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The capital load of global material footprints

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ABSTRACT

Despite calls for large-scale reductions in material use and efforts to initiate a “circular economy” that promotes recycling and reuse, a limited decoupling between overall resource extraction and economic growth has been historically found. This is particularly true if resource use is measured with the life-cycle or consumption-based material footprint (MF) indicator that allocates material extraction to final goods and services. However, this indicator treats capital goods as final products rather than part of the production process. In this paper, we introduce the capital-augmented material footprint (CAMF), a new indicator of material use that includes all the materials embedded in capital goods. Results for 49 countries and regions over the period 1995–2015 show that for mineral use, about 50–60% of the total footprint of final consumption is embodied in capital goods, whereas for biomass, the figure is around 10%. The largest increase in material requirements was observed in non-OECD countries and in service sectors in general. More countries achieve relative and absolute decoupling when using the CAMF as indicator of material use. Our results underpin the need for comprehensive indicators when assessing options to decrease the impacts of consumption.

1. Introduction

The concept of sustainable development was formally introduced in the 1987 Brundtland Report, as a development that “meets the needs of the present without compromising the ability of future generations to meet their own needs” (United Nations 1987, p41). Correspondingly, it is widely agreed that long-term sustainability cannot be achieved unless continued global growth in economic output and human well-being is decoupled from the use of resources (Schandl et al. 2016; Van der Voet, van Oers, and Nikolic 2004; UNEP 2011; Hatfield-Dodds et al. 2017; Krausmann et al. 2017). Although a relative decoupling of resource extraction from economic growth has been observed (Behrens et al. 2007), studies suggest that current material extraction rates are unsustainable (Hoekstra and Wiedmann 2014) and that an absolute decoupling is necessary, at least for the OECD economies (Schandl et al. 2016). Arguably, as the Earth's mineral reserves are finite, extraction of resources from the lithosphere cannot continue indefinitely, and a global absolute decoupling will ultimately be required.

Global material extraction for human use is, however, increasing at unprecedented rates. Between 1970 and 2010, raw material extraction more than tripled, from an estimated 22 billion tonnes (bt) to over 70bt (Schandl et al., 2017). During the same period, global population merely doubled, implying that the per-capita rate of material consumption increased by 150% (from 7t/cap to 10.5t/cap), and are at the highest ever recorded (Wiedmann et al., 2015). Construction minerals and associated capital goods have been the principal driver of the growth since the middle of the previous century with cement being a principal contributor (Krausmann et al., 2009). For some materials, including iron ore and bauxite (the main component of aluminium), extraction rates have risen faster than GDP (Wiedmann et al.,2015; Zheng et al., 2018). Along with the increase in material use, globalisation has led to an increase in the amount of traded goods and materials (Wood et al., 2018). Between 2000 and 2010, world production

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increased by 2% whereas export volumes increased by 3.5% (Bruckner et al., 2012). This entails that tracing the materials used and embodied in goods has become increasingly difficult.

In order to provide a more comprehensive measure of material use, several different indicators of material use have been developed in the last two decades (Schandl et al., 2017; Fischer-Kowalski et al., 2011). The nature of these indicators has evolved over time, changing from purely domestic measures of material use to indicators capturing all upstream material requirements. Traditionally, material flow analysis (MFA) has been the tool of choice for assessing the use of materials as well as deriving indicators relating to material extraction and consumption (Lutter et al.,2016; Fischer-Kowalski et al., 2011). Although the origins of MFA can be traced back to the studies analysing the metabolism of industrial society of the early 1970s (Fischer-Kowalski and Hüttler, 1998), the first tables of material flow data were produced in the 1990s (Fischer-Kowalski et al., 2011). Since then, MFA has been widely applied by statistical offices around the world (OECD, 2008; Eurostat, 2013) to derive a variety of indicators of material use. For instance, the domestic extraction (DE) indicator is defined as the annual amount of raw material extracted from a given territory (Behrens et al., 2007). When the direct material imports are added, it results in the domestic material input (DMI) (Schandl et al., 2017), and when exports are removed from the DMI, it yields the domestic material consumption (DMC) (Bringezu, 1997; Adriaanse et al., 1997; Wiedmann et al.,2015; Schandl et al., 2017). As international supply chains became more fragmented, it was argued that such indicators needed to be extended for the upstream material requirements of used extraction, referred to as the raw material equivalents (RME), which can be differentiated as RME of imports (RME_{imp}) respectively exports (RME_{exp}) (Wood et al.,2009; Fischer-Kowalski et al., 2011; Giljum et al.,2015; Schandl et al., 2017; Kovanda and Weinzettel, 2013). Consequently, the raw material trade balance was defined as the RME_{imp} minus the RME_{exp}. This led to indicators that included all direct and indirect requirements, such as the raw material consumption (RMC). The RMC was introduced as a consumption-based (CB) indicator of material use that allocates the upstream material requirements to the domestic final demand (Giljum et al., 2015; Schandl et al., 2017), and has therefore also been called the material footprint (MF) (Wiedmann et al., 2015; Schandl et al., 2017).

The estimation of such indicators that include the upstream material requirements is more difficult than for the DE and the DMC because of the need to capture material use along multiple stages of a supply chain. In fact, there are still different approaches used to calculate the indirect material flows of traded products (Fischer-Kowalski et al., 2011; Wiedmann et al.,2015; Feng et al., 2011; Kanemoto et al., 2012). For instance, Wiedmann et al. (2015) calculate it as the sum of the DE and the raw material trade balance. Other studies apply the Leontief demand-pull model directly to either domestic single-region IO tables or multi-regional IO (MRIO) tables in order to calculate the total material requirements associated with a final demand. Regardless of the approach, the difference with conventional indicators of material consumption has been shown to be substantial (Wood et al.,2009; Bruckner et al., 2012; Wiedmann et al., 2015), and CB measures of material use have been used extensively in the last few years to estimate the total upstream material use of nations and regions (Giljum et al.,2015; Wiebe et al. 2012; Bruckner et al., 2012; Wiedmann et al.,2015; O'Neill et al., 2018; Tian et al., 2017; Schaffartzik et al., 2014; Schoer et al., 2012; Kovanda et al., 2012; Schandl et al., 2017). This has provided important insights into how globalisation has transformed the way that materials are used and exchanged across the globe, both as raw materials and as materials embodied in fabricated goods. Furthermore, indicators such as the MF bring valuable insight to studies assessing the decoupling of environmental stress (such as resource use) from economic growth. When comparing the relative changes in material use and GDP over the period 1990–2008, Wiedmann et al., (2015) found that some of the decoupling trends that could be observed when studying material use indicators that only account for the materials directly used (such as DMC) are cancelled out (or even reversed) when the indirect upstream materials used are also taken into account (i.e. with the MF). The study shows, for instance, that the DMC of the US grew at a slower rate than the GDP (in Purchasing Power Parity – PPP) during the analysed period, i.e. that a relative decoupling occurred. However, the MF of the US grew faster than the GDP, which entailed a negative decoupling of economic growth from material use. The UK and Japan even experienced an absolute decoupling when considering the DMC (which implies that material use *decreased* over time despite that the GDP was increasing), but again, when taking a CB perspective, the material use not only increased but did so at a faster rate than the GDP.

