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High sensitivity of metal footprint to national GDP in part explained by capital formation

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Global metal ore extraction tripled between 1970 and 2010 as metals are widely used in new infrastructure and advanced technology. Meanwhile, the energy and environmental costs of metal mining increase as lower ore grades are being exploited. The domestic use of metals has been found to reach a plateau when gross domestic product reaches US$15,000 per person. Here we present a quantification of the annual metal footprint (that is, the amount of metal ore extracted to satisfy the final demand of a country, including metals used abroad to produce goods that are then imported, and excluding metals used domestically to produce exports) for 43 large economies during 1995–2013. We use a panel analysis to assess short-term drivers of changes in metal footprint, and find that a 1% rise in gross domestic product raises the metal footprint by as much as 1.9% in the same year. Further, every percentage point increase in gross capital formation as a share of gross domestic product increased the metal footprint by 2% when controlling for gross domestic product. Other socioeconomic variables did not significantly influence the metal footprint. Finding ways to break the strong coupling of economic development and investment with metal ore extraction may be required to ensure resource access and a low-carbon future.

Metals are a key enabler of economic development and human progress[1], and a requirement for the expansion of clean energy[2]. Anthropogenic usage of metals has grown steadily, especially in emerging economies[3]. From 1970 to 2010, global metal ore extraction tripled to 7.4 billion tons, 54% of which were used in the five BRICS (Brazil, Russia, India, China and South Africa) countries[4]. The growing use of metals, however, has also caused problems. On the one hand, mining and smelting are polluting processes, causing local pollution[5], land-use change[6], 10% of total global greenhouse gas emissions and 8% of global energy demand[7]. On the other hand, access to ore is increasingly restricted by the geographical concentration of mines[8,9], environmental concerns about extraction[8,9] and deteriorating grades of metal ores[10] that may reach economically extractable supply limits[11]. Although metals are infinitely recyclable in principle, the recycling process is often hampered by social behaviour, product design, lack of separation and sorting facilities, and inadequate technologies[12]. Governments in the United States[13], China[14], the European Union[15] and Japan[16] have developed policies to ensure the adequate supply of mineral resources, address environmental, social and security issues of supply, and limit the energy use[17–19].

Affluence measured as per capita gross domestic product (GDP) has been identified as the main economic driver of domestic metal use[20–22]. However, domestic metal use flattens with rising affluence, suggesting an increasing resource efficiency in high-income economies[23,24]. The environmental Kuznets curve (EKC) hypothesis postulates a peaking and eventual decline of metal use over the course of economic development. It has been tested using panel data, cross-sectional data and single-country samples[22,25–27]. However, due to the variances of data sets, country samples, time spans and metal types, the results have been contradictory, providing either support for[25,26] or against[22,28] the EKC. Despite the different results for EKC, these studies uniformly showed a significant correlation between metal use and GDP growth[21,26] and agreed that this correlation weakens once countries reach high-income status. The observed metal use–GDP relationships have been used to support scenarios of future metal use[26,29,30]. Most studies looked at the domestic use of either individual metals specifically[25,26,31] or as an aggregate[20,32,33].

Researchers have long pointed out that the sole consideration of domestic metal use can lead to misleading interpretations of national metal demand, because the consumption in one country can instigate metal use in another country[34–37]. Indeed, studies showed decoupling of material use from economic growth in some consuming countries to be overestimated, as resource-intensive industries were outsourced to other countries[38–41]. A correction of metal use for the effects of trade has become possible with the construction of global multiregional input–output (MRIO) models that are able to allocate the use of production factors through trade to final consumption. The metal footprint (MF) based on MRIO models accounts for the supply-chain-wide use of metal ores associated with the domestic final demand of a country or region. A cross-sectional analysis of the MF of 186 countries in 2008 found an elasticity of 0.9—that is, a 1% higher GDP per capita was associated with 0.9% higher MF per capita[37].

