in country $r = F_i^r / x_i^r$ = amount F of raw materials extracted by sector i in country r divided by total economic output x of sector i in country r

L_{ij}^{rt} = global Leontief inverse matrix (the derivation of L_{ij}^{rt} is provided in equation 5 in ref. 1)

y_j^{ts} = final demand for product j in country s (with y_j^{ss} = domestic final demand and $y_j^{t \neq s, s}$ = import of product j from country t to s)

We obtain RMEs associated with export by exchanging t and s:

$$\mathrm{RME}_{\mathrm{EX}} = \sum_{r} f_i^r \sum_{it \neq s} L_{ij}^{rs} y_j^{st}, \qquad \textbf{[S3]}$$

with:

s, t = country of last seller (s) and destination (t)

$y_j^{s, t \neq s}$ = export for product j from country s to t

Final demand, y, contains the following categories: household and government final consumption, gross fixed capital expenditure, and changes in inventories (y_j^{ss} and $y_j^{t \neq s, s}$) and exports ($y_j^{s, t \neq s}$). Furthermore, the following identity holds:

$$\mathrm{MF} = \mathrm{DE} + \mathrm{RME}_{\mathrm{IM}} - \mathrm{RME}_{\mathrm{EX}}. \qquad \textbf{[S4]}$$

The MRIO footprint calculations trace the whole production and supply chain of traded products and associated materials with a country's final demand back to the original source of primary material extraction. However, this approach does not explicitly calculate material flows associated with intermediate demand [only with final demand; a comparison of different approaches is provided by Feng et al. (3) and Kanemoto et al. (1)]. Furthermore, the MRIO approach is different from the bottom-up approach used by Dittrich et al. (4). Instead of using material equivalent factors derived from life cycle analysis (LCA) applied to bilateral trade data, MRIO intrinsically calculates total RMEs of final demand across multiple countries and sectors (see comparison below).

S2.2. Data Sources. The two data sources used in this work are the global MRIO database Eora and the Commonwealth Scientific and Industrial Research Organisation (CSIRO) Global Material Flow Database.

Eora is an MRIO database that provides a time series of input–output and trade tables with matching environmental and social satellite accounts for 186 countries. Lenzen et al. (2) provide an overview of the project; in particular, they describe (*i*) the United Nations System of National Accounts (UN SNA) sectoral data on value added and final demand used for modeling input–output matrices for countries where input–output data are unavailable, (*ii*) the development of a large-scale constrained optimization algorithm and its implementation on multicore scientific workstations, and (*iii*) the bridging and harmonization of the large range of disparate information using concordance tables. The tradeoffs between conflicting data sources and how these tradeoffs were quantified as source data uncertainty estimates and transformed into estimates for the SDs of MRIO table elements are described in detail in by Lenzen et al. (5).

The main characteristics of Eora are as follows:

One hundred eighty-six individual countries represented by a total of 14,787 sectors

Heterogeneous classification using the maximum number of sectors available for each country (an aggregated version of Eora can be generated in a 25-sector harmonized classification)

Continuous coverage for the period 1990–2011

Environmental indicators cover air pollution, greenhouse gas emissions, water use, ecological footprint, material flows, and human appropriation of net primary productivity

Raw data drawn from economic and trade databases from the United Nations, Eurostat, and numerous national agencies

Distinction between basic prices and purchasers' prices through five valuation tables

Reliability statistics (estimate of SD) for all results

The time series of MRIO tables in Eora was created in iterative steps of constrained optimization, starting with the year 2000 as the base year. Details of the fore- and back-casting procedures applied for the time series iterations are described in detail by Lenzen et al. (6). The UN SNA database contains information for constraints for every country and all years between 1990 and the current year, so that a situation with complete unsupported country and year never arises.

Eora data have been made available on the web at www.worldmrio.com.

The CSIRO Global Material Flow Database is a comprehensive compilation of global data for DE and physical trade of materials in yearly time steps for 1970–2008, and it was produced using standard material flow accounting principles following international guidelines (7). These data have been made available online for two world regions, namely, Asia and the Pacific (www.csiro.au/AsiaPacificMaterialFlows) and Latin America and the Caribbean (www.csiro.au/LatinAmericaCaribbeanResourceFlows). A technical annex available on these Web sites describes the data compilation methodology in detail. Main results from analyzing the database have been described in two reports (8, 9) and in the scholarly literature (10, 11). The data cover 191 countries and over 250 primary resource categories, which were aggregated to the 35 categories shown in Table S1 before adding them to the extensions in Eora. The matching of these 35 material categories with the extracting/producing industry sectors in the Eora MRIO was done by mapping both datasets to the six-digit subheadings of the Organization for Economic Cooperation and Development Harmonized Commodity Description and Coding System (HS6; www.oecd-ilibrary.org/trade/data/international-trade-by-commodity-statistics/harmonised-system-2007_data-00366-en).

