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 use in new infrastructure and advanced technology. Meanwhile, the energy and environmental costs of metal mining increase with lower ore grades. Previous work found that the domestic use of metals plateaus when gross domestic product (GDP) reaches \$ 15000 per person. In contrast, the metal footprint (MF) is the amount of metal ore extracted to satisfy the final demand of a country, including metals used abroad to produce goods imported and excluding metals used domestically to produce exports. Here we present a quantification of annual MFs for 43 major economies during 1995-2013 and a panel analysis to assess short-run drivers of MFs. We find that a 1% rise in GDP raises the MF by as much as 1.9% in the same year. Further, every percentage point increase in gross capital formation as a share of GDP increased the MF by 2% when controlling for GDP. Other socioeconomic variables did not significantly influence the MF. 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 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 behavior, 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 datasets, country samples, time spans, and metal types, the results have been contradictory, providing either support for[25,26] or falsification of[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[35-38]. 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[39-42]. A correction of metal use for the effects of trade has become possible with the construction of global multiregional input-output (MRIO) models which 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. Through a cross-sectional analysis of 186 countries in 2008, Wiedmann and colleagues found an elasticity of 0.9, i.e., a 1% higher GDP per capita was associated with 0.9% higher MF per capita.

Cross sectional analysis, however, only provides 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 Table S2 shows). We ask, what is the short-run elasticity[43] of MF with respect to GDP? What is the role of other drivers like investment and urbanization, which have been identified as important determinants, for example, of steel use[26]? Another knowledge gap is whether the metal footprint of a nation depends on different GDP sources, i.e., household and government consumption vs. 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 dataset[44]. The MF measures the extracted metal ores rather than the contained metal[38], 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, i.e. 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 gross capital formation (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 (i.e. the elasticity of per capita MF with respect per capita GDP) varied 1) at different affluence levels; 2) during economic expansions and recessions; and 3) with the composition of final demand. The employed panel analysis offers 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 dataset. The understanding of short-run effects is a first step to understanding dynamics that will also play out in the long run[43].

Evolution of Metal Footprints (1995-2013)

From 1995 to 2013, the global average per capita metal footprint increased by 61%, from 0.76 to 1.20 ton per capita (Figure 1). As shown by Figure 1(a), the MF of gross capital formation rose from 0.40 to 0.82 t/cap, 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/cap. The increase of the global MF was largely attributable to the consumption of iron ore, which grew from 0.18 t/cap in 1995 to 0.45 t/cap (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. Aluminum only accounted for ~3% of the global metal footprint due to its relatively high ore grade and low density. The MFs of individual countries do not follow a uniform pattern over time (Supplementary Figures S1-S3).

Drivers of Metal Footprints

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 gross capital formation 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, Table1). 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 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, 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.

To test if the same-year MF-GDP relationship varied with the affluence level of countries, we classified the sample countries into two groups, non-Annex B vs. 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 the MF-GDP relationship was stable across the years (Column 1, Table S3). 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 metal footprint (Table S3). Our results are broadly consistent with previous findings. A panel analysis of steel use in 26 OECD countries from 1970-2012 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.

Metal Footprint of Consumption, Investment, and by Purpose

Final demand is comprised of the consumption by households and government, and of GCF (i.e. investment). Thus the MF associated with consumption (MF^c) and investment (MF^i) are major components of a nation's total MF (Figure S4). 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 I, 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 I, 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 preeminence 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 Figure S5).

Economic growth has different effects on the MF associated with different products and services (denoted by MF^k) consumed by households and governments (Figure S6). The MF 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 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 metal footprint intensity (Figure S7).

Interpreting the metal footprint – GDP relationship

Using the metal footprint 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 one. 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 Table S4 and Table S5) 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 metal footprint from the economic growth if countries developed simply by moving up the cross-sectional distribution (Supplementary Table S4). In the cross-sectional analysis for each of the years, a significant influence of the share of GCF on per capita MF could only be detected in the years 2009-2013. It may be that the capital formation only causes 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 gross capital formation 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, e.g. China, Indonesia, and India, the booming investment in the past decades accounted for the high dependence of GDP growth on metal use (Supplementary Figure S8). The decoupling of per capita MF from GDP growth in some developed countries, such as UK and USA, resulted from a stable or even decreasing investment rate (Supplementary Figure S8). 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[45].