However, cross-sectional analysis provides only a snapshot of a specific point in time. Panel analysis of time-series observations of the same cross-section can detect both time and individual variations that are unobservable in cross-sections and hence gain more confidence about the cause-and-effect relationships. While researchers have performed panel analysis on domestic metal use, statistical analysis of MF has so far been limited to cross-sectional analysis (as Supplementary Table 2 shows). We ask, what is the short-run elasticity[42] of MF with respect to GDP? What is the role of other drivers such as investment and urbanization, which have been identified as important determinants, for example, of steel use[26]? Another knowledge gap is whether the MF of a nation depends on

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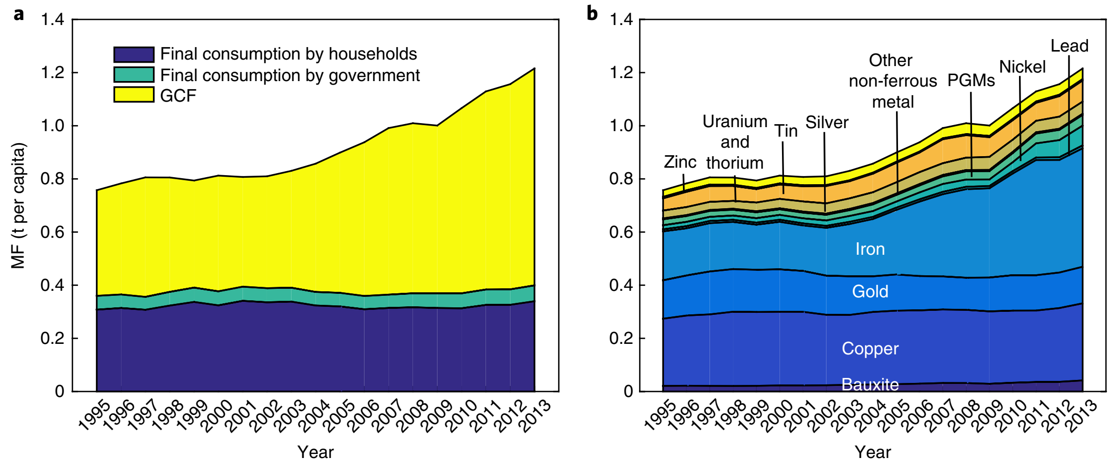

Fig. 1 | Global MF from 1995 to 2013. a,**b**, MF decomposed by expenditure (**a**) and metal type (**b**). PGMs, platinum group metals.

different GDP sources (that is, household and government consumption versus gross capital formation (GCF)).

This study aimed to identify the dynamics of the MF, extending the existing literature by employing panel regression models and taking multiple socioeconomic variables into consideration. We first quantified the MF of 43 major economies from 1995 to 2013, using the newly established EXIOBASE 3.3 MRIO data set[43]. The MF measures the extracted metal ores rather than the contained metal[37], as the environmental pressures of ore extraction and processing can be seen as scaling with the mass of ore extracted. Using a panel analysis approach, we tested the elasticities of per capita MF with respect to various explanatory variables (that is, the percentage change in per capita MF in response to a 1% change of explanatory variable(s)). The explanatory variables include GDP per capita adjusted for purchasing power parity (the affluence level), share of GCF in GDP (investment rate), the share of industry value added in GDP (reflecting the structure of the economy), urban population share, population density and domestic ore extraction (reflecting domestic resource availability). We next tested whether the MF–GDP relationship (that is, the elasticity of per capita MF with respect to per capita GDP) varied: at different affluence levels; during economic expansions and recessions; and with the composition of final demand. The employed panel analyses offer an estimate of short-run effects that control for the effects of unobserved time-invariant variables and are robust given the statistical properties of the data set. The understanding of short-run effects is a first step to understanding dynamics that will also play out in the long run[42].

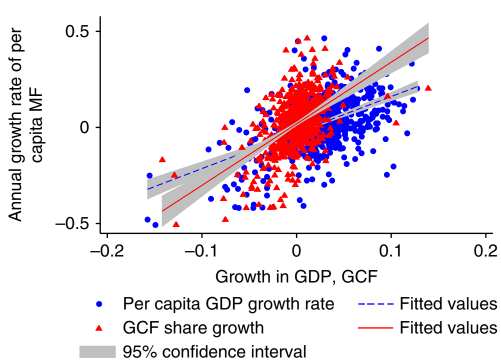

Fig. 2 | Growth rates of per capita MF versus per capita GDP or GCF share. The sample covers 774 country–year observations in 43 countries during 1996–2013. The growth rates were calculated using differenced natural logs. Annual changes of the GCF share were calculated as first differences. The shaded area represents the 95% confidential interval under robust estimations.