Although CB indicators provide an important insight into the emissions and materials that are embodied in the goods and services that we consume, they focus purely on the flow of materials and goods, and do not consider the inter-temporal nature of materials in stocks. IO and MRIO models have been established as the tool of choice to compute footprint-type CB indicators (Wiedmann, 2009), but as explained in recent studies by Södersten et al., (2018a) and Chen et al., (2018), MRIO databases do not currently treat capital goods (such as infrastructure, machinery, transport equipment, etc.) as inputs to the production system but as final goods. As such, while indicators describing the total upstream material requirements of a nation (such as the MF) do account for both current and capital requirements, they consider the latter as part of the final demand of a country. Capital goods, however, are used to provide further production services and may therefore also be used in the production of export. Hence, when calculating the material footprint of current consumption (household and government expenditures), capital inputs into the production process are left out, and these footprints are thus currently underestimated. This underestimation is likely to be substantial for material footprints, since construction materials are largely used to produce capital goods: half of the materials extracted annually as well as a quarter of the world's economic output is destined to build up and maintain in-use stocks (Krausmann et al., 2017; Södersten et al., 2018b).

From a life cycle perspective, it is desirable to incorporate these materials into the material footprints of consumption and it is likely that this leads to a substantial increase in the embodied material content of consumer goods and services, particularly the latter. As economies mature, the structure of final demand changes towards goods with lower material contents and services (Bernardini and Galli, 1993; Suh, 2006). Because the upstream material contents of services are typically less carbon and material-intensive, it has previously been argued that shifting consumption patterns towards an increased consumption of services would lead to an absolute reduction of material use and impacts on the environment (Pacala and Socolow, 2004; Jänicke et al., 1997). While CB accounting has already been used to show that including upstream requirements substantially increases the total impacts associated with services (Suh, 2006), no study has yet estimated the material requirements of the capital goods used to produce these services. Furthermore, recent studies have highlighted the limitations of technology in solving environmental problems such as climate change (Creutzig et al., 2018). The gains achieved through technology improvements have almost always been offset by increased household consumption (Wood, 2009) to an extent that future technological change would have to be unrealistic to stay within planetary limits (Lenzen et al., 2016). As such, there is a need to investigate ways that policy can be directed towards facilitating sustainable consumption (Akenji, 2014). Most critically, there is a need for better empirical work on the material basis of consumption as economies develop and move away from large consumption of basic goods towards urban service-based societies. Is it possible for consumption (and hence economies) to grow without leading to increased resource extraction? Or is the significant increase in material footprints of investments (Zheng et al., 2018) a sign that decoupling remains an illusion?

In this work we introduce a method for including the materials embodied in capital used to produce the goods and services for final consumption. We refer to this new indicator as Capital-Augmented Material Footprints (CAMF) and present the results for an analysis at the global level. We address questions central to the abovementioned challenge of reducing the extraction rates of materials: How much and what type of materials are embedded in the capital used to produce goods and services for final consumption? For which product categories does the material footprint increase the most when material embedded in capital is included in the final footprint? How does the endogenisation of capital affect material decoupling trends?

2. Materials and methods

We use global MRIO analysis to calculate consumption-based indicators of material use (see e.g. Miller and Blair, (2009) for an overview of IO basics). The calculations are performed using EXIOBASE v3.6 (Stadler et al., 2018), an environmentally extended MRIO database containing time series from 1995 to 2015 and covering 44 countries and five rest-of-the-world regions. One of the strengths of EXIOBASE compared with other available MRIO databases is the high level of environmental stressor detail, particularly regarding the use of resources and materials (Giljum et al., 2019; Owen, 2017). The environmental extensions include 227 types of material inputs that form part of the used domestic extraction (among which 12 are metal ores), and 223 types of associated "hidden flows" that constitute the unused domestic extraction. These hidden flows are sometimes included in the measure of material use with the rationale that they also contribute to the ecological rucksack (Eurostat, 2001), for instance in studies estimating the total material requirements (TMR) (Kosai and Yamasue, 2019; Watari et al., 2019). EXIOBASE is also relatively highly detailed compared to other available MRIO datasets (Wood et al., 2014; Inomata and Owen, 2014). Whilst disaggregated data sets generally show higher variability and uncertainty at the individual product/flow level, at the aggregate level, they often provide more accurate estimates (Lenzen, 2011; de Koning et al., 2015). However, the expected level of uncertainty at different levels of product aggregation is beyond the scope of this article. The updated time series in EXIOBASE3.6 is based on macroeconomic and trade data until the year 2015. However, empirical material flow data was only available until the year 2013, and The material extensions beyond that year have therefore been compiled by extrapolating earlier extensions (Stadler et al., 2018).

In order to include the materials embodied in the capital in our material footprint, we use the model described by Södersten et al., (2018a), in which the IO system has been closed for capital so that capital flows are endogenised in the inter-industry matrix. The model uses external data on capital use by asset and industries provided by the KLEMS and WORLD KLEMS databases. For this paper, the model has been updated with new KLEMS releases so that detailed capital data was available for 31 of the 44 countries included in EXIOBASE. For the countries not covered, capital tables were constructed based on a generic capital data distribution matrix adjusted for each individual country according to the procedure described by Södersten et al., (2018a).

