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Does Becoming Richer Lead to a Reduction in Natural Resource Consumption? An Empirical Refutation of the Kuznets Material Curve

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Abstract

Over the last three decades, many industrializing countries have experienced economic growth, which coincided with a substantial increase in the use of materials. This puts into question the relationship between economic growth and the use of biomass, fossil fuels and minerals. Using a Material Kuznets Curve framework, this study investigates whether material use automatically reaches a maximum at a given level of development and declines thereafter. Using a new indicator, the material footprint (which quantifies all materials extracted to produce a country's final demand, including imported materials), we investigate this nexus, comparing for the first time different methodologies in the same empirical study. Specifically, we measure the evolution of material footprint (per capita) elasticity to GDP (per capita) in four different ways. Our main results find that all the models lead in a similar direction, seeming to indicate a strong and permanent link between economic growth and development and raw material consumption: There is no sign of strong decoupling. Improving the development and adoption of material-conserving technologies is thus urgent.

Keywords: Decoupling; EKC; MKC; Dematerialization; Material footprint; sustainability; Leapfrogging

JEL codes: O13; Q32

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1. Introduction

In the coming decades, growing populations (9.7 billion in 2050, according to the United Nations) with higher incomes will drive a strong increase in the global demand for goods and services. The amount of materials used throughout the world tripled between 1970 and 1990 (UNEP, 2016). Economic growth is projected to quadruple between 2011 and 2060, and global materials use is projected to more than double, according to OECD scenarios (OECD, 2018). The extraction, processing and utilization of materials are responsible for many environmental problems ranging from greenhouse gas (GHG) emissions to water, air and soil pollution as well as a loss in biodiversity (Brandt, *et al.*, 2014; OECD, 2018; Schandl, *et al.*, 2018). In this context, growth in material use coupled with material extraction is likely to increase the pressure on resource bases and jeopardise future gains in well-being and global sustainability (Steffen, *et al.*, 2015). Today, more than half of greenhouse gas emissions are related to materials management activities (OECD, 2018).

There is now a tendency for empirical studies and technical reports to consider the existence of a decoupling between the level of development and consumption. For example, the OECD projects that material intensity will decline more rapidly than in the recent decades (-1.3% over 2017-2060), reflecting a relative decoupling (if global material intensity increases, it will do so more slowly than GDP). Since the service sectors have a lower material intensity (materials use per unit of output) than agriculture and industry, the organization contends, the global material intensity of the economy is likely to decrease by 2060 (OECD, 2018). We thus use the Environmental Kuznets Curve (EKC) hypothesis (see Appendix A for more details), which maintains that material use will fall at some point in income growth, to investigate the prospects of this decoupling of econometric growth and material use.

This paper makes four major contributions to the extensive literature on the EKC material use nexus. First, we investigate this relationship using material footprint as the dependent variable rather than Domestic Material Consumption (DMC), which is more commonly used in the economics literature. We use not only a new database on material footprint instead of the domestic material consumption indicator but also global material consumption instead of specific natural resources,[3] with the largest possible number of countries and time span (164 countries over 1990-2015). The material footprint of nations is considered a proxy for natural

[3] This avoids ignoring transmaterialisation (substitution between natural resources) leading to a perception of dematerialisation although we also test the assumption of decoupling for different subcategories of natural resources.

resource consumption, so we explore whether the data show evidence of decoupling or demand saturation.

Second, we consider the methodological problems related to the endogeneity between GDP and material footprint, a problem that has been largely neglected in empirical studies. Neglecting this problem leads to an overestimation of the relationship between growth and material footprint. To our best knowledge, only in Pothen and Welsch (2019) is this endogeneity corrected for. However, these authors use infant mortality as their main instrument, with no discussion of the validity of that instrument. Testing endogeneity with the same instrument, exogeneity is not found. We consider the lag in GDP to be a better instrument. Moreover, Pothen and Welsch (2019) analyse their dataset in a static way over a shorter period of time. In our paper, we also assume the persistence of the material footprint over time, which leads us to take a dynamic approach in a broader period. This approach of using static and dynamic panel data models is not taken by the three other studies using material footprint (MF) (cross-section, instrumented between estimator and difference in differences).

Third, we check and test for the elasticity of natural resource consumption relative to GDP per capita in different development stages, over time (different time periods) and with a large number of controls[4] (economic structure, effect of international trade, demographic structure, GDP content/capital formation, urbanization and population density). We also ensure that the results are robust when using other forms of the material Kuznets curve (MKC) (country consumption instead of consumption per capita). Fourth, we offer a simple and general framework to unify and clarify the literature on MKC, decoupling (delinking) and the bell-shaped intensity of use hypothesis.

A major contribution in our results comes from the use of different methodologies and sophisticated econometric models that all lead to similar results: All the models seem to indicate a strong and permanent link between economic growth and development and raw material consumption. Overall, we show that neither the global economy nor its various subgroups strongly decouple from natural resource consumption. There are neither signs of strong decoupling from economic growth over time nor saturation of raw material demand observable for richer countries. Even worse, the income per capita elasticity of material footprint is

[4] [4] Wiedmann, *et al.* (2015) control for population density and domestic extraction, Zheng et al. (2018) check – but do not necessarily control - for the importance of investment, population density, industrialization, domestic extraction and a time trend, while Pothen and Welsch (2019) do not control for any factor (except time trend in their static fixed-effects model).

constant across different levels of development. The GDP per capita elasticity to natural resources per capita is found to range from 0.43 to 1.061 depending on the chosen model. In this context, the empirical evidence fails to demonstrate spontaneous decoupling between raw material use and economic growth even as it has become urgent to decrease material use.

The rest of the paper is organized as follows. In the next section, we present a detailed literature review on the nexus between raw material consumption and economic growth. In the third part, we present the theoretical background of our econometric study, the IPAT identity framework. We then present the data and main descriptive statistics in section 4. In section 5, the methodological approach we have taken and the different empirical frameworks we have used are presented. In section 6, we present the general results; we discuss them in section 7. We conclude in section 8.

2. Literature

2.1 Limited resources and depletion: limits to growth and growth of limits

The sustainability of economies in terms of natural resources availability is likely to be traced to the beginning of economics. Indeed, research on the availability of materials with respect to the economy has a rather long history. Emerging from pre-classical economics, this debate has been progressively extended to a discussion between scientists in other fields, as can be seen in the multitude of studies on this topic disseminated in the last two centuries[5]. Progressively, the intense friction generated on this issue (called sometimes the issue of weak or strong substitutability of natural capital for human-made capital) has led to a scission of economists between environmental and resource economics and ecological economics. While the first view argues that technical progress and free markets have constantly overcome the threat of natural resource depletion (through substitution, exploration, efficiency, scale economies, backstop technologies, etc.), the other side stresses that natural resources and energy are essential factors of economics and cannot be fully replaced by technical or human capital in the long term

[5] Numerous examples are scattered throughout the literature: the dispute between classical economists about the stationary state and the decreasing marginal yield of natural resources (Robinson, 1989)(Robinson, 1989), the *coal question* described by Jevons (1865), the claims of the Conservation Movement at the end of the 19th century (Tilton, 2003), the seminal work of Hotelling Gray and Cassel on the exhaustible nature of natural resources (Cassel, 1923; Gray, 1914; Hotelling, 1931), the initiative launched by the President's Material Policy Commission (Commission, 1952) on the availability of natural resources for the US economy, the end of oil considered in the peak oil theory (Hubbert, 1956), the work on the cost and prices of natural resources initiated by Barnett and Morse (1963), the *Limits to Growth* report (Meadows*, et al.*, 1972) and the quick replies it generated among economists (Dasgupta and Heal, 1974; Goeller and Weinberg, 1978; Nordhaus*, et al.*, 1973; Solow, 1974; Solow, 1974; Stiglitz, 1974; Stiglitz, 1979).

(Boulding, 1966; Daly, 1979; Daly, 1987; Daly, 1997; Georgescu-Roegen, 1971; Georgescu-Roegen, 1975). From this perspective, the finitude of natural resources prevents perpetual long-term economic growth. The debate is then on who will have the last word, between the growth of limits (cornucopians) and the limits to growth (doomsdayers). This diverging view is still observable in opinion surveys among economists and scientists of other fields (Drews and van den Bergh, 2017).

2.2 Twin literatures: Linking the bell-shaped intensity of use hypothesis and the material Kuznets curve

With the 1986 oil counter-shock, the research agenda of environmental and resource economics has become increasingly focused on the capacity of the biosphere to absorb the waste generated by the anthroposphere (Fisher and Ward, 2000; Simpson, *et al.*, 2005). Many scientists in several fields are now warning that global planet boundaries are being crossed (Rockström, *et al.*, 2009; Steffen, *et al.*, 2015) and that this great acceleration has propelled us into a new, instable geological era: the anthropocene (Steffen, *et al.*, 2015). In this context, global warming is but one of the most prominent issues (IPCC, 2014). In addition, while some economists argue that environmental issues are distinct from natural resources issues (Giraud, 2014; Pearce, 1988) other scholars see the increasing emissions of wastes and other pollutants as the other face of unsustainable increasing natural resource consumption (Behrens, *et al.*, 2007; Brooks and Andrews, 1974; Krausmann, *et al.*, 2017; Schandl and West, 2010; Smil, 2013; UNEP, 2019).
Resource scarcity aside, other resource economists have been trying to demonstrate empirically that substitution, technical change and structural change lead economies to become "resource lighter" over time thanks to economic development (increasing GDP per capita). In this specific view, becoming richer naturally provides the solution to the natural resource scarcity issue[6] (Beckerman, 1992). First popularized by (Malenbaum, 1978), the intensity of use hypothesis refers to a bell-shaped relationship (inverted U) between natural resource intensity (natural resource consumption divided by GDP) and GDP per capita. The theory behind this stylized fact involves three main steps (Jaunky, 2012) . In the first step, the industrialization of the agrarian economy requires large quantities of metals and other resources per unit of wealth due to the great need for raw materials for infrastructure construction. The intensity of use increases

[6] If the economic growth of wealth is not too great to compensate for the efficiency obtained by the decreasing intensity of use of natural resources.

at the same time as GDP per capita. In the second step, the demand for industrial goods is saturated while the infrastructure already in place only claims limited quantities of raw materials for its maintenance and replacement, resulting in a peaking intensity of use in the country. In the third step, the economy makes a massive switch to services, and competition from alternative materials and technical change leads to a declining material intensity of use. According to a review by Cleveland and Ruth (1998), this hypothesis is regularly supported for different metals and materials during the 1980s and 1990s although most of these studies use the Domestic Material Consumption[7] (thereafter DMC), now well known to be an international production-biased indicator, and inadequate econometric or visual methods. Several authors have also improved this theory by adding complexity. For instance, Bernardini and Galli (1993) hypothesize that the peak of intensity of use declines when reached more belatedly due to the diffusion of technologies. In these conditions, developing economies switch directly to the best production technologies without necessarily having crossed all the steps (leapfrogging). Other scholars like Labys and Waddell (1989) argue that the bell-shaped intensity of use for one material is not an evidence of dematerialisation of the economy but simply proof of transmaterialisation. In other words, the substitution between materials leads to successive bell-shaped intensities of use.