Evolution of MFs (1995–2013)

From 1995 to 2013, the global average per capita MF increased by 61%, from 0.76 to 1.20 ton per capita (Fig. 1). As shown in Fig. 1a, the MF of GCF rose from 0.40 to 0.82 t per capita, accounting for 95% of the total growth. The metal use associated with household and government consumption stayed relatively stable, in the range of 0.36–0.40 t per capita. The increase of the global MF was largely attributable to the consumption of iron ore, which grew from 0.18 t per capita in 1995 to 0.45 t per capita (37% of the total) in 2013, accounting for 60% of the growth. In addition to iron, copper and gold ores constituted high shares of the global MF, accounting for 24% and 11%, respectively, in 2013. Aluminium accounted for only ~3% of the global MF due to its relatively high ore grade and low density. The MFs of individual countries do not follow a uniform pattern over time (Supplementary Figs. 1–3).

Drivers of MFs

Figure 2 illustrates two positive yet different short-run relationships between the annual growth rates of per capita MF and per capita GDP (blue dots) and per capita MF and GCF as a share of GDP (red triangles) over our study period. Those patterns were confirmed by the panel analysis results in Table 1. The annual changes of per capita MF and per capita GDP level were strongly coupled: a 1.9% increase in MF for every 1% of economic growth (column I, Table 1). The MF–GCF elasticity indicates an even stronger short-run coupling: a 1% increase of the GCF share was associated with a 2.7% increase of the per capita MF (column II, Table 1). Controlling for GCF share, the MF–GDP elasticity falls to about 1; controlling for per capita GDP, per capita MF varies by 2.1% for every 1% change in GCF share (column III, Table 1). Besides confirming the coupling between MF and economic growth, this finding further underlines MF's very high sensitivity to investment.

To test for potential asymmetry in the effect of GDP on the MF, we estimated the same-year MF–GDP elasticities for economic growth and decline separately. Our results indicate that the effect of economic decline on per capita MF was twice that of growth (column IV, Table 1). A possible explanation is that the decline of metal demand in recession years was due to households delaying vehicle purchases and housing renovation, and shifting to fulfilment of more basic needs such as nutrition while the increase of metal demand in growth years lagged by consuming the durable inventory created in previous years.

Table 1 | Short-run elasticities of per capita MF with respect to per capita GDP and GCF share in GDP

Predictors	I	II	III	IV	V	VI
$\Delta \ln A_{it}$	1.909***		0.837***		2.440***	1.264***
	(0.193)		(0.208)		(0.295)	(0.337)
	[0.000]		[0.434]		[0.000]	[0.434]
ΔC_{it}		2.663***	2.102***			2.082***
		(0.222)	(0.259)			(0.262)
		[0.000]	[0.000]			[0.000]
$\Delta \ln A_{it}^{+}$				1.131***		
				(0.271)		
$\Delta \ln A_{it}^{-}$				3.115***		
				(0.388)		
				[0.000]		
$\Delta \ln A_{it}$* Annex-B dummy					−0.700*	−0.550
					(0.377)	(0.366)
R-squared	0.356	0.412	0.427	0.370	0.360	0.429

The regression models are based on 774 observations of 43 countries, 1996–2013. $\Delta \ln A_{it}$ represents the annual growth rate of per capita GDP; GDP is measured in terms of purchasing power parity (2011 constant US dollars); annual growth rate of per capita GDP was also interacted with the Annex-B dummy or split into growth ($\Delta \ln A_{it}^{+}$) and recession ($\Delta \ln A_{it}^{-}$). ΔC_{it} represents the GCF share in GDP. $\Delta \ln A_{it}$* Annex-B dummy represents the interaction term between a dummy-coded variable for an Annex-B country and the per capita GDP growth rate. Coefficients of period-specific and country-specific dummy variables and constants were included in the models but are not reported here. The figures in square brackets in columns I–III, V and VI are P values for tests of equality to 1, and the figures in square brackets in column IV are P values for tests whether positive and negative terms have equal coefficients. Robust standard errors are shown in parentheses; ***$P < 0.01$, * $P < 0.1$.