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[2,46]. Climate change adaptation requires a more robust infrastructure. On the other hand, engineers have identified a wide range of opportunities for material efficiency which allow industries to provide the same services to society using less metals and keeping metals in use for longer[47]. 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[47] may actually change the metal intensity of different parts of the GDP, which may have significant impacts on the overall metal footprint. 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.

References

1 Graedel, T. E. & Cao, J. Metal spectra as indicators of development. *Proceedings of the National Academy of Sciences* **107**, 20905-20910, doi:10.1073/pnas.1011019107 (2010).

2 Vidal, O., Goffé, B. & Arndt, N. Metals for a low-carbon society. *Nature Geoscience* **6**, 894-896, doi:10.1038/ngeo1993 (2013).

3 Schandl, H. & West, J. Material flows and material productivity in China, Australia, and Japan. *Journal of Industrial Ecology* **16**, 352-364, doi:10.1111/j.1530-9290.2011.00420.x (2012).

4 Schaffartzik, A., Mayer, A., Eisenmenger, N. & Krausmann, F. Global patterns of metal extractivism, 1950–2010: Providing the bones for the industrial society's skeleton. *Ecological Economics* **122**, 101-110, doi:10.1016/j.ecolecon.2015.12.007 (2016).

5 Bridge, G. Contested terrain: Mining and the environment. *Annual Review of Environment and Resources* **29**, 205-259, doi:10.1146/annurev.energy.28.011503.163434 (2004).

6 Özkaynak, B. *et al.* Mining conflicts around the world: Common grounds from an Environmental Justice perspective. EJOLT Report No. 7, 198 (2012).

7 van der Voet, E. *et al.* Environmental risks and challenges of anthropogenic metals flows and cycles, A Report of the Working Group on the Global Metal Flows to the International Resource Panel (United Nations Environment Programme, Nairobi (Kenya) and Paris (France), 2013).

8 Franks, D. M. *et al.* Conflict translates environmental and social risk into business costs. *Proceedings of the National Academy of Sciences* **111**, 7576-7581 (2014).

9 Graedel, T. E., Harper, E. M., Nassar, N. T., Nuss, P. & Reck, B. K. Criticality of metals and metalloids. *Proceedings of the National Academy of Sciences* **112**, 4257-4262 (2015).

10 Prior, T., Giurco, D., Mudd, G., Mason, L. & Behrisch, J. Resource depletion, peak minerals and the implications for sustainable resource management. *Global Environmental Change* **22**, 577-587, doi:10.1016/j.gloenvcha.2011.08.009 (2012).

11 Northey, S., Mohr, S., Mudd, G., Weng, Z. & Giurco, D. Modelling future copper ore grade decline based on a detailed assessment of copper resources and mining. *Resources, Conservation and Recycling* **83**, 190-201 (2014).

12 Reck, B. K. & Graedel, T. E. Challenges in metal recycling. *Science* **337**, 690-695, doi:10.1126/science.1217501 (2012).

13 US Department of Energy. *The Department of Energy's Critical Materials Strategy*, <https://www.energy.gov/epsa/initiatives/department-energy-s-critical-materials-strategy> (2017).

14 China's State Council. *Integrated Reform Plan for Promoting Ecological Progress*, <http://www.gov.cn/guowuyuan/2015-09/21/content_2936327.htm> (2015).

15 European Commission. *Policy and strategy for raw materials*, <https://ec.europa.eu/growth/sectors/raw-materials/policy-strategy_en> (2017).

16 Ministry of Foreign Affairs of Japan. *Promoting Resource Diplomacy along with Foreign Direct Investment in Japan*, <http://www.mofa.go.jp/policy/other/bluebook/2017/html/chapter3/c030303.html> (2017).

17 Henckens, M., Driessen, P., Ryngaert, C. & Worrell, E. The set-up of an international agreement on the conservation and sustainable use of geologically scarce mineral resources. *Resources Policy* **49**, 92-101 (2016).

