Growth in environmental footprints and environmental impacts embodied in trade: Resource efficiency indicators from EXIOBASE3

Abstract

Most countries show a relative decoupling of economic growth from domestic resource use, implying increased resource efficiency. However, international trade facilitates the exchange of products between regions with disparate resource productivity. Hence, for an understanding of resource efficiency from a consumption perspective that takes into account the impacts in the upstream supply chains, there is a need to assess the environmental pressures embodied in trade. We use EXIOBASE3, a new multi-regional input-output database, to examine the rate of increase in resource efficiency, and investigate the ways in which international trade contributes to the displacement of pressures on the environment from the consumption of a population. We look at the environmental pressures of energy use, greenhouse gas (GHG) emissions, material use, water use and land use. Material use stands out as the only indicator growing in both absolute and relative terms to population and gross domestic product (GDP), whilst land use is the only indicator showing absolute decoupling from both references. Energy, GHG and water use show relative decoupling. As a percentage of total global environmental pressure, we calculate the net impact displaced through trade rising from 23% to 32% for material use (1995-2011), 23% to 26% for water use, 20% to 29% for energy use, 20% to 26% for land use, and 19% to 24% for GHG emissions. The results show a substantial disparity between trade related impacts for OECD and non-OECD countries. At the product group level, we observe the most rapid growth in environmental footprints in clothing and footwear. The analysis points to implications for future policies aiming to achieve environmental targets, while fully considering potential displacement effects through international trade.

<heading level 1>Introduction

Considering the current rate of economic growth, improving resource efficiency requires a strong decoupling between development and environmental impact. The United Nations Environment Program highlights the scale of the challenge (UNEP 2011) along with the urgency and potential of resource efficiency measures in achieving decoupling (UNEP 2014). However, the growing international flow of goods and services makes the relationship between trade and the environment increasingly important to understand (Liu et al. 2015). Knowledge about international spillovers of resources burdens or environmental impact will help in assessing progress towards national environmental targets and the United Nations Sustainable Development Goals (UNSDGs) (e.g. Peters et al 2011 for climate policy).

The rapid growth in trade prior to the 2008 global financial crisis, the subsequent stagnation, and the more recent push to re-liberalise global trade relationships in order to help economies recover from recession has put the trade agenda back in the spotlight. Over 50% of goods and over 70% of services traded are used as intermediate inputs to produce other goods and services (Lanz 2009). The average number of borders that an exported good crosses before final consumption is approximately 1.7 (Muradov 2016). This implies that most exported goods are not consumed within the country of import but are processed further. Previous research has shown that such trade flows have significant effects on the environment. Around one quarter of the global land use is embodied in trade (Weinzettel et al. 2013), as well as over 40% of materials (Wiedmann et al. 2013), 20-30% of global water use (Lenzen et al. 2013b), and over 20% of greenhouse gas (GHG) emissions (Peters and Hertwich 2008).

Recently, with the development of time series of global economic models for environmental analysis, studies have started to uncover the dynamics of consumption, trade and environmental impacts over time, as well as the role of outsourcing in the growth of emissions (Arto and Dietzenbacher 2014; Peters et al. 2011) and materials (Wiedmann et al. 2013). EXIOBASE3 (Stadler et al. 2017) is a global multi-regional input-output model that has been developed to analyse the change in the relationships between consumption, trade, and environmental impacts over time. The database has been developed to assess the major growth in trade since the mid-1990's, a time when most statistical offices around the world adopted the System of National Accounts (SNA) (United Nations Statistics Division 1993) in order to make international data current and comparable. EXIOBASE3 focuses on economic and associated environmental data from 1995 onwards (until 2011 for all indicators, but economic accounts and some environmental accounts are updated to later years) under the SNA and the associated System of Environmental and Economic Accounting (United Nations et al. 2014; Wood et al. 2015). EXIOBASE3 captures economic, environmental and trade data for all EU countries, 16 other major economies, and 5 rest of the world regions. With data on input-output transactions, labour inputs, energy supply and use, greenhouse gas emissions, material extraction, land and water use, as well as emissions to air, water and soil, it provides a comprehensive up-to-date coverage of the global economy. EXIOBASE3 provides the first time series with adequate disaggregation of the agricultural, forestry and mining sectors for proper consideration of the land, water and material pressures related to these sectors, as well as a detailed division of energy extraction and transformation industries. This puts EXIOBASE3 in a unique position compared to other existing MRIO databases, such as Eora or WIOD (for a comparison of MRIO databases see Tukker and Dietzenbacher (2013), or updated results on www.environmentalfootprints.org).

In this paper, we use EXIOBASE3 to investigate the role of international trade and consumption in relation to increased resource efficiency. We seek to understand the role of different global regions in the rapid growth of traded goods, and point towards the areas where consumption has seen the greatest growth in environmental impact, and reliance on traded goods. We present key results in the paper, and fully elucidated supporting information for additional country and regional analysis.

