Environ Econ Policy Stud (2015) 17:369–388
DOI 10.1007/s10018-014-0085-y

RESEARCH ARTICLE
Studies on Industrial Ecology

# The footprint of using metals: new metrics of consumption and productivity

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Received: 17 January 2014 / Accepted: 7 April 2014 / Published online: 26 June 2014


**Abstract** Metal use and modern society are intrinsically linked and it is no surprise that global processes of industrialization and urbanization have led to ever increasing amounts of metal use. In recent decades, global supply and demand networks for metals have become increasingly complex. Industrial Ecology research is well placed to unpack this complexity and to explore potential resource efficiencies for metals. This is especially important during the current period of rising ore prices. We examine patterns of supply and demand for iron ore and bauxite, and recent trends in resource productivity of these two important metal ores. We introduce a consumption perspective and compare the material footprint of metal ores to the GDP of countries to look at how much economic benefit countries achieve per unit of metal footprint. We find that for the past two decades global amounts of iron ore and bauxite extractions have risen faster than global GDP, that both supply and demand of iron ore and bauxite have been concentrated in a handful of countries and that resource productivity from a consumption perspective has fallen in developed nations, as well as globally. The research shows no saturation of

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metal ore consumption at any level of income. Policies will be required to enhance both the productivity of metal production and the economic productivity of consumption (GDP per metal footprint) through more efficient mining, product design, reuse and recycling.

**Keywords** Material footprint · Metal ores · Resource productivity · Multi-region input–output analysis · Sustainable resource management

**JEL Classification** C67 · F18 · F64 · Q31 · Q37 · Q56 · P17

## 1 Introduction

Throughout history, metals have played an important role in human development and large increases in metal use have been a symbol and a condition for the thriving of modern societies. The way we build, get around and communicate today critically depends on the availability of large amounts or iron and steel, copper and aluminium as well as a large variety of other metals (Chen and Graedel 2012; Gerst and Graedel 2008). Global metal ore extraction has grown rapidly in the past few decades and reached an unprecedented level of almost 7.4 billion tons (gigatons Gt) in 2008. This is twice as much as in 1985 and three times as much as in 1970 (CSIRO 2013; Krausmann et al. 2009). Metal consumption is set to grow in the future (Cullen and Allwood 2013; Cullen et al. 2012), not least because low-carbon energy infrastructure is also dependent on metals (Prior et al. 2012; Vidal et al. 2013).

Recent research has found a strong coupling of metal use and economic development suggesting a high income elasticity of consumption (Steinberger et al. 2013; Steinberger and Krausmann 2011). Rapid economic growth in China and other developing countries, especially since 2000 (Schandl and West 2010), has ratcheted up metal ore extraction and has led to increasing global metal ore prices for the first time in a century (McKinsey Global Institute 2011). Further processes of industrialization and urbanization and the growth of a new middle-class in many developing countries (Myers and Kent 2003) suggest that the global demand for iron ore and bauxite will further increase. This puts pressure on business strategies and policies to enhance resource productivity of metal use dramatically not to curb development and prosperity in many developing countries (Bleischwitz 2011; Bringezu and Bleischwitz 2009). Adequate metrics of resource productivity are required to inform effective policy design. Currently used measures, however, tend to mask the full reliance of consumption on primary resources from global supply chains (Wiedmann et al. 2013). One commonly used indicator, domestic material consumption (DMC), suggests that OECD countries have stabilized their use of metal ores (OECD 2011) when in reality material and energy intensive processes of production may have been outsourced to other countries.

In this research we look at global patterns of supply and demand for two economically critical metal ores—iron ore and bauxite—and take a novel look at the productivity of metal use proposing a consumption perspective.

Iron ore is the world's most commonly used metal and steel making is one of the world's largest industries with applications in structural engineering (buildings, bridges, and other large scale construction projects), in transport (ships, railways and automobiles) and other industry sectors such as machinery and tools (Cullen et al. 2012; Moynihan and Allwood 2012; Pauliuk et al. 2013b). Steel production accounts for 25 % of global industrial $CO_2$ emissions (Allwood and Cullen 2012). Because of the abundance of iron ore there is no immediate issue of supply scarcity for steel making. Mining of iron ore is a highly capital-intensive business with high physical volumes and low economic margins, undertaken by a handful of multinational companies including Vale (of Brazil), BHP Billiton and Rio Tinto. Bauxite—aluminium ore—is the most widely used non-ferrous metal ore. Aluminium has a wide range of applications including in transportation, packaging, construction (windows and doors), household items, and shells of consumer electronics and for electrical transmission lines, to mention the most important uses (Liu et al. 2013; Liu and Müller 2013a, b). Recycling rates for both metals are relatively high—end-of-life recycling rates for iron and aluminium are above 50 % (Reck and Graedel 2012) and can reach up to 90 % for iron and 70 % for aluminium (Graedel et al. 2011). These rates are enabled through the usage of scrap steel in steel production and the favourable energy balance of recycled aluminium when compared to virgin aluminium.

For iron and aluminium the primary sustainability concerns evolve around the energy and pollution intensity of ore processing (e.g. Milford et al. 2013). Liu and Müller (Liu and Müller 2013a, p.4882), for example, write: "The contemporary global aluminium stock in use (0.6 Gt or 90 kg/capita) has reached about 10 % of that in known bauxite reserves and represents an embodied energy amount that is equivalent to three-quarters of the present global annual electricity consumption". There are additional social, economic and environmental impacts of mining and increasing conflicts with other land uses, such as agriculture, that must be considered if further extension of current supply systems is to be considered. It may well be that constraints to increasing supply are social and environmental, not merely limits on resource availability (Martínez-Alier et al. 2010).