To test whether the same-year MF–GDP relationship varied with the affluence level of countries, we classified the sample countries into two groups, non-Annex B versus Annex B countries of the Kyoto Protocol. Without controlling for GCF share, the MF–GDP elasticity is lower for Annex B countries than non-Annex B countries (column V, Table 1). However, the difference was no longer significant after controlling for GCF share (column VI, Table 1). This result indicates that the non-Annex B countries had a higher share of investment over our study period (1995–2013).

Our results also suggested that the MF–GDP relationship was stable across the years (column 1, Supplementary Table 3). Urbanization, population density, industrialization, domestic ore extraction and the one-year lagged effect of the per capita GDP growth did not have significant effects on the per capita MF (Supplementary Table 3). Our results are broadly consistent with previous findings. A panel analysis of steel use in 26 Organisation for Economic Co-operation and Development countries from 1970 to 2012 demonstrated a steel-income elasticity of >1, which decreased with increasing income, and a strong influence of investment[26]. The study detected a significant additional influence of urbanization and industrialization. In our case, the effects of these variables were not significant when controlling for GDP and investment.

MF of consumption and investment, and by purpose

Final demand is comprised of the consumption by households and government, and of GCF (that is, investment). Thus, the MFs associated with consumption (MF^c) and investment (MF^i) are major components of a nation's total MF (Supplementary Fig. 4). We found that MF^i was extremely sensitive to economic growth, with the MF^i–GDP elasticity being 3.0; by contrast, the MF^c–GDP elasticity was only 0.8 (row 1, Table 2). To investigate this difference, we disaggregated per capital GDP into two expenditure-side GDP components: consumption (E^c) and investment (E^i). We found an MF^c–E^c elasticity of 1.8, while the MF^i–E^i elasticity was only 0.9 (row 1, Table 2). That is, the marginal final expenditures by household and government were on more metal-intensive goods, while marginal investments were in relatively less metal-intensive capital assets. However, 1% growth in affluence was associated with 2.8% growth of investment but only 0.7% growth of household and government expenditure in the same year. The pre-eminence of investment could explain the high MF–GDP elasticity since investment required, on average, five times as much metal per unit expenditure as consumption (Supplementary Fig. 5).

Economic growth has different effects on the MF associated with different products and services (denoted by MF^k) consumed by households and governments (Supplementary Fig. 6). The MFs associated with construction and manufactured products were particularly sensitive to changes in GDP. Estimates of the MF^k–GDP elasticity were 2.8 for the construction sector and 2.0 for manufacturing (Table 3). The respective elasticities for clothing and food were much smaller. The MFs of shelter, trade, mobility and service were not significantly affected by economic growth rates. The high

Table 2 | Short-run elasticities of per capita MF associated with final consumption and investment

		Explained versus explanatory variables	
		Consumption	Investment
(1)	$\Delta \ln M_{it}^{k}$ versus $\Delta \ln A_{it}$	0.760***	2.951***
		(0.244)	(0.405)
	R-squared	0.136	0.241
(2)	$\Delta \ln M_{it}^{k}$ versus $\Delta \ln E_{it}^{k}$	1.779***	0.901***
		(0.197)	(0.034)
	R-squared	0.246	0.634
(3)	$\Delta \ln E_{it}^{k}$ versus $\Delta \ln A_{it}$	0.714***	2.811***
		0.046	(0.365)
	R-squared	0.581	0.238

The regression models are based on 774 observations of 43 countries, 1996–2013. Δ represents the first-difference. Coefficients of period-specific and country-specific dummy variables and constants were included in the models but are not reported here. M^k denotes the MF associated with the kth expenditure type (that is, final consumption or investment), and E^k denotes the respective expenditure. Robust standard errors are shown in parentheses; ***$P < 0.01$.

Table 3 | Short-run elasticities of per capita MF associated with eight final consumption categories

Explained versus explanatory variables	Food	Clothing	Shelter	Trade	Construction	Manufactured products	Mobility	Service
$\Delta \ln M_{it}^{k}$ versus $\Delta \ln A_{it}$	0.622*	0.836***	−0.281	0.368	2.839***	2.350***	0.024	0.404
	(0.332)	(0.233)	(0.567)	(1.182)	(0.433)	(0.222)	(0.365)	(0.344)
R-squared	0.112	0.192	0.054	0.086	0.179	0.444	0.188	0.085
$\Delta \ln E_{it}^{k}$ versus $\Delta \ln A_{it}$	0.731***	1.163***	0.104	1.348***	2.835***	2.033***	0.672***	0.758***
	(0.074)	(0.144)	(0.188)	(0.445)	(0.264)	(0.149)	(0.146)	(0.056)
R-squared	0.294	0.277	0.115	0.136	0.346	0.566	0.368	0.505
$\Delta \ln M_{it}^{k}$ versus $\Delta \ln E_{it}^{k}$	0.828***	0.920***	0.778***	1.227***	1.104***	1.103***	1.036***	1.756***
	(0.174)	(0.062)	(0.105)	(0.142)	(0.051)	(0.058)	(0.094)	(0.185)
R-squared	0.150	0.377	0.113	0.308	0.430	0.659	0.268	0.154

