Resource use and its relation to economic growth: The Material Kuznets Curve

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Abstract

The use of natural resources underpins the functioning of the global economy. These raw materials are an important source of economic welfare, but their use also eventually leads to waste and pollution. Thus there exists the notion that if we wish to reduce our waste and emissions, we must reduce the use of the natural resources that cause these waste and emissions in the first place, consequently increasing our resource efficiency. This is otherwise known as the dematerialization of the economy. To achieve this it is crucial to quantify the amount of resources that go into and flow out of the economy, and this is the goal of economy-wide Material Flow Accounts (MFA) developed by EUROSTAT.

This bachelor thesis attempts to contribute to the discussion on dematerialization by investigating whether material use follows an inverted U-shaped relationship in relation to economic development, effectively testing the Material Kuznets Curve hypothesis. The dataset is a panel of 150 industrialized and developing countries for the period 1980-2008. In the case of this analysis, the material use indicator is an extended variant of direct material input (DMI_{ext}) per capita, and serves as the dependent variable in the panel-level and country-level MKC analysis. For the MKC analysis on specific material flows, total domestic consumption (TDE) per capita serves as the dependent variable. As per usual, the independent variable is gross domestic product (GDP) per capita. Results show that there is no indication for a within-sample turning point for DMI_{ext} per capita on the panel-level. The country-level analysis showed that some high-income economies do exhibit an inverted U-shaped relationship, although this is attributed to rising imports of raw materials from abroad. The analysis for separate material flows also gives tentative indications for an MKC, however further analysis shows that the results are sensitive to certain aspects of MKC investigation methodology.

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"When we objectively view the recent past—and two hundred years is recent even in terms of human evolution and certainly in terms of biological evolution—one fact becomes clear: the Industrial Revolution as we now know is not sustainable. We cannot keep using materials and resources the way we do now. But how are we to land softly?"

– Braden R. Allenby, research vice president, Technology and Environment, AT&T

Abbreviations

DEU = Domestic Extraction Used

DMC = Domestic Material Consumption

DMI = Direct Material Input

DMI_{ext} = extended Direct Material Input

EXP = Exports

GDP = Gross Domestic Product

IMP = Imports

PTB = Physical Trade Balance

TDE = Total Domestic Extraction

TMR = Total Material Requirement

UDE = Unused Domestic Extraction

1. Introduction

In his seminal work "The economics of the coming spaceship Earth" (1966), Kenneth Boulding painted a picture of the prevailing way of economic thinking and the changes needed to achieve the ever elusive, yet feasible, sustainable economy. He contrasted the out-dated image of the "cowboy" economy, with its illimitable plains, recklessly exploitative behaviour of its economic agents, and the dire consequences to the environment, against the sustainable economy of the future: the "spaceman" economy. In the spaceman economy, there is no concept of unlimited resources or infinite economic growth, but the acceptance and recognition that Earth is a single spaceship as it were, in which the outputs of economic activity must also serve as inputs for other processes. The measure of success therefore is not the magnitude of throughput of the production factors and the level of consumption, as the cowboy economy stipulates. Rather, in the spaceman economy, success is measured by the quality and extent of the human and natural capital stock in the economy. Any change, technological or otherwise, leading to a minimization of throughput while maintaining or even improving this capital stock is thus considered the highest form of economic success.

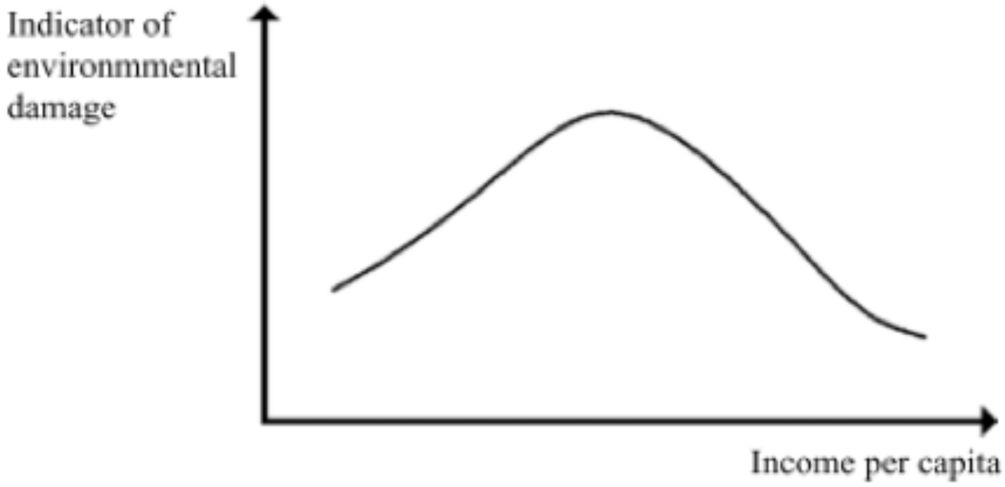
Continuing this train of thought, Ayres and Kneese (1969) also made the important observation that the amount of waste and emissions put out into the environment is the inevitable result of the scale of the economic processes that cause them, as per the fundamental principle of mass conservation[1]. In other words, the economy is inextricably linked to the environment, and its scale of production and consumption directly determine the amount of waste and pollution output. Put even more simply: what goes in, must eventually come out. Moreover, Ayres and Kneese infer that the ability of the environment to absorb this output in the form of pollution and waste is itself a precious natural resource, and steadily increases in value as economic development continues. This value can be interpreted as the environmental and economic cost of waste and pollution. Thus, it is essential to have as a primary objective in our economic processes the decrease of the use of materials with high potential waste and pollution. This way the growing problem of rising costs associated with these negative outputs, as well as resource scarcity, is tackled right at the source.

The European Comission (2011) defines resources in its report on the flagship initiative under the Europe 2020 strategy of creating "A Resource Efficient Europe"; these include raw materials such as fuels, metals, and minerals as well as food, soil, water, air, biomass, and ecosystems. One need only take a glance at trends in resource use to realize that that our current way of employing resources in our daily economic activities is unsustainable. In many ways we have still not let go of the economic state of mind Boulding elaborated on over fifty years ago. A projected 70% increase in demand by 2050 for food, feed and fibre is put into dark perspective by the fact that currently 60% of the world's major ecosystems that underpin the production of these resources have been depleted or are being used in an unsustainable way (European Comission, 2011). In part due to under priced resources and the subsidization of the use of these resources, firms are wrongfully stimulated to deplete and degrade resource stocks to their inevitable exhaustion, even without population growth included as a factor (Panayotou, 1996). This drives up prices of these resources and, paradoxically, businesses then feel the pressure through rising costs driven by the increased scarcity of their essential raw material inputs This vicious circle has long-term costs with short-term benefits. Setting resource efficiency standards and removing distortionary subsidies can stimulate businesses to improve their productivity, lowering the costs of their raw material inputs, and thus raising profitability. This in turn can improve the competitiveness of the European economy as a whole, as well as ensure a sustainable path out of the current economic crisis (European Commission, 2011).

The European Commission (2011) reports that the EU has already seen some improvements on resource efficiency through the promotion of recycling, which is currently a widespread practice across the continent. Waste processing has also been tackled by changing the entire legal framework to cover the whole product lifecycle, emphasized through the EU waste hierarchy of prevention, reuse, recycling and recovery, in an attempt to recapture essential materials from waste to inject these back into production processes. Still, even more so, additional concrete approaches are necessary to accelerate the process of sustainable economic growth. With respect to resource efficient development, the European Union has devised a plan of action with concrete milestones for the near future: the Europe 2020 Strategy. Under this strategy, with its "Roadmap to a Resource Efficient Europe", the EU hopes to achieve a sustainable economy by constructing policy that will aid in decoupling economic growth from resource use, effectively dematerializing the European economy. The Commission indicates current obstacles to resource efficiency: market failures through incorrect resource prices, the short-term vision of business, finance, and politics, knowledge gaps in research, and international competitiveness concerns of countries playing a significant role in the trade of raw materials. The vision of the EU brought to light in this Roadmap is to grow in a way that takes account of resource constraints, providing a high standard of living while lowering the environmental impact through sustainable management of all resources needed to deliver economic growth.

The income—environment relationship has already been investigated to a relatively decent extent, through empirical studies dealing with this relationship by testing the Environmental Kuznets Curve (EKC) hypothesis for different environmental deterioration indicators. Owing its name to Simon Kuznets (1955), who postulated an inverted U-shaped relationship between economic growth and income inequality, the EKC hypothesizes this same type of inverted parabolic relationship, but alternatively between the rate of environmental degradation and the level of economic development (Panayotou, 1993). If one employs empirical data on trends in material use, the theoretical principles derived from the EKC could be applied to investigate the case of dematerialization, by estimating same type of inverted U-shaped relationship between income and resource use indicators, consequently testing the Material Kuznets Curve (MKC) hypothesis (Focacci, 2005). The logic is that the income—resource relationship can be approached similarly to investigations regarding the EKC hypothesis, because if resource stocks reach unsustainable depletion levels, it poses a global environmental threat in the same way as high pollution levels do (Jaunky, 2012). Figure 1 illustrates this relationship. In the context of MKC analysis, the environmental damage indicator would be swapped for a material use indicator.

Figure 1. The Environmental Kuznets Curve



Source: Focacci (2005)

This bachelor thesis will consider if there is indeed any indication for an MKC regarding resource use indicators developed by Eurostat (2001). Continuing the practice of contemporary MKC estimations, this thesis will estimate polynomial regression equations with country-and-time-fixed effects, as well as a time trend to test whether the MKC hypothesis holds at the aggregate material use level, as well as for separate material flows. Country-specific regressions will also be done to gain insight into to what degree there is homogeneity across high-income countries with respect to their income—material use relationship. The most frequently utilized material use indicators have been considered as potential candidates for this analysis, but these are argued to give incorrect estimates on dematerialization as well as suffering from limited data availability. For this thesis, the focus will be on an extended direct material input indicator (DMI_{ext}) for the aggregate and country-level estimations, and total domestic extraction (TDE) for the separate material flows. Both these indicators are characterized by the inclusion of unused domestic extraction (UDE), which is shown to be an important component of resource extraction activities and thus merits inclusion in the MKC analysis. The data includes 150 industrialized and developing countries over the period 1980-2008, gathered from the Global Material Flow Database set up by leading MFA experts: the Sustainable Europe Research Institute (SERI, situated in Vienna, Austria) and the Wuppertal

Institute. At the onset of this study, there was no indication that such an extensive panel dataset had been used in contemporary MKC estimations. Thus this thesis will attempt to contribute to the understanding of the economic growth—material input interdependence, as well as provide an international perspective on whether continued economic growth is treading the desired path to increased resource efficiency.

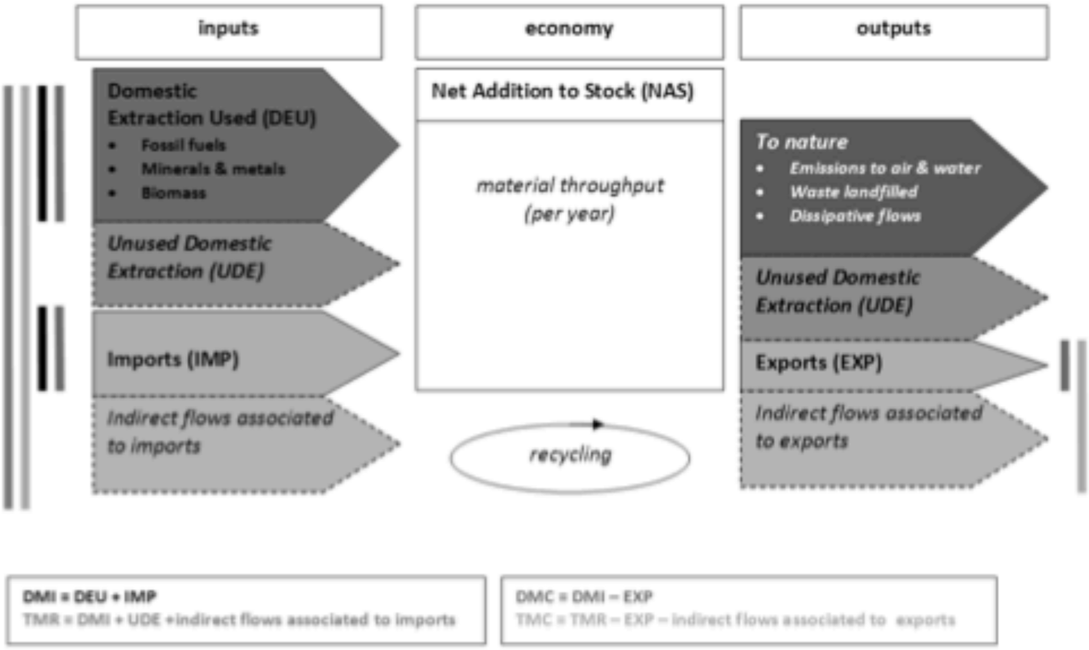
The rest of the thesis is organized as follows. The next section will present MFA and its frequently used indicators. Section 3 covers the main literature on EKC and MKC estimations. After that, section 4 develops the arguments for the chosen indicators. Section 5 shows descriptive statistics for the main variables, the composition of TDE, as well as the econometric methodology. The results of the MKC analysis are presented in section 6, and the implications are discussed in section 7. Finally, section 8 concludes this thesis, offering avenues for further research.

2. Material Flow Accounts and indicators

One of the most important aspects integral to resource efficient development is how to measure progress. In the Roadmap the European Commission stresses the importance of developing material use indicators similar to the system we currently employ for national account aggregates such as GDP. Consequently, Eurostat (2001) has published a Methodological Guide on deriving such a set of indicators using economy-wide Material Flow Accounts (MFA). In this guide, material flow accounts and balances measure the 'metabolism' of the economy, that is, the accounts show the amounts of physical inputs into an economy, material accumulation in the economy and outputs to other economies or back to nature. MFA can be applied to estimate the volume and composition of the material throughput to ascertain economic performance in terms of sustainable development (Bringezu et al., 2004). The accounts capture the aggregates of yearly mass, in tonnes, of materials extracted from the natural environment as well as resources imported to and exported from other economies. The intention of the European Commission is to derive indicators from these flow accounts and compare these to national accounts aggregates such as GDP to show the rate of material use in the economy, and eventually use these indicators side by side as measures of overall environmental and economic health. Due to the fact that water flows represent an enormous magnitude of flows, such that data on all other materials would be of negligible size, it has been excluded from material flow accounts to be analysed separately (Weber, 2011). Correspondingly, air has also been excluded as a material input.

A schematic overview of the economic metabolism and its indicators as specified by Eurostat can be seen in Figure 2. On the left side of the figure are shown all material inputs into the economy, which are then processed inside the economy to eventually exit at the right of the scheme as outputs. The basis for all indicators is domestic extraction used (DEU), which measures all biomass, fossil fuels, minerals and metals extracted for economic use in a country, and thus inherently includes materials that are eventually exported to other countries (Vehmas et al., 2007). Bringezu et al. (2004) also highlight the indirect flows associated with materials that are extracted or moved by domestic economic

Figure 2. Overview of frequently used MFA indicators.



Source: Watson et al. (2011)

activity but do not serve any further economic purpose, otherwise known as unused domestic extraction (UDE), seen as an input below DEU in figure 2. To access the raw materials that are intended for actual economic use, a significant mass of residual materials are also extracted in the process; thus there is no used extraction without unused extraction (Wuppertal Institute, 2013). Think for example of the soil erosion as a result of agriculture, earth excavated during mining activities, or by-catch in the fishing industry. These residual flows are subsequently treated as waste; being either directly dumped, translocated or just left at the extraction site (Wuppertal Institute, 2013). Either way, these residual wastes pose a very large burden to the environment and are important to consider in material flow analyses if one wishes to accurately convey dematerialization of the economy. Additionally, Bringezu et al. (2004) state there are indirect flows associated with upstream DEU and UDE (that is, the 'cradle-to-border' resource footprint) associated with importing goods from abroad, and thus also merit consideration in any analysis on the income—resource use relationship. Another indicator often mentioned that is not shown in the overview is the physical trade balance (PTB), which measures the difference between imported (IMP) and exported (EXP) materials, i.e. the net physical imports (Vehmas et al., 2007). Eurostat (2001) stated criteria against which indicators should be judged to determine whether they are good candidates as core indicators. Criteria included concepts such as the ease of understanding the meaning of the indicator, the level of difficulty and accuracy of compiling it, the extent to which data is available, and statistical compatibility with national accounts aggregates. According to these criteria, initial inspection by Eurostat led to the following three indicators as potential candidates: direct material input (DMI), domestic material consumption (DMC), and total material requirement (TMR). Below follows further explanation of these indicators.

2.1 Direct material input

$$\mathrm{DMI} = \mathrm{DEU} + \mathrm{IMP}$$

This indicator measures the main components of DEU such as biomass, fossil fuels, industrial and construction minerals, and metal ores, as well as imported raw materials and goods for use in economic activities and eventual export. In other words, DMI encompasses all solid, liquid and gaseous materials of economic value for use in production processes of a country (Eurostat, 2001). The inflow of DMI determines the eventual amount of waste and pollution from industry and households for mainly the originating country, but also partly other countries importing the exports produced from DMI in the originating country (Bringezu & Schütz, 2010).

It is common practice for developed countries to import raw materials from abroad, which may lead to a reduction in DMI by lowering the amount of resources extracted domestically (Bringezu et al. 2004). If taken at face value, this could give the indication that the economy could be dematerializing, when in fact it is merely shifting material flows from the domestic to foreign sphere. For example, over 2000-2007, the European economy shows a 2% disparity between its direct material use and total resource footprint. Moreover, annual average EU global resource use per capita is roughly 50 tonnes, of which it seems that only one third is directly used in the economy. The rest is made up of unused domestic extraction (UDE) and indirect flows contributed by imports. Trends in imports to the EU from other countries also show a steady increase since 2000 (Watson et al., 2011). These facts give the indication that DMI does not provide an entirely accurate estimate of the resource base of an economy, because it does not account for these growing domestic indirect flows associated with extraction, as well as those attributed to increasing imports.

Eurostat points out another explanation for the apparent illusion of dematerialization when using this indicator, which lies in the difference between the way domestic extraction is measured versus how the mass of imports are measured. Domestic extraction is measured by its weight in gross raw material (ore/harvest), whilst imports are measured in mass weight of goods crossing the border, irrespective of the extent to which these products have been processed. This poses a problem when trying to capture the global perspective of resource use, as the resource extraction needed for producing the imported goods in the exporting country is not included in the indicator. As mentioned before, if a country imports more goods from abroad, this could lead to a lower DMI due to the movement of extraction practices to other countries and importing goods in the form of processed raw materials that carry less weight than the gross raw material from which they are sourced.

2.2 Domestic material consumption

$$\text{DMC} = \text{DEU} + (\text{IMP} - \text{EXP})$$

Another frequently used MFA indicator considered in the analysis was domestic material consumption (DMC), which measures materials directly used in the economy plus imports minus exports, i.e. the physical trade balance (PTB). This provides a view on the amount of resources directly consumed in the domestic economy. Recent literature has shown a number of issues regarding the comparability of DMC as an indicator for resource use. For example, this indicator suffers from the same disparity as DMI when measuring domestic extraction versus imports, as well as the exclusion of indirect flows such as UDE and those associated with importing materials (Eurostat, 2001). However, set in the of the international context production chain and when interpreting DMC as "domestic waste potential" instead of as an indicator of material consumption per se, the reasoning of attributing upstream flows of trade to those countries where the waste eventually occurs by netting out exports from the equation may have some basis in logic (Weisz, 2004).

Although Eurostat (2001) claimed in its Methodological Guide that DMC appeared to be the "closest physical equivalent to GDP", according to Vehmas et al. (2007) there is a certain incompatibility between these indicators and it stems from the way the GDP and DMC define their respective trade balances. If one recalls the basic definition of GDP:

$$GDP = C + G + I + (E - M)$$

In this definition imports are subtracted from exports, but DMC defines the trade balance by subtracting exports from imports. However, the MFA methodological guide provides an intuitive explanation for this phenomenon; the difference in definition is due to the nature of material versus capital flows, which have opposite directions. If one imports material from abroad, one exports capital and vice versa.

A report by Weber (2011) also calls into question this compatibility and stresses the need for an adjustment of the DMC format. This is due to the fact that it is, as is obvious from its name, an indicator of consumption and as such should only be used in combination with national accounts aggregates of consumption or demand, which GDP is not. Vehmas et al. concur, and they proceed to use the ratio of DMC to Public and Private Consumption (PPC) as a measure of material intensity of consumption, instead of DMC/GDP. Weber further mentions a 2006 Norwegian report to Eurostat that raises an issue regarding the treatment of exports. The report states that it is pointless to compare DMC to GDP if exports have a large share in GDP and more so if imports are also relatively small. As DMC inherently nets out physical exports, it could seem that the ratio of DMC/GDP is improving due to the fact that exports contribute to the GDP, and will thus give the incorrect impression of relative dematerialization.

2.3 Total material requirement

TMR = DEU + UDE + IMP + (upstream DEU + UDE)

In addition to the flows captured by DMI, TMR also includes the before mentioned unused domestic extraction (UDE), as well as indirect flows associated with import (upstream DEU and UDE). Thus it measures the total 'material base' needed for the production and subsequent export of material goods, providing a more accurate account of the global resource footprint of a country (Eurostat, 2001). TMR is the most comprehensive resource use indicator inside the framework of economy-wide MFA, covering the physical basis of an economy that generates its wealth from global resources, as well as those intended for final domestic consumption and exports (Bringezu & Schütz, 2010).

At the time of conducting this study, there were no official international databases that provided extensive cross-country data on TMR. In a technical report published by the European Environment Agency, Bringezu and Schutz (2001) attempt to estimate TMR for the EU-15 and their efforts lead to a consistent but restricted timescale of TMR for 1995-1997. They state that the limited scope can be attributed to the gradual development of the EU and inconsistent accounting methods of different Member States. They amend this with data on TMR for the EU-12 from 1988 to 1994, but these estimates are also plagued by discrepancies caused by the German reunification in 1990. In a later publication Bringezu et al. (2004) continued the development of data on TMR, by consulting many different sources such as national material flow databases and personal communication with other authors. Furthermore, even though most of the countries they analyse for national data use similar accounting conventions and compatible coefficients, there were still some inconsistencies such as exclusions of certain indirect flows and limited data availability on domestic material extraction.