S2.3. Methodological Limitations. Recent advances in global MRIO modeling (2, 12) now provide the means to analyze and monitor the MF of nations more reliably than before. However, the method is not without limitations.

MRIO accounts are provided initially in monetary terms rather than physical terms. So-called "price errors" can be introduced where individual transactions occur with a different price (dollars per quantity) than average. Allocation errors can occur due to low sectoral or product resolution. For example, a kilogram of gold included in a broad category of materials (e.g., "ores") allocated to a broad production sector (e.g., "metals and mining") will not be traced to its final demand as accurately as if gold were differentiated as a distinct input category and the MRIO used distinguished, more specific "gold," "precious metals," or "nonferrous metals" sectors rather than a broad metals and mining sector.

In this study, we differentiated 35 types of materials and the MRIO used between 25 and 510 industrial sectors per country (5). For countries with more raw material-producing sectors, the allocation of DE data are therefore more accurate than for countries where fewer such sectors are available. For example, if there is just one "aggregate" extraction sector, a part of the "building stone" material flow might be allocated to the chemical industry because some limestone (which is also extracted by the aggregate sector) is used by that industry and not in construction. It would be possible to allocate limestone extraction directly to both the construction and chemical industries; however, the exact proportions for each industry would have to be known or collected, which is time-consuming and inefficient. We therefore argue that the allocation via HS6 is a reasonable and practical compromise.

The limited resolution of some national input–output tables also constrains the method's ability in addressing issues around critical metals and resource security due to the facts that (*i*) many of the critical metals are "specialty metals," which are used for very specific applications that cannot be easily represented by flows between aggregate sectors/products, and (*ii*) resource security problems often arise from the presence of mono- or oligopoly structures within a sector. This is an area where hybrid approaches can be very useful. Here, input–output analysis (IOA) is combined with elements from process-based life cycle assessment (LCA) methods, such as those applied by Schoer et al. (13) in a study of the raw material consumption (RMC) of the European Union (EU). The hybrid method takes advantage of truncation-free enumeration of supply chains via IOA and product-specific detail via LCA (14–16). The current framework provides an important first step toward understanding potential risks associated with the global resource supply chain. More detailed information can be added targeting the hotspots identified through a hybrid approach, where process-specific information and aggregate product-level information are integrated.

More general elaborations on the uncertainty of MRIO modeling have been published in the literature (12, 17–19). Current MRIO research is aimed at understanding the uncertainties of calculating footprint accounts for nations (20) and improving the data basis and the accuracy of MRIO calculations. These efforts will eventually lead to the adoption of common practices, guidelines, and possibly standards, which, in turn, will facilitate the adoption of footprint indicators in policy making.

We are aware that the MF does not provide information on actual environmental impacts of resource use (RU) but only on the potential for impacts. A true decoupling of environmental damage from economic growth, however, can only be achieved if not just the total mass of materials consumed but the associated environmental impact is reduced (21). Future research therefore needs to establish and quantify causal links between final demand in countries and regional or local environmental impacts in other parts of the world.

S2.4. Comparison with Other Material Flow Accounting Approaches. A number of approaches have been applied in the literature to account for the indirect material requirements of modern economies (22, 23). As an extension to DMC, the total material consumption (TMC) indicator explicitly takes into account the indirect raw materials required to produce imports and exports of materials, as well as the flows of unused (hidden) extraction of raw materials [likewise, the total material requirement (TMR) extends direct material input by indirect and hidden material flows (24)]. TMC and TMR thus allow estimating the "ecological rucksack" of the material basis of nations. To calculate TMC and TMR, material intensity factors of imports and exports are derived from simplified life cycle inventories (4, 25). A drawback of this LCA factor method is that "that the ecological rucksack of a good which is passing more than one border in one or different process stages is counted more than one time within the volume" (4). This double-counting problem does not occur in MF calculations based on IOA because DE volumes are merely reallocated from production to consumption in a mutually exclusive and collectively comprehensive way. A further complication of the factor method used in TMC/TMR calculations is that coefficients of indirect material flows of imports and exports are mostly derived from specific production systems, such as Germany or the EU (25). Deriving more country-specific coefficients or updating them to represent technological development over time is resource-intensive

(4). IOA, on the other hand, calculates raw material requirements intrinsically by reallocating DE as described above.