The regression models are based on 774 observations of 43 countries, 1996–2013. Δ represents the first-difference. Coefficients of period-specific and country-specific dummy variables and constants were included in the models but are not reported here. M^k denotes the MF associated with the kth consumption category, and E^k denotes the respective expenditure. Robust standard errors are shown in parentheses; ***$P < 0.01$, *$P < 0.1$.

MF^k–GDP elasticities for construction and manufacturing were reflected in the high GDP elasticity of investment in or demand for these services, which have high MF intensity (Supplementary Fig. 7).

Interpreting the MF–GDP relationship

Using the MF metric to account for the metal ores used to produce goods consumed or invested in a country, we identified a short-run MF–GDP elasticity that is significantly larger than 1. The primary explanation identified is that when GDP grew rapidly, investments in construction and machinery were particularly high.

Our analysis leaves open the possibility that, in the long run, increased recycling, a shift to new materials and the saturation of infrastructure demand might enable metal use to decouple from economic growth, but the short-term elasticities have not yet revealed such trends in the current data. Cross-sectional elasticities (Supplementary Tables 4 and 5) may be more reflective of long-term effects, or they may be influenced by other explanatory variables not controlled for in such studies. In our sample, the cross-sectional elasticity between per capita MF and per capita GDP is around 0.73 (significantly less than 1), indicating the potential for relative decoupling of the MF from the economic growth if countries developed simply by moving up the cross-sectional distribution (Supplementary Table 4). In the cross-sectional analysis for each of the years, a significant influence of the share of GCF on per capita MF could be detected only in the years 2009–2013. It may be that the capital formation causes only a transient metal demand, but a connection may also be obscured by the relatively small variations in the share of capital formation across countries compared to the absolute value of GDP per capita or the influence of unobserved variables.

This study identified GCF as a share of the GDP as an important determinant of MFs. This finding may help explain the great variance of country patterns regarding the MF–GDP correlations. In some developing countries (for example, China, Indonesia and India), the booming investment in the past decades accounted for the high dependence of GDP growth on metal use (Supplementary Fig. 8). The decoupling of per capita MF from GDP growth in some developed countries, such as the UK and USA, resulted from a stable or even decreasing investment rate (Supplementary Fig. 8). The identified importance of investments suggests that catch-up growth in other regions such as the Indian subcontinent and sub-Saharan Africa would result in similarly high metal demands. The findings are consistent with, and thus provide support to dynamic stock models[44].

Given governments' concern about access to metal resources, decreasing ore grades and large impacts of extraction, this strong MF–GDP coupling argues for more public attention for resource governance[17,18]. On the one hand, the increasing importance of renewable energy increases the demand for iron, copper and some minor metals, such as the rare-earth elements[2,45]. Climate change adaptation requires a more robust infrastructure. On the other hand, engineers have identified a wide range of opportunities for material efficiency that allow industries to provide the same services to society using less metals and keeping metals in use for longer[46]. The possibility of shifting transportation to a smaller number of self-driving vehicles, construction to wood-frame buildings and of providing the same structural integrity to a building with half of the amount of steel[46] may actually change the metal intensity of different parts of the GDP, which may have significant impacts on the overall MF. Policies targeting material efficiency within construction and manufactured products may allow governments to achieve the desired decoupling of development from metal use and associated environmental impacts.

Methods

Methods, including statements of data availability and any associated accession codes and references, are available at https://doi.org/10.1038/s41561-018-0091-y.

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Author contributions
E.G.H. led and designed the research, X.Z. and R.Wang performed the research, R.Wood assembled EXIOBASE. All authors contributed to the interpretation of the results and provided substantial input to the manuscript.