18 Ali, S. H. *et al.* Mineral supply for sustainable development requires resource governance. *Nature* **543**, 367-372 (2017).

19 Ekins, P. *et al.* Resource Efficiency: Potential and Economic Implications. (Report of the International Resource Panel, United Nations Environment Program (UNEP), Paris, 2016).

20 Schandl, H. & West, J. Resource use and resource efficiency in the Asia–Pacific region. *Global Environmental Change* **20**, 636-647, doi:10.1016/j.gloenvcha.2010.06.003 (2010).

21 Steinberger, J. K., Krausmann, F. & Eisenmenger, N. Global patterns of materials use: A socioeconomic and geophysical analysis. *Ecological Economics* **69**, 1148-1158, doi:10.1016/j.ecolecon.2009.12.009 (2010).

22 Binder, C. R., Graedel, T. E. & Reck, B. Explanatory variables for per capita stocks and flows of copper and zinc. *Journal of Industrial Ecology* **10**, 111-132 (2006).

23 Daniel B. Muller, T. W., Benjamin Duval. Patterns of Iron Use in Societal Evolution. *Environmental Science & Technology* **45**, 182-188 (2011).

24 Tilton, J. E. The OECD countries: demand trend Setters. *World Metal Demand: Trends and prospects, Resources for the Future, Washington DC*, 35-76 (2015).

25 Jaunky, V. C. Is there a material Kuznets curve for aluminium? evidence from rich countries. *Resources Policy* **37**, 296-307, doi:10.1016/j.resourpol.2012.04.001 (2012).

26 Crompton, P. Explaining variation in steel consumption in the OECD. *Resources Policy* **45**, 239-246, doi:10.1016/j.resourpol.2015.06.005 (2015).

27 Guzmán, J. I., Nishiyama, T. & Tilton, J. E. Trends in the Intensity of Copper Use in Japan Since 1960. *Resources Policy* **30**, 21-27 (2005).

28 Ghosh, S. Steel consumption and economic growth: Evidence from India. *Resources Policy* **31**, 7-11 (2006).

29 Rebiasz, B. Polish steel consumption, 1974–2008. *Resources Policy* **31**, 37-49, doi:10.1016/j.resourpol.2006.03.006 (2006).

30 Roberts, M. C. Metal use and the world economy. *Resources Policy* **22**, 183-196, doi:https://doi.org/10.1016/S0301-4207(97)84898-2 (1996).

31 Wårell, L. & Olsson, A. in *Securing the Future and 8th ICARD* (Curran Associates, Inc., Skelleftea, Sweden, 2009).

32 Canas, Â., Ferrão, P. & Conceição, P. A new environmental Kuznets curve? Relationship between direct material input and income per capita: evidence

from industrialised countries. *Ecological Economics* **46**, 217-229, doi:10.1016/s0921-8009(03)00123-x (2003).

33 Steinberger, J. K., Krausmann, F., Getzner, M., Schandl, H. & West, J. Development and dematerialization: an international study. *PLoS One* **8**, e70385, doi:10.1371/journal.pone.0070385 (2013).

34 Weisz, H. *et al.* Economy-wide material flow accounting. A compilation guide. (Eurostat and the European Commission, 2007).

35 Radetzki, M. & Tilton, J. E. in *World Metal Demand: Trends and Prospects* (ed John E Tilton) Ch. Conceptual and Methodological Issues, 13-34 (Resources for the Future, 1990).

36 Roberts, M. C. Predicting metal consumption: The case of US steel. *Resources Policy* **16**, 56-73, doi:https://doi.org/10.1016/0301-4207(90)90018-7 (1990).

37 Wiedmann, T. O., Schandl, H. & Moran, D. The footprint of using metals: new metrics of consumption and productivity. *Environmental Economics and Policy Studies* **17**, 369-388 (2015).

38 Wiedmann, T. O. *et al.* The material footprint of nations. *Proceedings of the National Academy of Sciences* **112**, 6271-6276, doi:10.1073/pnas.1220362110 (2015).