Further investigation on TMR led to an independent report conducted by Meyer (2011), which presents data for three countries (France, Germany, and Italy) for the years 1995, 2000, and 2005. The analysis is quite immersive; he analyses direct and indirect resource use for 59 separate domestic economic activities, as well as 59 product categories, to arrive at a very accurate estimation of TMR for these three countries. He then calculates unused domestic extraction by comparing the estimated TMR values for the three countries against Eurostat data on DMI. By expressing the ratio of DMI/TMR he determines average 'rucksack-factors' for different material flow categories (e.g. biomass, fossil fuels etc.). He continues by multiplying the DMI data for the EU-27 with these rucksack-factors, effectively arriving at an estimated dataset of TMR for all Member States over 2000-2007. However, even though Meyer executes a deep analysis on material use for a wide range of products and economic activities, the obtained time series still remains but an approximation of real values. Even Meyer himself considers "the estimation of TMR data for 24 Member States on base of observations for only three countries […] a second best solution" compared to separately estimating TMR for the EU-27 in the same manner as that was done for France, Germany and Italy. He suggests that this was beyond the scope of his analysis, but it is an avenue for further research, and similar methods were indeed applied in creating the Global Material Flow Database.

The frequently used indicators discussed here are shown to have multiple deficiencies and are the subject of much research in the field of MFA. Section 4 will further clarify as to which indicator has been judged as a proper candidate to be used in this research. The next section will cover the theoretical background, as well as contemporary literature on EKC and MKC estimations.

3. The Kuznets Curves

3.1 The Environmental Kuznets Curve

Due to its attractive economic implications, searching for empirical proof of the existence of an EKC has been subject of a heated debate since the early 1990's. Most of these studies estimate a variation of the following polynomial reduced form equation:

$$p_{it} = \beta_1 y_{it} + \beta_2 y_{it}^2 + \beta_3 y_{it}^3 + \alpha_i + \varphi_t + \varepsilon_{it} \tag{1}$$

where p_{it} represents the per capita environmental indicator level, y_{it} stands for income per capita, and β_k is the coefficient for the income variables. Subscripts i and t indicate country and year, respectively. Dinda (2004) specifies the different income—environment relationship possibilities:

(a) $\beta_1 = \beta_2 = \beta_3 = 0$. No relationship between income and the environmental indicator;
(b) $\beta_1 > 0$ and $\beta_2 = \beta_3 = 0$. A monotonic increasing linear relationship between income and the environmental indicator;
(c) $\beta_1 < 0$ and $\beta_2 = \beta_3 = 0$. A monotonic decreasing relationship;
(d) $\beta_1 > 0$, $\beta_2 < 0$, and $\beta_3 = 0$. An inverted U-shaped relationship;
(e) $\beta_1 < 0$, $\beta_2 > 0$, and $\beta_3 = 0$. A U-shaped relationship;
(f) $\beta_1 > 0$, $\beta_2 < 0$, and $\beta_3 > 0$. A cubic or N-shaped curve;
(g) $\beta_1 < 0$, $\beta_2 > 0$, and $\beta_3 < 0$. A reverse N-shaped curve.

If a relationship such as the one indicated by (d) has been found, we can say that there is evidence for an EKC. However, possible result (g) may also indicate decreasing environmental degradation at higher income levels, thus is also a desired result in the context of sustainable development. These results are of course highly dependent on whether the turning points occur within the observed income levels, calculated by solving ${}^{\delta p}/_{\delta y} = 0$. Moreover, it must also be noted that the resulting magnitudes of the parameters may also affect the shape of the curve, maybe even more so than the signs. This must also be taken into account when interpreting results of the estimations. It is clear that the EKC is only a single possible outcome and the literature further shows that there is indeed much variability in the discovered relationships.

Dinda (2004) further describes the general economic intuition behind the EKC as follows. In the initial stages of accelerating economic development, the rate of resource extraction exceeds the rate of resource generation due to scale effects caused by continued intensification of agriculture and other resource-intensive industries, bringing with it an increase in waste generation toxicity and quantity, leading to higher environmental deterioration. As economic growth reaches higher levels, the economy experiences a structural change in its composition towards more information-intensive industry and services. In addition, the effects of increased environmental expenditures, a heightened environmental awareness of the general public, more stringent enforcement of environmental policies, and most notably technological progress lead to a peak and gradual decline of environmental deterioration. The assumption is that after this turning point has been reached and economic development continues, the transition to consciously tackling environmental issues starts, leading to further improvements in environmental quality.

Although they do not call it as such, Grossman and Krueger (1995) investigated the existence of an EKC for a broad set of local urban air and water quality indicators, e.g. sulphur dioxide concentrations and heavy metal contamination of rivers. Applying reduced form equations to panel data gathered from the Global Environmental Monitoring System, they find some evidence for inverted U-shaped relationships between these indicators and income per capita. Further studies around that same time find similar results for other indicators such as deforestation (Shafik & Bandyopadhyay, 1992) and suspended particulate matter (Selden & Song, 1994). The increasing threat of climate change led more focus to be put on carbon dixiode emissions. Holtz-Eakin and Selden (1995) estimate the relationship between GDP per capita and carbon dioxide and conclude that emissions continue to grow indefinitely in a linear fashion even at high income levels comparable to prosperous countries, showing no signs of a turning point. Talukdar and Meisner (2001) also find some evidence on a monotonically increasing relationship between GDP per capita and carbon dioxide emissions. However, Friedl and Getzner (2003) focus on Austria for the period 1960-1999 and find an N-shaped curve, suggesting that at very high levels of income the scale effects of economic growth overpower any structural or technological effects, thus causing a rise in emissions again after the turning point had been reached. When looking at panel data for Canada over 1970-2000, Lantz and Feng (2006) conclude that there is no evidence for a relationship between GDP and carbon emissions. Thus, the jury still seems to be out on the existence of an EKC for a global pollutant such as carbon dioxide and empirical support for the EKC seems to be limited to localized pollutants that have direct and relatively short-term impacts on the environment (Dinda, 2004).

3.2 The Material Kuznets Curve

Dematerialization, among other factors, has been deemed a prerequisite for a future sustainable economy, and the hypothesis that economic growth may lead to or even be an essential requirement for the path to dematerialization was borne out of the research on the EKC hypothesis (Bringezu et al., 2004). Analogous to the EKC, the MKC hypothesis considers material use at different levels of economic development.

The economic argumentation behind the MKC hypothesis is quite similar to the EKC, as Jaunky (2012) succinctly elaborates as follows. At first, the initial structure of the economy is one of low resource use due to its non-mechanized agricultural and other relatively low impact economic activities. As the economy continues to develop and increase in scale, the use of materials intensifies as a result of industrialization and the increasing demand for main infrastructure such as roads, bridges, and buildings. This will eventually be followed by a gradual change in the economic composition to a service-based economy as higher levels of economic development are reached, through shift in consumer demand for more service-orientated products, continuous technological progress, and increased recycling activities, eventually reducing resource footprint size of the economy. Jaunky mentions an example of this development; telecommunications, of which we have seen the transition from copper cables travelling for miles and miles to the current wireless devices we use on a daily basis. The MKC hypothesis thus postulates an inverted U-shaped relationship between economic growth and material use. The latter part of the relationship can only be expected to decline if the decreasing effects on resource use caused by structural changes and technological progress overpower the increasing effects of the rising scale of economic activity (Vollebergh et al., 2009).

A distinction must be made between *relative* and *absolute dematerialization*. Relative dematerialization indicates that with economic growth, the amount of materials used per unit of GDP decreases (i.e. material intensity), whereas absolute dematerialization occurs when material use decreases with economic development in absolute terms, be that in total mass of materials (i.e. material use) or mass per capita (i.e. material use per capita) (Hinterberger et al., 1997). Vehmas et al. (2007) further elaborate that this needs to be taken into account during MKC analyses and policy considerations, as even though material intensity may be decreasing over time, absolute material use can simultaneously still be increasing, albeit at a lower rate than economic growth. They further imply that another distinction can be made between a *weak* and *strong* MKC, with the former projecting material intensity on the vertical axis, and the latter illustrated with material use or material use per capita on the vertical axis.

The relationship between income and resource use had been addressed some time before EKC and MKC investigations became common practice in the research. For example, Malenbaum (1977) pioneered the research on material use and economic growth by studying the trends of material intensity indices (defined in terms of mass consumed in tonnes per real GDP in constant 1971 US$) for 12 metals and mineral ores from 1950 to 1975, thus investigating relative dematerialization. He analyses the plotted graphs and concludes that there is some indication towards an inverted-U shaped relationship between material intensity and GDP, implying relative dematerialization at high incomes. Later on, Nishiyama (1996) investigated the world trend of copper consumption per capita and its relation to GDP per capita from 1950-1990, concluding from visual inspection that consumption rises at first, and then flattens out as GDP continues to increase, although the evidence is not very strong. Jänicke et al. (1996) analyse the development of a handful of materials for the period 1970-1991 in 32 industrialized countries and through linear calculation visually infer an overall decreasing trend for cement production, but an increase in the use of paper as the economy develops. In the study where the MKC was for the first time addressed as such in academic literature, Focacci (2005) estimates a polynomial regression equation for the material intensity[2] of key metals in five industrialized countries over the period 1960-1995 and supplements this with three other developing countries in another paper (Focacci, 2007). Neither study finds strong evidence to support the strict inverted U-shaped form of the MKC hypothesis, but instead find a declining trend of resource intensity with increasing income levels. More recently, Jaunky (2012) tested the MKC hypothesis for aluminium consumption in 20 developed countries for the years 1970 to 2009. He finds that the hypothesis holds at the individual country level as well as the panel level, even indicating unidirectional causality running from GDP per capita to aluminium intensity through the use of VECM models.

However, there is a limitation of focusing on only such specific material flows in MKC hypothesis testing caused by the risk of overlooking possible substitution effects between materials. It may very well be that over time certain specific material flows are reduced, but this does not necessarily mean that the overall resource use has been lowered. There could be a case of “trans-materialization” instead of dematerialization, and this implies that demand for materials occurs in phases, in which old, lower-quality materials that are used in out of date industrial processes undergo periodic substitution by higher-quality, technologically more suitable materials (Labys & Waddell, 1989). If MKC analysis only considers highly specific material flows such as aluminium or copper, this may not provide sufficient information on the overall dematerialization of an economy. Thus, other research has shown interest in MKC analysis on some aggregate level of material flows to consider dematerialization in broader terms, for example considering material flow analysis indicators such as those developed by EUROSTAT.

Canas et al. (2003) consider DMI for 16 industrialized countries over the period 1960-1998. They estimate quadratic and cubic functional forms for the relationship between DMI and GDP per capita, and find that both specifications hold statistical support. Vehmas et al. (2007) continue this work by analysing the material flow indicators DMC and DMI for the EU-15 over the years 1980-2000.

They use both the weak and strong MKC approaches, finding stronger indication for relative rather than for absolute dematerialization. An earlier paper by Bringezu et al. (2004) tries to break free of studying material flows within the political boundary, seeing that displacement of environmental burdens and resource requirements to other countries by way of increased imports had not been properly considered in the literature. They mention that Muradian and Martinez Alier (2001) correctly point out that if industrialized countries are lowering their domestic material use by importing resource intensive goods from abroad, then investigating their economic growth—material use from a global perspective is not applicable. Bringezu et al. correct for this by not only including domestic material flows, but also the upstream indirect flows, through the use of the TMR resource flow indicator. They analyse 11 countries in an unbalanced panel setting and find weak indication for relative dematerialization. More importantly, they conclude that changes in TMR were influenced more by a rise in indirect flows associated with imports than by DMI.

The next section will cover the justification for which resource use indicator shall be used in this MKC analysis.

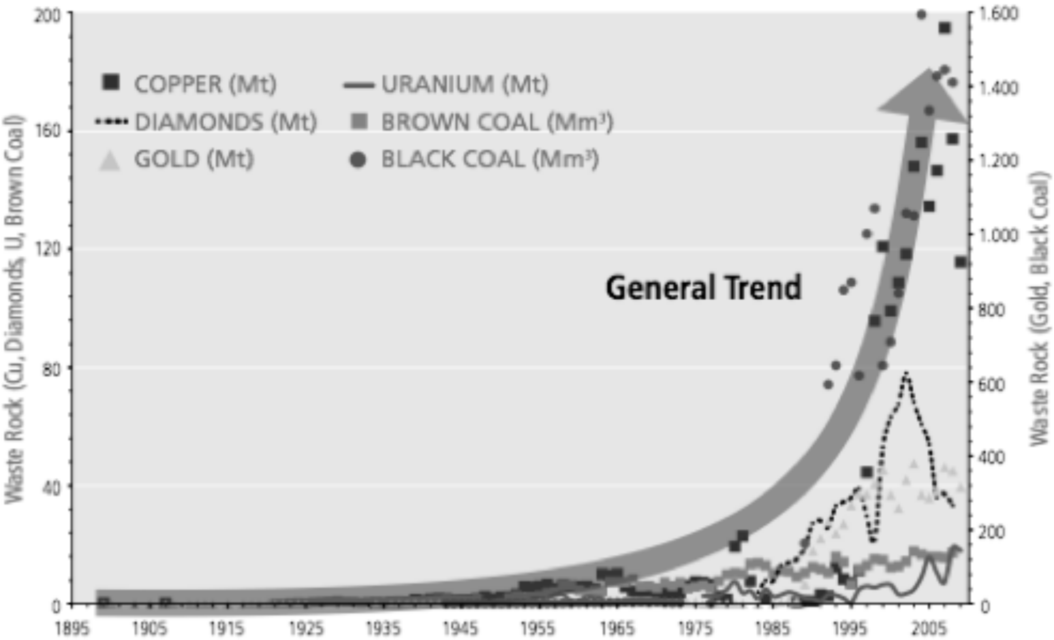
4. Indicator choice

Section 2 gave an informational overview of the three frequently used MFA indicators of resource use: DMI, DMC, and TMR. Of the three, the input indicator TMR is by far the most comprehensive, providing an extensive account of a country's resource footprint associated with production and eventual consumption. It not only includes UDE, but it also attempts to include upstream UDE associated with imported goods. Using this indicator in this MKC analysis could have provided valuable information on the effects of trade and global economic integration on the total resource footprint. Unfortunately, the very limited data availability does not make this analysis possible at the present moment. In concurrence with Meyer's (2011) reasoning that his methods are a second best solution, conducting empirical analysis on his TMR dataset for the EU-27 would not have been a relevant practice for this thesis. For the creation of their dataset, Bringezu et al. (2004) consulted national databases and corresponded personally with other authors; both practices fall out of the scope if this research. Although their work is essential to the development of the MFA field, Bringezu et al. (2004) arrive at a dataset on TMR development that is not quite as extensive as desired, and they had already done the relevant estimations for a handful of countries, as well as the EU-15.

The goal is thus to arrive at an indicator that provides the closest proxy to TMR, such that using this indicator can fulfil the somewhat difficult job of illustrating a country's total resource base that is the source of all its production and consumption, in the domestic as well as the international context. This criterion already leaves out DMC, as this is strictly a domestic consumption indicator rather than a material input indicator. The choice for using an input indicator is logical; the environmental impact of resource use flows from material inputs, not just material consumption. Reducing material inputs and simultaneously increasing economic value is the more accurate dematerialization measure, as material inputs contain domestic final consumption, while also covering a part of international final consumption. Indeed, the productivity measure GDP/DMI indicates the potential of economic value that can be produced per unit of material by domestic production and consumption activities, as well as the materials associated with exports (Bringezu & Schütz, 2010). In a report published by the European Environment Agency, Watson et al. (2011) state that GDP/DMI is therefore a more appropriate measure of resource productivity as it also includes materials used in domestic production for the export market. Watson et al. underpin this with the observed fact that the export market is the main driver behind the increase of material use caused by production and the subsequent demand on global resources, at least for four EU Member States[3]. Furthermore, as GDP contains income sourced from exporting goods, it is important to include the physical basis associated with this part of the national income, captured not only by domestic extraction but also raw material imports that are eventually exported as processed goods, for which the country in return receives capital. Compared to DMC, DMI is more comparable to GDP, as it does not exclude exports from its definition, as netting out exports if they cover a large share of GDP may give the incorrect impression of dematerialization (Weber, 2011).

Finally, diverging from previous research, it was decided to amend DMI with UDE, to improve the accuracy of the environmental pressure associated with material use, as excluding the indirect flows associated with domestic extraction activities may also lead to incorrect conclusions of dematerialization. This is due to the fact that true environmental impact associated with resource extraction is connected to the overall extraction of volume or mass, not only to the part of the extraction which has eventual economic value, i.e. the DEU. (Bringezu & Schütz, 2010). Moreover, as resource extraction continues towards a certain point where the stock is depleted to such a level it becomes more difficult to access, UDE will increase in relation to DEU, as an increasing volume of material must be extracted to access the same amount of valuable resources (Wuppertal Institute, 2013). This is illustrated by figure 3, which shows the exponentially increasing trend of waste rock of the Australian mining industry, a key player in the global resource extraction industry. It is thus safe to assume that as resource extraction practices continue over economic development, their burden to the environment in the form of UDE will increase, and failing to include this flow in MKC analyses does not provide an accurate overview of the dematerialization of the economy.

Figure 3. General trend of waste rock in Australian mining



Source: Wuppertal Institute (2013)

Refraining from netting out the exports and including UDE creates a more strict dematerialization indicator than the oftend used DMI; there is no shifting the burden of physical inputs to other countries in the form of exports (which DMC does), and the total resource use of domestic extraction practices is considered (which DMI and DMC do not). Hence, if a country is able to decrease this measure of resource use, it will be either through increasing its imports (which carry less weight than domestically extracted materials) and/or decreasing its domestic extraction, not through increasing export. If exports were additionally subtracted then this may give even more indication of dematerialization, although this export would eventually end up somewhere else in the world as finished goods and subsequently waste, adding to the global ecological burden of resource use. As it is not possible to account for indirect flows associated with imports or exports for this analysis, attributing the waste and emission potential of inputs to those countries that extract and import these materials, whether they eventually export them or use them for domestic purposes, may be a crude way to overcome the missing data with respect to the indirect flows associated with imports, by possibly attributing more material inputs to the country than may be necessary in the domestic sense. It is the goal of this analysis to gain the most international view on the income—material use relationship as possible, and by using an indicator that illustrates the closest equivalent to the indicator that covers the maximum physical basis of an economy (i.e. TMR), it is still possible to achieve a more comprehensive view than the other indicators for which data is currently available (i.e. DMC). This way not only 'domestic waste potential' (Weisz, 2004) is included, but also to some extent 'international waste potential', by capturing the waste potential of the countries receiving the exports produced by DMI (Bringezu & Schütz, 2010). At this moment, as data on upstream flows attributed to imports is not satisfactory, analysing DMI and additionally including UDE provides a better picture of a country's resource total base in the international use of resources context than DMI alone, and which DMC does not provide at all. The DMI indicator is in this case thus extended with UDE, becoming a closer proxy to TMR:

$$DMI_{ext} = DEU + UDE + IMP$$

Even though increased imports may lead to lower DMI, as these materials are weighed differently when they reach the border as opposed to their raw material equivalents, not including imports at all may lead to an even more distorted view of dematerialization. DMI_{ext} also captures countries that extract little from their own soil but satisfy domestic demand with imported goods, therefore adding to the global demand for resources and playing a role in increasing the burden of resource use to the environment. Until data on indirect flows attributed to trade becomes available to the same extent as DEU and UDE, using DMI_{ext} currently delivers the most comprehensive view on the global relationship between material use and economic growth.

DMI_{ext} aggregates all types of material flows into one indicator, as data on imports was only available at the aggregate level and does not specify material flow categories. In an independent report published by CE Delft, Bruyn et al. (2009) highlight this problem of aggregation across different material flows by posing the question of whether it is the aim of to increase aggregate resource efficiency or focus on the rate reduction of specific resource streams. They illustrate this by analysing the cradle-to-grave environmental impacts of Dutch consumption of a number of different resources and it is evident that each type of resource relates differently to the environment. For example, sand is very heavy but has a relatively low environmental impact in relation to its weight, whilst animal fats impact the environment enormously but carries relatively little weight. They even show that a simple regression analysis barely gives any indication of correlation between weight and impact at all[4]. It does not seem logical then to aggregate these two types of resources into a single indicator, if the aim is to gain knowledge on how to lower the overall environmental footprint by reducing the material flows that have the highest impact. So, one can conclude that for policy relevance it is still necessary to specify different types of resources in income—material flow analyses, which the data on DMI does not initially provide. However, only data for DEU and UDE was available at the separate material flow-level. The Global Material Flow Database estimates this for a large amount of countries and for many different material flow categories, providing the option to investigate the domestic income—resource *extraction* relationship for different material flows. Thus, for four main categories of resources (biomass, fossil fuels, industrial & construction minerals, and metal ores), the following total domestic extraction indicator will be used:

$$\text{TDE} = \text{DEU} + \text{UDE}$$

Eurostat (2001) specifies this indicator as domestic total material requirement (domestic TMR), but to keep the consistency of three-letter abbreviations this thesis will employ TDE. It is obvious that TDE does not provide an accurate account of dematerialization even in the domestic sense, but only a measure of the amount of resources extracted within the domestic boundary. However, it may still be interesting to investigate how domestic extraction of these specific material flows develops over economic growth, as certain flows fulfil different roles during economic development. Furthermore, material flows such as fossil fuels and metal ores for example concern resources that are often available in a certain region of the world, which leads to these countries extracting resources with the aim of exporting these to other countries, thus playing a role in the international trade market and its pressure on the environment. Considering TDE from the waste point of view, each ton of raw material that is extracted will sooner or later be released into the environment as waste or emissions, thus reducing TDE is a crucial pre-requisite towards sustaining the (non-renewable) resource stock and controlling waste accumulation (Bringezu, 2002). More details on the Global Material Flow Database methods of measuring DEU, UDE and IMP is given in the next section, as well as a specification of the included countries and categories of material flows.