Competing interests
The authors declare no competing interests.

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Methods

Metal footprint quantification. In this study, the metal footprint (MF) describes the metal ore usage associated with a country's final demand. We calculated it by applying the Leontief demand-pull model to the EXIOBASE 3.3 multi-regional input–output database. The central tenet of the model is the input–output market balance:

$$\mathbf{x} = \mathbf{Zi} + \mathbf{Y}\ \mathbf{i} \quad (1)$$

where **x** is a vector of total output, **Z** is a matrix that describes the intermediate flows of n commodities in a global economy consisting of r regions, **Y** is a matrix of final demand and **i** is a vector of 1s that serves to sum the columns of the preceding matrix. The balance states that for each commodity, total output equals the sale of commodities for intermediate production plus sales for final use. Constructing a technical coefficient matrix **B**, in which b_{ij} denotes the direct input of commodities i per unit output of j ($\mathbf{B} = \mathbf{Z}\hat{\mathbf{x}}^{-1}$), one can derive the Leontief model:

$$\mathbf{x} = (\mathbf{I} - \mathbf{B})^{-1}\mathbf{Y} \quad (2)$$

A matrix F of dimension (c, r*n) shows the input of c types of metal ores to the production of each of the respective commodities. The domestic metal ore extraction can be converted to coefficient form $\mathbf{S} = \mathbf{F}\hat{\mathbf{x}}^{-1}$. The MF **D** of an arbitrary final demand y_1 can then be calculated by equation (3), where i^T is the row vector of 1s that serves to sum the columns of the succeeding matrix:

$$\mathbf{D} = \mathbf{i}^T\mathbf{S}\mathbf{x} = \mathbf{i}^T\mathbf{S}(\mathbf{I} - \mathbf{B})^{-1}y_1 \quad (3)$$

The per capita MF is obtained by dividing D by the population. EXIOBASE 3.3 describes the world economy in terms of the annual production, trade, intermediate consumption and final consumption of 200 commodities between and within 43 countries, 1 territory, and 5 continental groups of countries for the period 1995 to 2013. Gross capital formation (GCF) is a category of final demand. Capital has not been endogenized in this analysis, so that the use of metals in machinery or ports to produce and ship goods is not included in the MF of consumer goods. This choice was undertaken for two reasons. One, good data on capital products and their use in different sectors are currently not available and one has to undertake a set of assumptions to allocate capital goods to final consumption. Two, capital goods distribute the use of invested metals over years of use, thereby potentially masking the time-series signal our panel analysis seeks to detect. Our analyses focused on the 43 individual countries in the database. Supplementary Table 1 provides a list of the countries.

EXIOBASE records the global annual usage of 12 groups of metal ores: iron, aluminium (bauxite), copper, lead, nickel, gold, other non-ferrous metal ores, platinum group metals, silver, tin, uranium and thorium, and zinc. Data for various metal uses were originally collected by members of the EXIOBASE team from the British Geological Survey[47], the US Geological Survey[48] and the literature[49]. Total ore quantities (rather than quantity of metal in the ore) were calculated in line with standards and conventions for material flow accounting[50]. In the case of co-produced metals, the EXIOBASE team allocated the non-metal portion of the ore to the primary metal, except in cases where the co-produced metals were of comparable economic importance (lead and zinc), in which case an allocation based on revenue had been used[50]. In this study, we aggregated the 12 groups of metals into a single indicator of metal ore use (ignoring the overburden) given metals are usually used as components of alloys or complex assembled products, rather than being employed one by one.

Panel estimation using first differences. We employed panel analysis to estimate the short-run elasticity of per capita MF with respect to key socioeconomic drivers. Given the non-stationarity and absence of co-integration detected in the data set (see Supplementary Table 6), we applied first-difference transformation to our data set. For our panel analyses, we then used the ordinary least squares estimator that considers country fixed effects and estimated panel-corrected standard error, which accounts for heteroscedasticity and cross-sectional dependence detected in the first-differenced data set.