39 Muñoz, P., Giljum, S. & Roca, J. The Raw Material Equivalents of International Trade Empirical Evidence for Latin America. *Journal of Industrial Ecology* **13**, 881-897 (2009).

40 Weinzettel, J. & Kovanda, J. Assessing socioeconomic metabolism through hybrid life cycle assessment. *Journal of Industrial Ecology* **13**, 607-621, doi:10.1111/j.1530-9290.2009.00144.x (2009).

41 Schoer, K., Weinzettel, J., Kovanda, J., Giegrich, J. r. & Lauwigi, C. Raw material consumption of the European Union–concept, calculation method, and results. *Environmental Science & Technology* **46**, 8903-8909 (2012).

42 Giljum, S., Bruckner, M. & Martinez, A. Material footprint assessment in a global input-output framework. *Journal of Industrial Ecology* **19**, 792-804, doi:10.1111/jiec.12214 (2015).

43 Burke, P. J., Shahiduzzaman, M. & Stern, D. I. Carbon dioxide emissions in the short run: The rate and sources of economic growth matter. *Global Environmental Change* **33**, 109-121, doi:10.1016/j.gloenvcha.2015.04.012 (2015).

44 Stadler, K. *et al*. EXIOBASE 3: Developing a Time Series of Detailed Environmentally Extended Multi-Regional Input-Output Tables. *Journal of Industrial Ecology*, doi:10.1111/jiec.12715 (2018).

45 Pauliuk, S. & Müller, D. B. The role of in-use stocks in the social metabolism and in climate change mitigation. *Global Environmental Change* **24**, 132-142 (2014).

46 Hertwich, E. G. *et al.* Integrated life-cycle assessment of electricity-supply scenarios confirms global environmental benefit of low-carbon technologies. *Proceedings of the National Academy of Sciences* **112**, 6277-6282 (2015).

47 Allwood, J. M., Gutowski, T. G., Serrenho, A. C., Ach, S. & Worrell, E. Industry 1.61803: the transition to an industry with reduced material demand fit for a low carbon future. *Philosophical Transactions* **375** (2017).

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Author contributions

E.H. led and designed the research, X.Z. and R.Wa. performed the research, R.Wo. assembled EXIOBASE. All authors contributed to the interpretation of the results and provided substantial input to the manuscript.

Competing financial interests

The authors declare no conflict of interest.

Additional information

Supplementary information is available in the online version of the paper.

Figure captions

Figure 1. Global metal footprint (in ton ore equivalent per person) from 1995 to 2013. The MF is decomposed by (a) expenditure and (b) metal type.

Figure 2. Growth rates of per capita MF vs. per capita GDP (blue dots) or GCF share (red triangles). 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 gross capital formation share were calculated as first differences. The shaded area represents the 95% confidential interval (CI) under robust estimations.

Tables

Table 1. Short-run elasticities of per capita metal footprint with respect to per capita GDP and gross capital formation share in GDP

Predictors	I	II	III	IV	V	VI
ΔlnA_{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]
ΔlnA_{it}^{+}				1.131***		
				(0.271)		
ΔlnA_{it}^{-}				3.115***		
				(0.388)		
				[0.000]		
ΔlnA_{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

Notes: (1) The regression models are based on 774 observations of 43 countries, 1996-2013; (2) ΔlnA_{it}: annual growth rate of per capita GDP; GDP is measured in PPP terms, 2011 constant dollars); Annual growth rate of per capita GDP were also interacted with Annex-B dummy or split into growth (ΔlnA_{it}^{+}) and recession (ΔlnA_{it}^{-}). (3) ΔC_{it}: gross capital formation share in GDP; (4) ΔlnA_{it} * Annex-B dummy represents the interaction term between a dummy-coded variable for Annex-B country and the per capita GDP growth rate; (5) Coefficients of period-specific and country-specific dummy variables and constants were included in the models but not reported here; (6) Figures in square brackets in columns I, II, III, V and VI are p-values for tests of equality to 1, and figures in square brackets in column IV are p-values for tests that positive and negative terms have equal coefficients; (7) Robust standard errors in the parentheses; *** p<0.01, ** p<0.05, * p<0.1.