5. Data and methodology

5.1 Data sources

The estimations are based on data covering used and unused domestic extraction (DEU and UDE), as well as imports for 150[5,6] countries over the period 1980-2008[7]. This data was gathered from the Global Material Flow Database, which was set up in 2006 and is routinely updated by SERI in collaboration with the Wuppertal Institute. Initially the focus will be on the overall DMI_{ext}, which includes, in addition to DEU and UDE, imports (IMP), of which the data is based on UN Comtrade global accounts of imports in physical mass units (SERI and Dittrich, M., 2012). The MFA database technical report states that DEU data for the four material flow categories is sourced from statistics published by official organizations such as the International Energy Agency (IEA), the British Geological Survey (BGS), US Geological Survey (USGS), World Mining Data (WMD), and the Food and Agriculture Organization of the United Nations. Overall, the data was found to be very reliable, however some gaps were present and had to be filled, mainly for construction minerals. For UDE, the data was not as satisfactory, having to be calculated by multiplying DEU data with factors expressing amounts of unused per used material (in tonne/tonne), following a similar method as Meyer (2011). These factors were, where possible, obtained from national level data and calculations were crosschecked and coordinated with UDE data compiled by the Wuppertal Institute. By summing up the two flows one arrives at total domestic extraction (TDE), and adding IMP to TDE leads to DMI_{ext}. Seeing as SERI and the Wuppertal Institute are both leading in the field of MFA, it can be assumed that the DEU, UDE, and IMP data is of the highest possible quality currently available.

The data on GDP for the included countries has been collected from the United Nations Statistics Division in the National Accounts Main Aggregates Database, and is expressed in constant 2005 US dollars. To ensure consistency in the per capita observations of TDE and GDP, instead of directly acquiring the per capita data separately from the before mentioned databases, it was decided to divide the absolute values by population data also sourced from the United Nations database. The population data is measured as of the 1st of January.

Table 1. Descriptive statistics of the main variables

	Mean	St. Dev.	Minimum	Maximum	Observations
Per capita MFA indicators (t)					
DMI_{ext}	22.21	33.01	1.48	413.14	4350[a]
TDE of biomass	4.85	5.49	0.1679[e]	46.46	4350[a]
TDE of fossil fuels	11.99	29.60	0.0119[e]	314.33	2569[b]
TDE of ind. & constr. minerals	4.37	6.36	0.01	88.30	4321[c]
TDE of metal ores	5.15	12.01	0.0013[e]	103.97	2743[d]
Other variables					
Per capita GDP (2005$)	8,879.83	13,197.49	80.94	82,619.64	4350[a]
Population (mln)	33.96	126.99	0.01	1,328.28	4350[a]

[a]Balanced panel data including 150 countries for the period 1980-2008
[b]Unbalanced panel data including 93 countries for the period 1980-2008
[c]Balanced panel data including 149 countries for the period 1980-2008
[d]Unbalanced panel data including 101 countries for the period 1980-2008
[e]Expressed in kg

5.2 Descriptive statistics

Descriptive statistics of the data are shown in table 1. As can be seen, the variables show a huge amount of variation; in the analysed economies, the dataset for DMI_{ext} fluctuates from roughly 1.5 tonnes per capita up to 413 tonnes per capita with a mean value of about 22 tonnes per capita. The datasets for TDE of the specific material flows were more restricted, except for biomass. The reason why biomass is the most extensive of the four material flow datasets is quite obvious as biomass is the most common domestically extracted raw material across the globe, forming the basis of all domestic extraction activities; it covers (renewable) resources such as animals, feed, food, and forestry (SERI and Dittrich, M., 2012). The TDE for biomass ranges from 0.17 kilograms[8] per capita to 46 tonnes per capita, with a per capita mean of 4.9 tonnes. Similar logic can be applied for explaining the extensive data available for industrial and construction minerals, which includes much utilized materials intended for industry or construction such as sand, gravel, and limestone. The mean for industrial and construction mineral TDE is 4.4 tonnes per capita. With the highest TDE mean of 12 tonnes per capita, fossil fuels carry fewer observations than the other material flows, as certain aspects (i.e. oil) of this type of raw material extraction are tied to a certain group of fossil-fuel rich countries due to naturally occurring resource endowments, thus not every country extracts this type of resource from its own soil. The data for metal ores was also less extensive for this same reason, ranging from a very low 0.0013 kilograms per capita up to

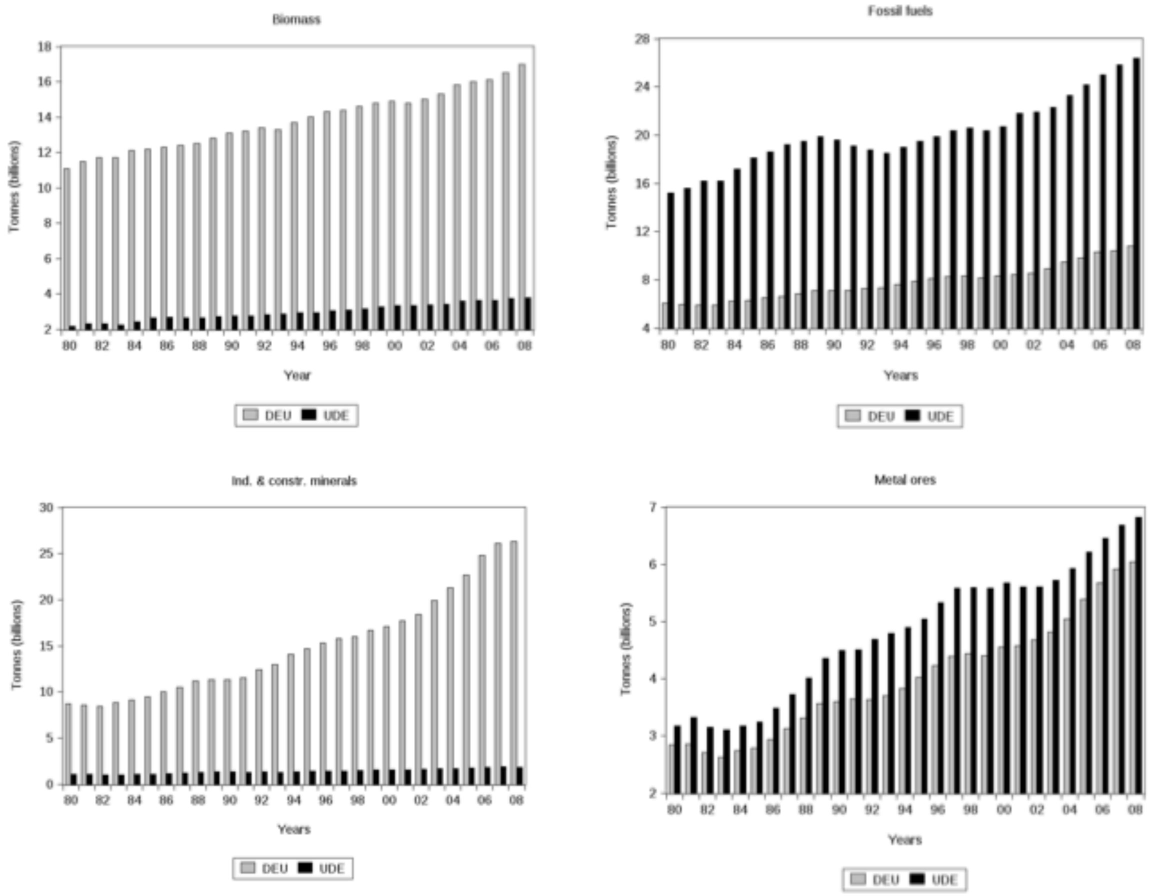
115 tonnes per capita. Rounding off the descriptive statistics of the main variables are the GDP per capita and population variables, carrying a mean of 8,900 2005$ per capita and 33 million persons, respectively. GDP per capita fluctuates from 80 to 83,000 2005$ per capita, covering a wide range of types of economies. This tentatively suggests that the estimation results obtained from this dataset can be generalized over a wide range of countries, and can thus be seen as an international estimate of the general relationship between DMI_{ext} per capita, TDE per capita and GDP per capita. However, caution should be taken when interpreting the results in the framework of dematerialization for TDE per capita, as this indicator only includes domestic extraction without regard for imported materials.

At first glance, the scatterplot (graph 1 in the appendix) for DMI_{ext} shows an increasing linear relationship, thus an educated guess would infer that this is the expected result of the analysis, rejecting the MKC hypothesis. For biomass (graph 2), the scatterplot shows a decline of TDE per capita at higher incomes, indicating a possible MKC-like relationship. Fossil fuels (graph 3) show a less clear relationship, mostly increasing but also enough observations at higher income that could indicate a decline of TDE per capita. Visual inspection of industrial and construction minerals (graph 4) indicate an increasing relationship. Lastly, the scatterplot for the material flow metal ores (graph 5) shows quite a clear indication for an inverted U-shaped relationship.

5.3 Composition of TDE

To gain a visual overview of the composition of TDE, as well as consider the importance of including UDE in the MKC analysis, yearly summations of DEU and UDE were descriptively analysed, of which the results can be seen in figure 4. What is immediately obvious is that the material flows fossil fuels and metal ores carry very large UDE, indicated by the black bars. Extraction of biomass and industrial & construction minerals are relatively efficient, carrying lower UDE in relation to their DEU. This difference in UDE may lie in the method of extracting these flows; fossil fuels and metal ores have very invasive and burdensome extraction techniques compared to biomass and industrial and construction minerals. These graphs further support the notion put forth by Bruyn et al.

***Figure 4*. Bar graphs of DEU and UDE for separate material flows**



(2009) that the differences of how certain material flows relate to the environment is lost in aggregated material flow indicators. To gain policy relevant an environmentally sound insights into dematerialization, specific material flows must be considered, as it is evident here that their extraction practices indeed relate differently to the environment compared to each other. It is also clear that excluding UDE from the MKC analysis, especially for the flows fossil fuels and metal ores, may lead to inconsistent results regarding dematerialization.

To consider a more updated picture, cross-section data on DEU and UDE from the year 2005 on the four material flows was also analysed in a descriptive manner. This was then sorted by region to gain further insight in the global state of resource extraction and the relation of DEU and UDE[9]. Results of this analysis are given in table 2. It must be said that no strong conclusions about the total amount of extractions should be made, due to each material flow having a

Table 2. Regional composition of TDE in 2005[a]

	Europe	North America	Latin America & Caribbean	Middle East & Asia	Oceania	Africa
TDE biomass	114	19	192	79	77	220
DEU	91	16	168	64	67	190
UDE	24	3	24	15	10	30
Share UDE/TDE[b]	21%	18%	13%	19%	13%	14%
TDE fossil fuels	208	61	65	412	318	92
DEU	79	16	40	330	24	42
UDE	129	46	25	82	295	50
Share UDE/TDE[b]	62%	75%	39%	20%	93%	55%
TDE industrial and construction minerals	260	22	130	218	45	100
DEU	225	20	128	209	42	66
UDE	35	2	2	9	3	33
Share UDE/TDE[b]	14%	10%	2%	4%	8%	33%
TDE metal ores	37	16	237	21	124	84
DEU	17	7	90	16	59	34
UDE	20	9	147	5	65	50
Share UDE/TDE[b]	54%	56%	62%	23%	53%	60%

[a] Values are expressed in tonnes per capita (t/cap)

[b] Values expressed in percentages (%)

different number of observations, thus it not being totally indicative for the global resource footprint of a region. What should be focused on in this case is the share of UDE in TDE, which can shed light on the resource extraction efficiency of a particular industry in a certain region. A high share of UDE in TDE indicates that the resource extraction industry has low extraction efficiency and vice versa.

Similar to the yearly summations results, the extraction of biomass is relatively efficient across all regions, with Europe being relatively the most inefficient in extracting biomass. The overall efficiency of this industry may be attributed to the fact that it is the first large-scale economic activity, thus many years have already been devoted to improving agricultural production. The two regions Latin America & Caribbean and Africa show the highest amount of biomass extraction, which could be explained by the fact that these regions are still largely agriculture-based when compared to the other regions. These regions are also more efficient in extracting biomass than other more developed regions such as Europe and North America.

The extraction of fossil fuels poses a very large burden on the environment in relatively all regions except the Middle East & Asia. Compared to the other regions, the region Middle East & Asia extracted the most fossil fuels from its own soil in 2005; Saudi Arabia is the world's leading oil-producing en exporting country, covering about 18% of global oil exports (Ria Novosti, 2012). It may be conjectured that the low UDE/TDE share is due to the high amount of oil endowment to the region and the relative ease of reaching this resource compared to other regions, which leads to less residual material being extracted along with the oil intended for economic use. Strikingly, the region Oceania shows a very high share of UDE in TDE (93%). Most of this is attributable to the Australian mining industry, it being Australia's primary industry, covering a large share of the Australian national income. Australia is the worlds largest net exporter of coal, capturing 29% of global coal exports, as well as being one of the world's leading miners of uranium (Trade Earthmovers Australia, 2013). In 2005, the Australian economy extracted roughly 21 tonnes per capita of fossil fuels intended for economic use, bringing with it a UDE of a staggering 289 tonnes per capita, signalling a very low resource extraction efficiency and high environmental burden of this industry on the environment.

Less noteworthy occurrences are observed for the material flow industrial and construction minerals; it is a relatively efficient industry across the board, with Africa the most inefficient of all the regions. The regions Latin America & Caribbean and Middle East & Asia exhibit very high resource extraction efficiency. Because of some significant data gaps (even in industrialized countries), this material flow was subject to some estimation procedures, which could lead to inaccurate estimates of true industrial and construction mineral extraction practices.

For the material flow metal ores, most regions exhibit some level of resource extraction inefficiency, which could be attributed to the highly environmentally invasive nature of acquiring this type of raw material: i.e. mining. Latin America & Caribbean exhibit the highest mass of metal ore extraction in 2005, with Chile leading this pack of countries at a very high TDE of 101 tonnes per capita. Chile has a burgeoning copper mining industry, which provides it with 20% of its GDP and 60% of its exports, and services the global copper export at 5% with just one of its mines at Escondida, the world largest of its kind (The Economist, 2013).

After initial analysis of the composition of TDE data, it seems that the extraction of fossil fuels and metal ores pose relatively the largest environmental burden due to their high share of UDE in TDE.

5.4 Econometric methodology

Due to the interest being in discovering the common trend between the observations, the data is pooled so that these can be characterized by the same regression equation (Bringezu et al., 2004). The calculations will largely follow previous research on EKC and MKC estimations, specifying polynomial reduced form equations with DMI_{ext} and TDE per capita as the dependent variables and GDP per capita as the explanatory variable. Yet it is important to allow for enough country-specific and time-specific heterogeneity by including both country and time fixed effects, as well as country-specific time trends and heterogeneous regression parameters to avoid the problem of omitted variable bias (List & Gallet, 1999; Dijkgraaf & Vollebergh, 2005). This is rather intuitive, as countries may differ with respect to their resource use in relation to their economic growth as a result of factors such as differences in resource endowments, infrastructure, public pressure and economic, social and political factors (Aslanidis, 2009). Thus, a model that follows the assumption of homogeneity is not able to capture the complex effects exhibited by heterogeneous objects such as countries (Brock & Durlauf, 2001).

However, Vollebergh et al. (2009) mention that country and time controls can be specified at different levels flexibility, which gives rise to the fundamental dilemma of how much flexibility to introduce in the reduced form equation estimation. Too much flexibil4ity and the independent variables lose their entire explanatory power; too little and their power is overestimated. For this research it has been opted to choose for the inclusion of country fixed effects, and expand this with time fixed effects as well as a time trend. The fixed effects are introduced through the use of dummies. The time trends is an additional independent variable start at the first observation of each cross-section and increase incrementally up to the last observation of each cross section, effectively capturing developments over time for the period 1980-2008.

The regressions roughly follow the previous EKC and MKC research by estimating various specifications of the following polynomial log-linear reduced form equation:

$$\ln(p_{it}) = \beta_1[\ln(y_{it})] + \beta_2[\ln(y_{it})]^2 + \beta_3[\ln(y_{it})]^3 + \alpha_i + \varphi_t + \beta_4 t + \varepsilon_{it}$$

$$i = 1, 2, \dots, 151; t = 1980, 1981, \dots, 2008 \qquad (2)$$

where p_{it} is dependent variable DMI_{ext} or TDE per capita, and y_{it} is explanatory variable GDP per capita. The slope coefficients to be estimated are represented by the unknown parameters β, whilst y_{it} represents the observed income values for country i at time t. The α_i term captures time-invariant country fixed effects, allowing for vertical shifts of the country specific income-resource use relationship, effectively capturing the before-mentioned country-specific differences. Time fixed effects (φ_t) and the time trend (t) are also included in the estimation, which control for year-specific influences such as technology in use, oil prices and resource policy, as well as trends these factors exhibit over the sample time period. Finally, ε_{it} is the contemporaneous error term. As is evident from the expression of the dependent variable (tonnes per capita), it has been chosen to investigate absolute dematerialization, to avoid any misrepresentations of the rate of sustainable development caused by expressions of ratios of resource use and income. Furthermore, natural logarithms have been taken from the variables to normalize the data and improve the interpretation of the estimation results, as the data was highly skewed and concentrated in the lower left corner of the initial scatter plots of the main variables.

The estimation procedure follows a few steps. Firstly, DMI_{ext} is subjected to regression in a balanced panel setting to gain an overall picture of the income—resource use relationship. Linear, quadratic and cubic models are estimated, to investigate the existence of a linear relationship, an inverted U-shaped relationship (MKC) as well as a possible cubic relationship. For all specifications, OLS regressions are performed for GDP per capita on DMI_{ext} per capita, then these models will be extended by accounting for country and time fixed effects, and after that including a time trend. Previous research has shown that fixed effects estimators are more suitable for MKC model calculations, so fixed effects specifications will be used in this research also (Bringezu et al., 2001; Canas et al., 2003). These steps are repeated to specify regressions for each of the four material flows, but in an unbalanced panel setting, as some countries do not extract certain materials from their own soil, or start extraction of materials after 1980. In this case GDP per capita is regressed on TDE per capita. For both indicators, *F*-tests are performed at every step to determine which model is superior in explaining the income-resource use relationship. Lastly, to gain rudimentary insight into possible income parameter heterogeneity, it was deemed to be interesting to make country-level comparisons of the resulting income parameters for $\mathrm{DMI}_{\mathrm{ext}}$ per capita, as well as visually inspect the individual scatterplots for a group of countries consisting of the largest economies of the dataset in absolute GDP terms[10]. These estimations serve the purpose of acquiring more information on where these high-income countries sit on the MKC and if these countries relate differently to $\mathrm{DMI}_{\mathrm{ext}}$ with respect to economic growth. As mentioned before, the MKC hypothesis holds only if the income parameters are estimated to be $\beta_1 > 0,\ \beta_2 < 0$ for the quadratic model, and additionally $\beta_3 = 0$ for the cubic specification. If $\beta_3 < 0$, this may also indicate a positive result with respect to dematerialization at higher income, though not necessarily exhibiting the inverted U-shaped relationship. Furthermore, in addition to the signs of the parameters, parameter magnitudes must also be considered at the same level as the parameter signs, as these also affect the shape of the income—material use curve. To see whether the resulting parameters lead to within-sample turning points, the following mathematical problem is solved, to arrive at y*: ${}^{\delta p}/_{\delta y} = 0$.

Even though the reduced form approach has a large advantage in its ease of use, it is not possible and thus not attempted in this investigation to make any inferences regarding causality in either direction or to ascertain how characteristics of income growth (i.e. composition of output, education, or regulations) or other variables influence the income—resource use relationship. Consequently, it must be stressed that it is the aim of this paper to ascertain *whether* the MKC hypothesis holds, but not to investigate as to *why* it holds or *what factors* influence the shape of this relationship; a practice which is currently outside of the scope if this thesis.

6. Results

6.1 Panel-level DMI_{ext}

The base model estimations shown in detailed table 1 in the appendix initially led to a linear model, but these specifications tend to show biased estimates, due to not accounting for unobserved differences between countries. To control for this, a country-fixed effects estimator is introduced in the models, which assumes that the variation between countries can be captured by differences in the constant term (Canas et al., 2003). F-tests indicate that country-fixed effects are a significant addition, improving the explanatory power of the model from 55% to 97%, leading to a cubic model specification providing the best fit for the data.

Table 3 presents a summary of the main relevant estimation results for cubic model parameter estimations for DMI_{ext} per capita. In addition to the country-fixed effects, a time-fixed effects estimator was also incorporated into the regressions and, as the *F*-test shows, is a significant improvement over the previous specification. This indicates that the factor of time significantly affects the relationship between GDP per capita and TDE per capita, and it also affects

Table 3. Summary results of cubic model parameter estimations for DMI_{ext}[a,b]

	Country-fixed effects[c]	Country-and-time fixed effects[c]	Country-fixed effects[c] and time trend
Independent variables			
Income	−0.62 [0.03]	−1.02 [0.00]	−0.99 [0.00]
$Income^2$	0.15 [0.00]	0.21 [0.00]	0.20 [0.00]
$Income^3$	−0.0063 [0.00]	−0.0079 [0.00]	−0.0077 [0.00]
Time trend	—	—	−0.0061 [0.00]
F-tests			
Country-fixed effects[d]	*F* (149, 4197) = 424.65 [0.00]	—	*F* (149, 4196) = 450.80 [0.00]
Time fixed-effects[e]	—	*F* (28,4169) = 9.15 [0.00]	—
Country-and-time fixed effects[f]	—	*F* (177,4169) = 378.36 [0.00]	—
Country-specific trend[g]	—	—	*F* (1, 4196) = 246.14 [0.00]
Model information			
Estimated turning point (2005$)	680,103	2,722,333	1,662,777
R^2	0.97	0.97	0.97
Observations	4350	4350	4350

[a] Dependent variable is the log of aggregate TDE per capita and independent variable is the log of GDP per capita.