The flows of capital differ from the flows described by the inter-industry matrix in traditional IO analysis. Firstly, capital goods (or fixed assets) are not transferred and transformed throughout the supply chain like other tangible production requirements, but rather provide productive services in the form of e.g. transportation, storage space, computational power, etc. Therefore, they cannot be measured in terms of quantity used (physical or monetary) but have to be estimated by the amount of service they supply. Secondly, while current goods are assumed to be acquired and utilised within one accounting period (which the System of National Accounts (OECD and UN, 2009) defines as one year), fixed assets are goods that are used in production processes for longer than a year and therefore overlap over several accounting periods. These characteristics make the accounting of capital complex. National accounts (and consequently IO tables that are based on them) have resorted to treating the acquisitions of capital goods as a separate final demand category (the gross fixed capital formation, or GFCF), despite that they are, per definition, used in the production and provision of other goods and services for final consumption (OECD and UN 2009). The assets that remain in use at the end of an accounting period are expected to provide productive services in subsequent periods and are therefore still valuable to the industries owning them. Consequently, these capital goods still in use are recorded as part of the value added (VA), under the term "consumption of fixed capital" (CFC).

The rationale behind the endogenisation of capital is to assign the environmental impacts associated with the capital goods to the footprint of goods and services they are used to produce. Hence, the amount of capital that each final product consumes ought to be estimated by the amount of service that the asset provides. We estimate the utilisation of capital across industries with the CFC available in EXIOBASE3 and argue that it constitutes the most adequate estimate of capital use readily available in today's MRIO databases. This choice can be contested; the CFC is an economic measure (expressing the depreciation of existing capital during the current accounting period), which is arguably not optimal for assessing physical usage (see further discussion in Södersten et al., (2018a)). Furthermore, the CFC is not an unequivocal estimation, and there are several ways to calculate it (of which the OECD capital measurement guide offers a comprehensive overview (OECD, 2009)). Indeed, many IO databases do not provide the CFC as a distinct entry but keep it embedded in the more general vector of gross operating surplus within the VA. This brings additional complexity to our approach, as the methods used to construct the CFC vector in EXIOBASE3 often relied on proxy data (Wood et al., 2015; Stadler et al., 2018). The only statistical global estimates of CFC found were those provided by the World Bank (2019), and these were only available as one aggregate figure per country and year. Nevertheless, these yearly estimates were deemed the most reliable and we have chosen to adjust the CFC of EXIOBASE to the World Bank data. In order to keep consistency across capital use and capital formation, we compared the GFCF figures from the World Bank against those available in EXIOBASE as well and rescaled the EXIOBASE CFC so that the total yearly ratio between the GFCF and CFC were the same. That is, for each year y:

$$\frac{\sum GFCF_y^{EXIO}}{\sum CFC_y^{EXIO}} = \frac{\sum GFCF_y^{WB}}{\sum CFC_y^{WB}} \tag{1}$$

Hence, each entry in the EXIOBASE CFC vector was multiplied by a factor β given by

$$\beta = \sum \frac{GFCF_y^{EXIO}}{GFCF_y^{WB}} \sum CFC_y^{WB} \tag{2}$$

The impacts of the rescaling varied a lot across countries. European countries were in general less affected (indicating that the original CFC estimates from EXIOBASE were close to those from the WB), while for certain non-European countries, the rescaling led to substantial changes (particularly for Brazil, Mexico, Russia and South Africa). Since Taiwan is not featured independently in the World Bank, we used the $\frac{\sum GFCF_y^{WB}}{\sum CFC_y^{WB}}$ ratio of China to rescale the Taiwanese data. Furthermore, for the rest-of-the-world regions, the GFCF over CFC ratio was compiled by summing the data of all relevant countries. For instance, for the rest-of-the-world Africa region (WWF),

$$\frac{\sum^G FCF_y^{WWF}}{\sum^C FC_y^{WWF}} = \frac{\sum_{C_i} (\sum^G FCF_y^{C_i})}{\sum_{C_i} (\sum^C FC_y^{C_i})}, \quad \forall \quad C_i \in \{\text{Africa}\} \tag{3}$$

The endogenisation is done with the flow matrix method (Lenzen and Treloar, 2004), which entails that a layer of capital flows is added to the regular, or "current", inter-industry flows. While the traditional Leontief inverse accounts for the total requirements of current goods, the new inverse accounts for both the current and capital requirements:

$$\mathbf{L}^{\mathrm{K}}=(\mathbf{I}-(\mathbf{A}+\mathbf{K}))^{-1} \tag{4}$$

where **A** is the inter-industry requirement matrix of current goods and **K** the inter-industry requirement matrix of capital goods. This new inverse can be used to calculate a new measure of material use. For instance, for a chosen vector of final goods **y** and a row vector **s** containing total material use per unit output, the total material use required to produce that vector of final goods **y** is

$$d = \mathbf{s}\mathbf{L}^{\mathrm{K}}\boldsymbol{y} \tag{5}$$

Here, d are the upstream (consumption-based) material requirements of final demand that account not only for the materials embodied in the final products, but also the materials embodied in the capital goods used in the production processes. Therefore, we refer to this measure as the Capital-Augmented Material Footprint (CAMF).

This way of accounting for materials embodied in capital goods is novel and perhaps less intuitive, and care needs to be taken when applying the suggested method to calculate footprints. For instance, one implication of this is that the total CAMF of a country will be difficult to compare with the total MF as it is traditionally estimated, since the CAMF includes the materials embodied in the CFC while the MF includes the materials embodied in the GFCF. The CFC and GFCF are two measures of capital that differ both conceptually and quantitatively; the GFCF is a measure of all new additions to the capital stock, whereas the CFC is a measure of the depreciation of the *current* in-use stock. Therefore, the CAMF and MF account for capital that stem from different age cohorts, and therefore differ as well. To enable the comparison, Södersten et al., (2018a) resort to the creation of a residual vector of GFCF (containing the net capital formation), but their approach entails other complications and is not without drawbacks. In this study, we wish to obtain a better understanding of what is driving the increase in the materials embodied in capital goods and which products and countries are ultimately responsible for their consumption, and the results therefore focus on the material contents of final consumption only (defined as the consumption of goods and services by households, government and non-profit institutions serving households).

3. Results

Treating capital goods as intermediate goods rather than final products entails that production processes will consume more inputs, i.e. that the requirements of goods and services per unit output will increase for all industries and countries. As a result, the associated use of materials to final consumption will increase as well, as can be seen in Fig. 1, which shows the footprints of final consumption of the OECD (red curves) and non-OECD (blue curves) economies for four types of materials (biomass, fossil fuels, metal ores and mineral ores). The areas show the increase in material use that occurs when capital is endogenised.