<heading level 1>Methods

Analyses of environmental impacts embodied in trade and consumption are based on the following elements: for a given country *r* we take trends in production-based accounts D_r^{prod} and consumption-based accounts D_r^{cons}. A detailed explanation on how to calculate production and consumption-based accounts can be found in Wood et al. (2015), and is summarized below.

The production-based account D_r^{prod}, also called footprint, is available directly as a sum of the direct inputs/emissions in each sector, whilst the consumption-based account D_r^{cons} is calculated through the Leontief model with environmental extensions (Miller and Blair 2009):

$$\mathbf{D}_r^{cons} = \mathbf{SLY} + \mathbf{Fh}$$

where $\mathbf{S}$ is the environmental intensity matrix showing environmental pressure per unit output of intermediate producers (industry); $\mathbf{L}$ is the Leontief Inverse or "total requirements matrix" showing intermediate inputs required per unit of final product; $\mathbf{Y}$ is the matrix of final demand by consuming country (source – or region of production – by consumer), and $\mathbf{Fh}$ is the direct environmental pressures by final consumers (for example, resource consumption in households). We use the EXIOBASE3 database, with time-series data from 1995 to 2011[1]. A full description of the database, methods to obtain the database, product and country coverage is available in a publication in this special issue (Stadler et al. 2017). This paper presents results from version 3.4 as of September 2017, a minor update to the v3.3 release at the end of the European funded DESIRE project (see www.fp7desire.eu).

We quantify five environmental pressures in this study: GHG emissions, energy use, material use, water consumption, and land use. For GHG emissions, we included emissions from fuel combustion, industrial emissions (including cement, chemicals, and other non-combustion processes), agriculture, and waste (IPCC categories 1 to 5 and 7). The aggregation of different well-mixed GHG (CO_2, CH_4, N_2O and SF_6) was performed using the GWP100 metric (Myhre 2013), which is widely applied in climate assessments and has been used extensively in life-cycle analysis to calculate the carbon footprints of product flows (Goedkoop et al. 1998; Heijungs et al. 2010). Energy consumption was quantified as emission relevant energy use – i.e. energy use at point of combustion or point of final production in the case of hydro, solar, etc. This excludes energy products used for non-energy purposes (e.g. lubricants or plastics). The energy accounts on EXIOBASE3 were constructed using statistics on energy consumption from the International Energy Agency. Material use comprises the domestic material extraction used, which is compiled based on the various available international data sources, including the Food and Agriculture Organization (FAO) of the United Nations, the International Energy Agency and the British and US Geological Surveys, and following the Eurostat material flow guidelines (EUROSTAT 2013). Water consumption covers the total blue water consumption in agriculture and livestock production, by industries and businesses, as well as direct consumption by final consumers, and corresponds to the amount of water extracted from nature minus the amount of water returned to nature. This indicator is used to account for anthropogenic water appropriation (Lutter et al. 2016), but does not account for its contribution to water stress (Yang et al. 2013). Land use was quantified by adding the total surface area of land occupied by agricultural production and permanent pasture, to that by forestry activities (for production of roundwood and industrial firewood) to that by infrastructure such as urban areas, dams and roads. This indicator does not differentiate between the productivity in different land areas (Haberl et al. 2007). However, because of the uncertainty surrounding impact metrics of land use (such as the impact on biodiversity of land use for forestry versus land use for farming), it is still useful to quantify the total land pressure as a resource constraint. Full details of the data used to construct these extensions is available in Stadler et al (2017).

We define environmental pressures displaced through trade (Ghertner and Fripp 2007), as the difference between the production-based account and the consumption-based account (cf. Peters et al. 2011):

$$\mathbf{T_r} = \mathbf{D_r^{prod}} - \mathbf{D_r^{cons}}$$

where $\mathbf{T_r}$ is positive for those countries which are net exporters of environmental pressure, and negative for those countries which are net importers of environmental pressure. In order to illustrate the impacts of globalisation on the patterns of displacement of environmental pressure, we focus in particular on the analysis of changes over time.

We calculate the percentage of imported environmental pressure by setting up a bilateral calculation of producer to consumer $\mathbf{D}_{r,s}$, such that:

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[1] EXIOBASE 3 additionally contains a now-casted time series from 2012 to 2016. This data is non-homogenous across the environmental pressures, and is not included in the results presented here. Contact the authors for further info.

$$\mathbf{D}_{r,s} = \mathbf{G}\hat{\mathbf{s}}\mathbf{L}\mathbf{Y}$$

where $\mathbf{Y}$ is the matrix of final demand by consuming country of dimensions $(p * n, n)$, where p is the number of production sectors in each country (200) and n is the number of countries (49), $\hat{\mathbf{s}}$ is each individual environmental pressure per unit output diagonalised, $\mathbf{L}$ is the Leontief Inverse, and $\mathbf{G}$ is an aggregation matrix that collapses the product-by-country dimension (p, n) to just countries (n). The percentage of imported emissions is then $\mathbf{D}_s^{imp} = \sum_{r \neq s} \mathbf{D}_{r,s} \, / \sum_r \mathbf{D}_{r,s}$. Globally it becomes $\mathbf{D}^{imp} = \sum_{r \neq s.s} \mathbf{D}_{r,s} \, / \sum_{r,s} \mathbf{D}_{r,s}$. Note that we are calculating net transfer or displacement here, and not all impacts embodied in gross trade flows (Peters 2008).