Beginning with the work of Grossman and Krueger (1995, 1991) and the World Bank's 1992 development report, the Environmental Kuznets Curve (EKC) applies the overall idea of the Kuznets (1955) curve to environmental issues. Although very close to the framework of the intensity of use inverted U, strangely enough, EKC applied to materials (MKC) is not explicitly connected to the work of Malenbaum (1978). The studies associated with this literature empirically try to understand whether per capita natural resource consumption can have an inverted U relationship with GDP per capita. Some other studies have related this question to the decoupling assumption[8] (UNEP, 2011; World Bank, 1992): that is to say, the possibility that GDP per capita increases without involving a proportional increase of natural resource consumption (weak decoupling) or without being accompanied by any absolute increase of natural resource consumption (NRC) at all (strong decoupling). In fact, we can easily show that bell-shaped intensity and MKC analyses are equivalent and follow the same general form (see Appendix A). Specifically, if the inverted U intensity of use of one country decreases more

[7] DMC is based on a production perspective (materials used within the national economy) and does not include the upstream natural resource flows associated with international trade (imports and exports). For instance, it does not include the feed needed for imported meat or the minerals and energy for the production of copper wire.

[8] The report uses the term delinking instead of decoupling

quickly (in the declining phase) than the growth of GDP per capita, we can observe MKC for the country. Scholars then mention the possibility of peak demand for natural resources (Pearce, 2012). A more complex path than EKC is also considered possible in Canas, *et al.* (2003) and de Bruyn and Opschoor (1997), where a third phase following MKC is characterized by technical change slowdown leading to an N-shaped curve. Moreover, less theoretically focused scholars estimate an inverted N-shaped curve (Pothen and Welsch, 2019), or R-shaped curve, for increasing and then stabilizing MKC[9] (Bleischwitz, *et al.*, 2018). Using a more robust measure of raw material consumption (material footprint) and based on a cross-section over the year 2008 for 137 countries, Wiedmann, *et al.* (2015) show that material footprint (as well as its subdivisions) is linearly linked to GDP per capita (see Table 1). Using the metal footprint of nations, the study of Zheng, *et al.* (2018) focuses on 43 countries over the 1995-2013 period to show that GDP per capita is strongly coupled to their dependent variable and that the importance of capital formation (as share of GDP) greatly impacts the relationship between the two variables. Lastly, another article by Pothen and Welsch (2019) examining 144 countries over 1990-2008 shows that a linear relationship between GDP per capita and material footprint is the most reasonable assumption[10].

Table 1 Main results found in recent studies estimating material footprint-GDP per capita elasticity.

Study	MF-GDP per capita elasticity	Period	Model	Comments
Wiedmann et al. 2015	0.6 (MF) 0.9 (ores) 0.86 (construction materials) 1.23 (fuel) 0.57 (crops) 0.46 (fodder)	2008 (137 countries)	Cross-section	All elasticities are significant. Controls: Domestic extraction and population density
Zheng et al. 2018	1.909 (no controls) 0.837 (control of investment share) 1.264 (control of developed Annex B countries)*	1995-2013 (43 countries)	DIF and DIF model	Metal footprint only. Developed countries only. No strict control of endogeneity. Controls: population density,

[9] The authors mainly explain the r curve with the saturation of the demand for materials. We then observe a plateau of demand.

[10] Compared to other assumptions like quadratic or cubic relationships and when taking endogeneity into account.

				industrialization, domestic extraction not correlated to MF.
Pothen and Welsch 2019	*Linear (full)* 0.276 *Quadratic (full)* $-0.74y+0.061y^2$ *Cubic (full)* $-6.952y+0.801y^2-0.029y^3$	1990-2008 (144 countries)	Static panel data (country fixed effects)	GDP per capita in cubic form seems to better fit although no correction of overfitting. Controls: time trends
Pothen and Welsch 2019	*Linear (full)* 0.752 (144 observation) 0.92 (Metal ore) 0.44 (MF bio) 1.027 (Construction Materials) 1.383 (Fossil fuels) 0.785 (OECD) 0.79 (non-OECD)	Average for each country	Instrumental variable between estimator	Control of endogeneity via instrumental variable and non-stationarity with between estimator (Country average for the whole period). No controls. Cubic form is no longer significant. Few observations in sub-regressions (<30)

Note: y denotes log of GDP per capita. * Annex B country growth interaction dummy is not significant when controlling for investment share.

All these studies can in fact be connected to the older theoretical debate of the limits to growth or growth of limits. Indeed, in a finite world in terms of materials[11], the consumption of natural resources can only decrease asymptotically to zero (Solow (1974); Stiglitz, 1974) . In order to maintain a constant growth of GDP, we would need a forever-increasing material efficiency (inverse of intensity of use) or a permanent and progressive unbounded substitution of natural resources by man-made capital. The proof that material efficiency can increase endlessly is under discussion in the empirical literature discussed above. If we substitute natural resources and material efficiency develops quickly enough, we should be able to observe a strong decoupling between economic growth and natural resource consumption. On the other hand, weak decoupling prevents the compatibility of economic growth and finite resources because resource consumption fails to diminish.

[11] The earth is not a stricto-sensus closed system due to yearly meteorite landings, but this mass is negligible for the earth and human consumption.

3. IPAT Identity framework

For our econometric modelling, we use the IPAT[12] identity framework developed by Ehrlich and Holdren (1971):

$$I(P, A, T) = P \times A \times T \qquad (1)$$

where I denotes the impact (consumption or waste), P the population (inhabitants), A the affluence (GDP per capita) and T the technology factor (pollution/material intensity of wealth). While the intensity of use literature has focused its analysis on the relationship between A and T, the MKC and decoupling studies directly examine the relationship between I/P and A. If we adapt the IPAT identity to the natural resource consumption (C) issue, we get:

$$C(P, A, T) = P \times A \times T \qquad (2)$$

where T is now the material intensity of wealth (C/GDP). More specifically, T depends on the material intensity of products from sector j and the share of the value added by this sector j to GDP (structural effect). Thus, we can formulate the previous equation as follows:

$$C(P, A, T) = P \times A \times \left(\sum_{j=1}^{N} \frac{C_j}{VA_j} \times \frac{VA_j}{GDP}\right) \qquad (3)$$

where C_j is the material consumption of sector j and VA_j the value added by sector j. In the literature, some scholars (Lohani and Tilton, 1993) assume that structural effect depends on GDP per capita (consumer preference schools) while material intensity of products depends on the effect of technology through time (leapfrogging school).

In this paper we regress C/P (approximated by the material footprint per capita[13]) against A (GDP per capita: y), year fixed effects capturing technological progress (alternatively, temporal trend) and other control factors (X) identified by the literature as main determinants of natural resource consumption per capita (Cleveland and Ruth, 1998; Dinda, 2004; Gan, *et al.*, 2013; Hwang and Tilton, 1990; Vehmas, *et al.*, 2007). We then have:

$$\ln\left(\frac{C}{P}\right)_{i,t} = \alpha_i + \alpha_t + \beta_1 \ln(y_{it}) + \sum_{h=1}^{P} \ln\left(X_{h,it}\right) \qquad (4)$$

where $\beta_1 = 1$ indicates strong coupling, $0 < \beta_1 < 1$ indicates weak decoupling and $\beta_1 < 0$ indicates strong decoupling. We also consider a quadratic relationship between C/P and y.

[12] Namely, Impact Population Affluence Technology.
[13] This form is sometimes called metabolic rate.

Put another way, similarly to Ausubel and Waggoner (2008), we try to identify through income elasticity whether raw materials are luxury goods, staples or inferior goods. Indeed, the compatibility of GDP growth with finite resources demands that raw materials fall into the class of inferior goods ($\beta_1 < 0$) in the long term. The other control factors are included and described in the next section.

4. Data

4.1 Variables

Using a panel of country data, we examine how material footprint changes as GDP per capita increases.

Dependent variable – Material footprint

There are two different ways to impute domestic extraction of natural resources at the global scale: domestic material consumption (DMC) and material footprint [14] (MF). According to Schaffartzik, *et al.* (2015),

> The DMC indicator reflects so-called apparent consumption and allocates materials used in the production of traded goods and services to the country where production occurs. Exported goods are accounted for in the material use of the importing country with their mass upon crossing the administrative boundary.

Therefore, the DMC is a production-based indicator of material use.

The second measure, MF, uses the global multi-region input-output database EORA and domestic extraction in order to get the Leontief inverse of each sector (raw material quantity required to serve one dollar of final demand for the output of the sector). Multiplying these figures by the final demand results in the material footprint (see Pothen and Welsch, 2019). Alternatively, material footprint equals domestic extraction plus the raw material equivalents of imports minus exports (direct trade flows + upstream material use). Material footprint only accounts for extraction materials in use (with an economic value) and does not include hidden flows associated with extraction (i.e. ecological rucksacks like mining waste, overburden or soil erosion)[15]. This indicator thus relies on a consumption-based approach.

[14] The term Raw Material Consumption (RMC) is sometime used as a synonym.

[15] For more information about indicators including these hidden flows, see the studies of Bringezu, *et al.* (2004) and Krausmann, *et al.* (2017).

For instance, consider the consumption of copper ore to produce copper wire in China for European country foreign final demand. With one approach (DMC), the copper is attached to China, while in the other approach (MF), the copper will be attributed to the European country.