The lower graphs in Fig. 1 illustrate the effects of endogenising capital on the footprints of final consumption. The relative increases vary substantially depending on material category. While the increase in biomass remains within 5% and 13%, the increase in metals and minerals is much larger, ranging from 20% to over 160%. This could be explained by the fact that most minerals are extracted for use in the construction sector and will subsequently be transformed into capital goods such as buildings, infrastructure, etc., whereas biomass is mostly consumed by the agriculture sector, i.e. is already accounted for in the traditional MF. The effects of endogenising capital are generally larger for OECD economies than for non-OECD economies, though this difference between the country groups diminishes over time and is even reversed at the end of the time series for biomass, fossil fuels and metals.

OECD countries' per-capita material footprints are still much higher than for non-OECD countries, but the gap between them is narrowing for both approaches. Whereas non-OECD countries are steadily increasing their consumption across all material groups, OECD countries have managed to reverse the consumption trends for biomass, fossil fuels and metals. As a result, non-OECD countries have overtaken OECD countries during the analysed period regarding the total use of fossil fuels, metals and materials (for both MF and CAMF). Total non-OECD consumption of biomass considerably exceeded that of OECD countries across the whole period. Biomass is principally used to produce food, a consumption product that is much less elastic with income than products containing fossil fuels (e.g. gasoline), metals (e.g. electronics) and minerals (e.g. dwellings). With a much larger population, non-OECD countries are consuming substantially more biomass in total than the OECD.

Underlying the increases in overall footprints are increases in product level footprints. In Fig. 2, we have plotted the footprints of the five most important (in terms of total material use of final consumption for each material type and over the analysed period) services and non-service products respectively for biomass and mineral use, aggregated over OECD and non-OECD countries. The shaded areas show the traditional footprints (i.e. the MF) and the dotted lines show the additional impacts that arise when the materials embodied in capital are included in the footprints (i.e. the CAMF). The plotted lines are cumulative, meaning that the upper line in each graph represents the total CAMF of the five product categories shown in the legend.

Several observations can be made from the figure. One recurrent trend across both material types and country groups is that services see their footprint increase substantially more than non-services when the materials embodied in capital goods are included. The five largest service categories are the same across both material types: health and social work services; education services; hotel and restaurant services; public administration and defence services; and real estate services. The latter two categories increased the most (the average mineral use of real estate services in the OECD over the whole period more than quintupled when including capital goods). There are two reasons for these steep increases. Firstly, services require less material in their production processes than non-services, which entails that their MF is relatively low. Secondly, services are typically capital-intensive – education services require schools; real estate services require dwellings; health services require hospitals, electronic equipment and machinery; public administration and defence services require offices, housing for military personnel, transport and defence equipment, etc. This increase in material use for services is particularly large for mineral use, where it more than doubles for certain years. For OECD countries, the increase appears homogenous for both materials, while for non-OECD countries, it becomes more important towards the end of the time series, indicating an increased dependence on material-intensive capital. The difference between service and non-service categories is particularly striking for biomass: the CAMF is substantially larger than the MF for service categories, but for non-service categories, the increase is negligible, for both country categories.

When we investigate the relationship between material type, type of capital good, and final product (Fig. 3), we see that construction (both residential and non-residential) is by far the largest intermediary capital good for the material footprint, with 80% of total (global) material flows embodied in capital due to construction activities. Most of these are from minerals, which include low-grade rock and stone. However, only about 30% of total materials embodied in capital are due to the final consumption of shelter. A similar proportion is included in manufactured products, but services are the largest category of final product. As a portion of total CAMF (including consumption of current goods as well as capital goods), services make up roughly 30%, manufactured products 46% and shelter 25% (global average, 2011 – details are given in the supporting information).