The apparent unsustainable and rising levels of global metal consumption require a step change in resource productivity, i.e. a much higher economic and physical efficiency of metal extraction, transformation and use (Ayres et al. 2013). The potential for efficiency improvements can be large, as has been shown for the steel production sector (von Weizsäcker et al. 2009). However, has there been any actual progress in the recent past in using metal resources more efficiently at the global or regional level? Have there been evident cases of relative or even absolute decoupling of metal ore use from economic growth (cf. UNEP 2011)?

These are the questions we are addressing in this research. We investigate the productivity of consuming metal ores in selected countries and world regions for the period 1990–2008. Resource productivity is defined as GDP output per resource input; sometimes the inverse—resource use per GDP—is measured as the resource intensity. An overview of the literature and brief discussion has been provided by Steinberger and Krausmann 2011 (see also Gan et al. 2013). Whilst gross domestic product over domestic material consumption (GDP/DMC) is currently being used by governments as an official indicator of resource productivity, it has recently been suggested to use the material footprint as the basis for measuring resource productivity (Wiedmann et al. 2013) to correct for shifts in environmental burden through trade.

The material footprint (MF) is a consumption-based material flow indicator (Wiedmann et al. 2013), most widely known under the term raw material consumption (RMC) (Bruckner et al. 2012; Kovanda et al. 2012; Kovanda and Weinzettel 2013; Muñoz et al. 2009; Schaffartzik et al. 2013; Schoer et al. 2012; Weinzettel and Kovanda 2009, 2011; Wiebe et al. 2012). Analysis of international flows of materials, and particularly critical and scarce materials, has been an area of increased research activity in the field of Industrial Ecology in recent years (Bleischwitz et al. 2012; Dittrich and Bringezu 2010; Dittrich et al. 2012; Eckelman et al. 2012; Elshkaki and Graedel 2013; Giljum et al. 2014; Nansai et al. 2014). The MF is conceptually equivalent to other footprint approaches for carbon emissions, energy and water (Čuček et al. 2012; Ewing et al. 2012; Fang et al. 2014; Galli et al. 2012, 2013; Giljum et al. 2013; Moran et al. 2013; Steen-Olsen et al. 2012) and summarizes the total amount of raw materials (metal ores in the case of the present study) associated with the domestic final demand of a country or region. An important idiosyncrasy of the MF is that it does not account for the actual physical movement of materials within and between countries but instead provides a quantitative link between producing countries (where natural resources are extracted) and consuming countries (where final products are consumed). The advantage of using MF instead of DMC to quantify resource productivity is grounded in the fact that DMC is limited to the amount of materials directly used by an economy and does not include upstream raw material requirements occurring in countries that export goods and services to that economy (Wiedmann et al. 2013). The MF accounts for these upstream raw material equivalents (RME) associated with imports, exports and consumption.

We approach resource productivity from a consumption perspective of metal ore use. This perspective compares the footprint of metal ore *mo* of a country to the total economic activity in this country, expressed as gross domestic product (GDP). Resource productivity of consumption can, therefore, be expressed as $RP_{cons} = GDP/MF_{mo}$. All numbers are expressed on an annual basis. This consumption-based indicator of RP is a novel way of assessing the resource productivity of metal use, addressing questions at the interface of economic and Industrial Ecology research.

The rest of the paper unfolds as follows. After a description of methodology and data in Sect. 2 we first identify important countries in terms of iron ore and bauxite production and consumption (3.1) and then analyse trends in metal ore productivity from the consumption perspective (3.2). We discuss our findings and conclude in Sects. 4 and 5.

## 2 Data and methodology

The methodology used in this work is based on the combination of material flow accounting (MFA) and global data for natural resource extraction (Fischer-Kowalski et al. 2011; Schandl and West 2010, 2012; West and Schandl 2013) and global, multi-region input–output (MRIO) analysis (Kanemoto and Murray 2013; Turner et al. 2007; Wiedmann 2009; Wiedmann et al. 2011).

Based on the well-known, Nobel Prize winning input–output calculus (Leontief 1936, 1970, 1986; Miller and Blair 2009) the method reallocates production inputs (e.g. resource use, emissions, labour, etc.) from the originating industrial sector in the producing country to final demand in consuming countries. In the case of this study, domestic extraction (DE) of iron ore and bauxite are inputs of production, measured in megatons (Mt) of ore extracted per annum. Based on monetary interrelationships between economic sectors and countries and taking into account intermediate demand by industries, DE is then globally reallocated to final demand elsewhere. Domestic final demand of a country is defined as household consumption expenditure plus government consumption expenditure plus capital investment plus changes in inventories (cf. Bergmann 2013).

The result of this global reallocation of DE is the material footprint (MF), representing the total direct and indirect material requirements of a country, independent of whether or not the materials have actually been physically moved. As such, the MF represents a notional concept of linking resource extraction to consumption elsewhere in the world through attribution (Wiedmann et al. 2013; see also Dittrich et al. 2012), rather than a physical description of material trade (Dittrich and Bringezu 2010). The concept of the MF is identical to other environmental footprint indicators (Galli et al. 2012; Hertwich and Peters 2009; Moran et al. 2013; Steen-Olsen et al. 2012).

We also calculated the raw material equivalents (RME) of economic trade flows by multiplying the monetary value of imports to final demand and exports of final products with MF multipliers derived from the multi-region input–output calculations. These multipliers represent all upstream, global material requirements associated with one dollar of final demand for a given product. Adding the RME of imports to the domestic raw material extraction (DE) of a country and subtracting the RME of exports results in the country’s material footprint (MF).

A detailed description of the MF methodology can be found in the Supporting Information of Wiedmann et al. (2013). The MF of individual countries and regions has also been presented in other studies, though mostly termed raw material consumption (RMC) rather than material footprint (Bruckner et al. 2012; Kovanda et al. 2012; Kovanda and Weinzettel, 2013; Muñoz et al. 2009; Schaffartzik et al. 2013; Schoer et al. 2012; Weinzettel and Kovanda 2009, 2011; Wiebe et al. 2012).