[b] Statistical significance inside square brackets

[c] Tables with country-and-time-fixed effects available upon request

[c] *F*-test with H_0: $\beta_2 = 0$

[d] F-test with H_0: $\alpha_i = 0$, against base model

[e] *F*-test with H_0: $\varphi_t = 0$, against model with country-fixed effects

[f] *F*-test with H_0: $\alpha_i = 0$ and $\varphi_t = 0$, against base model

[g] *F*-test with H_0: $\varphi_i t = 0$, against model with country-fixed effects

the income parameters, which increase in magnitude, indicating a stronger relationship between DMI_{ext} per capita and GDP per capita. The *F*-test for joint significance of the country-and-time-fixed effects indicates that their inclusion in the model is significant when compared to the base model. This model is also superior to the models only including country-fixed effects, as shown by the *F*-test for the significance of time-fixed effects, which rejects the null of no time-fixed effects at the 1% significance level. Introducing time as a factor thus improves the fit of the linear model. To gain more insights into the overall effect of time, time-fixed effects were swapped for a time trend. The inclusion of the time trend is also significant at the 1% level, when compared to the cubic model with only country-fixed effects. However, it does not seem to offer more information than the model including country-and-time-fixed effects, shown by the near identical parameters. The overall effect of the time-trends does show a slightly negative effect, which indicates that the passage of time has a decreasing effect on DMI_{ext}.

The estimation results lead to a cubic model, showing signs for a reverse N-shaped relationship, with a decreasing effect on DMI_{ext} per capita at higher income levels for the panel data set. In the case of DMI_{ext} per capita, the MKC hypothesis is not entirely rejected, however it must be considered wither the turning point occurs within sample. Table 3 shows estimated turning points for all specifications, and it is evident that these do not occur at any income levels observed in the panel, as the maximum observed value for GDP per capita is $83.000. This result is in line with the expectation derived from the scatterplot, which indicates an increasing relationship (graph 1). The conclusion that can be made on the basis of these results is that as the economy grows countries do not use less material in their production processes and subsequent consumption activities, for the observed income levels. This result differs from previous analyses, which have found an MKC for DMI per capita for 16 industrialized countries (Canas et al., 2003) and the EU-15 (Vehmas et al, 2007). Seeing as the dataset covers many countries, developed as well as industrialized, it can be concluded that the dominating international relationship between resource use and income is increasing, with no turning point at any GDP per capita levels included in this data set. The diverging results may also indicate that the inclusion of UDE is an important contributor to the overall relationship between DMI_{ext} per capita and GDP per capita. The parameter on the average time trend across countries shows that time has a negative effect on DMI_{ext} per capita, possibly the result of increased efficiency due to technological progress.

6.2 TDE of biomass

The initial base model estimations for TDE per capita of biomass shown in the detailed table 2 in the appendix led to a cubic model significant at the 1% level, with parameter signs showing an N-shaped relationship. But introducing country-and-time-fixed effects all but removed the explanatory power of the cubic term, thus it was opted to choose the quadratic model to explain the data. Looking at the scatter plot (graph 2), it also seems more logical that a quadratic model would fit the data, as there are many observations for low TDE per capita at higher GDP per capita levels. Summary of the results for different quadratic model specifications are given in table 4. The specification with country-fixed effects significantly improves upon the base model, with the signs on the parameters showing evidence for an inverted U-shaped relationship between TDE per capita of biomass and GDP per capita. Introducing time-fixed effects and time trends both yield significant improvements on the model with country-fixed

Table 4. Summary results of quadratic model parameter estimations for biomass TDE[a,b]

	Country-fixed effects[c]	Country-and-time fixed effects[c]	Country-fixed effects[c] and time trend
Independent variables			
Income	0.59 [0.00]	0.43 [0.00]	0.43 [0.00]
Income^2	−0.04 [0.00]	−0.02 [0.00]	−0.02 [0.00]
Time trend	—	—	−0.01 [0.00]
F-tests			
Country-fixed effects[d]	*F* (149, 4197) = 1082.21 [0.00]	—	*F* (149, 4196) =1213.44 [0.00]
Time-fixed effects[e]	—	*F* (28, 4169)= 18.97 [0.00]	—
Country-and-time fixed effects[f]	—	*F* (177, 4169) = 1023.20 [0.00]	—
Country-specific trend[g]	—	—	*F* (1, 4196) = 512.80 [0.00]
Model information			
Estimated turning point (2005$)	1,595	46,630	46,630
R^2	0.98	0.98	0.98
Observations	4350	4350	4350

[a] Dependent variable is the log of biomass TDE per capita and independent variable is the log of GDP per capita.
[b] Statistical significance inside square brackets
[c] Tables with country-and-time-fixed effects are available upon request
[d] *F*-test with H_0: $\alpha_i = 0$, against base model
[e] *F*-test with H_0: $\varphi_t = 0$, against model with country-fixed effects
[f] *F*-test with H_0: $\alpha_i = 0$ and $\varphi_t = 0$, against base model
[g] *F*-test with H_0: $\varphi_i t = 0$, against model with country-fixed effects

effects, with both specifications showing similar parameter magnitudes, explaining 98% of the variation in TDE per capita. The income parameter signs of both specifications clearly show evidence for an MKC. The model with the time trend does not improve upon the model with time-fixed effects, both showing similar parameter magnitudes and R^2. The latter model gives some insight into the effect of time, as the overall trend is negative, indicating that as time passes TDE per capita of biomass further decreases in addition to the negative quadratic income term. Finally, the turning points occur within sample, but introducing time effects dramatically increases the estimated point at which TDE per capita starts to decrease from a very low $1,600 to a moderately high $47,000 per capita.

The biomass material flow indeed follows the economic logic behind the MKC shape. As the economy grows out of its initial low-level income stages, it shifts away from agricultural activities to other economic activities such as manufacturing and other industrial processes, leading to lower biomass extractions from their own soil at higher levels of income. The linear term is still very strong in comparison to the negative quadratic term, indicating that many countries included in the dataset are still on the upward slope of the biomass extraction MKC. But the estimation results still show that an MKC for extraction of biomass is possible with economic growth.

6.2 TDE of fossil fuels

The first round of base specifications found in the detailed table 3 in the appendix indicate a quadratic relationship between TDE per capita of fossil fuel and income per capita. The second income term is significant at the 1% level and introducing this into the model increases the magnitude of the first income parameter five-fold. The main results of the additional specifications of the quadratic model are show in table 5. Including country-fixed effects leads to the quadratic specification explaining 92% of the variation in TDE, with the second income parameter significant at the 1% level. The country-fixed effects are a significant improvement over the model without any fixed effects, as shown by the results of the *F*-test. The signs show that there is some evidence for an inverted U-shaped relationship between TDE per capita of fossil fuels and GDP

Table 5. Summary results of quadratic model parameter estimations for fossil fuel TDE[a,b]

	Country-fixed effects[c]	Country-and-time fixed effects[c]	Country-fixed effects[c] and time trend
Independent variables			
Income	4.58 [0.00]	4.57 [0.00]	4.57 [0.00]
Income^2	−0.26 [0.00]	−0.25 [0.00]	−0.25 [0.00]
Time trend	—	—	−0.0006 [0.80]
F-tests			
Country-fixed effects[d]	*F* (92,2474) = 215.59 [0.00]	—	*F* (92, 2473) = 215.27 [0.00]
Time-fixed effects[e]	—	*F* (28,2446) = 0.45 [0.99]	—
Country-and-time fixed effects[f]	—	*F* (120,2446) = 164.36 [0.00]	—
Country-specific trend[g]	—	—	*F* (1, 2473) = 0.06 [0.80]
Model information			
Estimated turning point (2005$)	6,685	9,320	9,320
R^2	0.93	0.93	0.93
Observations	2569	2569	2569

[a] Dependent variable is the log of fossil fuel TDE per capita and independent variable is the log of GDP per capita.
[b] Statistical significance inside square brackets
[c] Tables with country-and-time-fixed effects are available upon request
[d] *F*-test with H_0: $\alpha_i = 0$, against base model
[e] *F*-test with H_0: $\varphi_t = 0$, against model with country-fixed effects
[f] *F*-test with H_0: $\alpha_i = 0$ and $\varphi_t = 0$, against base model
[g] *F*-test with H_0: $\varphi_i t = 0$, against model with country-fixed effects

per capita. Adding time-fixed effects garners the same results, although slightly decreasing magnitudes of both income terms. However, the results of the *F*-test show that including time-fixed effects is not a significant improvement over the model with only country-fixed effects. This result is similar for the model including a time trend, which also does not improve upon the model with country-fixed effects. The fact that the time-specific fixed effects and time trends are not significant indicate that time is not a factor in the extraction of fossil fuels. Rather, the income variables, as well as country-specific effects explain most of the variation in TDE per capita. Lastly, the estimated turning points occur well within the observed income levels of the panel, showing that when countries reach roughly a GDP of $6,700 per capita, their TDE per capita of fossil fuels starts to decrease.

Thus, the estimation results for TDE per capita of fossil fuel give some evidence for an MKC for fossil fuel extraction. This is also in line with the theoretical expectations of the MKC, showing increasing fossil fuel extraction at the developing and mid-level stages of economic growth, and eventually decreasing at the highest income levels. However, the linear effect is much larger than the negative effects of the quadratic income variable, and this should be considered a weak indication of, but possible MKC for domestic fossil fuel extraction.

6.3 TDE of industrial and construction minerals

The base models (detailed table 3 in the appendix) already carry relatively high R^2 of roughly 0.82, with the quadratic model significant at the 1% level. Surprisingly, all specifications show that introducing the cubic term changes the parameter of the linear term from a weak positive effect to a stronger negative effect, with the cubic model being significant at the 1% level. A summary of the main results for different specifications for the cubic model parameter estimations on industrial and construction minerals TDE per capita are presented in table 6. The inclusion of country-fixed effects bumps the variation explained by the models up to 96%. In this specification, the cubic model shows signs for a reverse N-shaped relationship. Attempting to further isolate the income effect by introducing time-fixed effects and time trend yields similar results with regard to parameter signs and both specifications are a significant improvement over the model with only country-fixed effects. However, the magnitudes of all parameters are lower than in the model with only country-

Table 6. Summary results of cubic model parameter estimations for ind. & constr. minerals TDE[a,b]

	Country-fixed effects[c]	Country-and-time fixed effects[c]	Country-fixed effects[c] and time trend
Independent variables			
Income	−3.80 [0.00]	−3.55 [0.00]	−3.53 [0.00]
$Income^2$	0.63 [0.00]	0.59 (0.06) [0.00]	0.59 [0.00]
$Income^3$	−0.03 [0.00]	−0.03 [0.00]	−0.03 [0.00]
Time trend	—	—	0.004 [0.00]
F-tests			
Country-fixed effects[d]	*F* (148, 4169) = 94.39 [0.00]	—	*F* (148,4168) =94.66 [0.00]
Time-fixed effects[e]	—	*F* (28 ,4141) =2.92 [0.00]	—
Country-and-time fixed effects[f]	—	*F* (176, 4141) = 80.86 [0.00]	—
Country-specific trend[g]	—	—	*F* (1, 4168) = 47.06 [0.00]
Model information			
Estimated turning point	36,315	18,645	18,645
R^2	0.96	0.96	0.96
Observations	4321	4321	4321

[a] Dependent variable is the log of ind. & constr. minerals TDE per capita and independent variable is the log of GDP per capita.

[b] Statistical significance inside square brackets

[c] Tables with country-and-time-fixed effects are available upon request

[d] *F*-test with H_0: $\alpha_i = 0$, against base model

[e] *F*-test with H_0: $\varphi_t = 0$, against model with country-fixed effects

[f] *F*-test with H_0: $\alpha_i = 0$ and $\varphi_t = 0$, against base model

[g] *F*-test with H_0: $\varphi_i t = 0$, against model with country-fixed effects

fixed effects indicating weaker income effects due to time having some influence over the variation in TDE per capita of industrial and construction minerals. Results for the estimated turning points show that introducing time effects lead to a lower within sample turning point, indicating that once countries reach moderate GDP levels of roughly $19,000 per capita, they will decrease domestic extraction of industrial and construction minerals.

The results for TDE per capita of industrial and construction minerals do not support the MKC hypothesis in the traditional sense per se, although the cubic term does indicate a turning point at moderate levels of income. The shape of the curve is intuitive when one thinks of the economic logic behind the MKC. At the start of economic development, production of infrastructure and manufactured goods is low, as the economy is mostly based on non-mechanized agricultural activities (Jaunky, 2012). As economic development continues, and the economic welfare of the public increases, rising demand for infrastructure and manufactured goods leads to increasing extractions of raw materials intended for construction and industrial processes. At the highest levels of development, due to shifts to tertiary sector activities, the extraction of industrial and construction minerals decreases.

6.4 TDE of metal ores

The base model estimations in the detailed table 5 found in the appendix yield a quadratic model significant at the 1% level with a very low R^2, indicating possible omitted variables. Table 7 presents the main results for different metal ore TDE quadratic model specifications. Entering country-fixed effects in to the quadratic model estimations results in a model explaining 89% of the variation in TDE per capita, with yet again signs showing support for the MKC hypothesis for TDE per capita of metal ores. Introducing time-fixed effects does not seem to significantly improve on the model with only country-fixed effects, only slightly increasing the magnitude of the income parameters. However, the introduction of a time trend does significantly improve the fit for the quadratic model, when compared to the specification with only country-fixed effects, although the magnitudes and signs of the parameters are similar to those found in the model with country-and-time-fixed effects. This indicates that there is a trend, rather

Table 7. Summary results of quadratic model parameter estimations for metal ores TDE[a,b]

	Country-fixed effects[c]	Country-and-time fixed effects[c]	Country-fixed effects[c] and time trend
Independent variables			
Income	6.09 [0.00]	6.39 [0.00]	6.40 [0.00]
Income^2	−0.36 [0.00]	−0.40 [0.00]	−0.40 [0.00]
Time trend	—	—	0.01 [0.00]
F-tests			
Country-fixed effects[d]	*F* (100, 2640) = 189.04 [0.00]	—	*F* (100,2639) = 189.59 [0.00]
Time-fixed effects[e]	—	*F* (28, 2612) = 0.88 [0.64]	—
Country-and-time fixed effects[f]	—	*F* (128, 2612) = 147.70 [0.00]	—
Country-specific trend[g]	—	—	*F* (1, 2639) = 16.27 [0.00]
Model information			
Estimated turning point	4,714	2,943	2,980
R^2	0.89	0.89	0.89
Observations	2743	2743	2743

[a] Dependent variable is the log of metal ores TDE per capita and independent variable is the log of GDP per capita.
[b] Statistical significance inside square brackets
[c] Tables with country-and-time-fixed effects are available upon request
[d] *F*-test with H_0: $\alpha_i = 0$, against base model
[e] *F*-test with H_0: $\varphi_t = 0$, against model with country-fixed effects
[f] *F*-test with H_0: $\alpha_i = 0$ and $\varphi_t = 0$, against base model
[g] *F*-test with H_0: $\varphi_i t = 0$, against model with country-fixed effects

than yearly fixed effects with respect to TDE of metal ores. Also notable is that the time-trend has an overall positive effect on TDE per capita, albeit not one of great magnitude. Finally, the turning points occur at very low levels of GDP per capita, and introducing time effects leads to an even lower turning point for TDE per capita of metal ores at $3,000 per capita.

Results for the final material flow metal ores supports the MKC hypothesis. A decrease of TDE of metal ores at higher income levels can be explained by increased resource efficiency and recycling of metals, a practice that increases as economies develop. However, another possible explanation could be increasing resource scarcity of this type, as this material flow also includes precious rare metals, leading to lower amounts extracted at higher economic development due to their depletion at mid-level economic development.

6.5 Country-level DMI$_{ext}$

As previously mentioned, heterogeneity does not only occur in the form of intercept-shifting fixed effects; slope parameters can also differ between countries, affecting the shape of the resulting income–material use relationship. To account for this to a certain extent, separate country-level estimations were done for the 15 largest economies in terms of total GDP in the year 2008[10]. Graph

6 in the appendix shows a combined scatterplot of the included countries and illustrates the fact that countries cover different stages of the MKC curve. Graph 7 in the appendix gives more insight into the country-specific relationship between DMI_{ext} per capita and GDP per capita. It is evident that although these are high (absolute) income countries, they do not all exhibit identical curves, although there are some rough similarities between certain included countries. Visual inspection leads to only Canada and USA showing the exact U-shaped relationship. Other countries that show tentative indication for a decreasing relationship are France, Germany, Japan and UK. The remaining countries either exhibit increasing or unclear relationships of DMI_{ext} per capita and GDP per capita. Detailed table 6 in the appendix shows results of all countries for different specifications and the key results from this analysis are presented in table 8. The results shown in table 8 are significant at the 1% level, except for France, for which the most significant result was found to be at the 5% level.

Initial analysis of the parameter sings show that of the fifteen analysed countries, eight countries exhibit a decrease of DMI_{ext} per capita as the economy develops, which gives some indication that to a certain extent there is homogeneity of the income—material use relationships. Parameter signs directly corresponding with an inverted U-shaped curve at the observed income levels are found for Australia, Canada, South Korea and USA, which all show within-sample turning points except for Australia. This leads to the conclusion that not eight, but seven countries show evidence for decreasing DMI_{ext} per capita at higher income levels. Canada and USA show similar relationships with respect to the magnitudes of the parameters: very strong positive linear effect and weak negative effect at higher incomes. This is less so for South Korea, for which the magnitudes are somewhat closer to each other in size. Regressions for Japan resulted in a cubic specification also showing the desired parameter sign at higher income levels and, similar to the before mentioned countries, the magnitude of the increasing part of the relationship is much larger than the negative effect of the cubic term. However, Canada, Japan, South Korea, the United Kingdom, and the United States of America all exhibit turning points around $30,000, indicating some extent of isomorphism of the income—material use curves. Countries finding themselves on the strictly decreasing part of the

Table 8. Summary results for country-specific MKC parameter estimations for DMI$_{ext}$[a,b]

	Income	Income^2	Income^3	Result	Turning point[c,d]
Australia	46.96 [0.00]	–2.21 [0.00]	—	MKC	41,109
Brazil	1.25 [0.00]	—	—	Linear increasing	
Canada	81.64 [0.00]	–3.97 [0.00]	—	MKC	29,202*
China	0.61 [0.00]	—	—	Linear increasing	
France	–0.10 [0.03]	—	—	Linear decreasing	
Germany	–1.63 [0.00]	—	—	Linear decreasing	
India	0.49 [0.00]	—	—	Linear increasing	
Italy	0.20 [0.00]	—	—	Linear increasing	
Japan	–2200.86 [0.00]	215.39 [0.00]	–7.025 [0.00]	Reverse N	31,824*
Mexico	0.52 [0.00]	—	—	Linear increasing	
Netherlands	0.20 [0.00]	—	—	Linear increasing	
South Korea	4.99 [0.00]	–0.24 [0.00]	—	MKC	32,728*
Spain	0.48 [0.00]	—	—	Linear increasing	
United Kingdom	–0.81 [0.00]	—	—	Linear decreasing	
United States of America	25.57 [0.00]	–1.22 [0.00]	—	MKC	35,596*

[a] Dependent variable is the log of DMI$_{ext}$ per capita and independent variable is the log of GDP per capita.

[b] Statistical significance in square brackets

[c] Expressed in 2005 US$

[d] Table with country-specific GDP per capita levels available upon request

*Turning point occurs within sample of country-specific GDP per capita levels

MKC curve are EU Member States France, Germany and UK, showing negative linear income parameters in their regressions. The regression results for these countries are in line with the MKC hypothesis, in that as countries develop towards higher levels of income they reduce their material use.

Regression results for the remaining countries show linear increasing relationship, indicating that these countries have not yet reached a turning point in their DMI$_{ext}$ per capita. This can be considered expected for Brazil, China, India, and Mexico, as these countries, although they are part of the top 15 highest income countries in absolute terms, still find themselves at rather low GDP per capita levels, thus not yet economically capable of dematerialization. Results are more surprising for EU Member States, the Netherlands and Spain, as these countries exhibit increasing DMI$_{ext}$ per capita at higher income levels. The expectation for these counties according to the MKC hypothesis is that they show decreasing levels of DMI$_{ext}$ per capita, similar to the other included EU Member States mentioned before. The increasing relationship for the Netherlands may be explained by its important role as international shipping hub, also known as the 'Rotterdam effect', indicating the huge role this city plays as European entry port for international trade (Weisz, 2004). Correcting for re-exported imported goods may provide a more accurate picture in the domestic sense (Weber, 2011). But as these imported goods can be considered as international waste potential, it is important to consider the role of the Netherlands in the global demand on resources.

7. Discussion

7.1 Results of the MKC analysis

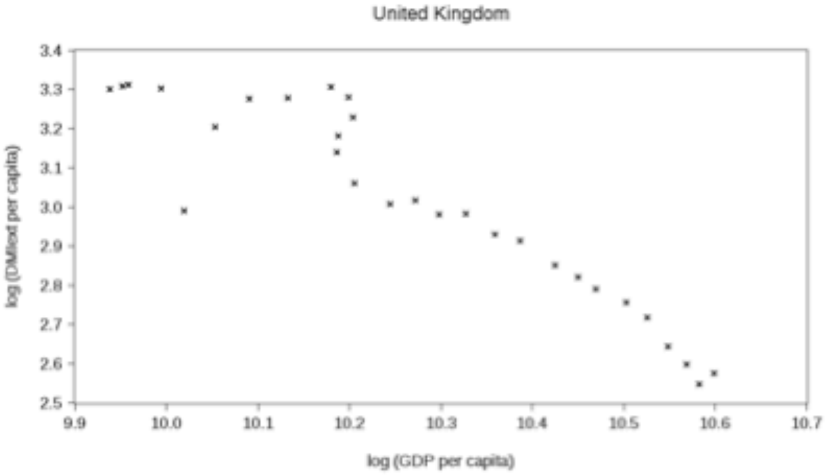
The regression results imply parameters showing decreasing effects of higher income levels on DMI_{ext} per capita. However, the estimated turning points occur well out of sample; the lowest estimation indicates a turning point at roughly $680,000 per capita. This gives no indication of an MKC for DMI_{ext} per capita at any of the currently observed income levels, and it remains to be seen whether the calculated turning point will ever be reached. Thus, higher income cannot be seen as a strict prerequisite for dematerialization. As the DMI_{ext} indicator attempts to cover the resource footprint of a country in the international perspective by including its imports to capture the full extent of its resource footprint, and the dataset covers many different types of countries, it may be concluded that on the whole, there has not yet been a general path to dematerialization over economic growth. The overall result thus shows that higher income is associated with higher resource use in the economy, either intended for domestic consumption as well as for export to other countries. As mentioned before, this result is in direct contradiction to the results of other studies considering MFA indicators, which do find an MKC (Canas et al., 2003; Vehmas et al., 2007).