Therefore, the dependent variable we have chosen is the material footprint of nations taken from the UNEP database (2016), which extends the work of Wiedmann, *et al.* (2015). Schandl, *et al.* (2018) provide the general evolutions of these data over time (descriptive statistics). Information is available on the MF for biomass (MFbiomass), metal ores (MFmetal), non-metallic minerals (MFminerals) and fossil fuels (MFfuels).

Explanatory variables

All explanatory variables are taken from the World Bank database. GDP per capita is expressed in purchasing power parity for the year 2011 (GDP PPP$2011).

Data on GDP, gross capital formation as share of GDP (GCF) and value-added share of agriculture (AGRI), services (SERVICES), and industry (INDUSTRY)[16] sectors come from World Bank World Development Indicators (WDI). For comparison across countries and over time, GDP per capita is expressed in PPP-based constant 2011 prices (GDP/CAP). WDI can also provide the share of imports (IMPORT) and exports (EXPORT) in the analysis.

We also control for other country characteristics, including population density (POPDENSITY) and age structure of the population (POP14, POP15-64 and POP65). All these factors may lead countries to converge to different steady-state levels of material footprint. Data on these variables are also obtained from WDI, as is the classification of countries into income groups. Indeed, some studies have demonstrated the role of structural factors such as country size, population structure and population density in demonstrating the use of materials (Giljum, *et al.*, 2014; Steinberger, *et al.*, 2010; Gan et al., 2013).

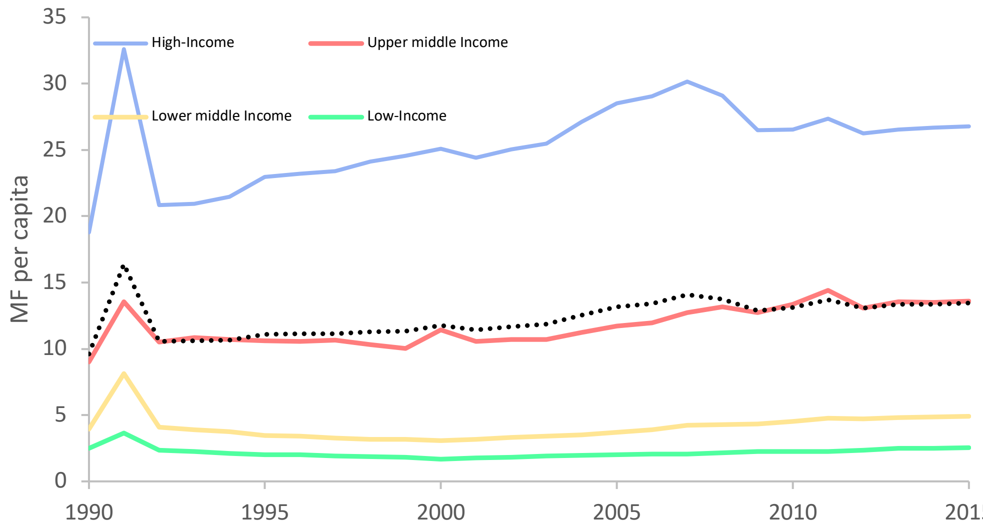
Finally, we have an unbalanced panel of 164 countries from 1990 to 2015, and a balanced panel of 122 countries over the same period for only MF and GDP/CAP.

[16] "The total value added of gross domestic product (GDP) for a country is made up of agriculture, industry, and services excluding financial intermediary services indirectly measured (FISIM). For countries which report value added at basic prices, net indirect taxes are reported as separate line item. Manufacturing value added is a subset of industry. The value-added shares presented in the World Development Indicators for agriculture, industry, and services may not always add up to a hundred percent due to FISIM and net indirect taxes. Note that GDP in the database is measured at purchaser prices. Information about a country's method of price valuation is available in DataBank."

4.2 Descriptive statistics

At first glance at Figure 1, we notice an increase in material footprint, especially for high-income groups, with a relative stabilization since 2010. We also notice an increase to the upper middle-income group.

Figure 1 Material footprint per capita average over time by level of economic development.



Note: The peak in 1991 corresponds to the Gulf War and is an anomaly mainly attributed to Middle Eastern and African countries (see UNEP report p.68).

The scatterplots provided in Figure 2 indicate that the relationship between log GDP per capita and log energy intensity seems linear and positively correlated. Seen descriptively, there does not seem to be a nonlinear relationship between GDP and material footprint: The relationship seems linear whatever the level of development. For instance, if we compute a static income elasticity of material footprint over the period 1990-2015, only 25 of the 122 countries experience absolute decoupling. This share decreases with increasing income quartile (see Table 2). The main descriptive statistics of the variables used in the empirical strategy are presented in Table 3.

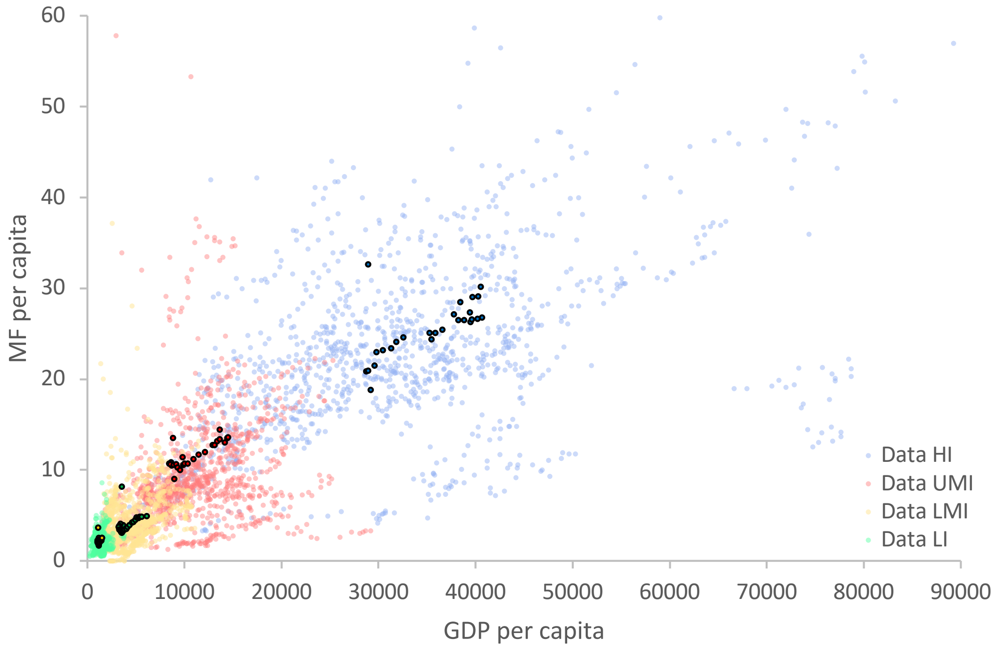
Table 2 Number of countries experiencing absolute decoupling between 1990 and 2015.

Sample	Absolute decoupling	No absolute decoupling	N
All	25	97	122
y<Q1	12	19	31

Q1<y<Q2	6	24	30
Q2<y<Q3	4	26	30
y>Q3	3	28	31

Note: y: average GDP per capita over the period, Q: quartile, Q1 = 3683$; Q2=8684$; Q3=24682$.

Figure 2 Relationship between material footprint per capita and GDP per capita.



Note: Levels of development are represented by colours (blue: high income, red: upper middle income, yellow: lower middle income, green: low income). Circles with thick borders are the means for each group over time.

Table 3 Descriptive statistics of variables

	MFtotal	GDPcap	GCF	Services	Industry	Agriculture	ImportGDP	ExportGDP	Popdensity	Age14	Age1564	Age65
Mean	12.325	15175.170	23.438	54.963	30.160	14.877	44.052	39.086	157.006	31.546	61.554	7.158
std. Deviation	15.373	18229.830	8.136	14.635	13.343	15.525	24.507	25.895	507.582	10.845	7.766	4.956
Min	0.026	246.671	-2.424	4.141	1.882	-173.510	0.016	0.005	1.406	12.991	45.633	0.750
Max	261.845	135321.700	67.911	104.347	213.690	93.977	236.392	231.195	7806.773	51.886	100	26.015
N	4269	4218	3945	3872	3872	3872	4133	4132	4442	4468	4498	4468
No. countries	168	168	165	168	168	168	169	169	172	172	173	172
						Correlation						
MFtotal	1.000											
GDPcap	0.613	1.000										
GCF	0.083	0.050	1.000									
Services	0.394	0.367	-0.057	1.000								
Industry	0.004	0.344	0.254	-0.381	1.000							
Agriculture	-0.370	-0.638	-0.168	-0.599	-0.512	1.000						
ImportGDP	0.370	0.131	0.208	0.130	-0.081	-0.051	1.000					
ExportGDP	0.510	0.433	0.134	0.116	0.215	-0.294	0.815	1.000				
Popdensity	0.259	0.230	0.054	0.149	-0.024	-0.118	0.454	0.520	1.000			
Age14	-0.496	-0.625	-0.125	-0.575	-0.123	0.642	-0.118	-0.288	-0.153	1.000		
Age15-64	0.463	0.625	0.218	0.441	0.279	-0.652	0.159	0.353	0.198	-0.924	1.000	
Age65	0.420	0.472	-0.030	0.615	-0.117	-0.470	0.035	0.131	0.055	-0.857	0.594	1.000