Resource efficiency indicators are calculated by dividing the consumption account $\mathbf{D}_{\mathbf{r}}^{\mathbf{cons}}$ by population statistics (World Bank 2015a) or gross domestic product in 2011 international dollars (corrected for purchasing power parity) (World Bank 2015b).

<heading level 1>Results

1.1. Growth in global environmental impacts

On a global scale, achievements in resource efficiency, which are characterized by either absolute or strong relative decoupling from gross domestic product (GDP), have been limited. Table 1 illustrates the development of various indicators in the period 1995 to 2011. Material use has shown the strongest increase, from 8.3 to 11.3 tonnes/capita (+36%), outstripping growth in GDP. We also see an equal growth of GHG emissions to emissions-relevant energy use, which implies that we have not achieved a global decarbonisation of the energy supply. Land and water resources, which are more directly subject to natural constraints, have increased the least, with blue water consumption rising from 190 to 200 m^3/capita for water consumption, and the total surface area of land used for productive purposes showing a reduction of 0.3 ha/capita. Land use area has slightly decreased on an absolute level, principally due to slight reductions in area of permanent meadows and pasture and non-planted forestland. It is the only indicator that presented (small) absolute decoupling from GDP.

Table 1 Growth of absolute, per-capita and per-GDP environmental pressures, GDP (PPP) and population between 1995-2011.

	UNITS	1995 (PER-CAPITA)	2011 (PER-CAPITA)	ABSOLUTE GROWTH	PER CAP GROWTH	PER GDP GROWTH
GHG emissions	t CO2 eq.	5.5	6.3	1.42	1.16	0.88
Energy use	GJ	56.0	64.4	1.41	1.15	0.87
Material use	tonnes	8.3	11.3	1.67	1.36	1.03
Blue water consumption	m3	190.6	200.1	1.28	1.05	0.80
Land use	ha	1.3	1.0	0.99	0.81	0.61
GDP (PPP)	2011int$	7,331	9,660	1.61	1.32	1.00
Population	billion	5.7	6.9	1.22	1.00	0.76

The strong growth in material use, as well as the strong link between material use and GHG emissions in capital intensive low-carbon technologies (Hertwich et al. 2014) and in infrastructure building due to the use of carbon-intensive materials such as cement and steel (Müller et al. 2013; Sodersten et al.

2017) provide a cause for concern for future growth. Likewise, the International Resource Panel (IRP) of the United Nations Environment Programme (UNEP) has recently shown that an increase in resource efficiency is key for meeting climate change targets in a cost-effective manner (Ekins et al. 2016).

On a regional scale, we observe substantial differences in growth rates. Figure 1 presents the growth in consumption-based footprints per capita and per GDP-PPP between 1995 and 2011 by region. GHG emissions per capita has grown slightly more slowly than energy use for all regions, except China, Africa and the Middle East. In Europe, the growth of the energy footprint per capita has been accompanied by a decline in emissions. North America has succeeded in reducing both energy and emission footprints per capita over the period under consideration. Most of the developing countries have been characterized by growing energy footprints per capita, which has helped fuel their rapid economic development, but relative decoupling between energy and emissions can also be observed. This decoupling, however, is not visible for China, where the increase in GHG emissions has outpaced the growth of emission relevant energy use. This implies the adoption of more carbon-intensive energy sources with the commissioning of a large number of coal-fired power plants during that period, (Lin et al. 2014; Feng et al. 2012). This fact is corroborated by the breakdown of Chinese emissions in the underlying data: from 1995 to 2011, the share of emissions from energy processes (production and combustion of fossil fuels) in total GHG emissions have grown from 75% to 82% for production-based accounts (D^{prod}), and from 75% to 79% for consumption-based accounts (footprints, D^{cons}). China was also an exceptional case regarding the growth of material footprints per capita, with footprints almost tripling, growing much faster compared to all other regions. This is related in particular to the building up of transport, housing and energy infrastructure, which is highly material intensive; for example, regarding the use of construction minerals, such as cement, sand and gravel (Giljum et al. 2016). Growth in land footprint per capita by 30% also separates China from other regions, as the land footprint per capita decreased between 9 and 38% for all other regions during the period.