Two main datasets have been used for this study. The *CSIRO* global material flow database (CSIRO 2013) contains a comprehensive compilation of global data for domestic extraction of materials as defined in standard material flow accounting guidelines (Eurostat 2011). Data for iron ore and bauxite extraction are in megatons (Mt) and annually from 1970 to 2008. For more information the reader is referred to the database website (www.csiro.au/AsiaPacificMaterialFlows) and the literature (Schandl and West 2010, 2012; West and Schandl 2013).

*Eora* is a high resolution, multi-region input–output (MRIO) database with global coverage and continuous time series from 1980 to 2011 (Lenzen et al. 2012). Matching environmental and social satellite accounts for 186 countries are part of the database. Eora is the most comprehensive and detailed MRIO model to date and allows the mapping of iron ore and bauxite flows in the structure of the world economy with unprecedented specificity. The Eora database can be accessed via http://worldmrio.com and all data from a previous study (Wiedmann et al. 2013) as well as this present study have been published on this website. A detailed methodological description of the MRIO system has been provided by Lenzen et al. (2013).

Data on the DE of iron ore and bauxite from the CSIRO database were allocated to metal ore mining sectors by country using a binary concordance matrix that matches 4-digit-level product categories as defined by the OECD Harmonised System. GDP data were taken from the World Bank World Development Indicators database (http://data.worldbank.org/data-catalog/world-development-indicators), expressed in purchasing power parity (PPP) and constant international $ for the year 2005 (denoted as "GDP-PPP-2005").

Details of the limitations and assumptions in MF-MRIO modelling have been described elsewhere (Wiedmann et al. 2013). In summary they include:

- Allocation of resource use to final demand is based on monetary rather than physical proxies;
- Inhomogeneity of prices and products within an economic sector;
- Sector aggregation (e.g. ferrous and non-ferrous metals aggregated in one sector);
- The MF is not a measure of the actual environmental *impact* of raw material consumption, just of its total amount.

With respect to the first point it has been argued that physical allocation methods for primary sector activities help to improve attribution from primary activities. This question has been the focus of recent (Schoer et al. 2012, 2013) and ongoing research (for a discussion of differences in physical, monetary and mixed-unit IO methods see Weisz and Duchin 2006).

## 3 Results

### 3.1 Top producers and consumers of iron ore and bauxite

For the year 2008, we find that mining of iron ore and bauxite is concentrated in a small number of countries: the top five producers and exporters are responsible for about 80 % of ore extraction and raw material embodied in exports ($RME_{EX}$) for both materials (Tables 1, 2). Consumption is somewhat less concentrated but the top five consumer countries still use 62 % of the global iron ore and 47 % of global bauxite production through their footprint of consumption. More remarkable perhaps is the large proportion of ores embedded in international trade: 62 % of the global iron ore extraction (1,380 out of 2,210 Mt) and 64 % of the global bauxite mined (136 out of 211 Mt) are associated with trade. This clearly shows that iron ore and bauxite are mostly not consumed in the country of origin but are directly or indirectly linked to economic activities in other countries.

**Table 1** Top 10 producers, exporters, importers and consumers of iron ore, measured as domestic extraction (DE) and raw material equivalents of exports ($RME_{EX}$), imports ($RME_{IM}$) and final demand (MF), respectively

| Production in 2008 | | | Exports in 2008 | | | Imports in 2008 | | | Consumption in 2008 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Country | DE (Mt) | (%) | Country | $RME_{EX}$ (Mt) | (%) | Country | $RME_{IM}$ (Mt) | (%) | Country | MF (Mt) | (%) |
| China | 824 | 37 | Brazil | 315 | 23 | China | 350 | 25 | China | 913 | 41 |
| Brazil | 351 | 16 | China | 261 | 19 | USA | 192 | 14 | USA | 230 | 10 |
| Australia | 342 | 15 | Australia | 250 | 18 | Japan | 87 | 6 | Australia | 102 | 5 |
| India | 220 | 10 | India | 219 | 16 | Germany | 46 | 3 | Japan | 87 | 4 |
| Russia | 100 | 5 | Russia | 97 | 7 | Poland | 46 | 3 | Germany | 46 | 2 |
| Ukraine | 73 | 3 | Ukraine | 71 | 5 | Hong Kong | 41 | 3 | Poland | 46 | 2 |
| USA | 54 | 2 | South Africa | 41 | 3 | UK | 38 | 3 | Iran | 45 | 2 |
| South Africa | 49 | 2 | Kazakhstan | 20 | 1 | Italy | 33 | 2 | Brazil | 44 | 2 |
| Iran | 32 | 1 | Sweden | 17 | 1 | France | 33 | 2 | Hong Kong | 41 | 2 |
| Canada | 31 | 1 | USA | 16 | 1 | India | 30 | 2 | Canada | 39 | 2 |
| All others | 135 | 6 | All others | 72 | 5 | All others | 483 | 35 | All others | 618 | 28 |
| Global total | 2,210 | 100 | Global total | 1,378 | 100 | Global total | 1,378 | 100 | Global total | 2,210 | 100 |