5. Empirical strategy

5.1 General strategy

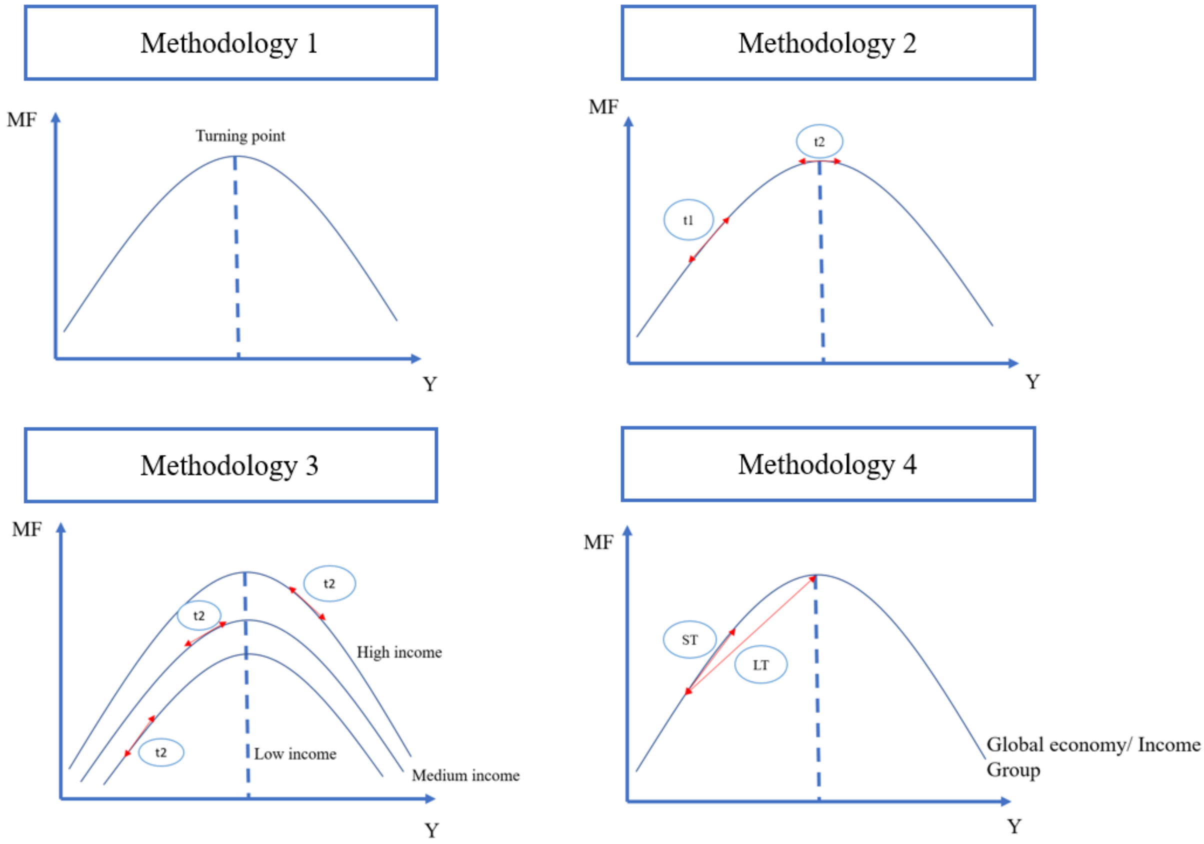
We begin with an unbalanced dataset in order to avoid hasty conclusions. It can also be difficult to tell whether a change over time indicates a real development or just a change in the composition of the sample. Moreover, eliminating countries with missing data could cause sample selection bias if the countries with missing data are systematically different from those that have complete observations over the study period.

We use four strategies to identify the nature of this relationship. First, we demonstrate that a linear relationship between material footprint and GDP per capita is the most likely assumption, especially in comparison to the quadratic assumptions (see Figure 3 below, method 1). Second, elasticities between sub-periods (method 2, Figure 3) are compared as well as elasticities between income groups (method 3, Figure 3). Finally, we examine the short- and long-term elasticity of material footprint per capita to GDP per capita (method 4, Figure 3).

Then, to check for robustness and in order to confirm our results with a different methodology, we also estimate the models using the balanced panel. The conclusions of the paper are robust to these alternative methodologies and data sources.

In order to avoid misspecification, we compare our results using static and dynamic modelling with unbalanced and balanced models and considering several methodological issues: the presence of heteroskedasticity, non-stationarity, serial correlation, reverse causality between material footprint and GDP as well as cross-sectional correlation.

Figure 3 Empirical strategy to identify nonlinearity (or decoupling).



Note: top left: method 1, presence of a quadratic relationship; top right: method 2, existence of a high positive linearity in the first period and a lower one in the second period; bottom left: method 3, a higher elasticity for low-income groups compared to high income, which should be negative; bottom right: different elasticities in the short term (ST) and long term (LT), with a higher value in the short term than in the long term.

5.2 Static model and treatment of endogeneity

A starting point in panel data analysis is to compare the two common models: the fixed-effects (FE) and the random-effects model (RE). In an RE model, the time-invariant variable α_0 is assumed to be uncorrelated with the other explanatory variables compared to the FE model. A Hausman test should be conducted to choose between the FE and RE models. The calculated test statistic was 68.86 (Table B1 in Appendix B), rejecting the null hypothesis that individual effects are uncorrelated with the other explanatory variables at the 1% significance level. Hence, the fixed-effects model is compatible with our study. We thus have:

$$lnMF_{it} = \alpha_0 + \alpha_i + \alpha_t + \beta \ln Y_{it} + \gamma X'_{it} + \varepsilon_{it} \tag{5}$$

where MF is the per capita material footprint for country i in year t, Y_{it} is income per capita for country i in year t, α_0 is the country-fixed effect (to control for unobserved time-invariant heterogeneity resulting from factors such as geographical differences), αi is a constant and α_t the year-fixed effect. We therefore introduce, on the right-hand-side of equation (1), X'_{it}, which is a vector of control variables for material footprint, namely INDUSTRY, AGRICULTURE, AGE14, AGE65, GCF, IMPORTS, EXPORTS and POPDENSITY. εit is the stochastic error term.

Then, in order to test for nonlinearity in the model, we introduce the square of GDP per capita into the previous equation. We now have:

$$MF_{it} = \alpha_0 + \alpha_i + \alpha_t + \beta_1 Y_{it} + \beta_2 Y_{it}^2 + \gamma X'_{it} + \varepsilon_{it} \quad (6)$$

All estimations are corrected for a potential heteroskedasticity problem. But an endogeneity problem may arise, indicating that the independent variable may be correlated with the error term. The problem of endogeneity would lead to biased estimates of the coefficient under an OLS approach. Generally, in the empirical literature, the endogeneity issue in energy consumption (emission or material footprint) is often excluded from the analysis of the EKC, except in the recent paper by Pothen and Welsch (2019). In this paper, we consider that this issue can arise, leading to a biased standard deviation and coefficient. In a context where the purpose is to estimate elasticities for GDP/CAP parameters and the existence of nonlinearities, endogeneity can become very problematic if it is not treated.

To determine whether the underlying endogeneity problem affects the results, we estimate the model using the instrumental variable (IV) method using the first, second and third lag of income per capita as the instrumental variables for income[17] $(Y_{i,t-1} + Y_{i,t-2} + Y_{i,t-3})$. The choice of instruments differs from those used in Pothen and Welsch (2019), where the authors use infant mortality as an instrument. Indeed, after conducting tests, their instrument explains GDP statistically, but it is correlated with the error term and incorrectly excluded from the estimated equation. In our case, the lags of GDP are both strong and valid instruments. Proofs are provided in Appendix B.2.3. We thus have:

$$lnMF_{it} = \alpha_0 + \alpha_i + \alpha_t + \beta_3 \hat{Y}_{it} + \gamma X'_{it} + \varepsilon_{it} \quad (7)$$

[17] We use the first, second and third lag of log per squared capita income as the instrumental variables for squared income per capita in the case where we estimate a nonlinear relationship, see Equation 2.

and

$$\widehat{Y_{i,t}} = \alpha_0 + \alpha_i + \alpha_t + \beta_4 Y_{i,t-1} + \beta_5 Y_{i,t-2} + \beta_6 Y_{i,t-3} + \gamma X'_{it} + \xi_{i,t} \qquad (8)$$

where $\widehat{Y_{i,t}}$ is the predicted value of $Y_{i,t}$. Results for the quality of our instruments are presented in Appendix B.2.

Finally, to consider potential nonlinearity, we also estimate IV models by subgroups (income groups) and sub-period. Results are presented in Table 2, section 6. However, several econometric problems may still arise from estimating previous equations. Autocorrelation is common in panel data, and OLS estimation will determine statistically inefficient coefficient estimates in the presence of autocorrelation. Hence, any inferences that we make could be misleading. To determine whether the data are autocorrelated, we employ the Modified Wald and Wooldridge tests. The statistic for the modified Wald test is 88.551, and the statistic for the Wooldridge test for autocorrelation in the panel is 33.8. Both tests reject the null hypothesis and indicate the presence of autocorrelation at the one-percent level. Finally, we should consider that the panel dataset has a short time dimension ($T = 25$) and a larger country dimension ($N = 173$).

5.3 Unit root test, cointegration and ECM model

Unit root test, stationarity and cointegration

With a long series in panel data (long T), the issue of non-stationarity becomes a concern. This is why we perform a different unit root test from the first generation, which assumes cross-section independence between series. The test of Levin, *et al.* (2002) assumes that all series contains a unit root as the null hypothesis against an alternative hypothesis that all panels are stationary. Conversely, Im, *et al.* (2003) as well as the Maddala and Wu (1999) Fisher-type test assume as alternative assumptions that at least one series is stationary, and some panels are stationary, respectively. Finally, the test of Hadri (2000) assumes that all panels are stationary as a null assumption against the alternative that some panels contain unit roots. Unfortunately, these tests also assume cross-section independence, which is unlikely to hold in most macroeconomic data. We thus also perform the Pesaran (2007) CADF test, which allows for cross-section dependence.

We also perform several tests of cointegration, among them Kao (1999), Pedroni (2004) and Westerlund (2007). All tests lead to the alternative assumption of cointegration.

Error correction model

Our procedure is based on a simple fixed-effects estimation approach, the Mean Group estimator provided by Pesaran and Smith (1995) and the Pooled Group estimator model introduced by Pesaran, *et al.* (1997) and Pesaran, *et al.* (1999). These models are implemented through an error correction model as described in Blackburne and Frank (2007). More formally, we use this error correction form:

$$\Delta MF = \sum_{j=1}^{p-1} \theta_{ij}\, \Delta MF_{i,t-j} + \sum_{j=0}^{p} \delta_{ij}\, \Delta Y_{i,t-j} + \varphi_i (MF_{it-1} - \beta_i Y_{it}) + \mu_i + \epsilon_{it} \qquad (9)$$

where φ_i is the error correction term for the speed of adjustment. It should be negative and significant to allow for the use of the error correction model and demonstrate a return to long-term equilibrium. β_i is the long-term elasticity of material footprint to GDP per capita, while δ_{ij} is short-term elasticity. The Dynamic Fixed Effects (DFE) models assume the homogeneity of all parameters across countries except for intercepts. The Pooled Group Model (PGM) allows heterogeneity for not only the correction speed adjustment term but also for slope and intercept in the short run while homogeneity holds for the long-term coefficient. The Mean Group estimator (MG) assumes heterogeneity across all parameters. Finally, because these models do not deal with cross-sectional dependence, we manually introduce cross-section averages for material footprint per capita and GDP per capita in order to mitigate the impact of this issue (CPMG model, see Binder and Offermanns, 2007). The estimation of these models requires balanced panel data. Our main results are presented in Table 4, section 6, and more detailed results are presented in Appendix B.3.