In our analysis, we compare the MF with DMC rather than with the more comprehensive indicator of TMR. This is for two main reasons.

First, although the indirect flows component of TMR is similar to the RMEs calculated by the MF, the component of unused extraction renders comparisons futile. This is not just because unused extraction has not been included within the MF (or RME concept) but because estimations of unused extractions compound the already considerable uncertainties embodied in estimates of DMC. Unused extractions are usually very poorly recorded, if at all. For example, although mining overburden often greatly outweighs ore mined, its calculation would require country-specific stripping ratios, which vary greatly among different ore body configurations. The stripping ratio increases linearly with depth if the ore body is in horizontal sheet form (e.g., coal seams), as the square of depth if it is in vertical sheet (vein) form, and as the cube of depth if it is in pod (point) form. Therefore, arriving at a usable average stripping ratio is practically difficult. Errors in determining stripping ratios would then compound with those already inherent in the original ore tonnage estimation. It is not unlikely that errors in the estimation of TMR attributable to mining would be greater than total ore tonnage mined in some cases.

Second, TMR magnifies the problem of adding together material categories that exert very dissimilar environmental impacts. This is an (often criticized) aspect of all material flow indicators, including both DMC and the MF (22–28). However, in TMR accounting, a ton of uranium can end up grouped together with a ton of topsoil. In some categories, relatively inert materials that have minimal direct and indirect environmental consequences can therefore overwhelm the materials of consequence.

S2.5. Multivariate Regression Analysis. A cross-country multivariate regression analysis for the year 2008 was carried out to test changes in RU per capita (MF/cap and DMC/cap) in dependence of (*i*) GDP/cap, (*ii*) DE/cap, and (*iii*) population per area as explanatory variables. We initially tested four explanatory variables by including the Human Development Index (HDI) as an indicator for the development status of nations. (In part, the selection of explanatory variables was also driven by the availability of suitable data.) However, HDI was highly correlated with GDP/cap, thus introducing multicollinearity into the regression (Pearson's linear correlation coefficient of 0.80). As a result, HDI was excluded from the analysis.

Elasticities α, β, and γ for explanatory variables were calculated as the regression coefficients of an ordinary least-squares estimation of the relationship expressed in Eqs. **S5** and **S6**, with F being RU per capita (MF/cap or DMC/cap) and k being a constant. We did not choose a weighted least-squares approach because the data underlying the regression are unlikely to be heteroscedastic. This is because even though estimates of A, B, C, and F span a wide range, they are based on national data collated to international standards, and therefore are likely to be measured with comparable SDs for small and large countries alike:

$$F = k \cdot A^{\alpha} \cdot B^{\beta} \cdot C^{\gamma} \qquad \textbf{[S5]}$$

$$\log(F) = \log(k) + \alpha\log(A) + \beta\log(B) + \gamma\log(C). \qquad \textbf{[S6]}$$

The elasticities represent the relative change in per-capita RU corresponding to a relative change in the explanatory variables (Eq. **S7**; further explanation is provided in section 2.4 of ref. 29):

$$\alpha = \frac{dF/F}{dA/A}, \quad \beta = \frac{dF/F}{dB/B}, \quad \gamma = \frac{dF/F}{dC/C}. \qquad \textbf{[S7]}$$

Relationships between resource productivity (GDP/RU, with RU being the MF or DMC) and explanatory variables can be derived from Eq. **S5** as follows:

$$\frac{RU}{pop} = k \cdot \left(\frac{GDP}{pop}\right)^{\alpha} \cdot \left(\frac{DE}{pop}\right)^{\beta} \cdot \left(\frac{pop}{area}\right)^{\gamma} \qquad \textbf{[S8]}$$

$$\frac{RU}{pop} \cdot pop \cdot GDP^{-1} = k \cdot \left(\frac{GDP}{pop}\right)^{\alpha} \cdot \left(\frac{DE}{pop}\right)^{\beta} \cdot \left(\frac{pop}{area}\right)^{\gamma} \cdot pop \cdot GDP^{-1} \qquad \textbf{[S9]}$$

$$\text{Resource intensity} = \frac{RU}{GDP} = k\left(\frac{GDP}{pop}\right)^{\alpha-1} \cdot \left(\frac{DE}{pop}\right)^{\beta} \cdot \left(\frac{pop}{area}\right)^{\gamma} \qquad \textbf{[S10]}$$