**Table 2** Top 10 producers, exporters, importers and consumers of bauxite, measured as domestic extraction (DE) and raw material equivalents of exports ($RME_{EX}$), imports ($RME_{IM}$) and final demand (MF), respectively

| Production in 2008 | | | Exports in 2008 | | | Imports in 2008 | | | Consumption in 2008 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Country | DE (Mt) | (%) | Country | $RME_{EX}$ (Mt) | (%) | Country | $RME_{IM}$ (Mt) | (%) | Country | MF (Mt) | (%) |
| Australia | 61.4 | 29 | Australia | 43.9 | 32 | USA | 23.6 | 17 | China | 28.8 | 14 |
| China | 35.0 | 17 | India | 19.7 | 14 | Japan | 12.5 | 9 | USA | 23.6 | 11 |
| Brazil | 28.1 | 13 | China | 18.3 | 13 | China | 12.0 | 9 | Australia | 18.1 | 9 |
| India | 21.2 | 10 | Guinea | 18.0 | 13 | Saudi Arabia | 5.4 | 4 | Brazil | 17.1 | 8 |
| Guinea | 18.4 | 9 | Brazil | 12.0 | 9 | Germany | 5.0 | 4 | Japan | 12.5 | 6 |
| Jamaica | 14.4 | 7 | Jamaica | 6.2 | 5 | UK | 4.5 | 3 | Jamaica | 8.2 | 4 |
| Russia | 5.7 | 3 | Russia | 5.5 | 4 | South Korea | 4.1 | 3 | Venezuela | 5.5 | 3 |
| Venezuela | 5.5 | 3 | Kazakhstan | 3.9 | 3 | France | 4.1 | 3 | Saudi Arabia | 5.4 | 3 |
| Suriname | 5.2 | 2 | Greece | 2.5 | 2 | Italy | 3.7 | 3 | Germany | 5.0 | 2 |
| Kazakhstan | 5.2 | 2 | Suriname | 2.1 | 2 | UAE | 3.6 | 3 | India | 4.7 | 2 |
| All others | 11.5 | 5 | All others | 4.0 | 3 | All others | 57.6 | 42 | All others | 82.6 | 39 |
| Global total | 211 | 100 | Global total | 136 | 100 | Global total | 136 | 100 | Global total | 211 | 100 |

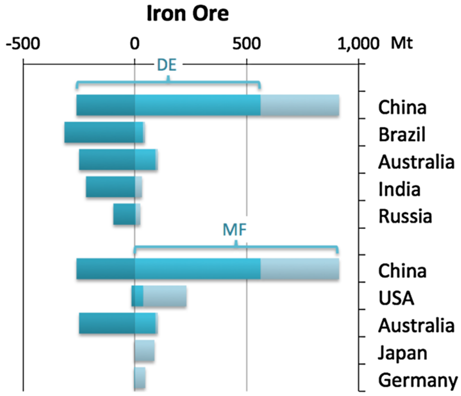


**Fig. 1** Top 5 producers (*top*) and consumers (*bottom*) of iron ore. Shown are megatonnes (Mt) of iron ore associated with exports (*dark shaded areas to the left*), with domestic activities (*medium shaded areas*) and with imports (*light shaded areas to the right*). *Dark and medium shaded areas* add up to domestic extraction (DE). *Medium and light shaded areas* add up to the national material footprint (MF) of iron ore

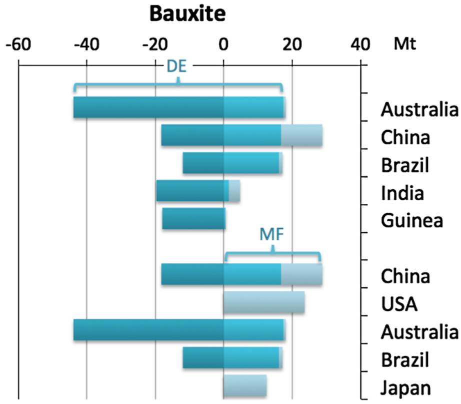


**Fig. 2** Top 5 producers (*top*) and consumers (*bottom*) of bauxite. Shown are megatonnes (Mt) of bauxite associated with exports (*dark shaded areas to the left*), with domestic activities (*medium shaded areas*) and with imports (*light shaded areas to the right*). *Dark and medium shaded areas* add up to domestic extraction (DE). *Medium and light shaded areas* add up to the national material footprint (MF) of bauxite

China is by far both the largest producer and consumer of iron ore globally (Fig. 1). The Chinese iron ore MF of 913 Mt is larger than its DE of 824 Mt and about four times larger than the iron ore MF of the second largest consumer, the USA with 230 Mt (Table 1). Other large producers of iron ore are Brazil, Australia and India (see also Yellishetty and Mudd 2014).

The world's largest producer of bauxite is Australia, with a domestic extraction of 61 Mt, 72 % of which are exported (Fig. 2; Table 2). This is followed by China (DE = 35 Mt) and Brazil (DE = 28 Mt). Interestingly, all three main bauxite-producing countries are also amongst the top five countries that consume bauxite directly and indirectly (see "Discussion" section for an explanation). China has the largest bauxite MF with 29 Mt. The USA comes second at 24 Mt MF. Neither the USA nor Japan produce any bauxite domestically and they are entirely dependent on imports to satisfy their (direct and indirect) demand.

In the next section we first take a look at the world as a whole and at the economically important world regions Europe (EU27) and OECD. We then present results for countries that are both large producers and consumers of iron ore and bauxite and finally turn our attention to countries that are either significant producers or consumers, but not both.

## 3.2 Trends in metal ore productivities

To explore changes in productivities over time we plot different metrics in indexed graphs where all values have been normalized to the year 1990. We compare relative changes in the total material footprint of iron ore and bauxite and in the GDP of countries, expressed on the basis of purchasing power parities of 2005 (GDP-PPP-2005). Relative changes in resource productivity $RP_{cons}$ can be derived from these plots: increasing resource productivity and decoupling are indicated by material footprint lines running below the blue line (GDP-PPP-2005) (i.e. when the MF has grown slower than the GDP).

### *3.2.1 World and developed world regions (OECD, EU27)*

During the past two decades, global extraction of iron ore and bauxite has grown faster than the world economy (GDP), in particular since 2002 (Fig. 3), which was triggered by the large increase in infrastructure investment and economic growth, first of all in China but also in other developing countries. As a result there has been no decoupling of iron ore or bauxite use with economic growth for the world as a whole. On the contrary, while GDP has grown by a factor of 1.5–1.8, the total iron ore MF has more than doubled, showing a significant re- or over-coupling. At the same time global trade in iron ore has grown even faster than extraction, by a factor of 2.7 (from 52 % of global DE in 1990 to 62 % in 2008).