As economies mature, a smaller portion of economic activity is

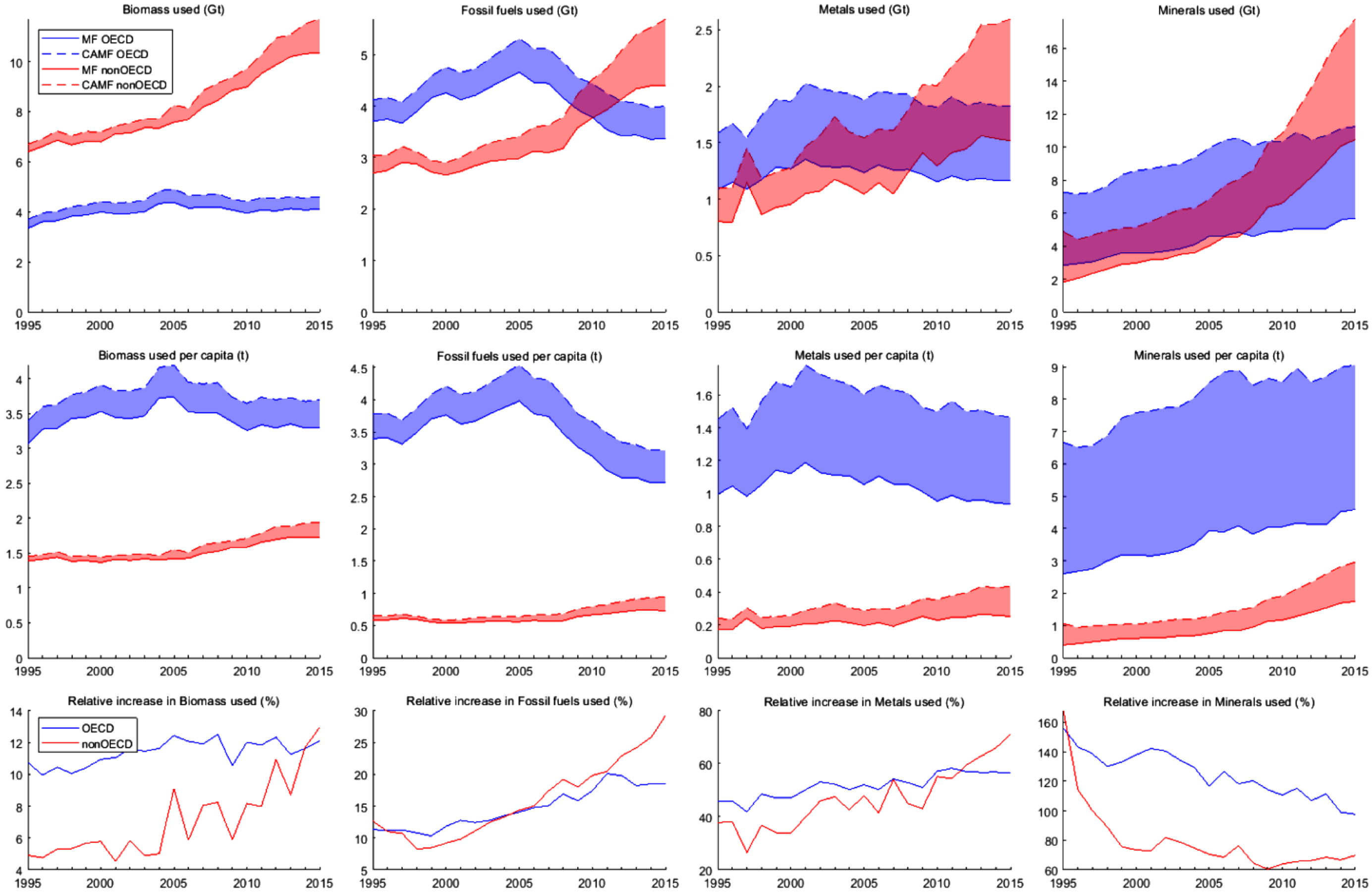
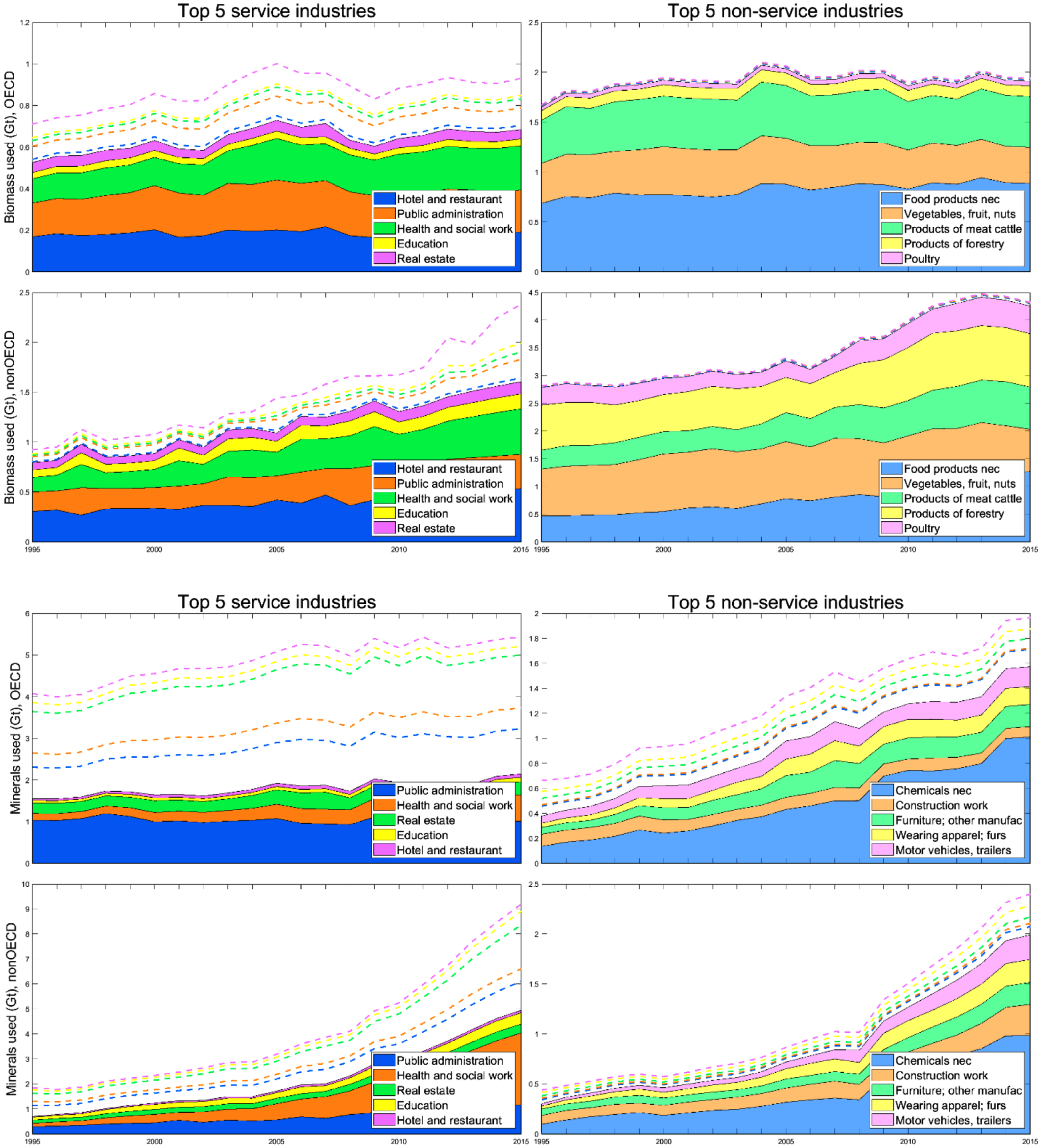


Fig. 1. Footprint of final consumption for OECD and non-OECD countries, with (CAMF, dotted lines) and without (MF, solid lines) capital endogenised. Upper graphs show total footprints, middle graphs show footprints per capita and lower graphs show the increase in footprints as materials embodied in capital are taken into account (calculated as (CAMF/MF)*100).

related to resource exploitation and more to services. Figs. 1 and 2 revealed that the total use of materials (both for current and capital requirements) increased substantially more for non-OECD countries than for OECD countries, indicating that a certain saturation – or at least a slower growth – of material use can be expected upon reaching a certain development level. In other words, we expect to see a decoupling of material use from GDP – relative for most countries but possibly absolute for some. Fig. 4 shows the mean annual growth rate of mineral use (the largest of the four material groups addressed in this study) of final consumption against the mean annual growth rate of GDP (PPP), with (CAMF) and without (MF) capital endogenised, for all countries available in EXIOBASE as well as five rest-of-the-world regions. The decoupling is calculated as the mean of $(x_{(i+1)} - x_i)/x_i$ over all years, where x is the variable considered (MF, CAMF or GDP). On the first graph, only a few countries achieve relative decoupling of material use from economic growth (FIN, ZAF, IRL, IND and TWN) and none sees their absolute MF decrease. When studying the CAMF however, 20 countries achieve relative decoupling and three reach absolute decoupling (FIN, SVN and RUS). These results may seem unintuitive at first since the CAMF is larger than the MF for all countries, but they can be explained by looking at the mineral use trends in Fig. 1. While both the MF and CAMF increase over time, the *relative* change (final year compared to initial year) of the MF indicator is higher than the relative change in the CAMF indicator (the example of the non-OECD is easiest to see, where MF increases from roughly 2 Gt to 10 Gt (factor 5), whilst CAMF increases from just over 4 Gt to just over 16 Gt (factor 4). This means that the relative increase in MF is larger than the relative increase in CAMF; therefore, the mean annual rate of change of the MF is higher than that of the CAMF.