$$\begin{aligned} \text{Resource productivity} &= \frac{GDP}{RU} \\ &= k^{-1} \cdot \left(\frac{GDP}{pop}\right)^{1-\alpha} \cdot \left(\frac{DE}{pop}\right)^{-\beta} \cdot \left(\frac{pop}{area}\right)^{-\gamma} \\ &= k^{-1} \cdot A^{1-\alpha} \cdot B^{-\beta} \cdot C^{-\gamma}. \end{aligned} \qquad \textbf{[S11]}$$

Eq. **S11** shows that the regression coefficient of resource productivity with income is $1 - \alpha$. This is equivalent to the definition provided by Ausubel and Waggoner (ref. 30, p. 12774), who see dematerialization (or the decrease of RU per GDP) as equal to income elasticity minus 1.

It is general practice to use GDP adjusted by purchasing power parity (PPP) for comparisons of resource productivity among countries and constant price GDP for comparisons over time (31). 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") for comparing among countries and over time.

We present regression coefficient (R^2) values as adjusted values that take into account the number of explanatory variables. Unlike the raw R^2, the adjusted R^2 will decrease if an additional explanatory variable adds insufficient explanatory power to the regression.

To test the robustness of our results and to investigate further how growing wealth influences the MF of nations, we repeated the multivariate regression for the GDP/cap for a subset of the entire population of country samples by moving a window of 70 countries across a ranked list of the regression data, starting with the poorest and ending with the richest 70 countries over the range of 137 countries. The result is 68 pairs of average GDP-PPP/cap values and their corresponding elasticities α presented as plots in Fig. S6, showing the following:

> The MF of crops, particularly those crops used for animal production, is clearly responsible for the overall increase of elasticity with wealth. Whereas every 10% increase of affluence in poorer countries only leads to an increase of 2% in the MF of fodder crops, this number is 6% at the high end of wealth. As countries become wealthier, they not only consume more food per capita; more importantly, the mix of food they consume tends to incorporate more animal products, which are often imported (32). As a consequence, the total MF/cap increases more steeply with income for wealthy countries where shifts to meat-based diets occur.

The MF of fossil fuels is more than proportional to the GDP across all income ranges. Elasticities range between $\alpha = 1.1$ and $\alpha = 1.4$ for all ensembles of countries. This result is a reflection of the well-known "energy ladder," where traditional biofuels are rapidly replaced by commercial fuels and electricity with larger material overheads as wealthier aspiring households acquire vehicles and appliances for convenience, comfort, and status (section 4.2.3.1 in ref. 33).

Elasticities for both metal ores and construction minerals decrease with affluence, starting at around $\alpha = 1$ at the lower end of wealth and ending up at around $\alpha = 0.8$ and $\alpha = 0.6$ at the higher end, respectively. This indicates a certain level of saturation for infrastructure and metal-based consumer goods (e.g., cars, household durables) with increasing income.

S3. Comparison with Other Studies

Some studies have calculated the RMEs of consumption or trade of individual countries or world regions. Table S2 provides a comparison of total MF results with this work. Although all studies are based on IOA, the underlying data sources and assumptions made when constructing the models, as well as the model design and scope, vary widely. A systematic cross-model comparison has not yet been undertaken [except for carbon footprint modeling (20)] and is recommended as an important future area of research.

S4. Note on the Term "Material Footprint"

The term "material footprint" was first mentioned in a report by Lettenmeier et al. (34), who use it as a synonym for ecological rucksack (ref. 34, p. 9) and define it as "the total input of natural resources required by any product from the cradle to the point of sale" (ref. 34, p. 50). Most previous studies that used IOA to allocate raw material extraction to final consumption (35–41) call the resulting indicator RMC rather than the MF. RMC was mentioned in the Eurostat handbook on economy-wide material flow accounting as a consumption indicator based on RMEs (42), although it was not further developed in that guide. The MF has been mentioned a couple of times (13, 43); however, more often, RMC has been used to identify the indicator.