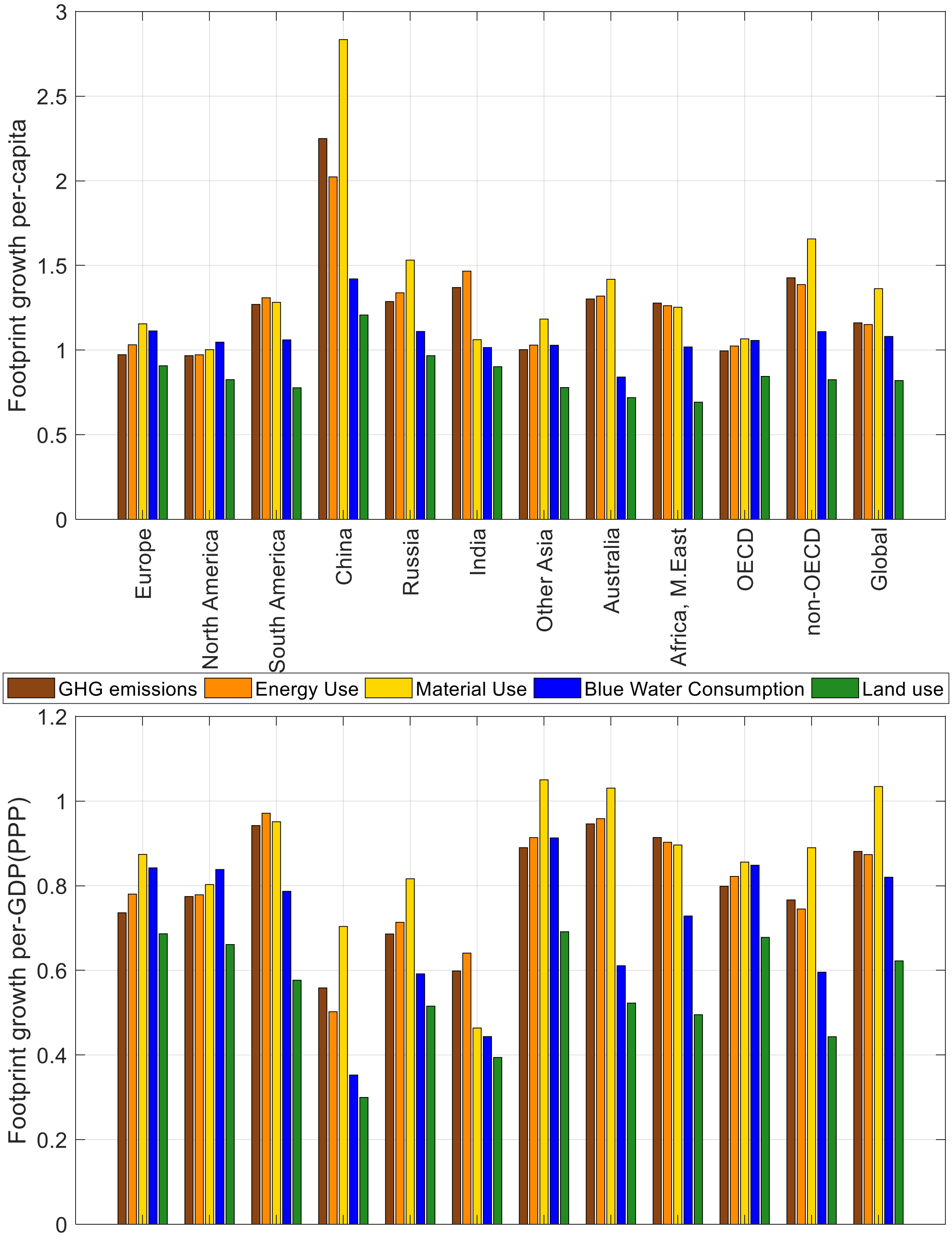

Figure 1 Growth in consumption-based footprints per capita and per GDP between 1995 and 2011 for 11 world regions (1995=1).

When we shift the analysis to account for resource efficiency, (environmental footprints per unit GDP) we notice a change in the narrative. In terms of resource efficiency, China and India have achieved the highest relative decoupling between environmental pressure and GDP growth. For every 1% of GDP growth, China increased its GHG emissions by 0.56%, while the OECD countries increased their emissions by 0.8%. The global average was 0.88% per percentage GDP growth. Again, land and water indicators show faster decoupling than material and energy indicators in general, and only India, South America and Africa are showing faster material decoupling than energy decoupling.

With regard to the net trade balance for 2011 (Figure 2), we confirm previous results showing that Europe has a resource deficit across the categories of greenhouse gas emissions, material use, water consumption, land use (Tukker et al. 2016) as well as for energy use. The pattern of net trade balance did not change much for Europe from 1995 to 2011, with some indicators slightly decreasing (land) and others increasing (material use). North America increased their resources deficit during the period, with the increase in net import of energy and materials being more pronounced over time. The region also became a net exporter of embodied land in 2011. China changed from being a small net exporter in 1995 to a large net importer in 2011, and by 2011 shifted to a larger trade surplus of material and energy embodied in Chinese products. By 2011, China was the largest single-country net exporter of embodied emissions and material. Russia remained, throughout the period, a large net exporter of embodied energy, amounting to the equivalent of 2.6% of global energy use in 2011. By 2011, Russia was also the country that had the highest exports of embodied land, alongside South America and Australia. All these regions are exporters of mineral, agricultural, and energy commodities, which are land-intensive. The remainder of Asian countries (Other Asia) is also significant in that it had a large net export of water while having a large net import of material and land use. The region was also a net importer of embodied energy and emissions in 1995, but in 2011 the production- and consumption-based indicators were almost in balance. All Asian regions (China, India, and Other Asia regions) were net exporters of water, which shows a large water intensity in goods produced in the region. This was due to the relatively water-intensive crops in the region. Africa and the Middle East region were net exporters of all environmental pressures assessed.