Although a regression analysis pointed towards an slight increase use of materials as the GDP increased we did not find any statistically significant correlation between the decoupling trends and the level of economic development (measured as GDP/cap in PPP), neither for the MF nor the CAMF. Both high- and low-income countries appear in all sections of Fig. 4. Furthermore, the decoupling trends observed for the use of mineral ores are more extreme than for other material categories. For metal ores, biomass and fossil fuels, the number of countries achieving relative and absolute decoupling over the analysed period are higher, both for the MF and the CAMF, and therefore also the decoupling trends of the total material footprints (figures available in the supplementary information online). However, and as discussed in the introduction, when comparing the increase of material use over time with the increase in population, the trends are less optimistic (the mean annual population growth over the analysed period varied between -1% and 2% for all but one of the 49 regions; the exception being rest-of-the-world Africa with a mean annual increase of 2.6%). It must be noted, however, that there are different ways to calculate the decoupling rates, and that the choice of method may affect the results considerably. One approach commonly used is to calculate the decoupling from a fixed base year, but this approach was dismissed as we noted that the cross-country results varied substantially depending on the year chosen. Furthermore, results vary considerably depending on the period chosen. For instance, using the current approach, the mean annual growth rate of mineral use in Russia goes from 8% for the MF to -4,6% with the CAMF. In comparison, when studying the period 2000-2015, Russia only realises relative decoupling.



Top 5 service industries

Top 5 non-service industries

Top 5 service industries

Top 5 non-service industries

Fig. 2. Biomass and mineral use of the five most important (in terms of total respective material use by final consumption) service respectively non-service product categories, aggregated over OECD and non-OECD countries. Shaded areas show the MF (without capital endogenised) and dotted lines show the additional impacts that arise when the materials embodied in capital are included in the footprints (CAMF). The colours in the legend refer to both metrics.

4. Discussion

The question we ultimately face is whether society can develop without a consequent dependence on material resources. In order to quantify the relationship, material flow indicators have been developed, and have, over time, evolved from a “production” basis to a “consumption” basis. However, the current status of consumption-based (or footprint) indicators are essentially a trade-adjustment of the production account and do not adequately account for the inter-temporal aspect of capital. Considering that capital is such a large driver of material (especially mineral) footprints, we propose here to endogenise it within the production process such that the total (including historical) material requirements are captured. As a result, the footprint calculated with the Leontief demand-pull model will account for both the current industry requirements and the capital industry requirements. Using this new model, we established a new metric for estimating the material use of final consumption, the capital-augmented material footprint (CAMF), which includes not only the upstream materials embodied in the production processes (i.e. the MF) but also the upstream materials embodied in the capital goods used to produce the products for final consumption. In establishing this indicator, we switch the system boundary of the indicator from accounting across domestic final demand (consumption plus investment) to a domestic final consumption basis.

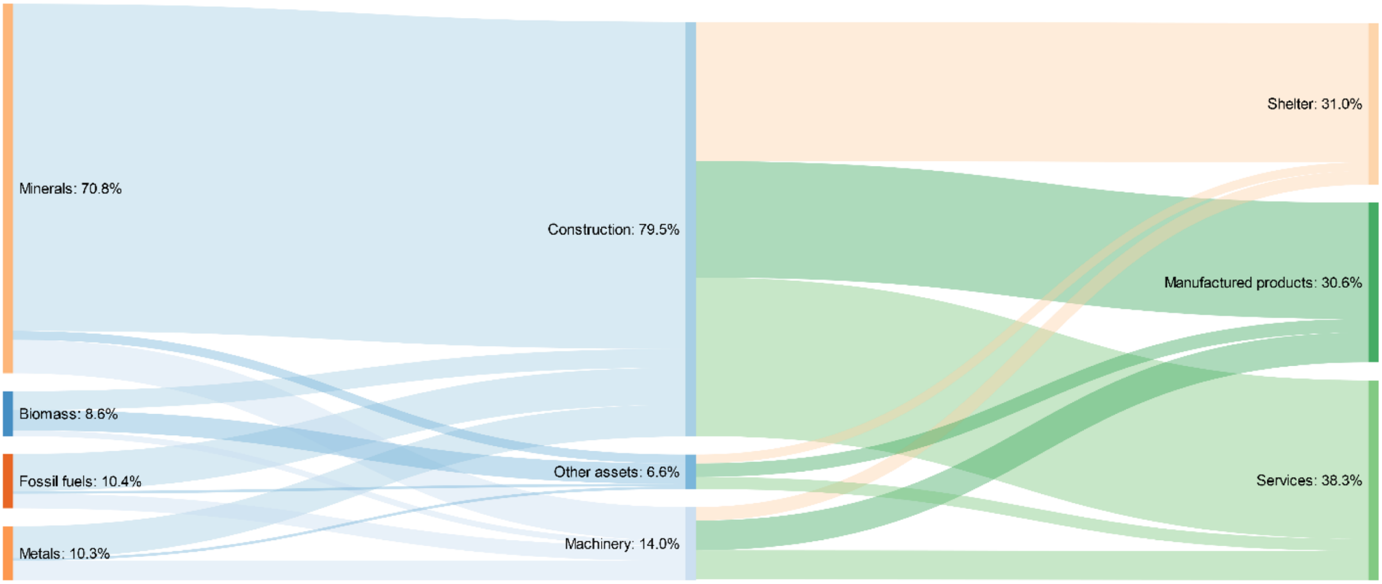


Fig. 3. Material footprints of capital consumption aggregated by asset type (for capital goods, middle axis), and by final product consumed (right hand axis). Results are for global totals, 2011.