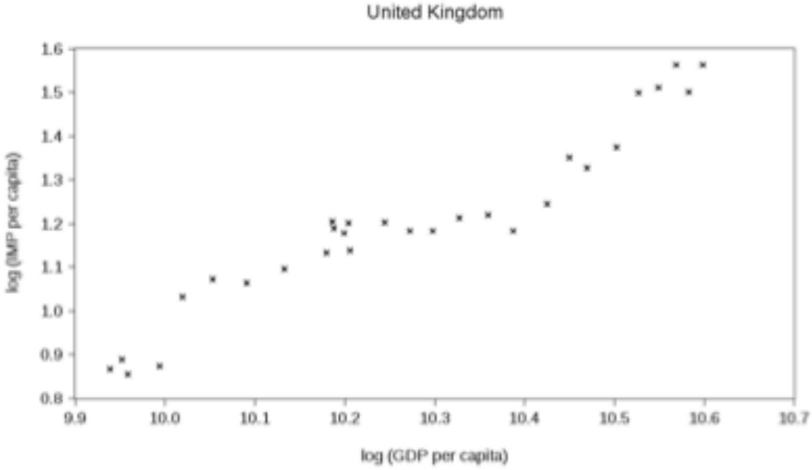
However, the results for TDE per capita of the four material flows show different relationships and give some insights into how countries relate to their local environment with respect to resource extraction. Regressions of the four material flows show evidence for turning points within the observed income levels for their TDE per capita. Yet it must not be forgotten that TDE does not include imports, and the country-level analyses presented further along will illustrate the way exclusion of imports affects the income—material use relationship for TDE versus DMI_{ext}. It would have been most useful to include imports in the specific material flow-level MKC analyses, but this data was unavailable. On the other hand, the magnitudes of the signs should also not be disregarded. The parameters on the income terms can be interpreted as follows: the first income term indicates the initial *scale* effects of economic growth, whilst the quadratic term (if negative) should indicate whether *composition* and *technological* effects have a decreasing effect on material use at higher income levels (Vukina et al., 1999). The material flows fossil fuels and metal ores both show relatively high magnitudes for their first income parameters, and relatively low indicators for their second income terms, indicating very strong scale effects, but rather weak negative effects on TDE per capita of the second income term. Undeniably, the strong scale effects dominate the main result of an increasing linear relationship for the DMI_{ext} per capita, indicating that it is highly unlikely composition and technological effects will lead to the eventual turning point. Moreover, it must be noted that even though an MKC is a definite possibility for material flows, it does not mean that the path followed is a sustainable one, as the ecological threshold can still be bypassed, nonetheless leading to irreversible environmental damage (Panayotou, 1993). What this means for resource extraction, is that even if a turning point has been observed at certain income levels, this does not give any solid indication if the resource stock has already been depleted to an unsustainable level. This is due to the material *flow* point of view of the MKC analysis, without consideration for the remaining *stocks* of resources.

Results from the country-level regressions for DMI_{ext} per capita reveal that countries appear to be at different stages of the MKC. As mentioned before, seven of the fifteen analysed countries show evidence for decreasing DMI_{ext} per capita levels at higher income levels. However, considering the international context of this analysis, previous EKC literature mentions that trade openness was also determined as causing emissions due to the effect of the "pollution haven hypothesis" (Aslanidis, 2009). This hypothesis argues that heavy polluters tend to move from high-income countries with strict environmental regulations to low-income countries with lax environmental regulations. This same type of reasoning can be used to explain the declining trend of eight of the fifteen high-income countries included in the analysis. For the period of 1980-2008, across economic development these countries all exhibited MKC-type relationships at higher income, but at the same time other countries such as Brazil, China, India and Mexico exhibit but only an increasing relationship at their respective income levels. This may indicate that resource-intensive industry and manufacturing has steadily been moving abroad from developed countries to developing countries, and may cause a decline of domestic raw material extraction activities in high-income countries. The dematerialization of high-income economies in terms of $\mathrm{DMI}_{\mathrm{ext}}$ can be explained by what Bringezu et al. (2004) mention in their paper: the decrease of DMI is caused by increasing imports of raw materials or intermediate goods from (developing) countries, as these weigh less than raw materials extracted from domestic soil. In their analysis Bringezu et al. indeed find results to support the notion that economic development of industrial countries is accompanied by a shift of the environmental burden of resource extraction from the domestic to the foreign environment. To investigate if this is also true for the countries exhibiting decreasing or MKC-like curves for $\mathrm{DMI}_{\mathrm{ext}}$ per capita in this current analysis, a series of graphs depicting IMP per capita and GDP per capita is included in the appendix (graph 8). As is evident, all countries show increasing imports, including those countries that were found to show decreasing trends over economic growth for $\mathrm{DMI}_{\mathrm{ext}}$ per capita. To further clarify this phenomenon, scatterplots for $\mathrm{DMI}_{\mathrm{ext}}$ and IMP per capita for the UK are directly compared, which can be seen in figure 5 and clearly show the contrasting relationship of $\mathrm{DMI}_{\mathrm{ext}}$ and IMP per capita over economic development. Thus, as countries exhibit MKC-like curves for $\mathrm{DMI}_{\mathrm{ext}}$, TDE any other type of material flow indicators that do not take account for this shift of resource extraction activities to other countries, wrong conclusions can be made on the basis of these results. This could then lead to policy applications that may have the intended effect in the best-case scenario, and significantly increase the burden on the environment in the worst-case scenario. Although the results show that some EU Member States are making strides in lowering their $\mathrm{DMI}_{\mathrm{ext}}$ per capita as they grow economically, it follows that if the EU wishes to reduce its global resource footprint, it must also take into account resource extraction activities of its international trading partners from which it receives its imports.

A point to consider nonetheless is that resource use is of a different nature than pollution. Resources are a crucial input to economic growth and natural resource endowments often determine whether a country decides to extract this raw material for economic use, with or without the intention of exporting it to other countries. Natural resources are of an immobile nature and are not uniformly distributed across space, thus there are comparative advantages that

Figure 5. Scatterplots of DMI$_{ext}$ (upper) and IMP (lower) per capita for the UK





allow for allocative efficiency gains (Van den Bergh & Verbruggen, 1999). One must then concede that if developing countries increase their resource extraction as a result of these resource endowments, and high-income countries decrease domestic extraction activities of these same types of raw materials and instead import them from those countries with the comparative advantage, that this is the optimal economic result of international specialization. If it leads to a higher environmental burden, then this is the price that must be paid for specialization. If it lowers environmental impact it can be considered as a benefit of specialization. Thus, it may not be fully appropriate to disapprove specialization from a sustainability point of view as some regions process certain raw materials with less burden to the environment than do other regions (Giljum & Eisenmenger, 2004). This is also illustrated by the cross-section analysis of TDE per capita in 2005: the region Middle East & Asia extracts the most fossil fuels with the lowest share of UDE in TDE, indicating its specialized role in this material flow.

However, it is not clear if the trade between developed countries and developing countries that results from specialization is more burdensome to the environment than the alternative, which may not even be possible for certain material flows: less trade and increased domestic extraction activities. Indeed, Van den Bergh & Verbruggen (1999) argue that trade can even disperse the environmental burden to the least sensitive natural systems, but only if these are accompanied by the correct incentives and policies, and international policy coordination concerning transboundary environmental issues. Until now, trade liberalization and openness has led to developing countries gaining comparative advantages through their less strict environmental policies (Dinda, 2004), which could be discussed on its humanitarian and ethical implications alone. Indeed, Giljum & Eisenmenger (2004) argue that if not supported by the appropriate policies, specialization may lead to an unequal distribution of the high intensity of energy, material, and land use of the primary sector production processes to the less developed countries, bringing with it huge amounts of hazardous wastes and emissions to these countries and their inhabitants. It has even been argued that global disparaties in sharing the environmental burden of industrial activity contribute to growing social discontent, increased threat of war, and even terrorism (Bringezu, 2002).

7.2 Critique on MKC hypothesis

Although the results of the MKC analysis of the material flow-specific TDE per capita and the country-level DMI_{ext} per capita find some tentative indications for an inverted U-shaped relationship, there are some reservations about the theory and methodology of MKC studies that should be taken into account.

First of all, it is not suggested that dematerialization is an inevitable result of economic growth, even though the country-level analysis may show that a declining DMI_{ext} per capita, if this is the case, occurs mainly at higher income level. Certainly, higher income levels are a necessary condition for demand (from citizens) of and supply (by firms and government) for environmental improvements to exist, but whether or not this translates into actual improvements is heavily dependent on government policies, as well as the quality of social institutions and functioning of markets (Panayotou, 1997). Surveying the literature on EKC, Dinda (2004) shows that many studies find local and national policies to be driving forces behind the income–environmental degradation relationship. It is reasonable to assume that this is also the case for dematerialization and increased resource efficiency. For resources, Vehmas et al. (2007) state that positive changes behind the income–material use relationship vary a lot depending on, among other factors, country–specific policy processes. Technological progress is also key to improving resource efficiency, as it makes it technologically possible to process goods with successively less use of natural resources and burden to the environment (Dinda, 2004). In the context of pollution, analysis on directing sustainable technological development through public expenditure on R&D has indeed yielded positive results for the possibilities of shifting from polluting to non- or less polluting industries (Vollebergh & Kemfert, 2005). Magnani, (2001) states other important factors contributing to the income–environmental relationship such as population density, openness to trade, and income inequality. Corruption can also negatively affect the income–material use relationship for a country, as the socio-politcal regime of a country is an important determinant for the implementation and enforcement of environmental policy (Dinda, 2004). It was not possible to include such factors in this current analysis due to the nature of reduced-form estimations.

Also, there has been some dispute about the use of per capita data for environmental and resource indicators in EKC/MKC estimations, justly pointed out by Vehmas et al. (2007). They mention that if environmental stress stays constant, whilst population growth increases, or environmental stress increases at a slower rate than population growth, EKC analyses using per capita values of environmental stress may yield misleading results about sustainable development, much in the same way as the weak EKC and relative dematerialization do. Taking absolute values instead of per capita figures may provide a different account of the state of resource use from the strict environmental perspective. To gain some insights into these possible differences

Table 9. Results of parameter estimations for absolute values of TDE and GDP[a,b]

	Biomass	Fossil fuels	Industrial & construction minerals	Metal ores
Independent variables				
Income	−0.11 [0.15]	8.49 [0.00]	−7.33 [0.00]	9.23 [0.00]
Income^2	0.01 [0.00]	−0.16 [0.00]	0.35 [0.00]	−0.16 [0.00]
Income^3	—	—	−0.005 [0.00]	—
Country-specific time trend	—	—	—	−0.01 [0.00]
Specifications[c]				
Country-fixed effects	Yes	Yes	Yes	Yes
Time-fixed effects	Yes	—	Yes	—
Country-specific time trends	—	—	—	Yes
Model information				
R^2	0.99	0.94	0.99	0.90

[a] Dependent variable is the log of TDE and independent variable is the log of GDP.
[b] Statistical significance inside square brackets
[c] Re-estimations according to best specifications of the preceding per capita parameter estimation results

in the results, graphs 9-12 in the appendix show the scatterplots for the four material flows, with absolute values of TDE and GDP on the axes. This yields some interesting visual differences with respect to the previously resulting inverted U-shaped relationships found for the material flows. Visual inspection of the plot for biomass roughly indicates increasing absolute TDE with economic development. This is in contrast to the scatterplot of biomass with TDE per capita values, which showed decreasing biomass extraction at higher income levels. An explanation for this could be that countries such as China and India are able to spread their high resource extraction over their large population (1.3 and 1 billion, respectively). When looking at the absolute values, this dispersion of the resource extraction is not visible, resulting in an increasing relationship. The scatterplots with absolute values for the other material flows also show differences compared to their per capita counterpart: the scatterplot for fossil fuels is much steeper and for industrial and construction minerals it is also very steep with a more obvious linear relationship. Metal ores shows the least divergence with its per capita scatterplot. In addition to the scatterplots, the main models from the per capita estimations were re-estimated with absolute values, the results of which can be found in table 9. The results here are in line with the expectations from the plots. For fossil fuels and metal ores, the magnitudes increase on the linear term, and the quadratic term decreases in power. The results for industrial and construction minerals yield the same signs, but a much less strong negative effect on TDE at higher income levels. Most interesting is the result for TDE of biomass, for which the linear term loses significance, and only a positive quadratic term remains to explain the relationship. It is clear that the per capita nature of the observations bias the results in favour of an MKC, especially for the material flow biomass.

7.2 Policy implications

Taking into account the overall results of DMI_{ext} per capita (cubic model with out of sample turning point), as well as the previous results with respect to the absolute values for TDE, whilst not forgetting that a turning point may come well after the ecological threshold has been crossed, it must be concluded that it would be wise to address the causes of over-use and extraction of raw materials and other natural resources. As was mentioned in the introduction, *environmentally harmful subsidies* (EHS) are one of the main factors causing the high intensity of raw material extraction. The costs associated to these types of government support is extremely high; it is estimated that world-wide EHS are worth at least $950 billion a year, or 3.6% of global GDP, indicating that governments around the globe are heavily engaged in subsidizing resource-intensive industries (van Beers & van den Bergh, 2001). The mechanism of these subsidies is that they lower the actual cost of extraction, production and eventual export, resulting in many primary raw materials being traded at needlessly high volumes against prices that do not fully reflect their social and environmental costs of extraction and production activities, leading to higher environmental burden than if these materials would be traded at their real prices (Giljum & Eisenmenger, 2004). Van Beers & Van den Bergh (2001) refer to these subsides as ‘perverse subsidies’ because of their damaging effects to the economy, the environment, or both. These subsidies are often put in place to lower production costs, secure employment or supply the local population, but current subsidy policy should also put greater weight to environmental goals without sacrificing these important objectives (Spangenberg et al., 1999). A distinction between consumer and producer subsidies must be made, with the latter having much more serious and far-reaching conseqences through affecting the resource side of of the economic chain, and are thus more significant in the context of dematerilization with respect to the elimination of environmentally harmful subsidies (van Beers & van den Bergh, 2001). Removing these types environmentally harmful subsidies can deliver improved resource efficiency as well as other economic, social, and environmental benefits, whilst also leveling the playing field and improving competitiveness (European Commission, 2011). However, Van Beers & van den Bergh (2001) justly mention that removal of these subsidies may prove to be quite difficult due to powerful vested interests in the agricultural and fossil fuel business, and the 'lock-in' we currently find ourselves in as a result of various (in)ternational policy and institutional failures being persistent over many decades. They argue that this 'lock-in' has heavily distorted natural comparative advantage patterns, affecting all aspects of international specialization; the location of firms, foreign investment decisions, and international trade flows. Thus, EHS not only lead to over-extraction and resource inefficiency in the local context, but also hinder the realization of the optimal international allocation of economic activity as a result of comparative advantages. If we indeed wish to disperse the environmental burdens of resource extraction to the least sensitive ecosystems through international trade and specialization, as suggested by Van den Bergh & Verbruggen (1999), removing these perverse subsidies would be a significant step in the direction towards more effective allocation of economic activity, and possibly lower the environmental impact of resource extraction activities.

Van Beers & van den Bergh (2001) suggest some key points that must be adressed towards realizing this goal: direct quantification of the extent of subsidies, revisiting the original motivations behind implementing these subsidies, and providing transitional support and assistance to the sectors affected by the removal of these subsidies. Spangenberg et al. (1999) argue that policies aimed at dematerializing economies should at least have consensus at the European level, and recently the European Comission (2011) indeed indicated that the goal is a phasing out of these EHS by 2020, also taking into account the welfare of the affected parties. Results for the country-level regression showed that certain EU Member States are indeed lowering their DMI_{ext}, and this could illustrate that joint policy coordination may yield some results. Still, although ambitious, international coordination on the removal of EHS is an important factor in the success of these policy changes, due to governments of developed and developing countries fearing the loss of their global competitive position in the economic sectors in which they operate profitably (van Beers & van den Bergh, 2001). As trade becomes increasingly global, and industries more mobile, environmental and resource policy must also become more internationally orientated to support sustainable trade and development to ensure their longevity and fairness to the parties involved.

Finally, in addition to addressing EHS and their effect on the overall trend of resource extraction, policy should also be directed at specifically lessening UDE during extraction activities, especially for fossil fuels and metal ores, as for these flows UDE takes up a large share of TDE (shown by descriptive analyses in section 5). Even if growing demand for materials leads to increased extraction activities, it must be made a high priority to lessen the unnecessary extra burden to the environment during extraction of these materials. Mining activities must take into account geographical as well as technological factors that allow for reduced UDE during resource extraction, farmers must have the incentive to lower soil erosion, and fisheries must be stimulated to reduce their by-catch (Wuppertal Institute, 2013). This also carries fewer costs with it due to the firms extracting these resources having to eventually process less waste. Waste that is then still generated should be further reduced through increased recycling. Setting extraction efficiency standards in the form of taxes on UDE may induce firms to operate with more consideration to the amount of residual extraction associated with their activities.

7.3 Limitations

Although the utmost effort has been done to ensure that this thesis is of the highest possible quality, certain concessions had to be made leading to some limitations with respect to the analysis.

The cross-section analysis for the year 2005 proved the importance of including UDE in analyses regarding material flows, but data collection on this type of flow is still rather in its infancy. SERI and the Wuppertal institute, as well as prominent authors in the MFA field are regularly improving upon the quality of the available data, but as of the present moment data on UDE is of relatively low quality on the global level (SERI and Dittrich, M., 2012). However, adding UDE into the analysis of resource use still provides a more accurate environmental picture of the resource footprint, than omitting it altogether. Furthermore, the exclusion of the indirect flows associated with imports must also not be forgotten when interpreting the results of the overall and country-specific MKC analysis. As import volumes tend to increase as economies develop (Bringezu et al., 2004), a measure excluding these indirect flows, may not accurately depict dematerialization. However, the other indicator for which reasonable data was available, i.e. DMC, also suffers from this problem and, due to netting out exports, may even create the impression of domestic dematerialization when this is not the case in the international context, as these exported materials flow to other countries to end up as waste eventually. Even then, the results presented here only show part of the income—material use picture and should be interpreted accordingly.

Another limitation arises due to the strict macroeconomic consideration of the production side (i.e. resource input and extraction) of this MKC analysis. An unwanted, but possible consequence of only approaching this from a macroeconomic and production point of view is that if resource efficiency increases, it may directly or indirectly encourage increased consumption of these types of resources (Vehmas et al. 2007). Previous research has already shown that this has been the case for energy (Greening et al., 2000). Indeed, country-level regressions for DMI_{ext} for Australia, Brazil, and the Netherlands show parameter signs for an N-shaped curve significant at the 5% level, and Mexico also shows these signs at the 10% level (detailed table 6 in the appendix), which could indicate a rebound effect with respect to DMI_{ext} per capita. Due to the aggregated nature of DMI_{ext} per capita it could also be that there is a case of the beforementioned trans-materialization; raw materials taking part in outdated production processes are swapped for newer materials needed for the most recent manufacturing activities (Labys & Waddell, 1989). The European Comission (2011) has taken note of the possible phenomenon of a rebound effect due to technological improvements, and state that in shaping policy and setting targets towards dematerialization, this must be taken into account. An example of this type of policy is one that promotes firms to lease, instead of sell, their products to consumers (European Commission, 2011). In The Netherlands, telecom company KPN now leases their mobile phones to consumers; taking the phones back for use in repairing other phones after the consumer has exhausted its use value, thus further closing the material use loop. This type of policy stimulates firms to increase the life span of the product, as well as reuse and recycle their products to a greater extent than is the case nowadays (Spangenberg et al., 1999). The European Comission (2011) has included this in its roadmap and facilitating the development of this new type of business model is crucial to dematerializing the economy.

Certain econometric issues also call into question the validity of the found relationships. Simple OLS approaches to panel data such as the one used in this paper may lead to problems with respect to, among other issues, unit roots and cointegration. A unit root test for the dataset of DMI_{ext} per capita does not reject the null of a unit root process[11], and this is also the case for GDP per capita[12]. Testing both series for cointegration does not reject the null of no cointegration, also giving indication of a shared external shock[13]. Due to the limited scope of this current analysis, these problems were not corrected for and this must be considered when interpreting the results. Other research has already addressed these issues. For example Bringezu et al. (2004) use a feasible general least squares (FGLS) estimator, capable of accounting for the panel data structure of their dataset, and possible violations of the OLS assumptions. Causality running from income to resource or environmental degradation is also contested in contemporary EKC and MKC research. As mentioned before, reduced-form estimations cannot adequately arrive at determining if causality exists in whichever direction. Jaunky (2012) approaches causality investigations on an MKC for aluminium in a panel vector error correction model (VECM) setting, and uses short and long run elasticities to determine the direction of causality. Another issue in MKC investigations could be a case of a feedback effect from resource extraction to income and vice versa, otherwise known as endogeneity. As resources use contributes to the GDP of a country, not accounting for this fact may lead to inconsistent results. This could be corrected for using a two-stage least squares (2SLS) method, applying an appropriate instrumental variable and then re-estimating the model.