A similar trend can be observed for bauxite, albeit less pronounced. The global extraction of bauxite has grown in line with GDP for most of the time but faster than GDP since 2002, especially in the EU27. The absolute amount of bauxite mined has doubled (factor 2.1) between 1990 and 2008 and trade between countries has grown by a factor of 2.4 (from 56 % of global DE to 64 %). Developed regions used ever more bauxite, directly and indirectly, to grow their economies and this trend even emerges at the global level.

As a consequence of these trends resource productivity of consumption, $RP_{cons}$, has declined for both ores, globally, in the OECD and in the EU27, clearly indicating that developed economies, as well as the world as a whole, has gained less economic welfare from the use of resources in the last 20 years.

### *3.2.2 Countries that are both large producers and consumers of iron ore and bauxite*

China, Australia and Brazil are the top three producers of both iron ore and bauxite in the world and they are amongst the top five countries for which these ores are associated with exports (Tables 1, 2). At the same time they are also top consumers when measured by the material footprint, ranked number 1, 3 and 8 for iron ore (Table 1) and number 1, 3 and 4 for bauxite (Table 2).

Despite large volumes of embodied exports, the metal ore footprints of these countries increased in line with GDP or even faster which means that metal ore use remains coupled to the significant increase in economic growth and infrastructure investment in these countries (Fig. 4). The exceptions to this are the bauxite MF for

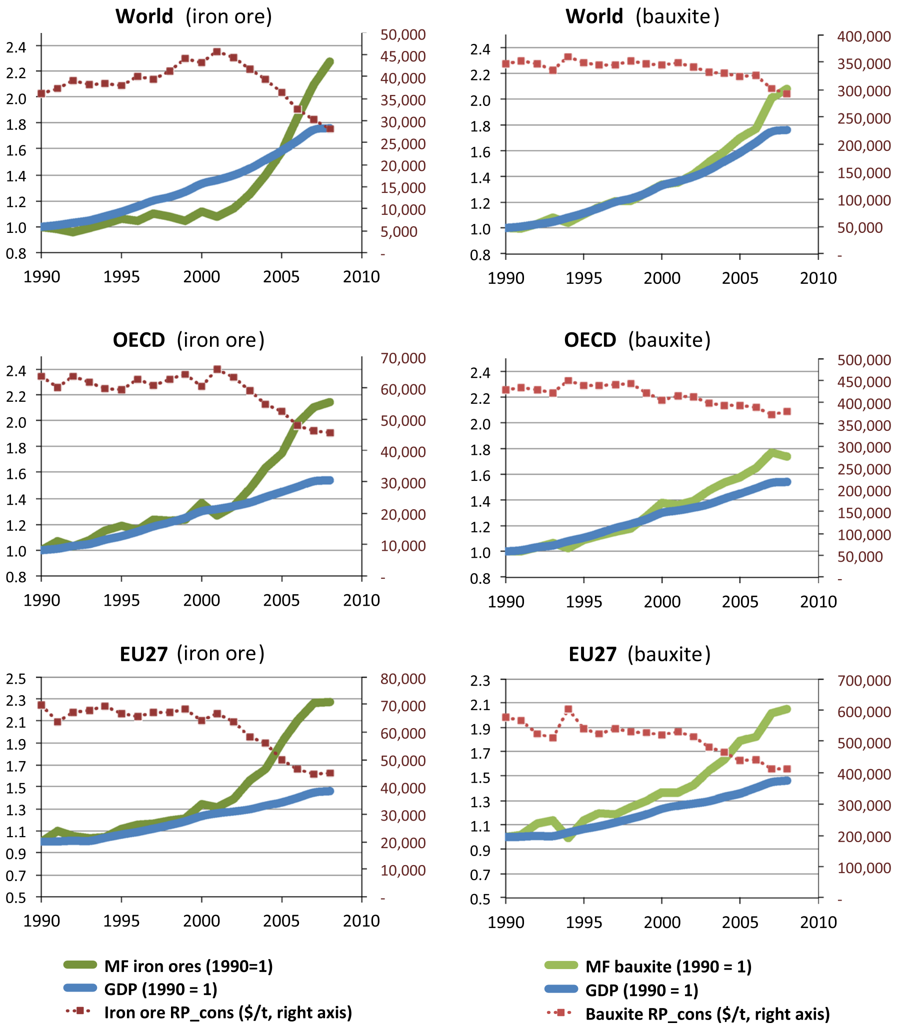


**Fig. 3** Relative changes in total resource use (MF) and GDP-PPP-2005 for the world and developed world regions between 1990 and 2008 (values are plotted as $X_{t2}/X_{t1}$; t1 = 1990, *left* axis). Resource productivity of consumption in $/t (*right* axis)

Australia (hardly any change from 1990 to 2008) and the iron ore MF for Brazil (large increases and decreases over time but coming back to 1990 levels in 2008).

### 3.2.3 Major consumers of metal ores

Apart from China, Australia and Brazil other major consumers of metal ores include the USA, Japan and Germany (top 5 MF for iron ore and top 10 MF for bauxite; Tables 1, 2).