5.4 Dynamic model with cross-sectional dependence

As mentioned previously, using a CD-test for cross-sectional dependence (Chudik and Pesaran, 2015; Pesaran, 2004), we reject the null hypothesis of cross-section independence. Moreover, the GDP variables in *GDPit* are assumed to be endogenous. Because causality may run in both directions – from GDP to material footprint and vice versa – these regressors may be correlated with the error term. In addition, time-invariant country characteristics (fixed effects), such as geography and time-invariant, may be correlated with the explanatory variables. The fixed effects are contained in the error term in equation 10, which consists of the unobserved country-specific effects, *vi* and observation-specific errors *eit*: *uit* =*vi* +*eit.* Finally, the presence of the lagged dependent variable *MFit-1* gives rise to autocorrelation.

Taking into consideration this last assumption, we consider cross-section dependence and estimate a dynamic panel-data model with heterogeneous coefficients. This model fits a heterogeneous coefficient model in a dynamic panel with dependence between cross-sectional units. The model tests for cross-sectional dependence (CD) and also supports instrumental-variable estimations. Assuming a dynamic panel-data model with heterogeneous coefficients, we have:

$$MF_{i,t} = \alpha_i + \beta 0_i + \beta 1_i MF_{i,t-1} + \beta 2_i Y_{i,t} + \beta 3_i X_{i,t} + \mu_{i,t} \quad (10)$$

$$\mu_{it} = g_i f_t + \varepsilon_{it} \quad (11)$$

where α_i is individual fixed effects, f_t is an unobserved common factor, g_i is heterogeneous factor loading, $X_{i,t}$ is a (1 x K) vector, $\beta 2_i$ is the coefficient of GDP per capita and $\beta 3_i$ is the coefficient vector. The error $\varepsilon_{i,t}$ is independent and identically distributed, and the heterogeneous coefficients are randomly distributed around a common mean. It is assumed that $X_{i,t}$, our vector of control variables for material footprint, is strictly exogenous. In the case when static panel model $\beta 1_i$ = 0, Pesaran (2006) shows that the mean of the coefficients $\beta 1$ can be consistently estimated by adding cross-sectional means of the dependent and all independent variables. The cross-sectional means approximate the unobserved factors. In a dynamic panel-data model, $T^{1/3}$ lags of the cross-sectional means are added to achieve consistency (Chudik and Pesaran, 2015). In our case, we consider 2 lags.

The empirical model is estimated using the dynamic common-correlated effects estimator (DCCE) proposed by Chudik and Pesaran, 2015:

$$MF_{i,t} = \alpha_i + \beta 0_i + \beta 1_i MF_{i,t-1} + \beta 2_i Y_{i,t} + \beta 3_i X_{i,t} + \sum (d_i z_{i,s}) + \mu_{i,t} \quad (12)$$

where $z_{i,s}$ is a (1 x K+1) vector including the cross-sectional means at time s and the sum is over s=t...t-$T^{1/}$3. When we introduce the lag of the dependent variable, endogeneity occurs, so adding solely contemporaneous cross-sectional averages is no longer sufficient to achieve consistency. However, Chudik and Pesaran (2015) show that consistency is gained if lags of the cross-sectional averages are added.

Finally, considering endogeneity of GDP/CAP, we have:

$$MF_{i,t} = \alpha_i + \beta 0_i + \beta 1_i MF_{i,t-1} + \beta 2_i \hat{Y}_{i,t} + \beta 3_i X_{i,t} + \sum (d_i z_{i,s}) + \mu_{i,t} \qquad (13)$$

with

$$\widehat{Y_{i,t}} = \alpha_0 + \alpha_i + \beta_4 \, Y_{i,t-1} + \beta_5 \, Y_{i,t-2} + \beta_6 \, Y_{i,t-3} + \gamma X'_{it} + \xi_{i,t} \qquad (14)$$

6. Results: Relationship between material footprint and economic development

The main results we obtained with our empirical strategy are summarized below in Table 4. We focus on the relationship between material footprint per capita and GDP per capita. Detailed results about each step are provided in Appendices B.1, B.2, B.3 and B.4.

Table 4 Main results of material footprint per capita elasticity to GDP per capita

Model	Coeff. (std. errors)	Correction of…				Introduction of…			
		Heteroskedasticity	Serial correlation	Cross-sectional correlation	Non-stationarity	Instruments	Controls	Time fixed-effects	Obs.
				Linear					
Static FE	0.647 ***(0.051)	Yes	No	No	No	No	No	No	4,042
Static FE	0.742*** (0.084)	Yes	No	No	No	No	Yes	Yes	3,377
Static IV	0.739***(0.091)	Yes	No	No	No	Yes	Yes	Yes	3,066
DCCE	0.888*** (0.077)	Yes	Yes	Yes	No	No	No	No	3,550
DCCE IV	0.544*** (0.114)	Yes	Yes	Yes	No	Yes	No	No	3,211
				Polynomial (Method 1)					
Static FE									
Y	0.166 (0.568)	Yes	No	No	No	No	Yes	Yes	3,377
Y^2	0.035 (0.034)								
Static IV									
Y	0.923 (0.689)	Yes	No	No	No	Yes	Yes	Yes	3,066
Y^2	-0.011 (0.041)								
DCCE									
Y	5.668 (10.953)	Yes	Yes	Yes	No	No	No	No	3,550
Y^2	-0.228 (0.585)								
				Sub-periods (Method 2)					
Static									
1990-2003	0.893***(0.118)	Yes	No	No	No	No	Yes	Yes	1,660
2004-2015	0.756*** (0.110)								1,717
Static IV									
1990-2003	1.031*** (0.155)	Yes	No	No	No	Yes	Yes	Yes	1,350
2004-2015	0.800*** (0.117)								1,716
Static FD		Yes	No	No	Yes	No	Yes	Yes	

1990-2003	0.882***(0.136)								1,553
2004-2015	0.672***(0.103)								1,715
DCCE[a]									
1990-2003	1.330***(0.397)	Yes	Yes	Yes	No	No	No	No	1,595
2004-2015	1.256***(0.356)								1,576
Subgroups (Method 3)									
Static FE									
Non-OECD	0.689*** (0.092)								2,586
OECD	0.788***(0.158)								791
		Yes	No	No	No	No	Yes	Yes	
LI	0.616***(0.128)								524
LMI	0.699***(0.202)								885
UMI	0.608***(0.072)								925
HI	1.114***(0.158)								1,043
Static IV									
Non-OECD	0.685***(0.102)								2,337
OECD	0.954***(0.179)								729
		Yes	No	No	No	Yes	Yes	Yes	
LI	0.703***(0.159)								470
LMI	0.751***(0.240)								805
UMI	0.608***(0.092)								837
HI	1.017***(0.155)								954
DCCE[b]									
Non-OECD	0.651***(0.083)								2,764
OECD	0.752***(0.106)								786
		Yes	Yes	Yes	No	No	No	No	
LI	0.512***(0.164)								537
LMI	0.437***(0.140)								968
UMI	0.845***(0.118)								930
HI	0.748***(0.119)								1,115
Short-term and Long-term (Method 4)									

ECM PMG									
LT	0.520***(0.021)	No	Yes	No	Yes	No	No	No	3,050
ST	0.710***(0.123)								
ECM MG									
LT	0.647***(0.119)	No	Yes	No	Yes	No	No	No	3,050
ST	0.486***(0.122)								
ECM CPMG									
LT	0.867***(0.035)								
ST	0.608***(0.092)	No	Yes	No	Yes	No	No	No	2,928
ECM CMG									
LT	1.061***(0.125)	No	Yes	No	Yes	No	No	No	2,928
ST	0.430***(0.089)								

Notes: *, **, *** denote significant at 10, 5 and 1% respectively.
LT (Long Term), ST (Short Term), LI (Low Income), LMI (Lower Middle Income), HI (High Income), UMI (Upper Middle Income).
a: results have not been computed due to the lack of observations with a DCCE IV framework
b: results confirmed with DCCE IV (Non-OECD, 0.587***(0.198), OECD 0.783***(0.213), LI: 0.285 (0.287), LMI: 0.199 (0.208), UMI: 0.805*** (0149), HI: 0.549***(0.172)

First of all, whatever the method used, the results show the significance of the GDP/CAP parameter on material footprint. All models seem to indicate a strong and permanent link between economic growth and development and raw material consumption. In the static approach, the results are quite similar, and the values are between 0.64 and 0.74 regardless of the estimate model that we adopted or the assumptions and methodological approaches (see linear part of Table 4). Another interesting result is obtained for the elasticity of GDP when the dynamics of the material footprint are taken into account: The value of GDP is decreasing. Ignoring the persistence of material footprint can lead to underestimating the magnitude of GDP. The inclusion of dynamics and correction of different econometric issues do not change the outcomes (see DCCE and IV DCCE in Appendix B.4 for details). Therefore, the different models indicate, at best, relative decoupling.

The use of a quadratic polynomial relationship in order to capture a nonlinear effect is fruitless. Indeed, the parameter to capture a nonlinear effect of income is not significant whatever the econometric models used (see the polynomial section of Table 4). This last result argues in favour of the absence of a nonlinear relationship between income and material footprint.

Using methodology 2 (sub-periods), we observe a small decrease of the income elasticities over time (see the sub-period section of Table 4). But in any case, the nature of the results does not change: Income elasticities are always above zero.

We also estimate models by income groups[18] (see sub-group part of Table 4). Again, the results do not show obvious differences in the elasticities of income parameters. All income elasticities are always above zero, and there is no sign of decreasing income elasticities through the level of development. The use of World Bank or OECD classification does not change the result.

Lastly, using cointegration models, we measure the difference between long- and short-term income elasticities (see the short-term and long-term part of Table 4). All models except ECM PMG show increasing income elasticity when passing from the short to the long term.