8. Conclusion

This thesis presents an analysis of the relationship between material use and economic growth for indicators DMI_{ext} and TDE. These indicators were developed for the purpose of this specific thesis after careful consideration of the characteristics of other frequently used MFA indicators. The overall trend shows no indication for an MKC regarding DMI_{ext}, with the estimated turning points occurring well outside of the observed GDP per capita levels of the panel dataset. For the four material flows there is some evidence for an MKC, although the results were shown to be sensitive to the per capita basis of the calculations, thus questioning the methodology of investigations on the MKC hypothesis. The descriptive analysis of the composition of TDE proved that the inclusion of UDE was an important decision, mainly for the material flows fossil fuels and metal ores, as UDE takes up a significant share of TDE for these two flows, being larger than DEU. Consequently, MKC analyses that do not take UDE into account do not provide an accurate picture of dematerialization of the economy. Country-specific investigations resulted in eight of the fifteen included economies showing decreasing material use at higher income levels, lending some support to the MKC hypothesis as well as some degree of isomorphic income—material use relationships. However, it was also shown that this decrease in DMI_{ext} per capita is contrasted with an increase in imports per capita, explaining the decreasing or MKC-like curves due to the lower weight of imported goods versus domestically extracted raw materials.

Furthermore, it cannot be said that these MKC-like or decreasing relationships do not cross ecological thresholds, beyond which resource stocks have been depleted to unsustainable levels, consequently threatening the continued use of these resources. Further research would take into account ecological thresholds of unsustainable resource extraction as well as the economic and environmental consequences of crossing that threshold. If one was to determine what the ecological threshold is for a certain type of resource, one could even use the MKC hypothesis as a means to map out a path of optimal resource extraction that delivers the highest economic growth, whilst simultaneously respecting the ecological threshold. MKC analysis on stock depletion may also provide a more clear picture of the sustainable development of the economy. Moreover, it was shown that the decrease in DMI_{ext} per capita over economic growth is paired with increasing imports, which supports the notion brought forward by Bringezu et al. (2004) that there is indeed a shift of indirect flows from the domestic to the foreign sphere. One of the MFA indicators that attempts to account for this shift of the resource extraction burden is TMR, and further development of this indicator, in the same manner as the research conducted by Meyer (2011), must be high priority of future MFA-orientated investigations.

Also, it is not yet entirely clear how comparative advantages and the resulting international trade affect the environment compared to a more domestically orientated system, if this is even possible or desireable. Research has argued that countries gain comparative advantages through low environmental standards, shifting trade patterns (Dinda, 2004). Coupled with environmentally harmful subsidies (EHS), which further distort the optimal allocation of global economic activity (van Beers & van den Bergh, 2001), these policies lead to increased environmental burden to these countries. More research into the precise environmental impacts of international specialization and the resulting trade specifically in the framework of dematerialization is needed to gain insights into how trade and sustainable development can complement each other. Another avenue for empirical research on material flow MKC should also include a variable capturing the effects of EHS, to see if these perverse subsidies indeed influence the level of raw material extraction and use.

As previously stated, reduced-form analyses do not offer insights into how certain factors, such as environmental policy and technological progress, affect the income—material use relationship. However, there are certain methods to arrive at a clearer picture with respect to the extent of their influence. For example, Panayotou (1997) attempts to shed light on the 'black-box' of the income effect by decomposing the income effect into its constituent scale and composition effects, as well as including the growth rate and environmental policy to ascertain whether they have an effect on the shape of the EKC for SO_2. He finds that the share of industry, the rate of economic growth, but most importantly that the proxy variable for the quality of environmental policies and institutions indeed significantly aid in 'flattening' the EKC curve. Decomposition analysis along these lines, adding factors that influence the trend of material flows such as those analysed in this thesis, would be a relevant practice and significant step in the direction to better understand the drivers of the income–material use relationship. Factors such as the share of environmental tax revenue in total tax revenue, or number of patents filed for resource efficient technologies would be interesting to include in the decomposition analysis.

There are also some avenues for improving the quality of the employed data and methodology of this type of MKC research. Improving the reliability of unused domestic extraction (UDE) data should be high priority for future research, as these seem to cover a large share of the TDE for the material flows fossil fuels and metal ores. To further investigate the development of UDE over economic growth, it would also be interesting to conduct MKC analysis on UDE. The reasonable expectation is that UDE should eventually decrease at higher income levels, due to increased resource efficiency, however the cross-section results for the composition of TDE show that UDE still covers a large share of TDE for certain material flows such as fossil fuels and metal ores. Furthermore, future research on MKC for material flows would do well to take the before mentioned econometric issues of this current analysis into consideration, to improve the validity of MKC analysis.

Considering MKC methodology, the previous section illustrated that the use of per capita values in MKC estimations can lead to misleading results and conclusions. A recent UN publication on World Population Prospects predicts a dramatic rise from 7.2 billion people today to 9.6 billion in 2050, with the bulk of the growth occurring in India, China and Africa (United Nations , 2013). These areas are still on the increasing parts of the MKC, and if future research on the relationship between economic growth and material use is to provide an accurate overview of dematerialization of the economy, population growth must always be taken into account, as solely basing conclusions on per capita calculations may cause overly optimistic inferences regarding material use. It may also be wise to include a measure of the pressure of population growth or population density in future MKC investigations, to see if population growth itself also affects the shape of the MKC.

Seeing as there is no governing institutional body at the global-level, it may not seem to be relevant or econometrically interesting to approach the decoupling of economic growth from material use from the global perspective as of yet, but it may provide some insights into the global MKC and how countries differ from this global relationship. Doing MKC analysis at this level is very straightforward, as only data on TDE is needed, because it covers the two raw material flows (DEU and UDE) that are the source of all global production and consumption. The logic is that, seen from a global perspective, there are no imports and exports, and thus only the domestic material extraction practices of (importing and exporting) countries contribute to the global resource footprint. The resources needed for the transportation of imported or exported materials can be considered in the same light as indirect flows of imports, in that these resources also stem from domestic extraction activities somewhere in the world. Recalling the Law of Conservation of Mass, which states that in a closed system (the closed system in this case being the Earth) mass must remain constant over time, it becomes clear that when one does an analysis that includes resource extraction covering a large amount of (trading) countries, a global picture of the economic development—material use relationship can be obtained. By using TDE and investigating the amount of resources extracted over economic development on a global level it is possible to gain a more accurate insight as to whether the global economy is lowering its resource footprint. Global TDE can be considered the only true measure of dematerialization; a reduction of global TDE as global economic growth continues means that fewer raw materials are extracted from the Earth for use in the economy, indicating improved resource efficiency. This type of analysis may thus be inherently limited to the global level, but due to increasing globalization and international trade, it may be relevant to research the economic growth—resource use at the highest macro-level. This way it is indeed possible to approach sustainable development from a spaceman economy perspective as Boulding (1966) envisioned.

Finally, dematerialization of the economy alone should not be the end-all goal of sustainable development, for it should be but a phase of transition towards something even better. Quantity is not the only factor, but finding out how to improve the quality of the ecological footprint must also be in the front of the minds of those steering the economy towards a more environmentally responsible direction. Indeed, in the book explaining their "Cradle-to-Cradle" philosophy, William McDonough and Michael Braungart (2002) argue that the current concept of ecological improvement is mainly focused on increasing the efficiency of processes that are inherently damaging to the environment. Instead, the goal must be to set up a framework in which the outputs of economic processes actually improve the environment. They envision this as follows:

"We see a world of abundance, not limits. In the midst of a great deal of talk about reducing the human ecological footprint, we offer a different vision. What if humans designed products and systems that celebrate an abundance of human creativity, culture, and productivity? That are so intelligent and safe, our species leaves an ecological footprint to delight in, not lament?"

We must not take for granted our position as intelligent beings capable of actually improving the world around us, not just causing damage to it by merely being in existence. We must design industrial processes that not only focus on getting the most out of the inputs by increasing efficiency, but also consider how other firms as well as nature can benefit from the outputs of our economic processes, to the extent that one man's trash indeed becomes another man's treasure.

With this bachelor thesis I hope to have contributed to the knowledge base needed to improve our economic system towards one that is more in harmony with the natural world we are inextricably a part of.

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Notes

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[1] Antoine Lavoisier first discovered in 1789 that mass is neither created nor destroyed in chemical reactions, which became known as the Law of Conservation of Mass.

[2] Focacci (2005, 2007) expresses material intensity as the ratio of Total Consumption—GDP per capita in tonnes per billion of currency

[3] The global resource use of exports for Germany, Denmark, The Netherlands, Sweden increased by 40-60% for the period 1995-2005, while domestic resource consumption of households remained stable.

[4] The regression analysis had an R^2 of 0.0275

[5] Countries included in the main dataset are: Afghanistan, Albania, Algeria, Angola, Antigua and Barbuda, Argentina, Australia, Austria, Bahrain, Bangladesh, Barbados, Belgium, Belize, Benin, Bermuda, Bhutan, Bolivia, Botswana, Brazil, Brunei Darussalam, Bulgaria, Burundi, Cambodia, Cameroon, Canada, Cape Verde, Central African Republic, Chad, Chile, China, Colombia, Comoros, Cook Islands, Costa Rica, Cote d'Ivoire, Cuba, Cyprus, Denmark, Djibouti, Dominica, Dominican Republic, Ecuador, Egypt, El Salvador, Fiji Islands, Finland, France, French Polynesia, Gabon, Gambia, Germany, Ghana, Greece, Grenada, Guatemala, Guinea, Guinea-Bissau, Guyana, Haiti, Honduras, Hungary, Iceland, India, Indonesia, Iran, Iraq, Ireland, Israel, Italy, Jamaica, Japan, Jordan, Kenya, Kuwait, Lesotho, Liberia, Libya, Madagascar, Malawi, Malaysia, Maldives, Mali, Malta, Mauritania, Mauritius, Mexico, Mongolia, Morocco, Mozambique, Myanmar, Namibia, Nepal, Netherlands, Netherlands Antilles, New Caledonia, New Zealand, Nicaragua, Niger, Nigeria, Norway, Oman, Pakistan, Panama, Papua New Guinea, Paraguay, Peru, Philippines, Poland, Portugal, Qatar, Romania, Rwanda, Saint Kitts and Nevis, Saint Lucia, Saint Vincent/Grenadines, Sao Tome and Principe, Saudi Arabia, Senegal, Seychelles, Sierra Leone, Singapore, Solomon Islands, Somalia, South Africa, South Korea, Spain, Sri Lanka, Sudan, Suriname, Swaziland, Sweden, Switzerland, Syria, Tanzania, Thailand, Tonga, Trinidad and Tobago, Tunisia, Turkey, Tuvalu, Uganda, United Arab Emirates, United Kingdom, United States of America, Uruguay, Vanuatu, Venezuela, Vietnam, Zambia, and Zimbabwe.

[6] For the analyses considering the specific material flows certain countries were excluded due to missing data points or other likewise statistical anomalies. An exception was Kuwait, for which observations fell to almost non-existent amounts during the period 1990-1992. This is attributable to the invasion of Kuwait by Iraq, which subsequently led to the Persian Gulf War. However, over the period 1980-2008 Kuwait showed reliable data, thus a trend was introduced from 1990-1992. As Kuwait also showed high values for TDE and is a key fossil fuel producing country, it was deemed as too important to exclude from the analysis.

[7] All datasets are available upon request.

[8] The minima of biomass, fossil fuels, and metal ores are expressed in kilograms, the reason for this being that when taken in tonnes per capita values, the TDE for some countries was almost close to zero.

[9] Detailed information on country-specific DEU and UDE is available upon request.

[10] Countries analysed are: Australia, Brazil, Canada, China, France, Germany, India, Italy, Japan, Mexico, Netherlands, South Korea, Spain, the United Kingdom, and the United State of America.

[11] ADF – Fisher Chi-square = 327.04 [0.13]

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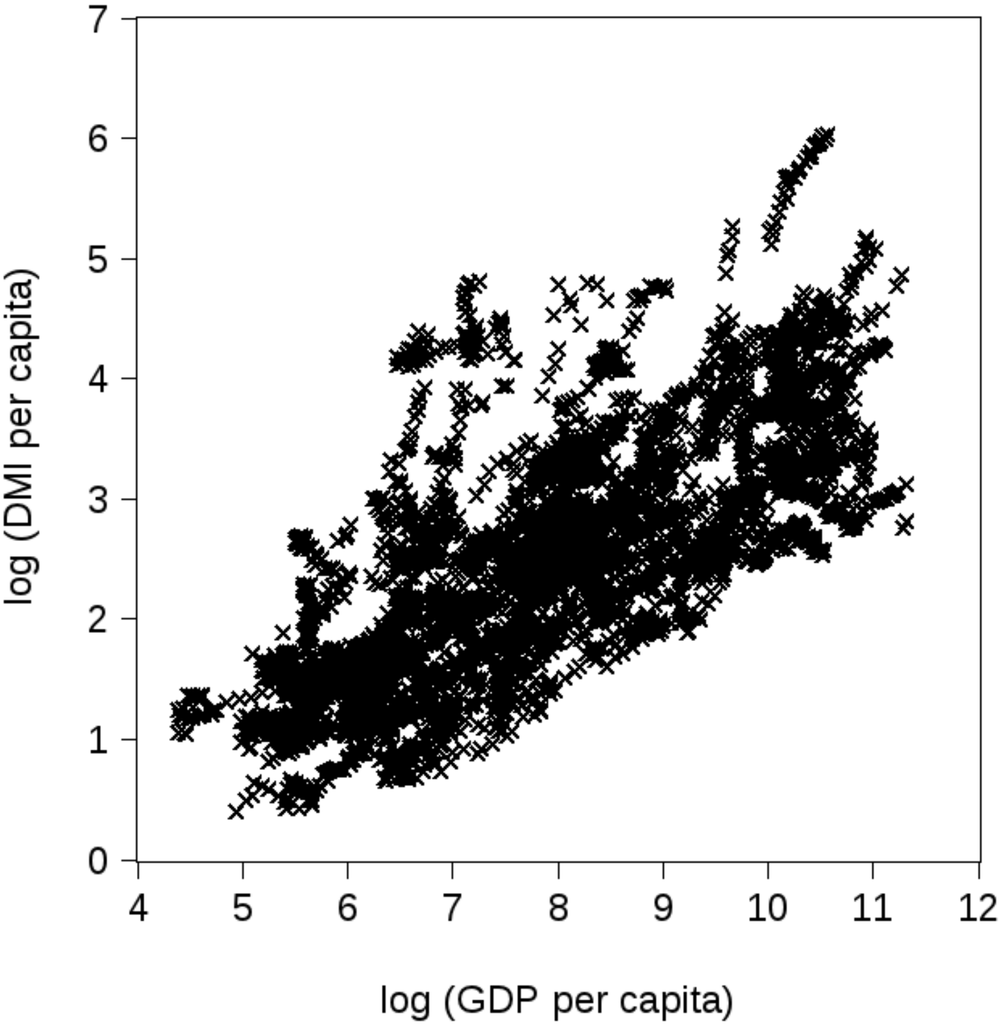
[12] ADF – Fisher Chi-square = 225.51 [0.99]

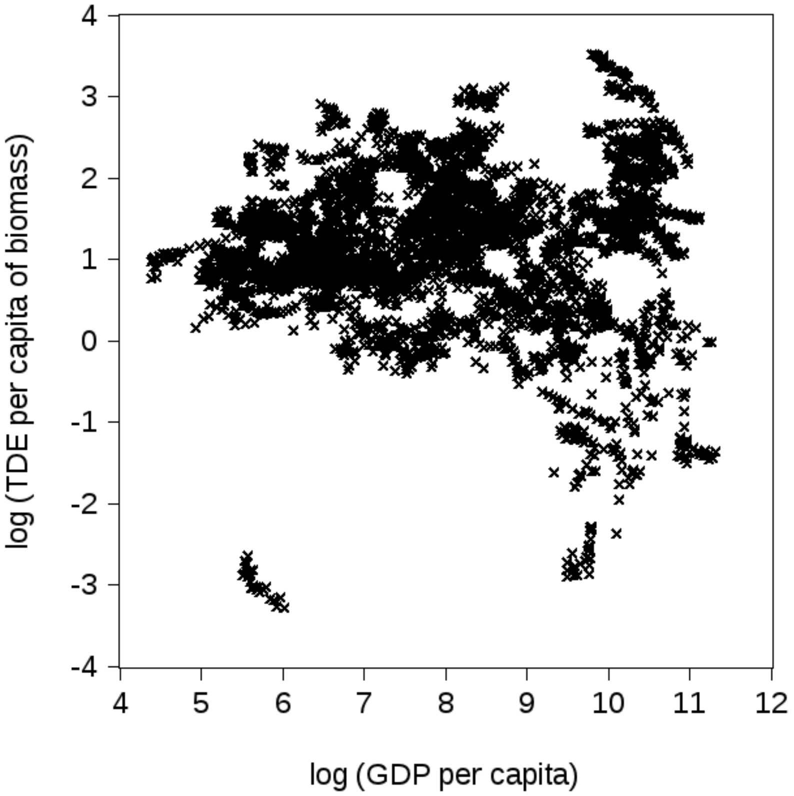
[13] Panel ADF-statistic = 1.74 [0.99]

Appendix

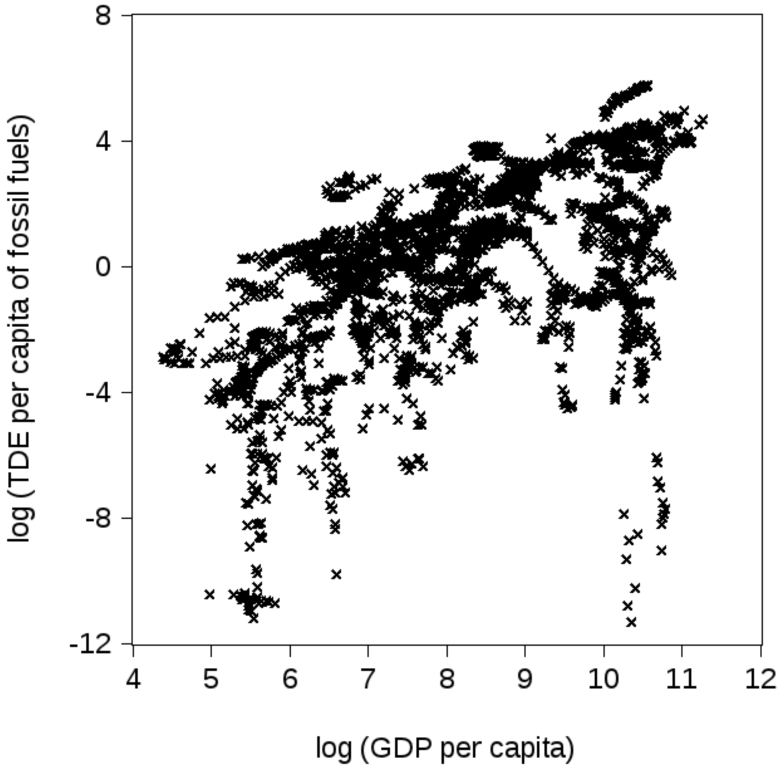
Graph 1. Scatterplot of DMI_{ext} per capita and GDP per capita



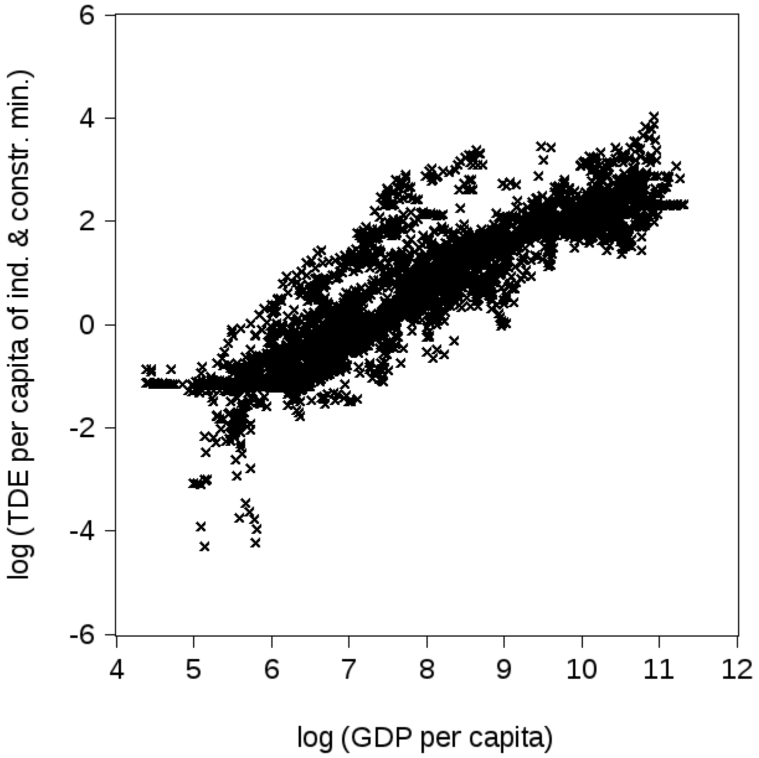
Graph 2. Scatterplot of biomass TDE per capita and GDP per capita