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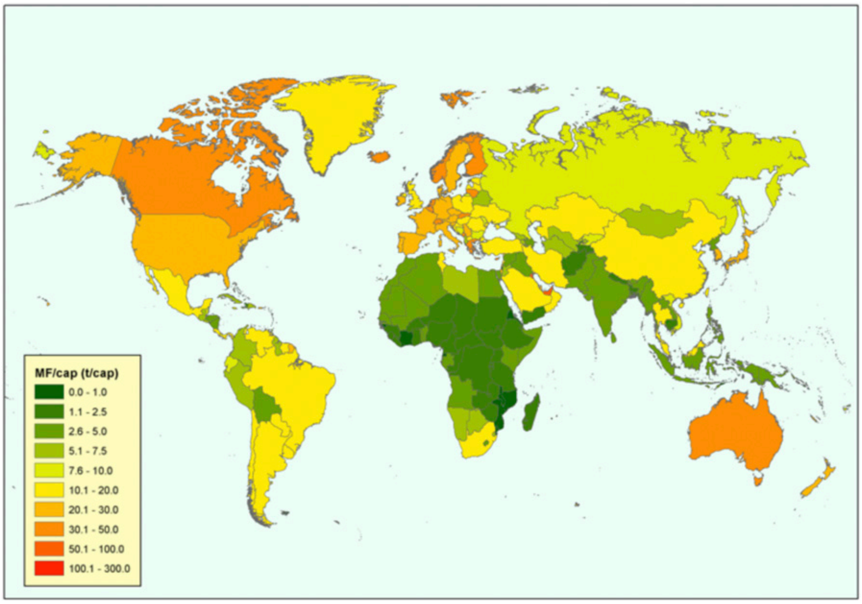

Fig. S1. MF/cap of nations in 2008.