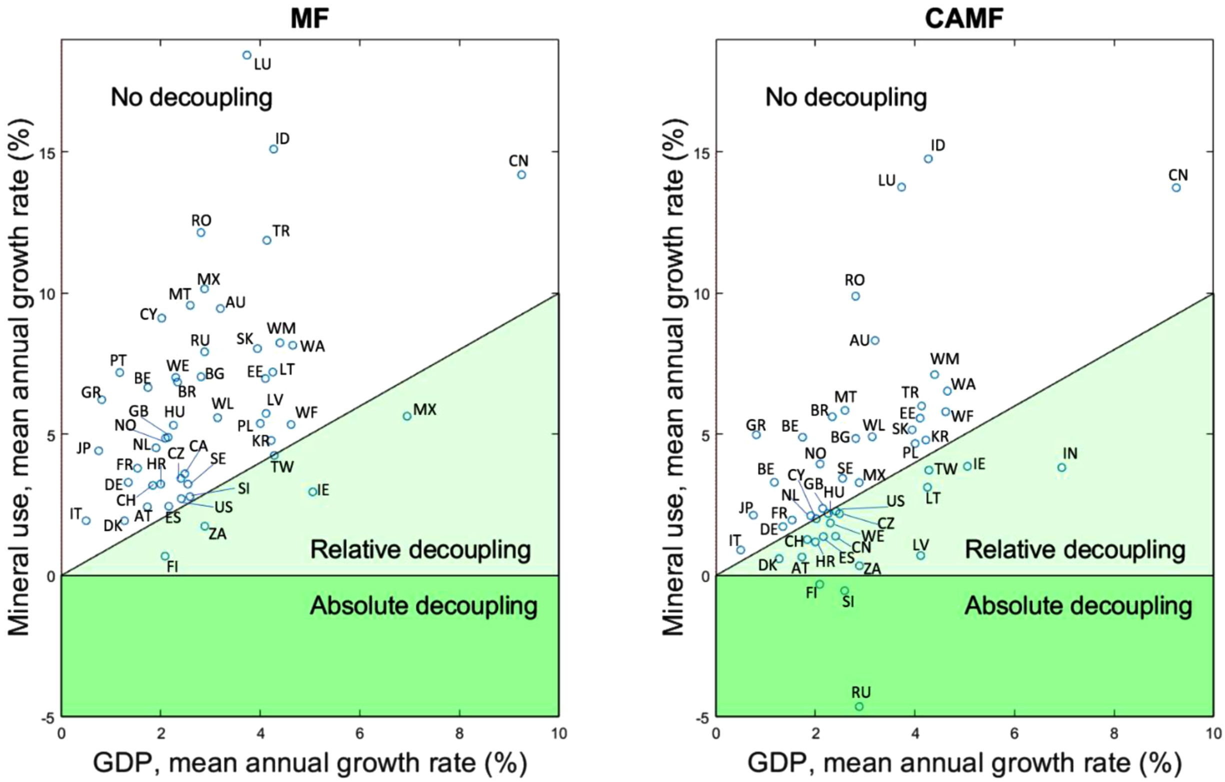


Fig. 4. Mean annual growth rate of mineral use of final consumption and mean annual growth rate of GDP (PPP), with (CAMF) and without (MF) capital endogenised, for all countries available in EXIOBASE as well as five rest-of-the-world regions. Full country names can be found in Table 1, and detailed values can be found in the supplementary information.

We showed that the CB material use of final consumption increased substantially when comparing the CAMF with the MF. By partitioning materials into four types (biomass, fossil fuels, metals and minerals), we found that the increase was particularly large for the latter two categories, with metal use increasing by around 45% for non-OECD countries and 50% for OECD countries, and mineral use averaging 80% respectively 120% increase over the analysed period. The average increase of fossil fuel use was around 15% for both country categories and the increase in biomass still lower, averaging 7% for non-OECD countries and 11% for OECD countries. The trends over the analysed period were found to be different for the two country groups. The material use of OECD countries stabilised and even decreased for the first three material categories, but the mineral use kept increasing. For non-OECD countries, all four material types kept increasing steadily across the time series.

By looking at the material use by product categories, we found that endogenising capital affected service categories much more than non-service categories, particularly real estate and public administration

Table 1
List of (non-trivial) acronyms and abbreviations used in the manuscript and figures.

MF	Material footprint	LU	Luxembourg
CAMF	Capital-augmented material footprint	LV	Latvia
MFA	Material flow analysis	MT	Malta
DE	Domestic extraction	NL	Netherlands
DMI	Domestic material input	PL	Poland
DMC	Domestic material consumption	PT	Portugal
RME	Raw material equivalents	RO	Romania
RME_{imp}	RME of imports	SE	Sweden
RME_{exp}	RME of exports	SI	Slovenia
RMC	Raw material consumption	SK	Slovakia
CB	Consumption-based	GB	United Kingdom
IO	Input-output	US	United States
MRIO	Multi-regional IO	JP	Japan
PPP	Purchasing power parity	CN	China
GFCF	Gross fixed capital formation	CA	Canada
CFC	Consumption of fixed capital	KR	South Korea
AT	Austria	BR	Brazil
BE	Belgium	IN	India
BG	Bulgaria	MX	Mexico
CY	Cyprus	RU	Russia
CZ	Czech Republic	AU	Australia
DE	Germany	CH	Switzerland
DK	Denmark	TR	Turkey
EE	Estonia	TW	Taiwan
ES	Spain	NO	Norway
FI	Finland	ID	Indonesia
FR	France	ZA	South Africa
GR	Greece	WA	Rest-of-the-world Asia and Pacific
HR	Croatia	WL	Rest-of-the-world America
HU	Hungary	WE	Rest-of-the-world Europe
IE	Ireland	WF	Rest-of-the-world Africa
IT	Italy	WE	Rest-of-the-world Middle East
LT	Lithuania		

services: the average mineral use associated with real estate services in the OECD more than quintupled over the analysed period when including the minerals embodied in capital. The reason for the substantial increased in the material use by services is twofold. Firstly, the intermediate material requirements of service sectors are relatively small (compared to non-service sectors). Secondly, service sectors rely on significant amounts of material-intensive capital goods to provide their services: real estate services require dwellings and other buildings, health services require buildings, laboratories, clinics, etc.