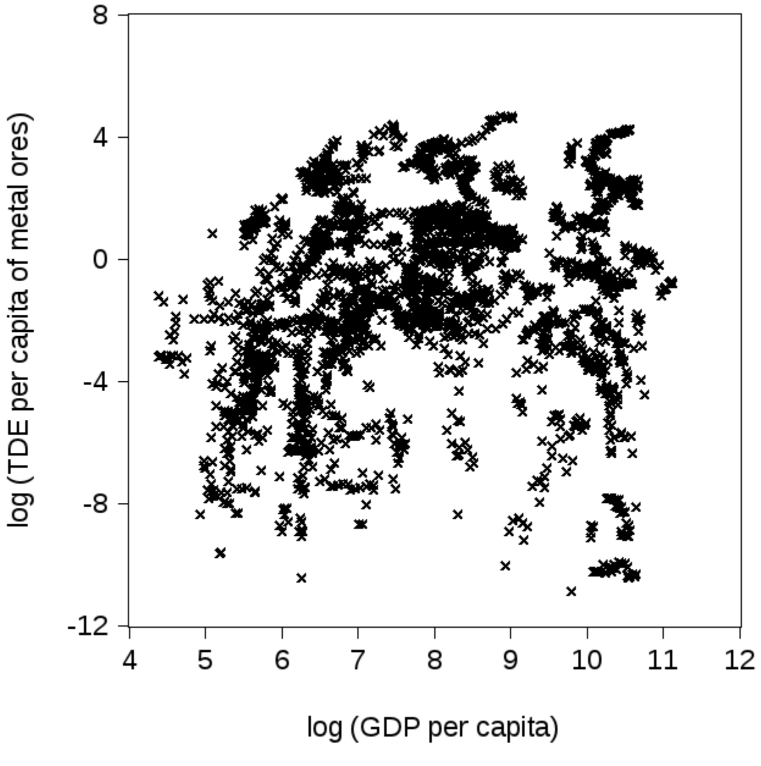
Graph 3. Scatterplot of fossil fuel TDE per capita and GDP per capita



Graph 4. Scatterplot of ind. & constr. minerals TDE per capita and GDP per capita



Graph 5. Scatterplot of metal ores TDE per capita and GDP per capita



Detailed table 1. Results of MKC parameter estimations for $\mathbf{DMI}_{\mathbf{ext}}$[a,b]

	Base	Country-fixed effects	Country-and-time fixed effects	Country-fixed effects and country-specific time trend
Linear model				
Income	0.4676 (0.0064) [0.0000]	0.5658 (0.0115) [0.0000]	0.6716 (0.01378) [0.0000]	0.6741 (0.0135) [0.0000]
Country-specific time trend	—	—	—	−0.0053 (0.0004) [0.0000]
R^2	0.5487	0.9718	0.9732	0.9731
Quadratic model				
Income	0.5684 (0.0662) [0.0000]	0.4991 (0.0568) [0.0000]	0.3758 (0.0561) [0.0000]	0.3724 (0.0559) [0.0000]
Income^2	−0.0063 (0.0041) [0.1265]	0.0043 (0.0037) [0.2302]	0.0203 (0.0037) [0.0000]	0.0206 (0.0037) [0.0000]
Country-specific time trend	—	—	—	−0.0060 (0.0004) [0.0000]
R^2	0.5489	0.9718	0.9734	0.9733
Cubic model				
Income	−0.0505 (0.4881) [0.9175]	−0.6164 (0.2816) [0.0286]	−1.0172 (0.2756) [0.0002]	−0.9937 0.2748) [0.0003]
Income^2	0.0735 (0.0625) [0.2393]	0.1530 0.0369) [0.0000]	0.2059 (0.0362) [0.0000]	0.2027 0.0360) [0.0000]
Income^3	−0.0033 (0.0026) [0.2007]	−0.0063 (0.0016) [0.0001]	−0.0079 (0.0015) [0.0000]	−0.0077 [0.0015) [0.0000]
Country-specific time trend	—	—	—	−0.0061 (0.0004) [0.0000]
R^2	0.5491	0.9720	0.9736	0.9735
F-tests for income variables				
Quadratic term[c]	F (1, 4347) = 2.3357 [0.1265]	F (1, 4198) = 1.4399 [0.2302]	F (1, 4170) = 29.6005 [0.0000]	F (1, 4197) = 30.9598 [0.0000]
Cubic term[d]	F (1, 4346) = 1.6380 [0.2007]	F (1, 4197) = 16.3575 [0.0001]	F (1, 4169) = 26.6335 [0.0000]	F (1, 4196) = 25.7802 [0.0000]
F-tests for country-fixed effects[e]				
Linear model	—	F (149, 4199) = 423.3489 [0.0000]	—	F (149,4198) = 445.0027 [0.0000]
Quadratic model	—	F (149, 4198) = 423.1604 [0.0000]	—	F (149, 4197) = 448.1436 [0.0000]
Cubic model	—	F (149, 4197) = 424.6476 [0.0000]	—	F (149, 4196) = 450.8068 [0.0000]
F-tests for time-fixed effects[f]				
Linear model	—	—	F (28,4171) = 7.7072 [0.0000]	—
Quadratic model	—	—	F (28,4170) = 8.7632 [0.0000]	—
Cubic model	—	—	F (28,4169) = 9.1522 [0.0000]	—
F-tests for country-and-time fixed effects[g]				
Linear model	—	—	F (177,4171) = 373.5370 [0.0000]	—
Quadratic model	—	—	F (177,4170) = 376.0508 [0.0000]	—
Cubic model	—	—	F (177,4169) = 378.3614 [0.0000]	—
F-tests for country-specific trend[h]				
Linear model	—	—	—	F (1, 4198) = 205.3760 [0.0000]
Quadratic model	—	—	—	F (1, 4197) = 236.2809 [0.0000]
Cubic model	—	—	—	F (1, 4196) = 246.1433 [0.0000]
Observations	4350	4350	4350	4350

[a] Dependent variable is the log of DMI_{ext} per capita and independent variable is the log of GDP per capita.

[b] Standard error of estimates inside round brackets and statistical significance inside square brackets

[c] F-test with H_0: $\beta_2 = 0$

[d] F-test with H_0: $\beta_3 = 0$

[e] F-test with H_0: $\alpha_i = 0$, against base model

[f] F-test with H_0: $\varphi_t = 0$, against model with country-fixed effects

[g] F-test with H_0: $\alpha_i = 0$ and $\varphi_t = 0$, against base model

[h] F-test with H_0: $\varphi_i t = 0$, against model with country-fixed effects

Detailed table 2. Summary results of MKC parameter estimations **biomass TDE**[a,b]

	Base	Country-fixed effects	Country-and-time fixed effects	Country-fixed effects and country-specific time trend
Linear model				
Income	0.0045 (0.0089) [0.6085]	–0.0491 (0.0102) [0.0000]	0.1118 (0.0116) [0.0000]	0.1156 (0.0114) [0.0000]
Country-specific time trend	—	—	—	–0.0081 (0.0003) [0.0000]
R^2	0.0001	0.9739	0.9776	0.9775
Quadratic model				
Income	0.7269 (0.0905) [0.0000]	0.5921 (0.0495) [0.0000]	0.4372 (0.0473) [0.0000]	0.4332 (0.0472) [0.0000]
Income^2	–0.044876 (0.0056) [0.0000]	–0.0421 (0.0032) [0.0000]	–0.0223 (0.0031) [0.0000]	–0.0217 (0.0031) [0.0000]
Country-specific time trend	—	—	—	–0.0075 (0.0003) [0.0000]
R^2	0.0146	0.9750	0.9779	0.9778
Cubic model				
Income	3.2759 (0.6659) [0.0000]	1.5778 (0.2453) [0.0000]	1.1023 (0.2330) [0.0000]	1.1171 (0.2325) [0.0000]
Income^2	–0.3734 (0.0852) [0.0000]	–0.1735 (0.0322) [0.0000]	–0.1109 (0.0306) [0.0003]	–0.1129 (0.0305) [0.0002]
Income^3	0.0137 (0.0036) [0.0001]	0.0056 (0.0014) [0.0000]	0.0038 (0.0013) [0.0036]	0.0039 (0.0013) [0.0027]
Country-specific time trend	—	—	—	–0.0074 (0.0003) [0.0000]
R^2	0.0180	0.9751	0.9779	0.9778
F-tests for income variables				
Quadratic term[c]	*F* (1, 4347) = 64.2907 [0.0000]	*F* (1, 4198) = 175.0929 [0.0000]	*F* (1, 4170) = 50.34308 [0.0000]	*F* (1, 4197) = 48.0991 [0.0000][c]
Cubic term[d]	*F* (1, 4346) = 14.926 [0.0001]	*F* (1, 4197) = 16.8261 [0.0000]	*F* (1, 4169) = 8.4969 [0.0036]	*F* (1, 4196) = 9.0241 [0.0027][d]
F-tests for country-fixed effects[e]				
Linear model	—	*F* (149, 4199) =1053.3978[0.0000]	—	*F* (149, 4198) = 1219.8467 [0.0000][e]
Quadratic model	—	*F* (149, 4198) = 1081.8308 [0.0000]	—	*F* (149, 4197) = 1215.7979 [0.0000][e]
Cubic model	—	*F* (149, 4197) = 1082.2086 [0.0000]	—	*F* (149, 4196) =1213.4437 [0.0000][e]
F-tests for time-fixed effects[f]				
Linear model	—	—	*F* (28, 4171) = 24.2319 [0.0000]	—
Quadratic model	—	—	*F* (28, 4170) = 19.2999 [0.0000]	—
Cubic model	—	—	*F* (28, 4169)= 18.9651 [0.0000]	—
F-tests for country-and-time fixed effects[g]				
Linear model	—	—	*F* (177, 4171) = 1027.9649 [0.0000]	—
Quadratic model	—	—	*F* (177, 4170) = 1024.9038 [0.0000]	—
Cubic model	—	—	*F* (177, 4169) = 1023.1993 [0.0000]	—
F-tests for country-specific trend[h]				
Linear model	—	—	—	*F* (1, 4198) = 662.9288 [0.0000][f]
Quadratic model	—	—	—	*F* (1, 4197) = 521.6568 [0.0000][f]
Cubic model	—	—	—	*F* (1, 4196) = 512.8002 [0.0000][f]
Observations	4350	4350	4350	4350

[a] Dependent variable is the log of biomass TDE per capita and independent variable is the log of GDP per capita.

[b] Standard error of estimates inside round brackets and statistical significance inside square brackets

[c] *F*-test with H_0: $\beta_2 = 0$

[d] *F*-test with H_0: $\beta_3 = 0$

[e] *F*-test with H_0: $\alpha_i = 0$, against base model

[f] *F*-test with H_0: $\varphi_t = 0$, against model with country-fixed effects

[g] *F*-test with H_0: $\alpha_i = 0$ and $\varphi_t = 0$, against base model

[h] *F*-test with H_0: $\varphi_i t = 0$, against model with country-fixed effects

Detailed table 3. Summary results of MKC parameter estimations for **fossil fuel TDE**[a,b]

	Base	Country-fixed effects	Country-and-time fixed effects	Country-fixed effects and country-specific time trend
Linear model				
Income	0.9683 (0.0287) [0.0000]	0.6237 (0.0702 [0.0000]	0.8223 (0.0872) [0.0000]	0.7656 (0.0843) [0.0000]
Country-specific time trend	—	—	—	–0.0071(0.0023) [0.0025]
R^2	0.3067	0.9243	0.9739	0.9246
Quadratic model				
Income	5.1073 (0.2899) [0.0000]	4.5760 (0.3228) [0.0000]	4.5651 (0.3254) [0.0000]	4.569135 (0.3239) [0.0000]
Income^2	–0.2545 (0.0177) [0.0000]	–0.2559 (0.0037) [0.0000]	–0.2514 (0.0211) [0.0000]	–0.2547 (0.020989) [0.0000]
Country-specific time trend	—	—	—	–0.0006 (0.0023) [0.8021]
R^2	0.3581	0.9288	0.9292	0.9288
Cubic model				
Income	0.7814 (0.5442) [0.1511]	7.8843 (1.6948) [0.0000]	7.8004 (1.7037) 0.0000]	7.8724 (1.6959) [0.0000]
Income^2	0.1894 (0.2717) [0.4859]	–0.6912 (0.2199) [0.0017]	–0.6773 (0.2211) [0.0022]	–0.6894 (0.2200) [0.0018]
Income^3	–0.0186 (0.0114) [0.1017]	0.0182 (0.0092) [0.0469]	0.0178 (0.0092) [0.0531]	0.0182 (0.0092) [0.0473]
Country-specific time trend	—	—	—	–0.0005 (0.0023) [0.8265]
R^2	0.3587	0.9289	0.9293	0.9289
F-tests for income variables				
Quadratic term[c]	*F* (1, 2566) = 205.7295 [0.0000]	*F* (1, 2474) = 156.9385 [0.0000]	*F* (1, 2446) = 141.8937 [0.0000]	*F* (1, 2473) = 147.2384 [0.0000][c]
Cubic term[d]	*F* (1, 2565) = 2.680270 [0.1017]	*F* (1, 2473) = 3.953581 [0.0469]	*F* (1, 2445) = 3.74287 [0.0531]	*F* (1, 2472) = 3.937221 [0.0473][d]
F-tests for country-fixed effects[e]				
Linear model	—	*F* (92,2475) = 219.4992 [0.0000]	—	*F* (92, 2474) = 220.131360 [0.0000][e]
Quadratic model	—	*F* (92,2474) = 215.593451 [0.0000]	—	*F* (92, 2473) = 215.274065 [0.0000]
Cubic model	—	*F* (92,2473) = 215.640391[0.0000]	—	*F* (92,2472) = 215.276932 [0.0000]
F-tests for time-fixed effects[f]				
Linear model	—	—	*F* (28,2447) = 0.897443 [0.6206]	—
Quadratic model	—	—	*F* (28,2446) = 0.446890 [0.9947]	—
Cubic model	—	—	*F* (28,2445) = 0.440760 [0.9953]	—
F-tests for country-and-time fixed effects[g]				
Linear model	—	—	*F* (120,2447) = 168.296882 [0.0000]	—
Quadratic model	—	—	*F* (120,2446) = 164.357893 [0.0000]	—
Cubic model	—	—	*F* (120,2445) = 164.380332 [0.0000]	—
F-tests for country-specific trend[h]				
Linear model	—	—	—	*F* (1, 2474) = 9.161923 [0.0025]
Quadratic model	—	—	—	*F* (1, 2473) = 0.062830 [0.8021]
Cubic model	—	—	—	*F* (1, 2472) = 0.048066 [0.8265]
Observations	2569	2569	2569	2569

[a] Dependent variable is the log of fossil fuel TDE per capita and independent variable is the log of GDP per capita.

[b] Standard error of estimates inside round brackets and statistical significance inside square brackets

[c] *F*-test with H_0: $\beta_2 = 0$

[d] *F*-test with H_0: $\beta_3 = 0$

[e] *F*-test with H_0: $\alpha_i = 0$, against base model

[f] *F*-test with H_0: $\varphi_t = 0$, against model with country-fixed effects

[g] *F*-test with H_0: $\alpha_i = 0$ and $\varphi_t = 0$, against base model

[h] *F*-test with H_0: $\varphi_i t = 0$, against model with country-fixed effects

Detailed table 4. Summary results of MKC parameter estimations for **ind. & constr. minerals TDE**[a,b]

	Base	Country-fixed effects	Country-and-time fixed effects	Country-fixed effects and country-specific time trend
Linear model				
Income	0.7314 (0.0053) [0.0000]	0.8914 (0.0180) [0.0000]	0.7884 (0.0220) [0.0000]	0.8042 (0.0217) [0.0000]
Country-specific time trend	—	—	—	0.0043 (0.0006) [0.0000]
R^2	0.8122	0.9582	0.9590	0.9587
Quadratic model				
Income	1.4719 (0.0539) [0.0000]	0.8884 (0.0892) [0.0000]	0.9938 (0.0896) [0.0000]	0.9858 (0.0896) [0.0000]
$Income^2$	–0.0460 (0.0033) [0.0000]	0.0002 (0.0057) [0.9722]	–0.014080 (0.0060) [0.0181]	–0.0124 (0.0060) [0.0366]
Country-specific time trend	—	—	—	0.0047 0(.0006) [0.0000]
R^2	0.8201	0.9582	0.9590	0.9587
Cubic model				
Income	–1.8826 (0.3951) [0.0000]	–3.8023 (0.4368) [0.0000]	–3.5464 (0.4364) [0.0000]	–3.5312 (0.4362) [0.0000]
$Income^2$	0.1894 (0.2717) [0.4859]	0.6254 (0.0573) [0.0000]	0.5901 (0.0573) [0.0000]	0.5896 (0.0572) [0.0000]
$Income^3$	–0.0181 (0.0021) [0.0000]	–0.0266 (0.0024) [0.0000]	–0.0257 (0.0024) [0.0000]	–0.0256 (0.0024) [0.0000]
Country-specific time trend	—	—	—	0.0042 (0.0006) [0.0000]
R^2	0.8231	0.9593	0.9601	0.9598
F-tests for income variables				
Quadratic term[c]	*F* (1, 4318) = 190.2364 [0.0000]	*F* (1, 4170) = 0.0012 [0.9722]	*F* (1, 4142) = 5.590088 [0.0181]	*F* (1, 4169) = 4.3700 [0.0366]
Cubic term[d]	*F* (1, 4317) = 73.43101 [0.0000]	*F* (1, 4169) = 120.1795 [0.0000]	*F* (1, 4141) = 112.8752 [0.0000]	*F* (1, 4168) = 111.8201 [0.0000]
F-tests for country-fixed effects[e]				
Linear model	—	*F* (148, 4171) = 98.371169 [0.0000]	—	*F* (148,4170) = 99.0803 [0.0000]
Quadratic model	—	*F* (148, 4170) = 93.0087 [0.0000]	—	*F* (148,4169) = 93.6807 [0.0000]
Cubic model	—	*F* (148, 4169) = 94.3941 [0.0000]	—	*F* (148,4168) =94.6569 [0.0000]
F-tests for time-fixed effects[f]				
Linear model	—	—	*F* (28, 4143)= 2.945992 [0.0000]	—
Quadratic model	—	—	*F* (28, 4142) = 3.148858 [0.0000]	—
Cubic model	—	—	*F* (28 ,4141) =2.9178 [0.0000]	—
F-tests for country-and-time fixed effects[g]				
Linear model	—	—	*F* (176, 4143) = 84.270518 [0.0000]	—
Quadratic model	—	—	F (176, 4142) = 79.841277 [0.0000]	—
Cubic model	—	—	*F* (176, 4141) = 80.8634 [0.0000]	—
F-tests for country-specific trend[h]				
Linear model	—	—	—	*F* (1, 4170) = 50.8704 [0.0000]
Quadratic model	—	—	—	*F* (1, 4169) = 55.2802 [0.0000]
Cubic model	—	—	—	*F* (1, 4168) = 47.0625 [0.0000]
Observations	4321	4321	4321	4321

[a] Dependent variable is the log of ind. & constr. minerals TDE per capita and independent variable is the log of GDP per capita.

[b] Standard error of estimates inside round brackets and statistical significance inside square brackets

[c] *F*-test with H_0: $\beta_2 = 0$

[d] *F*-test with H_0: $\beta_3 = 0$

[e] *F*-test with H_0: $\alpha_i = 0$, against base model

[f] *F*-test with H_0: $\varphi_t = 0$, against model with country-fixed effects

[g] *F*-test with H_0: $\alpha_i = 0$ and $\varphi_t = 0$, against base model

[h] *F*-test with H_0: $\varphi_i t = 0$, against model with country-fixed effects

Detailed table 5. Summary results of MKC parameter estimations for **metal ores TDE**[a,b]

	Base	Country-fixed effects	Country-and-time fixed effects	Country-fixed effects and country-specific time trend
Linear model				
Income	0.3190 (0.0368) [0.0000]	0.6842 (0.0945) [0.0000]	0.7884 (0.0220) [0.0000]	0.7162 (0.1173) [0.0000]
Country-specific time trend	—	—	—	–0.0015 (0.0032) [0.6451]
R^2	0.0266	0.8843	0.8847	0.8843
Quadratic model				
Income	6.1499 (0.3624) [0.0000]	6.0922 (0.4294) [0.0000]	6.3912 (0.4369) [0.0000]	6.3974 (0.4348) [0.0000]
Income^2	–0.3646 (0.0226) [0.0000]	–0.3608 (0.0290) [0.0000]	–0.3987 (0.0297) [0.0000]	–0.4003 (0.0296) [0.0000]
Country-specific time trend	—	—	—	0.0131 (0.0032) [0.0001]
R^2	0.1114	0.8911	0.8921	0.8918
Cubic model				
Income	3.8030 (2.6999) [0.1591]	9.9792 (2.1798) [0.0000]	10.3656 (2.1896) [0.0000]	10.4146 (2.1761) [0.0000]
Income^2	–0.0581 (0.3501) [0.8683]	–0.8839 (0.2890) [0.0022]	–0.9337 (0.2903) 0.0013]	–0.9409 (0.2885) [0.0011]
Income^3	–0.0130 (0.0148) [0.3804]	0.0224 (0.0123) [0.0691]	0.0229 (0.0123) [0.0641]	0.0231 (0.0122) [0.0597]
Country-specific time trend	—	—	—	0.0131 (0.0032) [0.0000]
R^2	0.1116	0.8912	0.8922	0.8919
F-tests for income variables				
Quadratic term[c]	*F* (1, 2740) = 261.2980 [0.0000]	*F* (1, 2640) = 166.2137 [0.0000]	*F* (1, 2612) = 180.1060 [0.0000][c]	*F* (1, 2639) = 183.2231 [0.0000]
Cubic term[d]	*F* (1, 2739) = 0.769591 [0.3804]	*F* (1, 2639) = 3.307928 [0.0691]	*F* (1, 2611) = 3.4311 [0.0641][d]	*F* (1, 2638) = 3.5495 [0.0597]
F-tests for country-fixed effects[e]				
Linear model	—	*F* (100, 2641) =195.6839 [0.0000]	—	*F* (100,2640) = 195.0221 [0.0000]
Quadratic model	—	*F* (100, 2640) = 189.0420 [0.0000]	—	*F* (100,2639) = 189.5964 [0.0000]
Cubic model	—	*F* (100, 2639) = 189.1797 [0.0000]	—	*F* (100,2638) = 189.7034 [0.0000]
F-tests for time-fixed effects[f]				
Linear model	—	—	*F* (28, 2613) = 0.3531 [0.9994]	—
Quadratic model	—	—	*F* (28, 2612) = 0.8810 [0.6456]	—
Cubic model	—	—	*F* (28, 2611)= 0.8863 [0.6375]	—
F-tests for country-and-time fixed effects[g]				
Linear model	—	—	*F* (128, 2613) = 151.9068 [0.0000]	—
Quadratic model	—	—	*F* (128, 2612) = 147.6953 [0.0000]	—
Cubic model	—	—	*F* (128, 2611) = 147.8123 [0.0000]	—
F-tests for country-specific trend[h]				
Linear model	—	—	—	*F* (1, 2640) = 0.2122 [0.6451]
Quadratic model	—	—	—	*F* (1, 2639) = 16.2746 [0.0001]
Cubic model	—	—	—	*F* (1, 2638) = 16.5125 [0.0000]
Observations	2743	2743	2743	2743

[a] Dependent variable is the log of metal ores TDE per capita and independent variable is the log of GDP per capita.