Looking at the development of the footprint balance between OECD and non-OECD countries over time, two things become apparent. First, there was a displacement, through international trade, of all environmental pressures from OECD to non-OECD countries both in 1995 and in 2011. Second, between 1995 and 2011, the imbalance between the two regions became more pronounced for material use (from 7.5% to 9.5%), energy use (from 3.9% to 4.6%), and GHG emissions (from 6.1% to 6.3%), while the difference in the net trade of water (from 8.1% to 7.2%) and land footprints (from 7.2% to 5.3%) decreased.

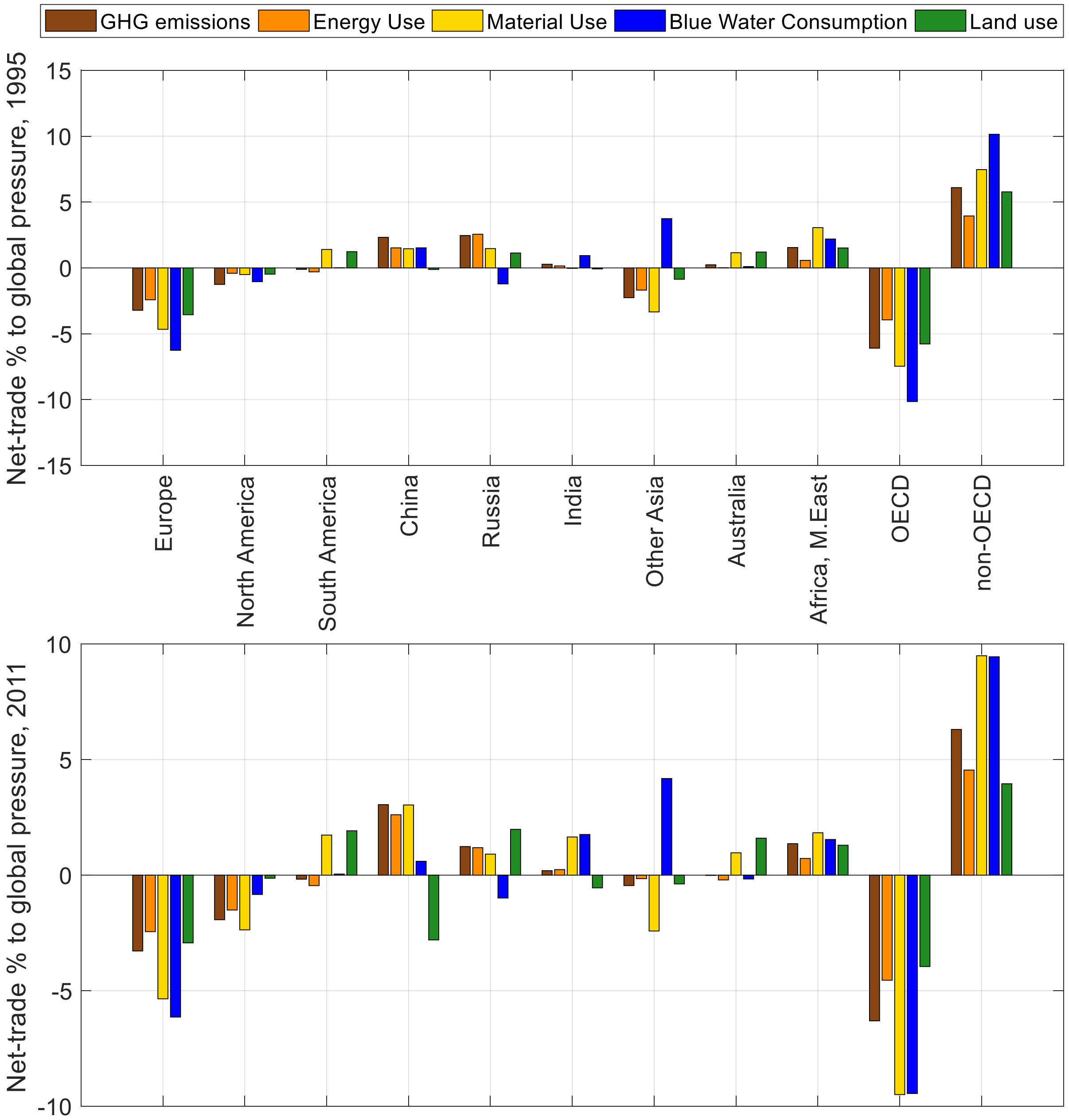

Figure 2 Net trade of environmental pressures (consumption - production) relative to global pressure in different regions for 1995 (top) and 2011 (bottom)

1.2. Increasing role of international trade

International trade can promote more efficient access to natural resources and is thus an important driver of economic growth (WTO 2010). However, there is concern for potentially unequal ecological exchange in trade (Moran et al. 2013) and for having consonant environmental protection embodied in traded goods (Copeland and Taylor 2004).