Table 2. Short-run elasticities of per capita metal footprint associated with final consumption and investment

Explained vs. Explanatory Variables		I Consumption	II Investment
(1)	$\Delta lnM_{it}^{k}\ vs. \Delta lnA_{it}$	0.760*** (0.244)	2.951*** (0.405)
	R-squared	0.136	0.241
(2)	$\Delta lnM_{it}^{k}\ vs. \Delta lnE_{it}^{k}$	1.779*** (0.197)	0.901*** (0.034)
	R-squared	0.246	0.634
(3)	$\Delta lnE_{it}^{k}\ vs. \Delta lnA_{it}$	0.714*** 0.046	2.811*** (0.365)
	R-squared	0.581	0.238

Notes: (1) The regression models are based on 774 observations of 43 countries, 1996-2013; (2) Δ represents all the variables are first-differenced; (3) Coefficients of period-specific and country-specific dummy variables and constants were included in the models but not reported here; (4) M^k denotes the metal footprint associated with the kth expenditure type (i.e., final consumption or investment), and E^k denotes the respective expenditure; (5) Robust standard errors in the parentheses; *** p<0.01, ** p<0.05, * p<0.1.

Table 3. Short-run elasticities of per capita metal footprint associated with 8 final consumption categories

Explained vs. Explanatory Variables	Food	Clothing	Shelter	Trade	Construction	Manufactured products	Mobility	Service
ΔlnM_{it}^{k} $vs. \Delta lnA_{it}$	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
ΔlnE_{it}^{k} $vs. \Delta lnA_{it}$	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
ΔlnM_{it}^{k} $vs. \Delta lnE_{it}^{k}$	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

Notes: (1) The regression models are based on 774 observations of 43 countries, 1996-2013; (2) Δ represents all the variables are first-differenced; (3) Coefficients of period-specific and country-specific dummy variables and constants were included in the models but not reported here; (4) M^k denotes the metal footprint associated with the kth consumption category, and E^k denotes the respective expenditure; (5) Robust standard errors in the parentheses; *** p<0.01, ** p<0.05, * p<0.1.

Methods

Metal Footprint Quantification

In this study, the 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 (MRIO) database. The central tenet of the model is the IO market balance:

$$\mathbf{x} \ = \mathbf{Z1} + \mathbf{Y1} \ \ (1)$$

Where $\mathbf{x}$ is a vector of total output, $\mathbf{Z}$ is a matrix which describes the intermediate flows of n commodities in a global economy consisting of r regions, $\mathbf{Y}$ is a matrix of final demand, and **1** 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 $\mathbf{A}$, in which a_{ij} denotes the direct input of commodities i per unit output of j $(\mathbf{A} = \mathbf{Z}\hat{\mathbf{x}}^{-1})$, one can derive the Leontief model:

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

A matrix F of dimension $(\mathrm{c}, \mathrm{r} * \mathrm{n})$ 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 metal footprint **D** of an arbitrary final demand y_1 can then be calculated by equation 3, where i^T is the row vector of ones which serves to sum the columns of the succeeding matrix:

$$\mathbf{D} = \mathbf{i}^{\mathbf{T}}\mathbf{S}\mathbf{x} = \mathbf{i}^{\mathbf{T}}\mathbf{S} \ (\mathbf{I} - \mathbf{A})^{-1}\boldsymbol{y}_{\mathbf{1}} \quad \mathbf{(3)}$$

The per capita metal footprint 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 five continental groups of countries for the period 1995 to 2013. Gross capital formation is a category of final demand. Capital has not been endogenised in this analysis, so that the use of metals in machinery or ports to produce and ship goods is not included in the metal footprint 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 using years, thereby potentially masking the time-series signal our panel analysis seeks to detect. Our analyses focused on the 43 individual countries in the database. The Supplementary Information provides a list of the countries (Table S1).