The results confirm that the choice of indicator substantially affects the estimations of material use associated with final products. The introduction of CB indicators in the early 2000s already led to significant changes in the measures of material use. By also including the materials embodied in capital goods, the total material content of goods and services increased again, and this increase varied greatly across product groups and countries. This has important implications for product footprint studies and for the focus on final demand composition as a strategy to reduce material requirements and ensuing environmental impacts (for example, through anthropogenically induced climatic change). Multiple studies have analysed the environmental impacts associated with household consumption (Ivanova et al., 2016; Kerkhof et al., 2009; Markaki et al., 2017; Steen-Olsen et al., 2016; Druckman and Jackson, 2009) or of individual products or technologies (Gerbens-Leenes et al., 2009; Minx et al., 2009) to draw conclusions regarding e.g. how to design environmental policies, inform consumers about the environmental impacts associated with their consumption, etc. The endogenisation of capital is a further necessary step in ensuring that such policy prescriptions will realise their expected benefits instead of perpetuating a lock-in through investment-heavy consumption.

Understanding the role and use of capital is a prerequisite for designing measures to reduce global material use (Jiang et al., 2019; Ball, 2020) and is a central component for circular economy and climate mitigation strategies (Gao et al., 2020; Jacobi et al., 2018; Hertwich et al., 2019; Mayer et al., 2019). Analysing the final uses of capital stock (and the materials embedded in it) is an important step in understanding these linkages further. Firstly, we are "locking away" materials in infrastructure faster than we are using the infrastructure (i.e. the CAMF indicator grows slower than the MF indicator for most countries). Under such continued growth, it will be impossible to realise a circular economy, and investment should perhaps focus on intangibles more than physical structures, for example, education, research and development. Secondly, it is often service sectors, which are not usually associated with material use (such as government and health services), that have a significant reliance on embodied materials in capital. Failing to include the materials embedded in services strongly underestimates their total impact. Using the CAMF brings new important insights into recent studies showing that service sectors have achieved the largest reductions in CB material use (e.g. (Schmidt et al., 2019)). Whilst large scale construction activities often occur in these sectors to stimulate the economy, it may be that focussing investment in people might produce better short and long-term outcomes – certainly so for material indicators, but potentially for other socio-economic outcomes.

From a development perspective, our results showed that more countries achieved absolute decoupling with the CAMF indicator than the MF indicator (when looking at development measured by GDP/cap in PPP). This does imply that our final consumption footprints, whilst larger, are either reducing or not growing as fast when we include capital consumption. This provides some hope that society will start to reduce its resource dependence further in the future. However, it comes with some caveats. As investment growth is currently outpacing GDP growth in many countries, we are slowly accumulating more and more embodied materials in future consumption (Zheng et al., 2018). As investments are depreciated over future years, the corresponding growth of the CFC appears with a certain time lag, and the effects of the recent substantial growth in e.g. Chinese investments (Minx et al., 2011; Ball, 2020) is not yet fully captured in the CAMF. Hence CAMF indicators in later years are unlikely to show the level of decoupling that we have previously seen. Furthermore, the rate of decoupling, regardless of indicator, is unlikely to be in the range of decoupling necessary to stay within planetary boundaries (Tukker et al., 2016) unless a strong break is made between environmental impact and the extraction and use of material resources. Considering the strong emphasis being placed on "circular economy" initiatives to break the link between consumption and resource use, the intertemporal time-lag of this capital consumption will provide a challenge for making strong reductions in resource requirements (Haas et al., 2015).

While the CAMF provides novel and relevant information about the total material content of final products, there are certain drawbacks and intricacies involved in our approach. One uncertainty concerns the use of the CFC as estimation of capital usage by industries. The CFC is a measure of economic depreciation of capital assets over several years, sometimes decades, and it is prone to be affected by tumultuous events in the economy, such as major devaluations (e.g. the Mexican peso in the 1990s and the Russian rouble following the collapse of the Soviet Union), introduction of new currencies (e.g. the Brazilian real in 1994) and periods of political uncertainty (e.g. the end of Apartheid in South Africa, leading to subsequent substantial fluctuations of the rand). For instance, with the CFC estimates from the World Bank that we use in the study, the CFC of Russia decreased almost 5-fold between 1995 and 1999, while the GDP decreased only 2-fold during the same period. Such a decrease in the CFC does affect the resulting CAMF, and it could hence be sensible to study the CFC in more detail. As there is no agreed standard on how to compute it, CFC estimates can vary between sources, which may affect the results considerably. As such, the CFC may not be the best metric for measuring capital use, but as mentioned in the introduction, it is currently the only metric of capital use available on a global scale.

Our approach to endogenise capital is further based on some simplifications regarding intertemporality, as we essentially assume that the technology (and hence material requirements) used in the goods that are embodied in the CFC is the same as the year of the CAMF analysis. Relaxing this assumption requires a dynamic model with explicit stock cohorts (see Chen et al., (2018) for a simplified example). The choice to focus on annual accounting may also be seen as an implicit normative choice in our methods, rather than, for example, looking at cumulative material footprints over time. Considering the longevity of many material-intensive investments, it may be argued that a cumulative approach over long time periods would provide the most insight into whether we can see a plateauing of our resource dependency as we aim for sustainable development. Such an approach would, however, require significant improvements in data availability.

5. Conclusions

Capital is a significant driver of our resource requirements. Nevertheless, the relationship between resource extraction, capital usage, and the final consumption of goods and services has hardly been explored. In this work, we introduced the capital-augmented material footprint (CAMF) as a new indicator of material use that includes all the materials embedded in capital goods. This indicator results in substantial increases in the material footprints of final consumption as capital is endogenised, particularly for mineral use. The increase was generally stronger in more developed countries and can be traced back to the additional capital-based material load of services. By analysing decoupling trends, we concluded that more countries achieve decoupling with the CAMF approach than with the MF. The indirect material requirements of capital investments therefore seem less dependent on GDP growth when compared to the MF of consumption alone. However, whether we can realise absolute decoupling more broadly will depend on much stronger mitigation measures that target the material-capital link. As such, linking capital use to final consumption by endogenising it in MRIO models provides new important insights into how materials are being used, which is a crucial step in the endeavour to make the economy more "circular" and ultimately towards implementing and realising climate mitigation strategies.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2020.104811.

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