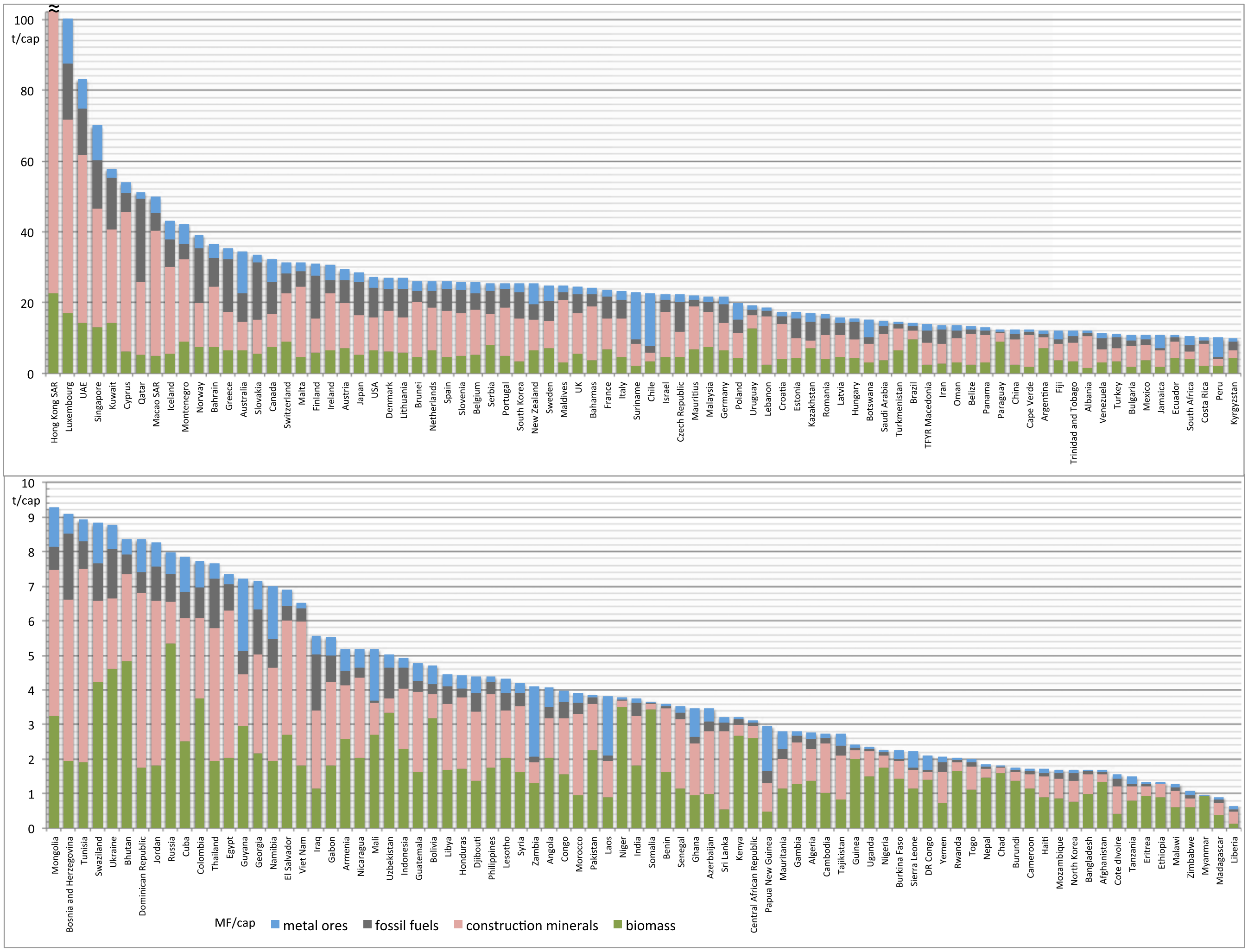

Fig. S2. MF/cap of all nations with a population larger than 300,000 for the year 2008 (note different scales for the two halves of the graph).

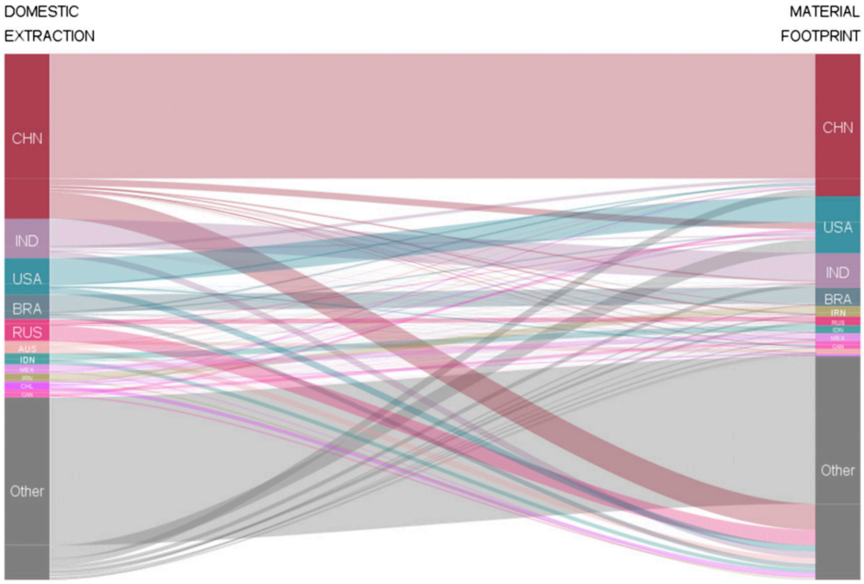

Fig. S3. Visualization of DE (*Left*), the MF (*Right*), and RMEs of domestic and international trade flows in 2008 (total of all material categories). (See also www.truthstudio.com/code/code_2012_csiro.html.)

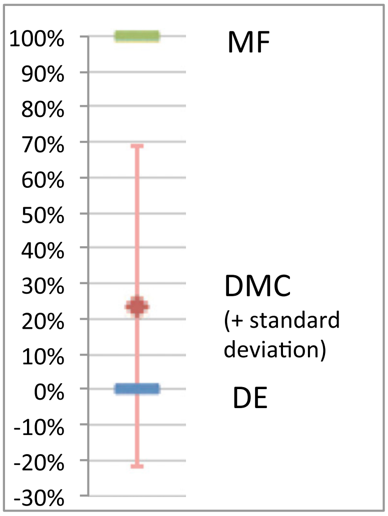

Fig. S4. Average relative distance of DMC from DE and the MF. The distance between DE and the MF has been normalized to 100% (114 countries for the year 2008; full plot is shown in Fig. S5).

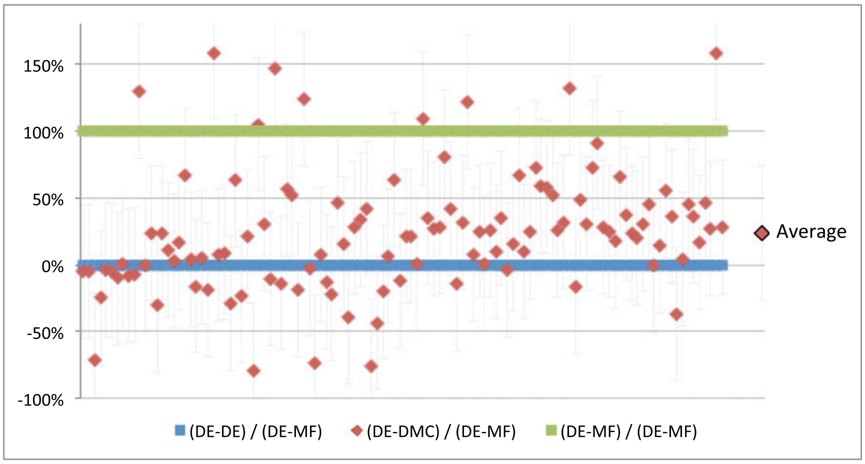

Fig. S5. Relative distance of DMC from DE and the MF for 114 countries for the year 2008. The distance between DE and the MF has been normalized to 100%.