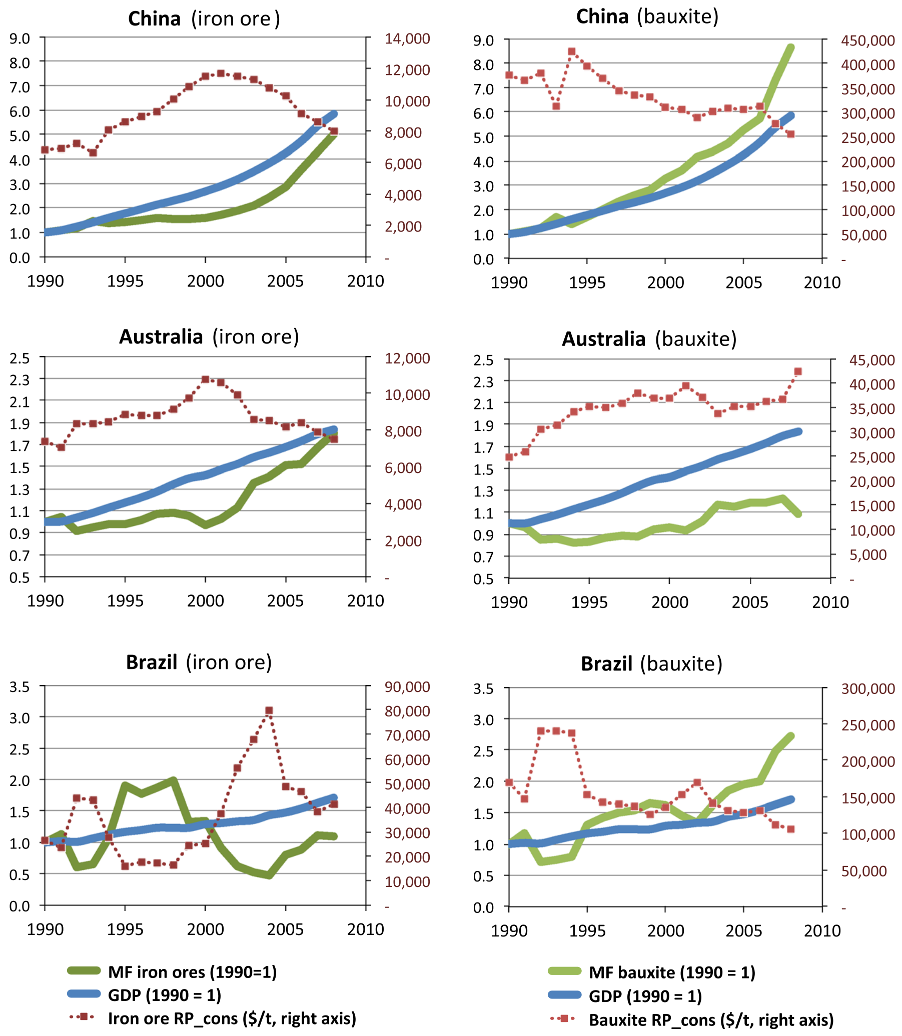


**Fig. 4** Relative changes in total resource use (MF) and GDP-PPP-2005 for countries that are both large producers and consumers of iron ore and bauxite (values are plotted as $X_{t2}/X_{t1}$; t1 = 1990, *left* axis). Resource productivity of consumption in $/t (*right* axis)

Typical for industrialized, developed economies, USA, Japan and Germany showed a moderate economic growth between 1990 and 2008 with no decoupling of total metal ore use (Fig. 5). The metal ore footprint has increased more rapidly than GDP, especially in the early 2000s. One notable exception is the MF of bauxite in Japan which shows a modest decline of 10 % over the whole time period, meaning that there was an absolute decoupling of bauxite use from economic growth and, therefore, an increase in resource productivity of bauxite consumption.