EXIOBASE records the global annual usage of twelve groups of metal ores: iron, aluminum (bauxite), copper, lead, nickel, gold, other non-ferrous metal ores, platinum group metals (PGM), silver, tin, uranium and thorium, and zinc. Data for various metal usage were originally collected by members of the EXIOBASE team from the British Geological Survey[48], the US Geological Survey[49], and literature[50]. Total ore quantities (rather than quantity of metal in the ore) were calculated in line with material flow accounting standards and conventions. 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[34]. In this study, we aggregated the twelve 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 cointegration detected in the dataset (see Supplementary Table S6), we applied first-difference transformation to our dataset. For our panel analyses, we then used the OLS estimator that considers country-fixed effects and estimated panel-corrected standard error (PCSE), which accounts for heteroscedasticity and cross-sectional dependence detected in the first-differenced dataset.

The estimation equation for measuring the average effect of growth in per capita GDP, i.e. affluence, on growth in per capita metal footprint is:

$$\Delta lnM_{it} = a_i + a_t + \beta_1 \Delta lnA_{it} + e_{it} \text{ (4)}$$

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

$$\Delta lnM_{it} = a_i + a_t + \beta_1 \Delta lnA_{it} + \beta_2 \Delta C_{it} + e_{it} \ (5)$$

where C_{it} denotes the gross capital formation 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 metal footprint. Through Eq. (6), we tested whether positive GDP growth rate (i.e. ΔlnA_{it}^{+}) and negative GDP growth rate (ΔlnA_{it}^{-}) affect changes of metal footprints differently.

$$\Delta lnM_{it} = a_i + a_t + \eta_1 \Delta lnA_{it}^{+} + \eta_2 \Delta lnA_{it}^{-} + e_{it} \ (6)$$

In addition, we investigate the effects of economic growth on per capita metal footprint in subsequent years. One-year lag of GDP per capita growth ($lag(\Delta lnA_{it})$) was added to Eq.(4) as follows.

$$\Delta lnM_{it} = a_i + a_t + \beta_1 \Delta lnA_{it} + \beta_3 lag(\Delta lnA_{it}) + e_{it} \ (7)$$

We further decompose the MF-GDP relationship according to expenditure type or consumption category. For expenditure type, we explored the metal footprint associated with final consumption expenditure and gross capital formation. For consumption category, we aggregated the 200 commodities in the final demand to 8 categories (i.e., food, clothing, shelter, trade, construction, manufactured products, mobility and services), as used in previous consumption analysis[52]. The metal footprint 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

(MRIO) database. The data for E^k were calculated by applying the expenditure shares in final demand in EXIOBASE 3.3 to the GDP-PPP obtained from the World Development Indicators[51].

We investigated affluence's effects on the per capita MF associated with different expenditure types (i.e. final consumption by household and government and gross capital formation) or categories of goods and services consumed, as Eq. (8) shows.

$$\Delta lnM_{it}^{k} = a_i + a_t + \lambda_k \Delta lnA_{it} + e_{it} \ (8)$$

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

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

$$\Delta lnM_{it}^{k} = a_i + a_t + \psi_k \Delta lnE_{it}^{k} + e_{it} \ (9)$$

$$\Delta lnE_{it}^{k} = a_i + a_t + \omega_k \Delta lnA_{it} + e_{it} \ (10)$$

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

Data availability

EXIOBASE3.3 is available on request from the authors. It will be made available on www.exiobase.eu, once copyright issues to all the pieces of data have been resolved. Data for the dependent and independent variables used in the panel analysis are available online at https://figshare.com/ (DOI: 10.6084/m9.figshare.5797377).

Code availability

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

References

34 Weisz, H. *et al.* Economy-wide material flow accounting. A compilation guide. (Eurostat and the European Commission, 2007).

48 BGS. World Mineral Statistics. (British Geological Survey, London, 2014).

49 USGS. International minerals statistics and information. (US Geological Survey, Washington D.C., 2014).

50 Reichl, C., Schatz, M. & Zsak, G. World mining data. *Minerals Production International Organizing Committee for the World Mining Congresses, Vienna*, 261 (2014).

51 The World Bank. *World Development Indicators*, <http://data.worldbank.org/data-catalog/world-development-indicators> (2017).

52 Hertwich, E. G. & Peters, G. P. Carbon footprint of nations: A global, trade-linked analysis. *Environmental Science & Technology* **43**, 6414-6420 (2009).