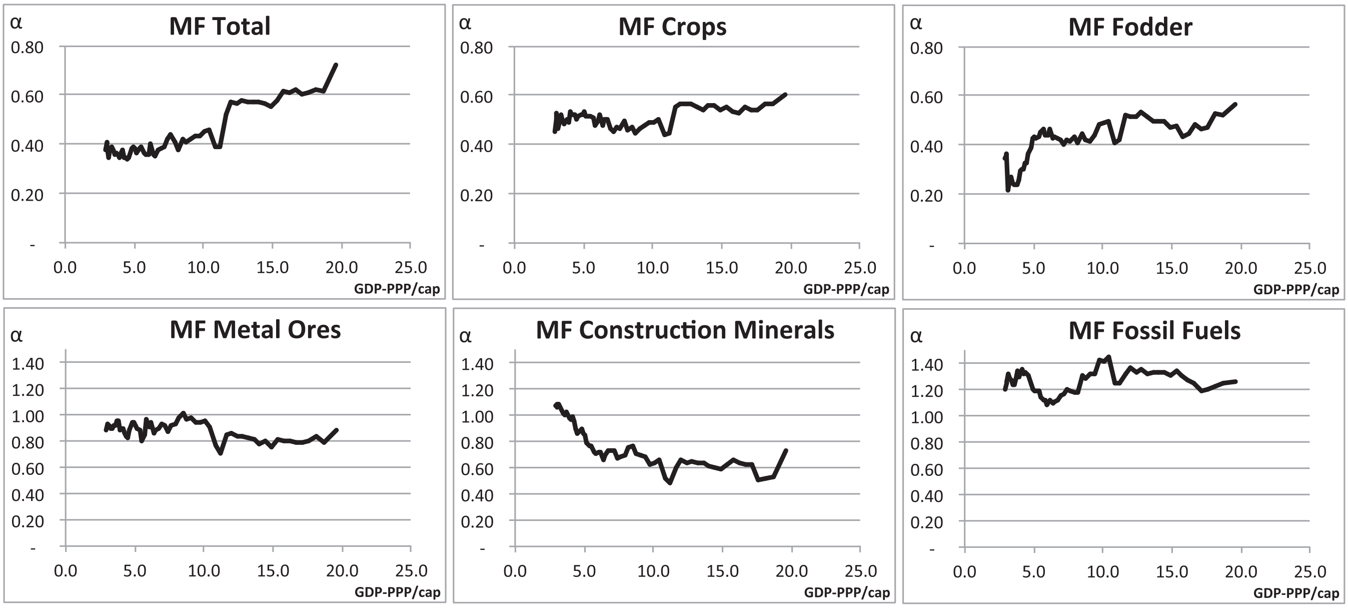

Fig. S6. Regression coefficients (elasticities α) for the dependence of MF categories on the changing wealth of nations (moving 70-country average of GDP-PPP-2005/cap).