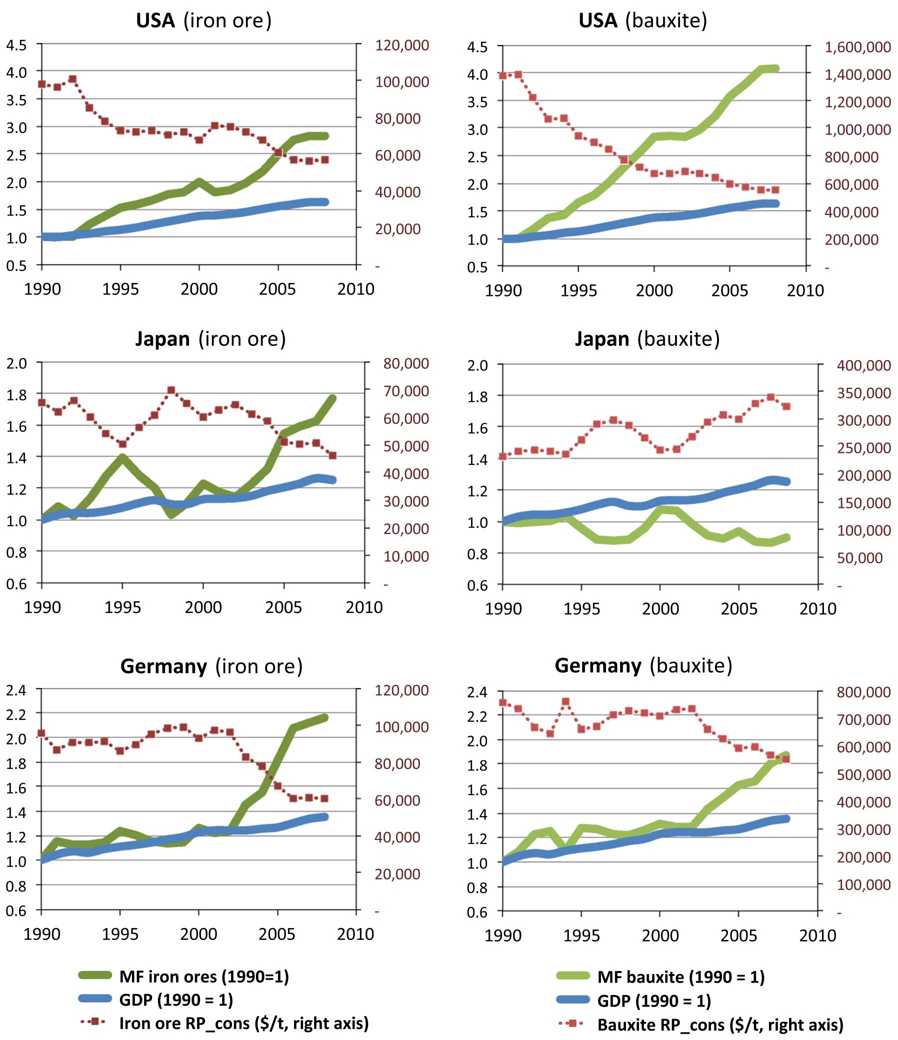


**Fig. 5** Relative changes in total resource use (MF) and GDP-PPP-2005 for major consumers of metal ores (values are plotted as $X_{t2}/X_{t1}$; t1 = 1990, *left* axis). Resource productivity of consumption in $/t (*right* axis)

### *3.2.4 Major producers of metal ores*

India is the fourth largest producer of both iron ore (Table 1) and bauxite (Table 2) in the world. In fifth place are Russia for iron ore and Guinea for bauxite, respectively.

With more than 90 % of their metal ores being exported (cf. Tables 1, 2) the MF of iron ore and bauxite of India and Guinea remains small and shows a relative or absolute decoupling from economic growth in most cases (except for the iron ore MF in Guinea) (Fig. 6). Decoupling has also occurred in Russia, especially in the

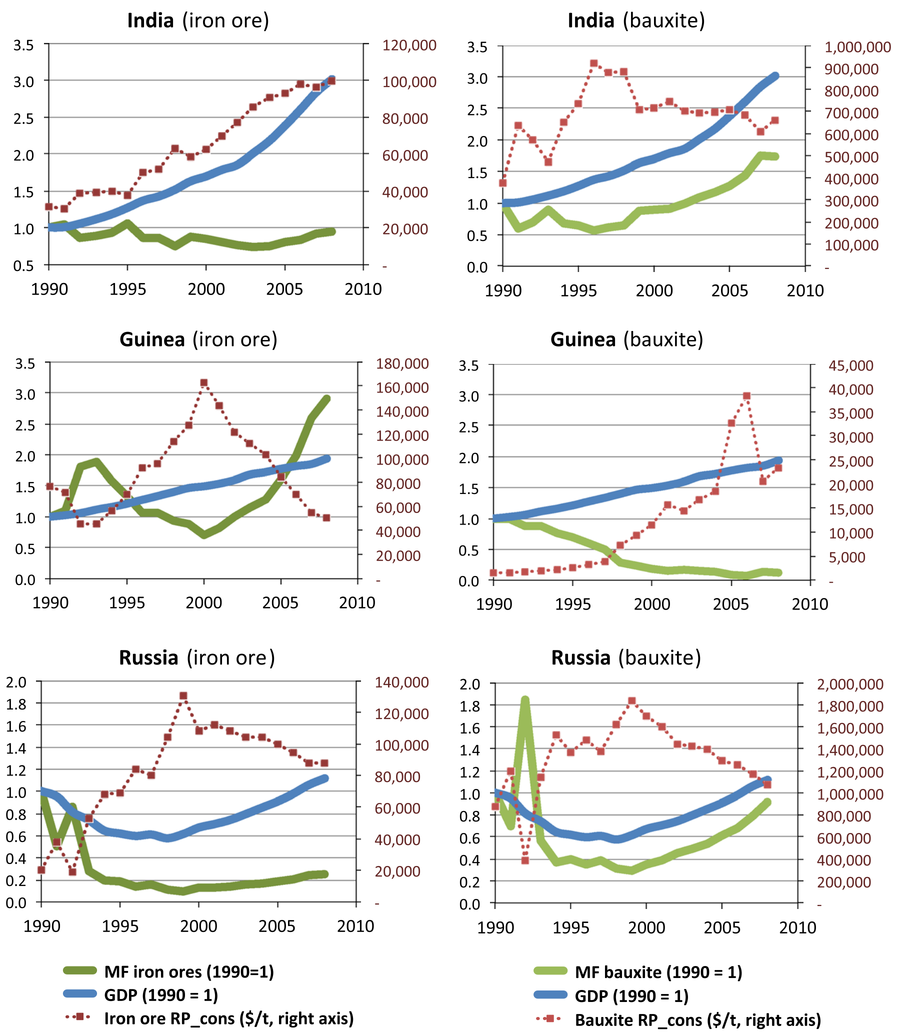


**Fig. 6** Relative changes in total resource use (MF) and GDP-PPP-2005 for major producers of metal ores (values are plotted as $X_{t2}/X_{t1}$; t1 = 1990, *left* axis). Resource productivity of consumption in \$/t (*right* axis)

1990s, a period of relative political and economic instability. Since 2000 both GDP and the MFs of iron ore and bauxite have increased again.

## 4 Discussion

Metal flows have been extensively studied in Industrial Ecology research, mostly from the perspective of the metals themselves, such as iron, aluminium or copper. Studies have looked at global and individual countries from a producer or territorial perspective. This is the first study that looks at the consumption aspects of two important metal ores employing a material footprint approach. Unlike a bottom-up material flow or life cycle analysis, a top-down footprint approach to looking at consumption ensures that all metal use is accounted for and none is double counted or omitted. Bottom-up approaches to measuring embodied metal use also often trail off after following just one or two steps into the upstream supply chain of a product. In contrast the footprint approach evaluates the complete upstream chain, tracing hundreds or thousands of upstream links, within national economies and across borders, to ensure the footprint associated with consumption is complete and covered globally.