In a nutshell, we have checked and tested the elasticity of natural resource consumption relative to GDP per capita for different development stages, for different time periods and with a large number of controls (economic structure, effect of international trade, demographic structure, GDP content/capital formation, urbanization, population density and temporal technological

[18] Our results do not show differences in value of income parameter when using quantile regression models. Quantile regression results are also available on request.

trend). Using different ways to classify countries[19], our results show consistency in magnitude for GDP elasticities among country groups. We also ensure that the result is robust when using other forms of MKC (country consumption instead of consumption per capita)[20].

Overall, we show that the global economy as well as its subgroups do not spontaneously strongly decouple from natural resource consumption. There is neither any sign of strong decoupling from economic growth nor saturation of raw material demand observable for richer countries in different time periods. Even worse, the income per capita elasticity of material footprint is relatively constant across different levels of development. Indeed, out of the four methodologies employed in this paper, only one is able to weakly confirm a decrease in income elasticity of material footprint per capita.

Robustness checks

We also check for the robustness of our results by altering our sample (see Appendices B.5 and B.6). We reproduce the estimations for different subsections of natural resource consumption, see Appendix B.5 (biomass, metals, construction materials, fossil fuels). We get the same results (relative decoupling) although we observe, in line with the literature (Krausmann et al., 2017, 2009; Pothen and Welsch, 2019b; Wiedmann et al., 2015), that biomass has the lowest income elasticity.

Removing three country outliers (Guyana, Brunei, United Arab Emirates) does not impact our results (income elasticity increases moderately at 0.898***). If we remove the year 1991 with its very specific context, again the income elasticity increases to 0.935 and moves closer to unity. Like Pothen and Welsch (2019), we also assess the impact of temporal trend instead of using the time-fixed effect. Again, the results are not impacted, and the time trend is not significant. Finally, we use a moving average (in order to smooth out cycles) of order 3 and order 7 instead of using GDP/CAP as a dependent variable. The results remain consistent for elasticity and decoupling (see Appendix B.6).

Impact of other variables on material footprint

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[19] Indeed, income groups are based on the World Bank definition and the countries stay in one group only over the period. Using the quantile of GDP allows us to see the evolution of one country over the period, but it does not change our conclusions.
[20] Results can be provided on request.

The observation of the impact of other controls on material footprint is also informative. In contrast to other works based on DMC, structural effect (share of services and industry) seems to change the value of material footprint very slightly (elasticity below 0.01). As expected, due to the way material footprint is constructed, the higher the share of export in GDP, the lower the material footprint is. The reverse is also true when using imports as share of GDP. Again, the magnitude of these elasticities is very low. The impact of population density is larger and negative (-0.14 and -0.46). We observe no systematic (same sign) or significant impact for the other variables.

7. Discussion

7.1 Main limitations of the study

Since our results are based on an aggregated weight indicator, heavy and large flow materials dominate the evolution of material footprint. In addition, the results could change through the use of other units like volume (see Rogich (1996) for alternative indicators). Other scholars argue that economies consume material functionality, which is not a function of the weight or volume of raw materials (Cleveland and Ruth, 1998). While we agree with this critique of the aggregative weight indicator, we also note that perpetually rising natural resource consumption (in weight) is not sustainable, and yet an increasing GDP per capita correlates (at least relatively) to increasing material consumption. Moreover, several recent studies show that a large portion of energy use and GHG emissions are associated with the extraction of primary natural resources (Krausmann, *et al.*, 2017; Smil, 2013; UNEP, 2019); consequently, more GDP per capita means more natural resource extraction and thus more energy use and GHG emissions (at least in the short term). Some other scholars like Ashby (2013) and Cleveland and Ruth (1998) have even shown that lower natural resource consumption does not necessarily lead to less pollution when lightweight but energy-consuming materials are substituted for heavy materials that use less energy. For instance, in the construction sector, the substitution of traditional materials (stone, timber) with alloys and composites often reduces natural resource consumption in terms of weight, but the energy and environmental impact of these new materials is higher by three to four orders of magnitude (Gutowski, *et al.*, 2017).

In parallel to this debate on the relationship between primary natural resource consumption flow and GDP per capita, another part of the literature using material flow analysis (MFA) pays more attention to the stock in use rather than the flow of raw materials (Müller, *et al.*, 2011) . At the same time, this literature tends to corroborate the assumption of saturation of stock in use as a function of GDP per capita (logistic growth curve function) although it does not statistically show that this evidence outweighs other possibilities (Krausmann, *et al.*, 2017). Moreover, the timing of the inverted U relationship in reaching the peak of global raw material demand (if possible) is incompatible with the factor 4 claims made as part of the fight against global warming (Gutowski, *et al.*, 2017; Krausmann, *et al.*, 2017). One can draw the same conclusion for the environmental degradation that would carry on through an increasing flow of raw material consumption (even at a decreasing rate). The rare recent studies that have found confirmation for the MKC curve have demonstrated that the inflection point[21] would be well ahead of the current GDP per capita of most countries. For instance, Pothen and Welsch (2019) provide a figure of $125,959 per capita for a potential inflection point, which is higher than the maximum income of their sample. Even if we suppose that this is true, at the current rate of progress of global GDP per capita (2% per year), it would take more than a century to reach this level. Unfortunately this timing is inadequate for the most pressing environmental and resource issues (Steffen, *et al.*, 2015).

We confirm here the results of Wiedmann, *et al.* (2015) indicating that conversely to the DMC indicator, material footprint does not confirm the MKC hypothesis through the impact of development (previously due to the effect of development on structural country production composition). However, we should be cautious about these first results because we are not able to control for the precise nature of GDP consumption (composition of goods and services in final demand). Nevertheless, we think that the potential bias resulting from this omission should not be so decisive. First, reversing the results obtained here would require that higher income countries experience a smaller increase in the services/goods ratio of their final demand consumption. Second, according to two different arguments put forward by Simpson, *et al.* (2005) and Kander (2005), it is unlikely that increasing the share of services over goods in final demand consumption naturally leads to less demand for materials. To begin with, if we follow the Baumol disease argument, we can scarcely grasp whether or not our economies are gradually switching to services because service sectors have seen lower productivity gains than have industrial sectors. The increasing share of services in GDP (in terms of added value) or the surge of the share of labour working in this area thus does not mean that we consume more

[21] The inflection point corresponds to the level of GDP per capita from which the material consumption starts to decline (income elasticity <0).

services and fewer goods. Furthermore, lifecycle analysis is now increasingly showing that most services have a substantial material and energy base. The high energy and raw material requirements for internet infrastructure and data centres are good examples.

7.2 Future studies and other issues to consider

With regard to the role of public policies, as promoted and conceptualized by international organizations and several scholars, decoupling economic growth from material footprint is a widespread attempt to decarbonize economic activities and ensure well-being; however, there is no empirical evidence of this phenomenon. It is also true that there is no proof that strong decoupling is definitively out of reach because the incentives for decoupling are fairly weak (due to low commodity prices). The UNEP has laid out the challenges and opportunities for decoupling if the appropriate policies are considered. This require reducing pressures on limited resources, climate and the environment in general through technological innovation, infrastructure conducive to resource-efficient and low material intensity manufacturing and living, and appropriate attitudes and consumption patterns (UNEP, 2011; UNEP, 2014). For instance, the technical potential to reduce demand for energy through energy efficiency appears to be on the order of 50-80 per cent (factor two-five) for most technical systems (Smith, *et al.*, 2007). Yet institutional, behavioural, organizational and technological barriers to decoupling still exist. Facilitating decoupling will thus require removing these barriers and overcoming the "lock-in".

With regard to the role of technical change, several international organizations and scholars are also calling for an increasing role for R&D investments in material efficiency in order to decouple GDP per capita (and economic growth) from natural resource consumption. In this context, many specialized studies and books have shown that great efficiency gains are always possible (UNEP, 2011). Unfortunately, again, strong decoupling is hindered by material rebound effects in many sectors (Cleveland and Ruth, 1998). For instance, according to different scholars (Gutowski, *et al.*, 2017; Smil, 2013), despite an unprecedented pre-emptive technical change (silicon material efficiency per unit of computation has been multiplied by 10 million between 1970 and 2010[22]), the silicone consumption of the informatics sector has increased by a factor of 60 in the same period. The inability of material efficiency to compensate for economic growth in material consumption is also pointed to by Dahmus (2014) at the

[22] Thanks to Moore's law.

sectorial scale. In particular, this study shows that the reach of absolute decoupling is more likely associated with a low growth in sales than with fast growth in material efficiency.

We also need to go beyond pro-growth or de-growth concerns. Simon Kuznets, considered the father of the modern concept of GDP, warned the US Congress in 1934, "The welfare of a nation can scarcely be inferred from a measurement of national income." We can directly deduce from this quote that it is high time to explore the relationship between raw material consumption and welfare rather than the link between economic growth and natural resources. Economists often point out that economic growth is not an indicator (not even a proxy) of a country's welfare. But we observe that the existing literature is heavily focused on the GDP indicator rather than welfare indicators (exceptions are Mayer, *et al.* (2017); Steinberger and Roberts (2010); Steinberger, *et al.* (2012)). If governments follow the growth of national welfare rather than the increase of economic activity, they urgently need detailed economic studies on how to measure welfare and decouple it, if possible, from raw material consumption.

8. Conclusion

In this study, thanks to a new index of raw material consumption (material footprint), we analyse the relationship between material footprint per capita and GDP per capita for 164 countries over the 1990-2015 period. Using this large panel dataset and four different methodologies, we test whether economic development leads spontaneously to absolute decoupling of raw materials. This assumption is often known as the intensity of use hypothesis or the Material Kuznets Curve. Applying a wide range of econometric models to the largest material footprint database, we observe signs neither of absolute decoupling nor of the possibility of an inflection point (decreasing raw material income elasticity). Our results also underline the need for new studies on the possibility of decoupling welfare from economic growth and raw material consumption.

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Appendix

Appendix A– demonstration of the relationship between the bell-shaped intensity of use hypothesis and the Material Kuznets Curve

As indicated in the introduction, two independent corpora on the relationship between material consumption and income propose to demonstrate a nonlinear relationship. We can link the two streams of literature by slightly adapting some of the methods of Steinberger and Krausmann (2011).