The estimation equation for measuring the average effect of growth in per capita GDP (that is, affluence) on growth in per capita MF is:

$$\Delta \ln M_{it} = a_i + a_t + \beta_1 \Delta \ln A_{it} + e_{it} \quad (4)$$

ln$M$ denotes the logarithmic form of per capita MF. ln$A$ is the logarithmic form of per capita GDP at purchasing power parity, measured in 2011 international dollars. Δ is the first-difference operator (for a given series X, $\Delta X = X_t - X_{t-1}$). The subscript i denotes the individual observations (that is, countries in this study); t denotes the year. β_1 is the MF–GDP elasticity. Intercepts a_t were included to control for year-specific effects. Intercepts a_i are country fixed effects that were included to control for time-invariant factors (for example, geography and resource endowment) that may affect the growth rates of the MF. e is the idiosyncratic error term. Besides GDP per capita, investment (that is, GDP share of GCF), industrialization (that is, GDP share of industrial value added), population density, domestic ore extraction and time trend may be critical determinants of a country's per capita MF and so we also tested them as explanatory variables. We obtained the data for the socioeconomic variables from the World Development Indicators[51] and the data for domestic ore extraction from EXIOBASE3.3, and tested their impacts on the per capita MF. However, most of these variables had little influence on the MF. Only the effects of affluence and investment (C) were statistically significant, see equation (5).

$$\Delta \ln M_{it} = a_i + a_t + \beta_1 \Delta \ln A_{it} + \beta_2 \Delta C_{it} + e_{it} \quad (5)$$

where C_{it} denotes the GCF share in GDP and β_2 indicates the MF–GCF elasticity.

Additional specifications. One of the extensions in the analysis is a check for asymmetric effects of economic growth on the MF. Through equation (6), we tested whether positive GDP growth rate (that is, $\Delta \ln A_{it}^+$) and negative GDP growth rate ($\Delta \ln A_{it}^-$) affect changes of MFs differently.

$$\Delta \ln M_{it} = a_i + a_t + \eta_1 \Delta \ln A_{it}^+ + \eta_2 \Delta \ln A_{it}^- + e_{it} \quad (6)$$

In addition, we investigate the effects of economic growth on per capita MF in subsequent years. One-year lag of GDP per capita growth (l$ag(\Delta \ln A_{it})$) was added to equation (4) as follows.

$$\Delta \ln M_{it} = a_i + a_t + \beta_1 \Delta \ln A_{it} + \beta_3 lag(\Delta \ln A_{it}) + e_{it} \quad (7)$$

We further decompose the MF–GDP relationship according to expenditure type or consumption category. For expenditure type, we explored the MF associated with final consumption expenditure and GCF. For consumption category, we aggregated the 200 commodities in the final demand to 8 categories (that is, food, clothing, shelter, trade, construction, manufactured products, mobility and services), as used in previous consumption analysis[52]. The MF attributable to the kth expenditure type or consumption category (denoted as M^k) can be calculated by applying the final demand vector describing the respective expenditures to the Leontief model. The respective expenditures (denoted as E^k) were calculated by reformatting the final demand in the EXIOBASE 3.3 multi-regional input–output database. The data for E^k were calculated by applying the expenditure shares in final demand in EXIOBASE 3.3 to the per capita GDP at purchasing power parity obtained from the World Development Indicators[51].

We investigated affluence's effects on the per capita MF associated with different expenditure types (that is, final consumption by household and government and GCF) or categories of goods and services consumed, as equation (8) shows.

$$\Delta \ln M_{it}^k = a_i + a_t + \lambda_k \Delta \ln A_{it} + e_{it} \quad (8)$$

where λ_k denotes the affluence elasticity of per capita MF associated with the kth expenditure type or consumption category.

We further explored the relationship between M^k and E^k (equation (9)), and the relationship between E^k and affluence (equation (10)).

$$\Delta \ln M_{it}^k = a_i + a_t + \psi_k \Delta \ln E_{it}^k + e_{it} \quad (9)$$

$$\Delta \ln E_{it}^k = a_i + a_t + \omega_k \Delta \ln A_{it} + e_{it} \quad (10)$$

For the kth expenditure type or consumption category, ψ_k denotes the expenditure elasticity of per capita MF induced; ω_k denotes the affluence elasticity of the expenditure on the kth category.

Code availability. The code for the panel analysis is available online at https://figshare.com/ (https://doi.org/10.6084/m9.figshare.5797383).

Data availability. EXIOBASE3.3 will become available at http://www.exiobase.eu/. Data for the dependent and independent variables used in the panel analysis are available online at https://figshare.com/ (https://doi.org/10.6084/m9.figshare.5797377).

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