Figure 3 shows the percentage of global pressures displaced through trade – that is, the amount of pressure that occurs in the upstream supply chain of a country different from that where the final consumption occurs. This share grew from 24% to 33% for material use, 25% to 28% for water use, 20% to 26% for land use, 20% to 24% for GHG emissions, and 16% to 21% for energy use. Material use is the pressure with the highest displacement through international trade. One of the reasons for that might be that materials such as biomass, fossil fuels, minerals and metals are commonly exported products, both as raw materials and further processed and embodied in exported goods.

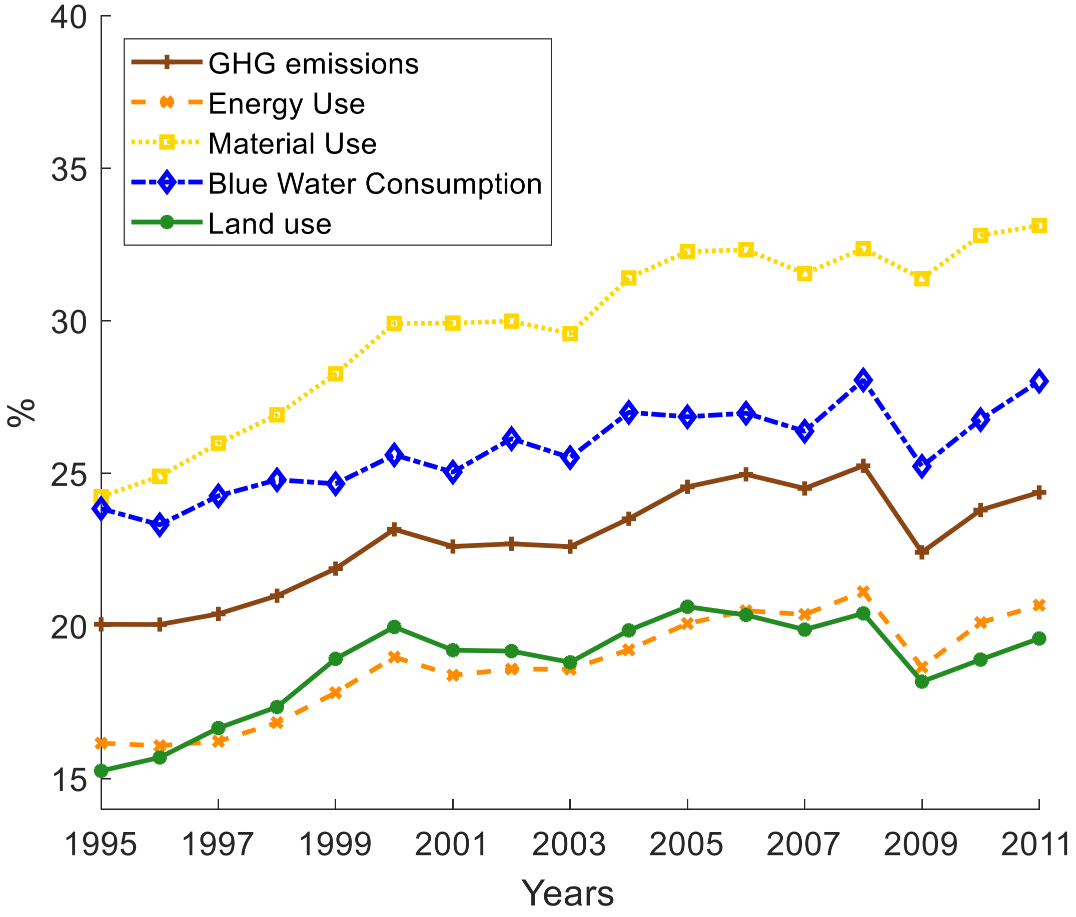

Figure 3 Percentage of impacts displaced through international trade, relative to total global footprints

Whilst the magnitude of these results is affected by the aggregation of the Rest of the World regions (we only look at trade between regions, not trade within a region), the growth rates are generally insensitive to this aggregation. All indicators show a clear pattern of growth between 1995 and 2007. The financial crisis of 2008 resulted in a decline in 2009, lowering the import share of embodied environmental indicators in the total footprints, as well as reducing the footprint itself. Economic recovery from 2010 brought back the imports to the pre-crisis levels.

1.3. Product level drivers

The analysis at product level can help understand which of the final products consumed are driving the change in overall footprints, and can thus inform policy. Figure 4 shows the growth of absolute footprints by six consumption categories (see SI for aggregation of detailed products to product category): shelter (i.e. housing), food, clothing and footwear, mobility, manufactured products, and services. For the OECD, we see the most rapid growth in footprints in the apparel product category, with the material footprint doubling from 1995 values, the water footprint increasing by 50%, and GHG emissions by 20%. Likewise, material use has increased by close to 100% for manufactured products. This could be the result of the shift in products consumed, from higher-priced clothes and footwear to a higher volume of cheaper goods produced in sweatshops (cf. Steen-Olsen et al. 2016) and higher availability and lower prices of goods, such as electronics. This creates a higher volume of consumption at similar price levels, which will have lower effects on value-added than on environmental impacts associated with the production of these goods. For some of the most polluting product groups (e.g. shelter and mobility), on the other hand, growth is low in the OECD. For the Non-OECD, we see the same strong growth in apparel and manufactured products, but also strong growth in shelter and services.