The first one – the bell-shaped intensity of use hypothesis - explores the relationship between natural resource intensity of income and income:

$$\frac{C}{Y} = f(y) \leftrightarrow \frac{\frac{C}{P}}{\frac{Y}{P}} = f(y) \leftrightarrow \frac{c}{y} = f(y)$$

where C is total material consumption, Y the GDP, P the population, c material consumption per capita and y GDP per capita.

The second one, Material Kuznet Curve (MKC), posits a relationship between material consumption per capita (metabolic rate) and GDP per capita:

$$c = f(y)$$

Most of the studies in this second corpus have found that the following log-log relationship exists:

$$\mathrm{c} = \exp(\mathrm{a}) * \mathrm{y}^{\mathrm{b}} \leftrightarrow \log(c) = a + b * \log(y)$$

If we substitute the description of c in the previous equation into the definition of resource intensity, we have:

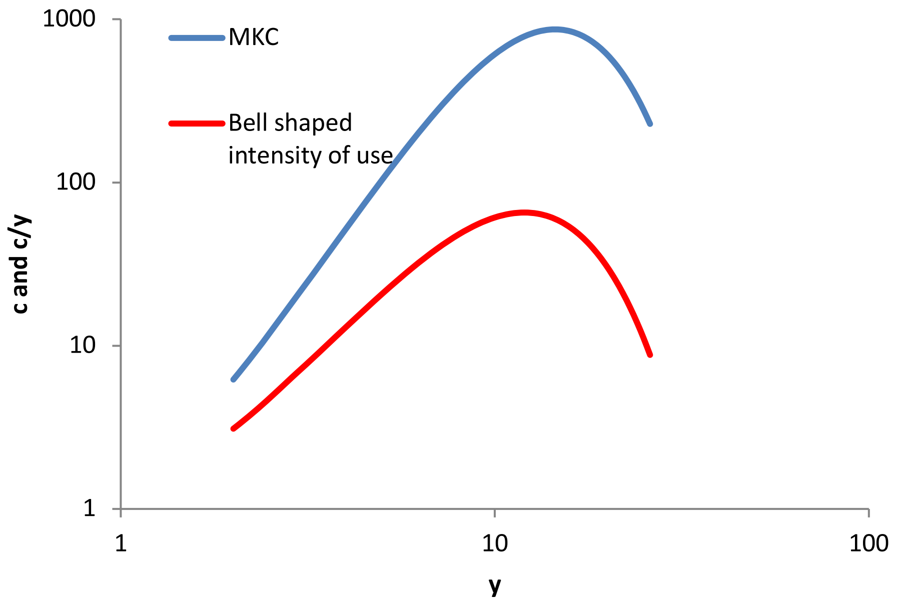
$$Intensity = \frac{c}{y} = \frac{\exp(a) * y^{b}}{y}$$

which we reformulate as:

$$Intensity = \exp(a) * y^{b-1}$$

Thanks to this last equation, we see that the income elasticity of intensity (d=b-1) and the income elasticity of material consumption per capita (b) have a similar form.

Now suppose that there is a nonlinear inverted-U relationship between c and y. This means that the income elasticity of c (b) will be sizable for low-income countries, then lower for medium-income countries and even lower for high-income countries. We can even imagine that b becomes negative and a decrease in consumption (MKC) appears after a certain income threshold. In this context, the MKC will translate mechanically to a bell-shaped intensity of use, confirming that the two literatures examine the same question (see application in the figure below).



B. Empirical results

B. 1 Detailed results for RE, FE, FGLS and IV methods

Table B.1 presents all of the results presented above using RE, FE, FGLS and IV methods.

Table B.1: RE, FE and IV methods.

VARIABLES	FE W/o Year Fixed effects – No control	FE W/o Year Fixed effects	FE	RE	FE NL	IV	IV NL
GDP/CAP (log)	0.632*** (0.0220)	0.796*** (0.0331)	0.742*** (0.0330)	0.756*** (0.0263)	0.166 (0.203)	0.739*** (0.0914)	0.923 (0.689)
GDP2/CAP (log)					0.0345*** (0.0121)		-0.0108 (0.0405)
Gross Capital Formation		0.000505 (0.00111)	0.000658 (0.00105)	0.000393 (0.00101)	0.000869 (0.00102)	0.00223 (0.00180)	0.00216 (0.00183)
SERV %		-0.00100 (0.00142)	-0.00205 (0.00137)	-0.00366*** (0.00134)	-0.00281** (0.00134)	-0.00243 (0.00353)	-0.00219 (0.00323)
INDUS %		-0.00351** (0.00145)	-0.00427*** (0.00131)	-0.00525*** (0.00131)	-0.00453*** (0.00128)	-0.00540 (0.00339)	-0.00531* (0.00320)
IMPORT % GDP		0.00357*** (0.000917)	0.00300*** (0.000862)	0.00321*** (0.000825)	0.00293*** (0.000867)	-0.503** (0.245)	-0.528* (0.296)
EXPORT % GDP		-0.00350*** (0.000906)	-0.00274*** (0.000831)	-0.00269*** (0.000788)	-0.00271*** (0.000848)	-0.00549 (0.00810)	-0.00563 (0.00841)
POPDENSITY (log)		-0.460*** (0.0485)	-0.462*** (0.0847)	-0.141*** (0.0211)	-0.382*** (0.0990)	-0.0356 (0.0251)	-0.0351 (0.0239)
Age<14		-0.00200 (0.00299)	-0.00241 (0.00272)	-0.00235 (0.00260)	-0.00196 (0.00276)	0.00254* (0.00138)	0.00257* (0.00140)
Age>65		-0.0143** (0.00658)	-0.0208** (0.00950)	0.00350 (0.00554)	-0.0229** (0.00934)	-0.00224 (0.00152)	-0.00226 (0.00152)
Constant			0.281*** (0.0515)	0.273*** (0.0520)	0.281*** (0.0504)	-2.019 (1.742)	-2.678 (2.307)
Year fixed effects	No	No	Yes	Yes	Yes	Yes	Yes
Observations	4,042	3,377	3,377	3,377	3,377	3,066	3,066
R-squared	0.276	0.377	0.428	0.4206	0.430	0.4555	0.4554
Number of countries	163	154	154	154	154	154	154

Notes: Robust bootstrapped (5000 replications) standard errors in parentheses *** p<0.01, ** p<0.05, * p<0.1. NL (Nonlinear). The second, third and fourth lag of income log and square of income log are used as instruments in IV estimations for income log and square of income log. For more details about the quality of instruments, see Appendix B.2.

B.2 IV estimates – Tests

B2.1 GDP/CAP only

B2.1.1 Lagged variables as instruments

To consider the potential endogeneity of the GDP per capita variable, we use an instrumental variable with fixed effects. We rely on the two-stage least-squares within estimator (Baltagi, 2008). As instruments, we use the lags of GDP per capita (lag 1, lag 2 and lag 3). According to Robert (2015), lagged variables can be suitable instruments.

We can test for both under-identification and weak identification. The under-identification test is an LM test of whether the equation is identified, i.e. that the excluded instruments are relevant, meaning that they are correlated with the endogenous regressors. Weak identification arises when the excluded instruments are only weakly correlated with the endogenous regressors (Stock and Yogo, 2005).

We explore the degree of correlation between the instruments and the endogenous regressor. Our exogenous variable can be considered a valid instrument if it is correlated with the included endogenous regressors but uncorrelated with the error term.

We can gauge the validity of the instruments. The null hypothesis of each test is that the set of instruments is weak. To perform the Wald tests, we choose a relative rejection rate of 5%. If the test statistic exceeds the critical value, we can conclude that our instruments are not weak. In our model, the Cragg-Donald Wald F statistic is 2621.218 and largely exceeds the critical value (10%, 22.30; 15%,12.83; 20%, 9.54; 10%, 7.80). Our instruments are not weak. These results are corroborated with the Anderson-Rubin test and the Stock-Wright LM statistic, where the respective F statistic is equal to 38.70 and chi-square (3) equals 117.26.

In an instrumental variables (IV) estimation, it is also important to test whether the excluded instruments are valid IVs or not, i.e., whether they are uncorrelated with the error term and correctly excluded from the estimated equation. We perform the Sargan test of the null hypothesis that the excluded instruments are valid instruments. The p-value of χ_2 is equal to 0.169 for a Sargan statistic equal to 3.551. The instruments are therefore valid, and the GDP/cap is endogenous to the material footprint per capita. Finally, we apply a bootstrap correction on the variance covariance matrix to avoid bias in the interpretation of the coefficient's significance level. The results are presented in Table B.2.1 below. The results show that we need to introduce the three lags of GDP/cap to avoid endogeneity.

Table B.2.1: Summary results for first-stage regressions

GDP/CAP (log)	Coef.	Std. Err.	
GCF	0.0010	0.0004	**
Agriculture	-0.0005	0.0003	NS

Industry	0.0003	0.0004	NS
ImportGDP	-0.0001	0.0003	NS
ExportGDP	0.0003	0.0003	NS
Popdensity	-0.0183	0.0197	NS
Age14	-0.0026	0.0008	***
Age65	-0.0021	0.0016	NS
Lag 1 GDP/CAP (log)	1.1556	0.0510	***
Lag 2 GDP/CAP (log)	-0.1413	0.0552	**
Lag 3 GDP/CAP (log)	-0.1025	0.0283	***
F(3, 153) = 1835.59			
R^2		0.99	

*, **, *** denotes significance at 10, 5 and 1% respectively. Test without time-series operator.

The same tests are then performed with more lags (lag 2, lag 3 and lag 4; and lag 3, lag 4 and lag 5). The results are the same. The instruments are only slightly exogenous (the p-value of the Sargan test equals 0.19 and 0.33 respectively). However, considering the loss of observations, we prefer the regression with the first three lags.

B.2.2 GDP/CAP and square of GDP/CAP

In this step, we proceed in the same way as previously except we consider two endogenous variables, the GDP/CAP and the square of GDP/CAP. As instruments, we use the lags of GDP per capita (lag 1, lag 2 and lag 3) and the lags of GDP squared per capita (lag 1, lag 2 and lag 3) respectively.

In our model, the Cragg-Donald Wald F statistic is 1491.5 and largely exceeds the critical value (10%, 21.68; 15%,12.33; 20%, 9.10; 10%, 7.42). Our instruments are not weak. These results are corroborated with the Anderson-Rubin test and the Stock-Wright LM statistic, where the respective F statistic is equal to 20.27 and chi-square (3) equals 122.92.