Table S1. Material categories of the CSIRO Global Material Flow Database

Main category	EW-MFA category and name One-digit	 Two-digit	 Three-digit
Biomass	A.1: Biomass	A.1.1: Crops (excluding fodder crops)	A.1.1.1: Cereals
			A.1.1.2: Roots and tubers
			A.1.1.3: Sugar crops
			A.1.1.4: Pulses
			A.1.1.5: Nuts
			A.1.1.6: Oil-bearing crops
			A.1.1.7: Vegetables
			A.1.1.8: Fruits
			A.1.1.9: Fibers
			A.1.1.10: Other crops
		A.1.2: Crop residues (used), fodder crops, and grazed biomass	A.1.2.1: Crop residues (used)
			A.1.2.2: Grazed biomass
		A.1.3: Wood	A.1.3.1: Timber (industrial round wood)
			A.1.3.2: Wood fuel and other extraction
		A.1.4: Wild fish catch, aquatic plants/animals, and hunting and gathering*	
Metal ores and industrial minerals	A.2: Metal ores (gross ores)	A.2.1: Iron	A.2.1.1: Iron ores
		A.2.2: Nonferrous metals	A.2.2.1: Copper ores (gross ore)
			A.2.2.2: Nickel ores (gross ore)
			A.2.2.3: Lead ores (gross ore)
			A.2.2.4: Zinc ores (gross ore)
			A.2.2.5: Tin ores (gross ore)
			A.2.2.6: Gold, silver, platinum, and other precious metal ores (gross ore)
			A.2.2.7: Bauxite and other aluminum ores (gross ore)
			A.2.2.8: Uranium and thorium ores (gross ore)
			A.2.2.9: Other metal ores (gross ore)
Construction materials	A.3: Nonmetallic minerals	A.3.1: Nonmetallic minerals	A.3.1.1: Ornamental or building stone (including A.3.1.3 slate)
			A.3.1.2: Chalk and dolomite
			A.3.1.4: Chemical and fertilizer minerals
			A.3.1.5: Salt
			A.3.1.6: Other mining and quarrying products not elsewhere classified
		A.3.2: Nonmetallic minerals, primarily construction	
Fossil fuels	A.4: Fossil energy materials/carriers	A.4.1: Coal and other solid energy materials/carriers	A.4.1.1: Brown coal (lignite)
			A.4.1.2: Hard coal
			A.4.1.3: Oil shale and tar sands*
			A.4.1.4: Peat
		A.4.2: Liquid and gaseous energy materials/carriers	A.4.2.1: Crude oil, condensate and natural gas liquids
			A.4.2.2: Natural gas

The MF analysis was carried out at the three-digit level of the economy-wide material flow accounting classification (EW-MFA) (7).

*Not used in the CSIRO database.

Table S2. Cross-study comparison of MF results for individual countries and world regions (total MF = RMC)

Source	Muñoz et al., 2009 (35)	Weinzettel and Kovanda, 2009 (36) and 2011 (37)	Bruckner et al., 2012 (38)	Wiebe et al., 2012 (39)	Schoer et al., 2012 (13)*	Tukker et al., 2013 (43)	Wiedmann et al. (this study)
Method used	Hybrid SRIO[†]	Hybrid SRIO[†]	Global MRIO	Global MRIO	Hybrid SRIO[†]	Global MRIO	Global MRIO
Country, year							
Argentina, 1995				689			438
Argentina, 2000				766			508
Argentina, 2005			637	637			437
Brazil, 1995				2,263			1,748
Brazil, 2000				2,378			1,914
Brazil, 2003	2,787						1,904
Brazil, 2005			2,575	2,575			2,048
Chile, 1996	95						299
Chile, 2003	140						335
Chile, 2005			394				363
China, 1995				4,234			7,014
China, 2000				4,822			9,217
China, 2005			6,660	6,660			12,759
Colombia, 2003	327						269
Czech Republic, 2000		196					290
Czech Republic, 2003		228					269
Czech Republic, 2007		213					333
Ecuador, 2003	91						107
France, 2005			1,272				1,424
Germany, 2005			1,731				1,726
India, 1995				2,298			2,905
India, 2000				2,616			3,023
India, 2005			2,951	2,951			3,657
Italy, 2005			949				1,351
Japan, 2005			2,577				3,811
Mexico, 2003	1,157						1,062
The Netherlands, 2005			528				399
Russia, 1995				1,557			765
Russia, 2000				1,068			666
Russia, 2005			1,546	1,546			892
South Africa, 1995				557			549
South Africa, 2000				566			504
South Africa, 2005				656			538
Switzerland, 2005			216				243
United Kingdom, 2005			1,166				1,486
United States, 2003	8,942						7,966
United States, 2005			12,445				8,655
Region, year							
EU27, 20050						10,095	9,113
EU27, 2005					8,435		11,075
OECD, 1995				25,173			21,524
OECD, 2000				27,966			24,537
OECD, 2005				30,327			27,637

All values are cited in million metric tons (Mt). MRIO, multiregion input–output (analysis); OECD, Organization for Economic Cooperation and Development; SRIO, single-region input–output (analysis).

*Noninternalized fixed capital formation (fixed capital formation treated as final use category).

[†] The word "hybrid" refers to the use of life cycle inventory data to adapt input–output tables and environmental extensions.

Other Supporting Information Files

Dataset S1 (XLSX)