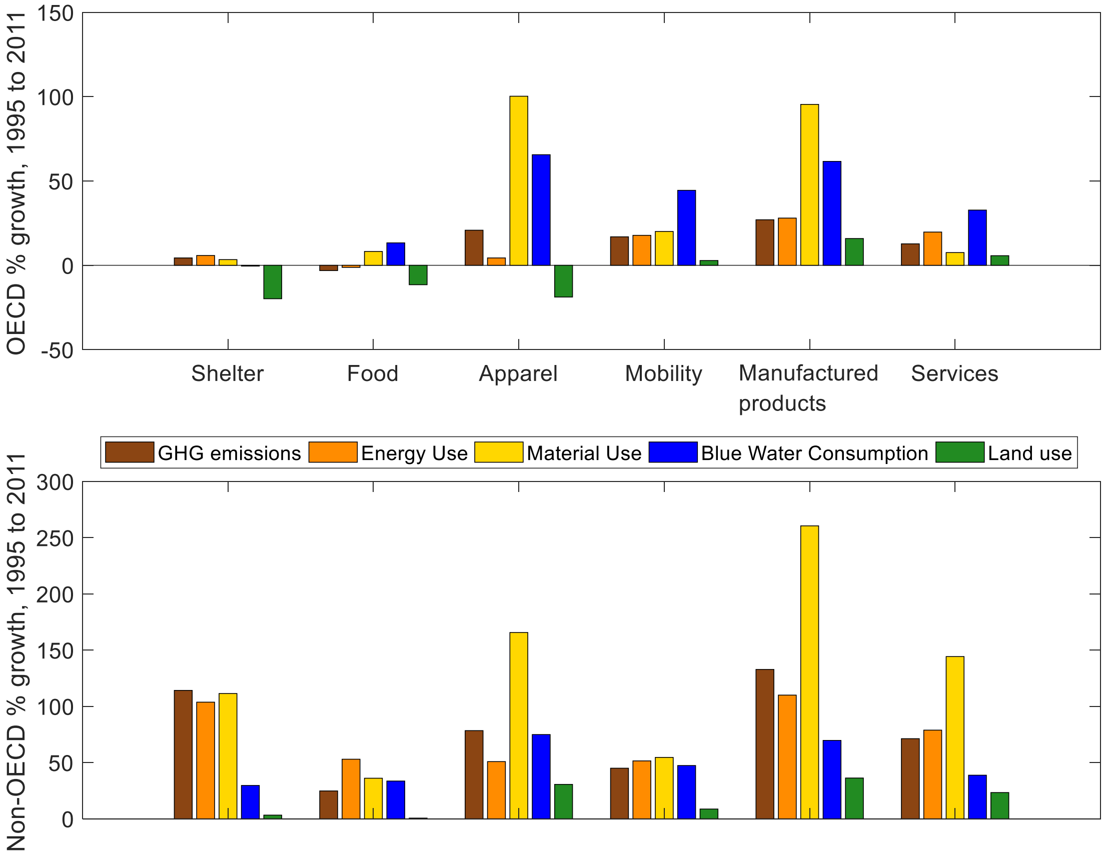

Figure 4. Growth in environmental footprints by consumption category, 1995-2011, OECD and Non-OECD.

When looking at the effect of trade on footprints of different products, we see that it depends on the product category and on the environmental indicator. Figure 5 shows the growth in the footprints of GHG emissions, material use, water consumption, and land use for the six product categories. We excluded energy use, because of a similar trend observed in GHG emissions and energy use. The upper parts of the figures show the total global environmental pressure driven by each of the product categories, while the lower parts of the figures show the share of pressures displaced through international trade in relation to the total footprint of the final products. Shelter is the largest driver of GHG and material use and second largest driver of land use, though most impacts occur domestically. This is likely due to the construction of infrastructure, which is emission- and material-intensive, and mostly relies on domestically sourced goods (such as gravel and cement). Food is responsible for the majority of the impacts on water consumption, and has a significantly higher share of impacts on land use than all other products. As for material use, most environmental impacts happen domestically.