[b] Standard error of estimates inside round brackets and statistical significance inside square brackets

[c] *F*-test with H_0: $\beta_2 = 0$

[d] *F*-test with H_0: $\beta_3 = 0$

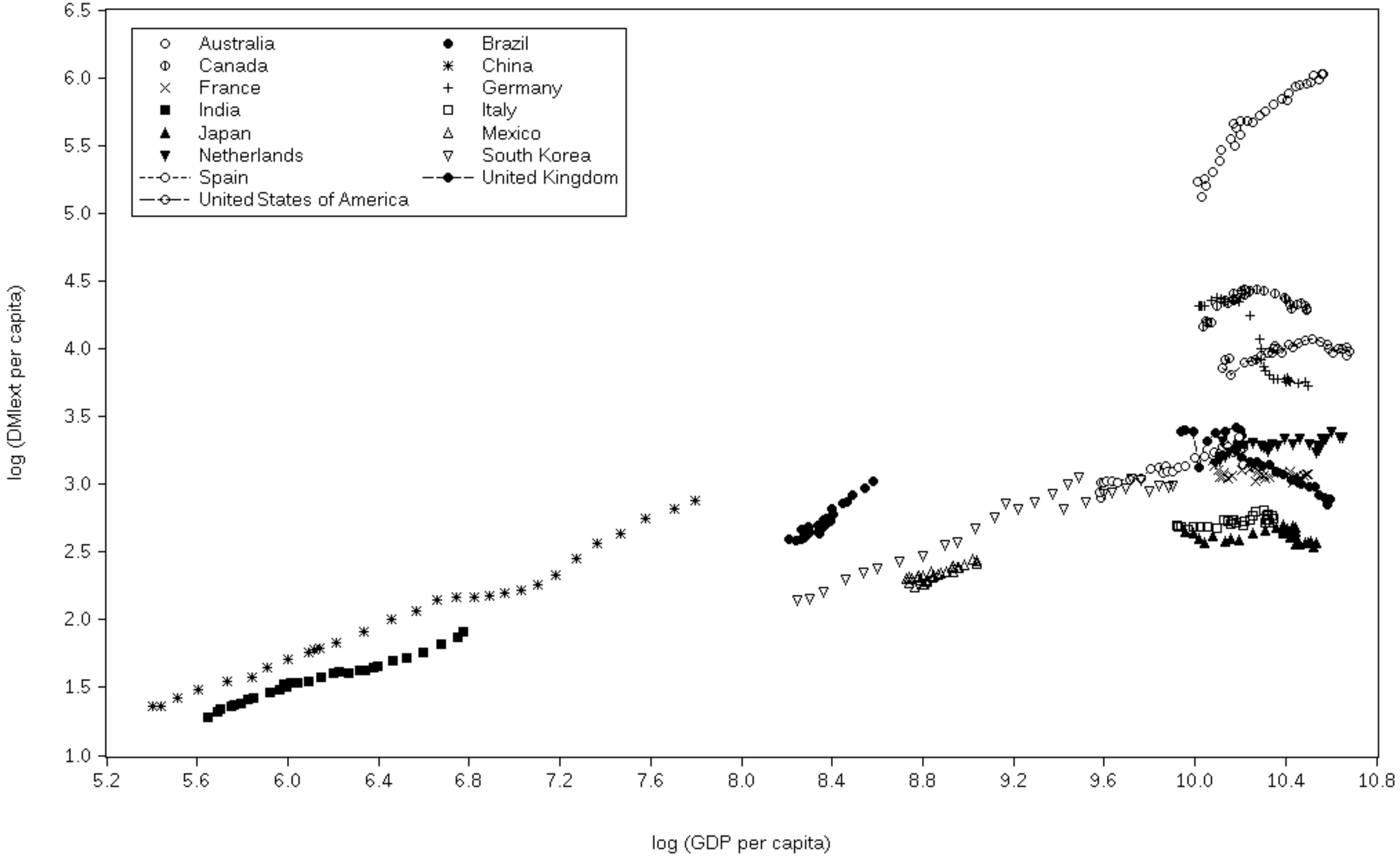
[e] *F*-test with H_0: $\alpha_i = 0$, against base model

[f] *F*-test with H_0: $\varphi_t = 0$, against model with country-fixed effects

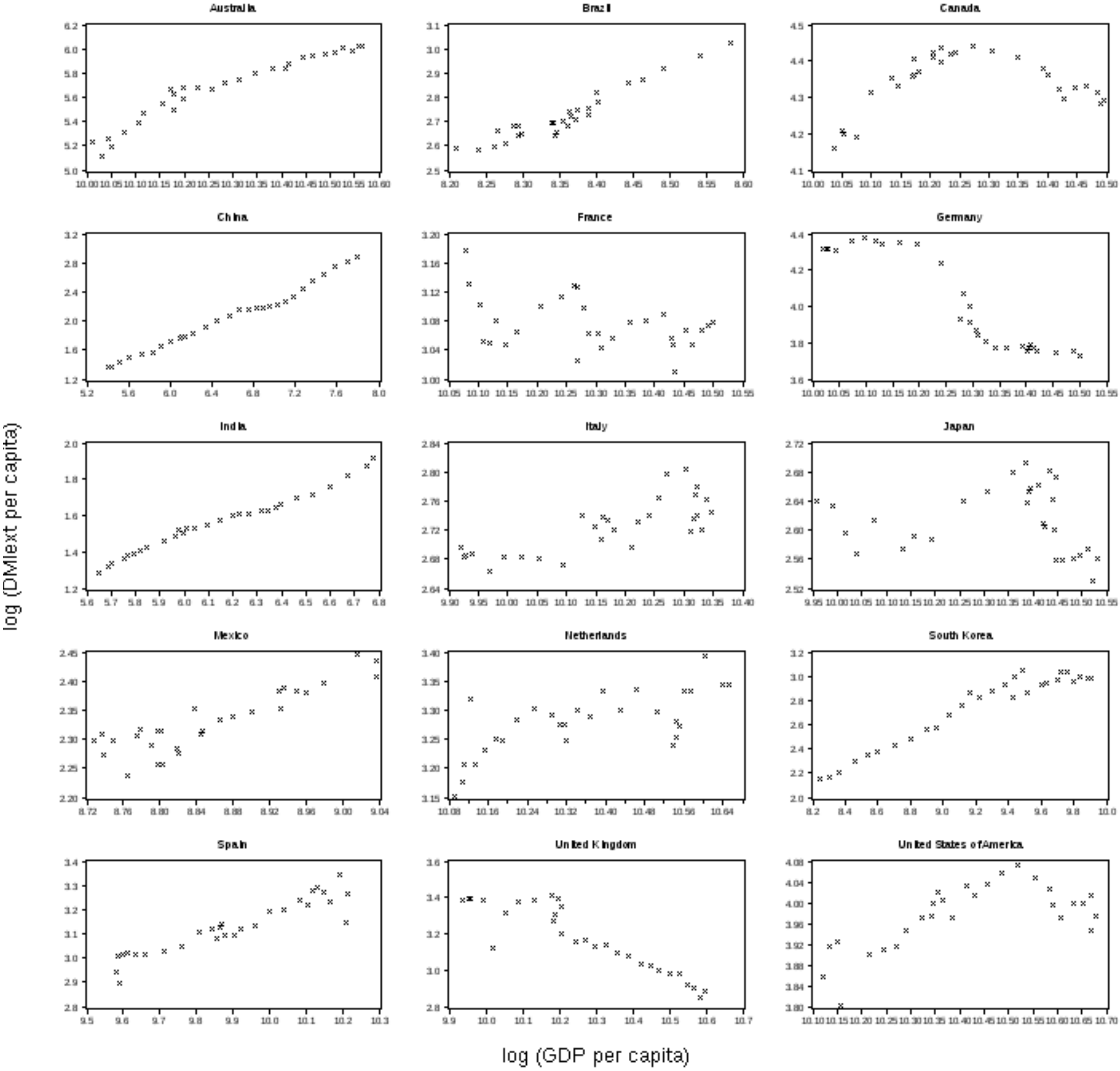
[g] *F*-test with H_0: $\alpha_i = 0$ and $\varphi_t = 0$, against base model

[h] *F*-test with H_0: $\varphi_i t = 0$, against model with country-fixed effects

Graph 6. Combined scatterplot of country-level DMI_{ext} per capita and GDP per capita



Graph 7. Individual scatterplots of country-level DMI$_{\text{ext}}$ per capita and GDP per capita



Detailed table 6. Summary results for country-specific MKC parameter estimations for DMI_{ext}[a,b]

	Linear model	Quadratic model		Cubic Model[c]			Result
	Income	Income	Income^2	Income	Income^2	Income^3	
Australia	1.48 [0.00]	46.96 [0.00]	−2.21 [0.00]	1658.62 [0.03]	−158.90 [0.03]	5.08 [0.04]	MKC**, N*
Brazil	1.25 [0.00]	−23.18 [0.01]	1.46 [0.01]	10.60 [0.02]	−2.56 [0.02]	0.16 [0.02]	Linear increasing**, U*, N*
Canada	0.12 [0.23]	81.64 [0.00]	−3.97 [0.00]	−39.85 [0.00]	7.87 [0.00]	−0.38 [0.00]	MKC**, Reverse N**
China	0.61 [0.00]	−0.12 [0.64]	0.06 [0.01]	0.10 [0.42]	0.02 [0.68]	0.002 [0.44]	Linear increasing**
France	−0.10 [0.03]	−5.68 [0.50]	0.27 [0.51]	3.87 [0.36]	−0.65 [0.43]	0.03 [0.46]	Linear increasing*
Germany	−1.63 [0.00]	7.12 [0.72]	−0.43 [0.66]	0.60 [0.95]	0.16 [0.94]	−0.02 [0.8552]	Linear decreasing**
India	0.49 [0.00]	0.58 [0.25]	−0.01 0.85]	−0.20 [0.43]	0.11 [0.18]	−0.01 [0.38]	Linear increasing**
Italy	0.20 [0.00]	−2.24 [0.70]	0.12 [0.67]	1.56 [0.59]	−0.25 [0.66]	0.01 [0.67]	Linear increasing**
Japan	−0.02 [0.67]	17.16 [0.02]	−0.84 [0.02]	−2200.86 [0.00]	215.39 [0.00]	−7.025 [0.00]	Reverse N**, MKC*
Mexico	0.52 [0.00]	−17.99 [0.09]	1.04 [0.08]	8.91 [0.09]	−1.98 [0.09]	0.11 [0.09]	Linear increasing**
Netherlands	0.20 [0.00]	7.22 [0.24]	−0.34 [0.25]	1453.54 [0.02]	−139.89 [0.02]	4.49 [0.02]	Linear increasing**, N*
South Korea	0.55 [0.00]	4.99 [0.00]	−0.24 [0.00]	−69.07 [0.01]	7.91 [0.01]	−0.30 [0.00]	MKC**, reverse N*
Spain	0.48 [0.00]	2.17 [0.60]	−0.086 [0.69]	−421.50 [0.34]	42.76 [0.34]	−1.44 [0.34]	Linear increasing**
United Kingdom	−0.81 [0.00]	19.15 [0.01]	−0.97 [0.01]	820.11 [0.25]	−79.034 [0.25]	2.54 [0.26]	Linear decreasing**, MKC*
United States of America	0.23 [0.00]	25.57 [0.00]	−1.22 [0.00]	−1275.6 [0.01]	123.93 [0.01]	−4.01 [0.01]	MKC**, reverse N*

[a] Dependent variable is the log of DMI_{ext} per capita and independent variable is the log of GDP per capita.

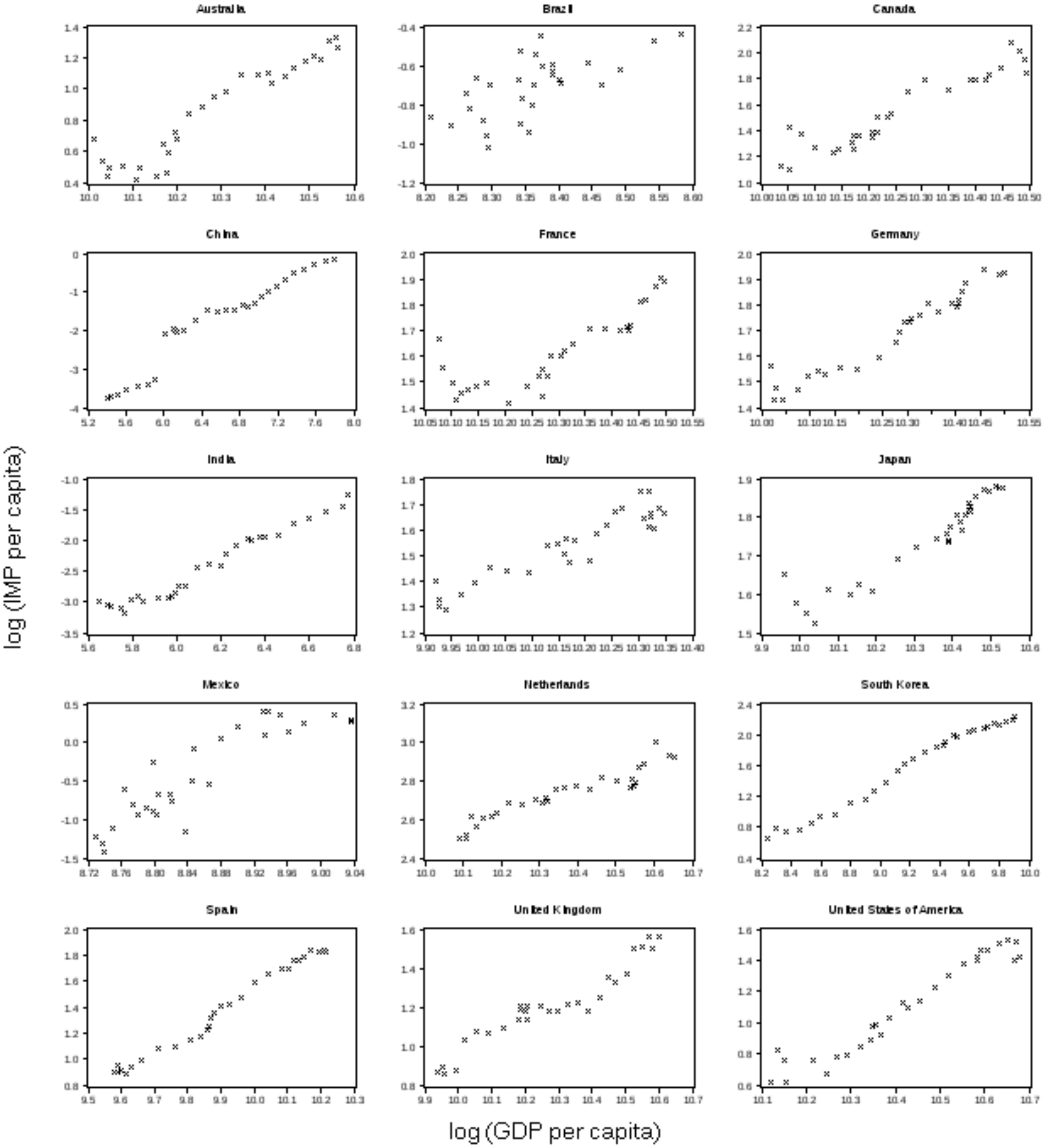
[b] Statistical significance in square brackets

[c] For some countries constant term was omitted due to its inclusion causing a singular matrix

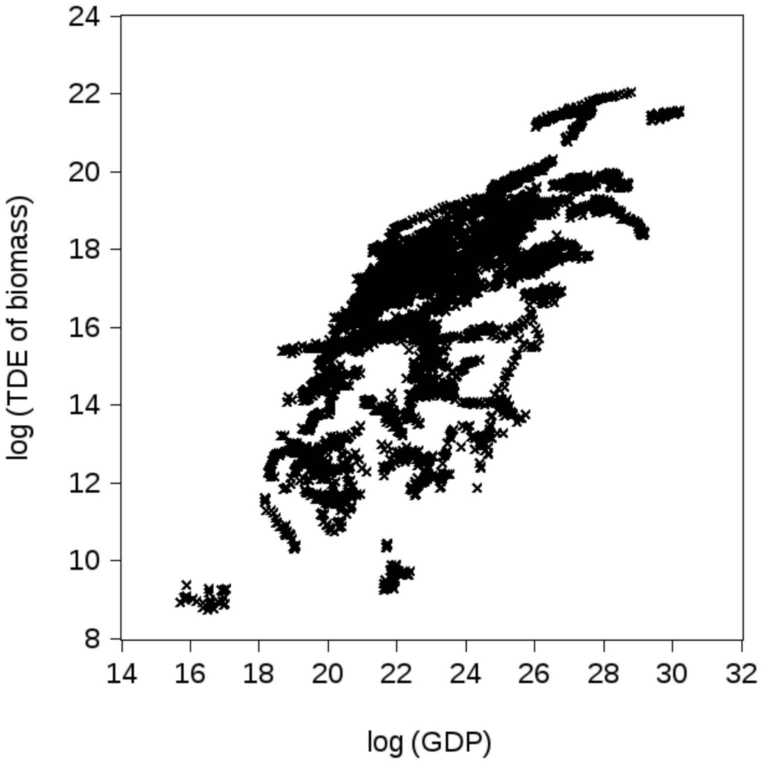
*Significant at the 5% level

**Significant at the 1% level

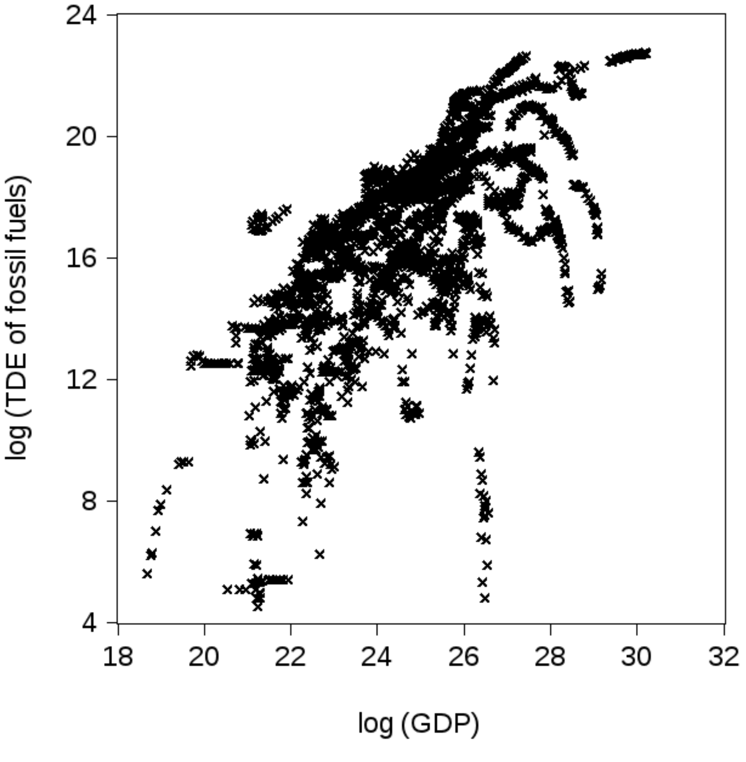
Graph 8. Individual scatter plots for country-level IMP per capita and GDP per capita



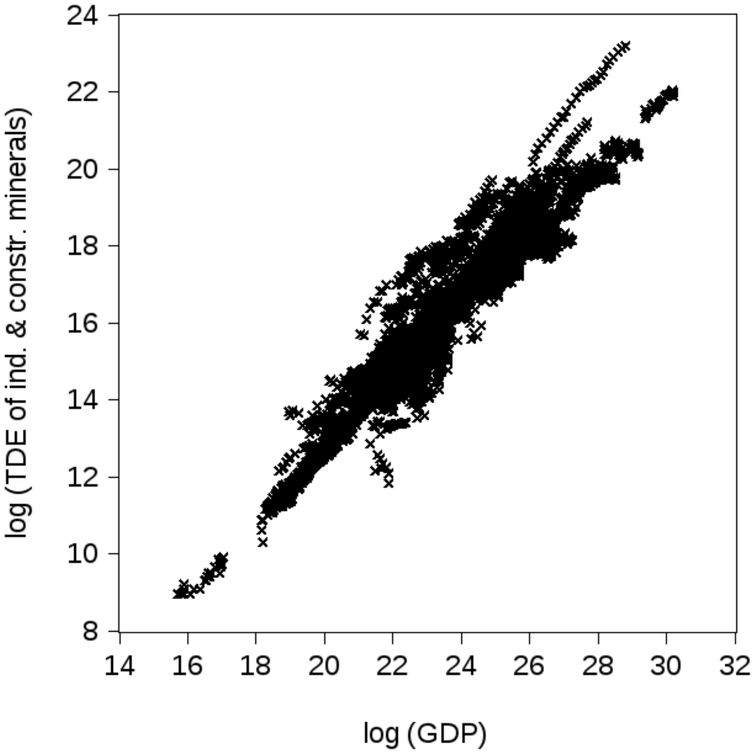
Graph 9. Scatterplot of absolute values of TDE biomass and GDP



Graph 10. Scatterplot of absolute values of fossil fuel TDE and GDP



Graph 11. Scatterplot of absolute values for ind. & constr. minerals



Graph 12. Scatterplot of absolute values for metal ores TDE and GDP