We perform the Sargan test of the null hypothesis that the excluded instruments are valid. The p-value of $\chi 2$ is equal to 0.131 for a Sargan statistic equal to 7.077.

B.2.3 Infant mortality variables as instruments

There are theoretical issues related to the exogeneity to material footprint of the instrument used in Pothen and Welsch (2019) to perform their IV regression. It is true that we need huge quantities of raw materials in order to ensure an adequate and effective health system. Thus, it is very likely that there is a relationship between the infant mortality rate and material footprint. We are, however, sceptical about the use of the infant mortality rate (and the lag of this same variable) as an instrument of GDP/CAP in an instrumental regression of material footprint. We also question the econometric validity of this instrument as demonstrated below.

In our model, the Cragg-Donald Wald F statistic is 20.165 and exceeds the critical value (10%, 19.93; 15%,11.59; 20%, 8.75; 10%, 7.25). This instrument is not weak. These results are corroborated with the Anderson Rubin test and the Stock-Wright LM statistic, where the respective F statistic is equal to 9.03 and chi-square (3) equals 16.49

In an instrumental variables (IV) estimation, it also is important to conduct a test on whether the excluded instruments are valid IVs or not, i.e., whether they are uncorrelated with the error term and correctly excluded from the estimated equation. We perform the Sargan test of the null hypothesis that the excluded instruments are valid. The p-value of χ_2 is equal to 0.0390 The instrument is therefore not valid and the lagged for GDP/cap variables are more suitable.

B.3 Unit root test, cointegration and VCE model

Unit Root test and Cointegration

At the end of the process, the different results do not converge. Indeed, the Hadri test assumes that material footprint per capita and GDP per capita are I(1), opening the possibility to check for cointegration behaviour. Maddala and Wu (Maddala and Wu, 1999), LLC and IPS tests find that material footprint per capita is I(0) while GDP per capita is I(1), thus forcing us to analyse the relation in difference where the two series are I(0). Finally, Pesaran CADF tests point to two stationary variables in level (I(0)). To ensure the robustness of our results, we check successively the relationship in level only, in difference and through an error correction model. All other control variables follow an I(0) process according to the Maddala and Wu test.

Test	MF cap	MF cap (diff)	GDP cap	GDP cap (diff)
IPS (lags = AIC)	-10.0469***	-64.68***	7.22	-31.87***
Levin-Lin-Chu* (Lags = AIC)	-8.7873***	-55.05***	0.33	-27.49***
Hadri*	91.23***	-4.32	154.95***	6.83***
Maddala and Wu (lags =1)	885.7***	6791.89***	276.4	2152.66***
CIPS (lags =0)	-6.888***	-38.904***	-1.599*	-25.523***
CIPS (lags =1)	-12.887***	-24.988***	-4.216***	-15.597***

Note: When possible, we use the AIC to select the number of lags for each country. The tests indicated an optimal average number of lags of 0.99. *For Hadri and LLC tests, we need balanced data (this reduces the number of countries from 168 to 122). *, **, *** denote significance at 10, 5 and 1% respectively.

Controls	Maddala and Wu (lags =1)
Industry share	457.53***
Agriculture share	898.37***
GCF	655.88***
AGE14-	1201.75***
AGE65+	438.94***
Popdensity	2861.74***
Export GDP share	613.68***

Import GDP share	593,37***

*, **, *** denote significance at 10, 5 and 1% respectively.

For our data, all the tests in their different configurations converge toward the alternative assumption of cointegration. We favour the Westerlund test, which is robust to cross-section dependence with the use of bootstrap replications in order to obtain robust critical values (see Persyn and Westerlund, 2008).

Statistic	Value	Z-value	P-value	Robust P-value
Gt	-2.780	-12.325	0.000	0.000
Ga	-8.445	-2.644	0.004	0.020
Pt	-36.764	-20.896	0.000	0.000
Pa	-8.929	-11.690	0.000	0.000

Table Results from Westerlund cointegration test with 100 bootstrap replications

Table B.3 Results for ECM model

d.lMFtotalhab	DFE	MG	PMG	C-PGM	C-MG
Long run					
GDP/CAP	0.6016574*** (.0371275)	.6466052*** (.1189762)	0.5203143*** (.0206745)	0.8665027*** (.0352299)	1.0613*** (.1252769)
Short run					
Ect	-.3364829*** (0.01312)	-.4957123*** (0.0268271)	-.3477536*** (0.0225852)	-.5589647*** (0.0298074)	-.7110084*** (0.0275359)
d.GDP cap	.3504556*** (0.0538777)	.4862356*** (0.1219066)	.7104061*** (0.1233366)	.6081304 *** (0.0924806)	.4297495*** (0.0890504)
Intercept	-1.147546*** (0.1204579)	-1.393537*** (0.3560395)	-.9273284*** (0.0611587)	.3454524*** (0.4393837)	.4807935 (0.7274385)
Av. Cross-section	NO	NO	NO	YES	YES
Av. Cross-section lags 1	NO	NO	NO	YES	YES
Av. Cross-section lags 2	NO	NO	NO	YES	YES
CD test		70.87***	80.75***	-1.17	4.60***

Note: according to Hausman tests, c-mg estimators are not different from c-pmg estimators. H=1.92 (p=0.15). *, **, *** denote significance at 10, 5 and 1% respectively.

B.4 Results for dynamic common-correlated effects estimator (DCCE)

	Linear	IV						
VARIABLES	DCCE	DCCE	Non-OECD	OECD	LI	LMI	UMI	HI
GDP/CAP	0.888***	0.544***	0.587***	0.783***	0.284	0.199	0.804***	0.549***
	(0.0766)	(0.114)	(0.197)	(0.213)	(0.287)	(0.209)	(0.149)	(0.172)
MF/CAP (lag)	0.191***	0.243***	0.170***	0.256***	0.179**	0.258***	0.192***	0.377***
	(0.0237)	(0.030)	(0.035)	(0.055)	(0.077)	(0.051)	(0.042)	(0.047)
Observations	3550	3211	2499	712	489	872	840	1010
No. countries	160	157	122	35	24	42	41	50
R-squared	0.47	0.40	0.16	0.62	0.34	0.22	0.47	0.54

Notes: *, **, *** denote significance at 10, 5 and 1% respectively.
LI (Low Income), LMI (Lower Middle Income), HI (High Income), UMI (Upper Middle Income).

B.5 Regression by subcomponent of material footprint

VARIABLES		Non-OECD	OECD	LI	LMI	UMI	HI
				Metal			
GDP/CAP (log)	0.818***	0.663***	0.505***	0.752	0.648*	0.497***	0.668***
	(0.201)	(0.214)	(0.151)	(0.598)	(0.350)	(0.181)	(0.161)
MF metal/CAP (lag)	0.338***	0.348***	0.488***	0.389***	0.385***	0.377***	0.424***
	(0.0241)	(0.0274)	(0.0422)	(0.0720)	(0.0469)	(0.0452)	(0.0411)
Observations	3,406	2,643	763	508	922	909	1,067
R-squared	0.485	0.481	0.346	0.444	0.390	0.420	0.432
				Mineral			
GDP/CAP (log)	0.471***	0.412***	0.485	0.0495	0.223	0.594***	0.714***
	(0.133)	(0.129)	(0.336)	(0.270)	(0.296)	(0.189)	(0.274)
MF minerals/CAP(lag)	0.263***	0.265***	0.411***	0.164***	0.358***	0.252***	0.388***
	(0.0257)	(0.0279)	(0.0483)	(0.0569)	(0.0491)	(0.0510)	(0.0401)
Observations	3,406	2,643	763	508	922	909	1,067
R-squared	0.531	0.595	0.386	0.758	0.487	0.544	0.440
				Biomass			
GDP/CAP (log)	0.293***	0.236***	0.0854	0.397**	-0.0762	0.0408	0.440***
	(0.0806)	(0.0898)	(0.146)	(0.171)	(0.193)	(0.132)	(0.143)
MF biomass/CAP(lag)	0.204***	0.199***	0.392***	0.203***	0.176***	0.291***	0.409***
	(0.0254)	(0.0327)	(0.0527)	(0.0576)	(0.0607)	(0.0574)	(0.0442)
Observations	3,406	2,643	763	508	922	909	1,067
R-squared	0.629	0.678	0.533	0.708	0.541	0.618	0.407
				Fossil fuels			
GDP/CAP (log)	0.598***	0.0513	0.462***	0.224**	0.749***	0.518***	0.584
	(0.145)	(0.130)	(0.121)	(0.104)	(0.163)	(0.196)	(0.453)
MF biomass/CAP(lag)	0.284***	0.526***	0.270***	0.515***	0.247***	0.333***	0.287***
	(0.0256)	(0.0466)	(0.0301)	(0.0400)	(0.0466)	(0.0513)	(0.0673)
Observations	3,406	763	2,643	1,067	909	922	508
R-squared	154	0.393	0.399	0.359	0.580	0.535	0.219

Notes: *, **, *** denotes significance at 10, 5 and 1% respectively.
LI (Low Income), LMI (Lower Middle Income), HI (High Income), UMI (Upper Middle Income).

B.6 Robustness checks

VARIABLES	without 1991	without outliers	Moving average (MA) order 3			Moving average (MA) order 7		
				Non-OECD	OECD		Non-OECD	OECD
GDP/CAP	0.935***	0.898***						
	(0.0799)	(0.0780)						
MF/CAP(lag)	0.152***	0.190***	0.128***	0.155***	0.315***	0.209***	0.146***	0.253***
	(0.0230)	(0.0240)	(0.0262)	(0.0299)	(0.0570)	(0.0304)	(0.0343)	(0.0650)
MA order 3			1.064***	0.762***	0.832***			
			(0.106)	(0.118)	(0.147)			
MA order 7						0.586***	0.730**	0.840***
				2,63	746	(0.210)	(0.323)	(0.243)
				0.589	0.347			
Observations	3,417	3,481	3,376	2,133	607	2,740	2,133	607
R-squared	0.514	0.452	0.513	0.589	0.347	0.576	0.648	0.320
No. of countries	160	157	160	125	35	157	122	35

Notes: *, **, *** denote significance at 10, 5 and 1% respectively.