The main observations from our results are that there has been no easing off at the world level: iron ore use has more than doubled, showing a significant re- or over-coupling. Resource productivity of consumption has gone down, and the same trend has occurred for bauxite, albeit more moderately.[1] In short, there has been no improvement whatsoever with respect to improving the economic efficiency of metal ore use. Wealthy countries and world regions have a deteriorating $RP_{cons}$ of metal ores: less GDP for a unit of iron ore MF and hardly any improvement for bauxite MF.

Most of the global iron ore and bauxite production takes place in only a few countries (the top five producers extracted 83 % of the global iron ore in 2008 and 78 % of the bauxite) and is operated by a small number of multinational mining companies due to the increasing capital-intensive character of the mining industry. More surprisingly, however, consumption is also quite concentrated. The top five consumer countries exert 62 % of the global iron ore footprint and 47 % of the bauxite footprint. China is leading the league table and has become the largest producer and consumer of iron ore and bauxite—only Australia is producing more bauxite.

Differentiation between producing and consuming countries is growing due to resource availability and economics of globalization. This suggests a further specialization of countries in the primary production of non-renewable resources. The trend of specialization means that the policy context for resource efficiency (RE) is increasingly polarized between countries which focus on RE to avoid supply security issues that may negatively impact on their economy whilst "mining" countries have little incentive for RE and are further hampered by the vested interest of mining companies. Centres of consumption also seem to be more concentrated especially because a number of population-rich countries, such as China or India have grown their per-capita use extensively. While this appears to be a process of concentration, it also means that the usage of iron ore and bauxite in infrastructure and consumer goods is more evenly distributed among the global population. This has to do with China's massive investments into urban and production infrastructure, which have been accompanied by a large growth in China's mining sector, especially with regard to iron ore. The numbers are particularly striking for iron ore where China produces more than twice (2.3 times in 2008) as much as the second largest producer (Brazil) but also consumes four times as much—in material

[1] We note that global average ore grades for iron ore and bauxite are not thought to have changed significantly in the last fifty years (West 2013).

footprint terms—as the second largest consumer (USA). This underpins China's dual role as a global producer *and* consumer. It has to be noted, however, that the *per-capita* iron ore footprint in China in 2008 (0.69 t/cap) was still smaller than that of the USA (0.76 t/cap).

Not all of the consumption, however, that drives metal ore footprints is due to household and government expenditure. Some of it (around 19 % globally) is in the form of capital investment in new infrastructure and technology. The large MF of iron ore and bauxite in China can be explained by the strong growth in built infrastructure, enabled by large investments in the construction sector. In Australia, for example, capital investment in the construction sector alone accounted for 62 % of national investment and 16 % of total national final demand in 2008 (ABS 2011). The metal ore footprint of construction takes up an even higher share of the total as construction relies heavily on steel and aluminium (both directly and indirectly through the supply chain). The situation is similar for Brazil, explaining the relatively large MF rankings of these two countries. The only exporting country where the MF of bauxite has consistently decreased while its GDP has increased just as consistently is Guinea. A decrease of iron ore and bauxite MF can also be noted in Russia in the 1990s, though this has been accompanied by an economic downturn.

Interestingly, Japan is the only developed country that shows an absolute decoupling of bauxite MF from GDP. One possible explanation for this remarkable development is a decrease in the build-up of aluminium stock in the country. According to Müller et al. (2013) the total in-use aluminium stock in Japan grew from 23.9 Mt (194 kg/cap) in 1990 to 40.7 Mt (318 kg/cap), however, the rate of growth slowed down significantly, from +1.48 Mt/year in 1990 to +0.21 Mt/year in 2008. As a consequence, Japan needed less and less bauxite to sustain its aluminium stock. It is not clear, though unlikely, that Japan has simply replaced aluminium for other metals; the growth rate in Japan's steel stock, for example, has also decreased from +49 Mt/year in 1990 to +16 Mt/year in 2008 (Müller et al. 2013). Yet, the iron ore footprint has grown stronger than GDP (Fig. 5). This seeming dichotomy suggests that the indirect component of the metal footprint may play a decisive role. Not only the direct use of aluminium and steel in Japan determines their respective footprints, but also, and increasingly, the indirect use of metal resources in other countries. The moderate economic growth in Japan over the twenty-year period saw a slowing down of investments while final consumption remained stable or increased. This change in composition of final demand might have contributed to an increase in imported goods and services, effectively helping to increase infrastructure development elsewhere in the world. Depending on the trading partners, this might have caused a shift from aluminium to steel-based infrastructure, though further research would need to confirm this.

## 5 Conclusions

Coming back to the questions that we posed at the beginning: has there been progress in using metal resources more efficiently, and has there been any decoupling of metal ore use from economic growth? At the global level the answer is a clear no. Global economic growth between 1990 and 2008 was accompanied by even stronger growth in the extraction and the use of both iron ore and bauxite.

At the country level there is a more differentiated picture. Iron ore and bauxite consumption (embedded in products and infrastructure) rises with national income and wealth, and virtually all high income countries continue to depend on a rising footprint of those two important metal ores (and hence applications of metals). Even though the demand for construction materials has reached a certain level of saturation in developed nations (for the case of steel see Müller et al. 2011 and Pauliuk et al. 2013a), no level of income can be determined at which a saturation of metal ore MFs would occur. While a number of countries have stopped mining metal ores and bauxite, those countries continue to depend on a growing availability of ores for their infrastructure development and as precursors for imported goods and services. Producer countries, which export most of their metal ores, have also experienced an increase in their metal ore footprint due to an increase in national wealth, boosting both final consumer expenditure as well as capital investments.

## 6 Supplementary data

Data for domestic extractions, RME imports and exports and material footprints of iron ore and bauxite for all countries have been published on http://worldmrio.com.

**Acknowledgments** We thank James West for his advice on metal ore grades. Heinz Schandl acknowledges financial support from the Commonwealth Scientific and Industrial Research Organisation's Climate Adaptation Flagship and Integrated Carbon Pathways Initiative and the United Nations Environment Program (UNEP).

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