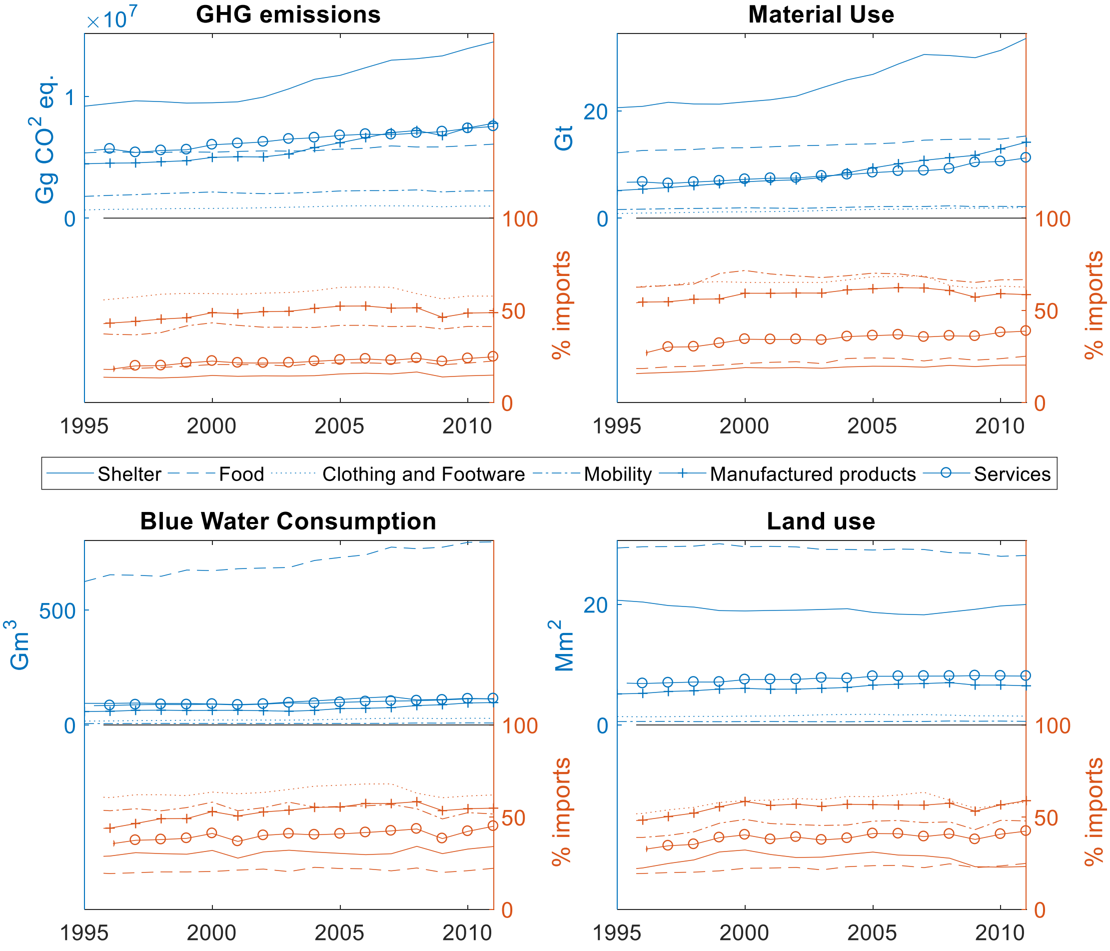

Figure 5. Environmental footprints by consumption category, global footprints, absolute quantity (left axis), percentage of imports (right axis).

Globally, imports are responsible for at least 50-70% of the environmental pressures associated with clothing and footwear, while for manufactured products they account for about 40-60%. Whilst clothing and footwear represent a low share of the total absolute environmental impacts, manufactured products' GHG emissions and material use have risen rapidly since the first half of the 2000s. When looking at specific regions, however (see SI), we see that imports are important for OECD countries and have increased considerably since the 2000s, and especially so for Europe, where up to 80% of environmental pressures occurred outside the country where the final goods are being consumed in 2011.

<heading level 1>Discussion

Distance to environmental targets In Tukker et al. (2016), four of the environmental indicators on carbon, water, land and materials were assessed in comparison to an indicative target. These were defined as: a carbon footprint of 2-2.5 tonnes of CO_2 per capita to stay within a 2° target; a material footprint of 5-10 tonnes per capita (see Bringezu 2015); a water footprint of circa 150m^3 per capita (with ranges of 100-600m^3); a land use footprint of 10ha per capita (Hoekstra and Wiedmann 2014). In light of these indicative targets, we see that already since the work of Tukker et al. (2016) based on 2007 data, the global economy further exceeded these limits for material extractions, water use and greenhouse gas emissions. It was only in the case of land use that a slowdown in growth could be observed. However, besides global per-capita averages, one should pay attention to the unequal distribution of the footprints per inhabitant. High per-capita footprint levels in industrialised countries, in combination with the increasing pressure through open trade, drove the global economy further away from achieving these targets. With the increasing growth of developing nations, this again poses questions related to the limits of achieving the required decoupling of global and regional environmental pressures from economic growth, in order to keep socio-economic activities within the planetary boundaries (Steffen et al. 2015). While international trade can improve the efficiency in resource use for production worldwide (Cole 2004), a decrease of environmental pressures at the global level could not be observed, and the net transfer of environmental pressures from non-OECD to OECD countries has not decreased. Further investigation of the role of international trade in the relative decoupling of economic growth and environmental pressures is needed to assess whether international trade is contributing to linking resource availability with production, without leading to socio-economic losses or increasing non-regulated and/or non-financial environmental impacts.

Environmental leakage. In the trade discourse, there has been strong concern that environmental regulation will cause the relocation of industry to other regions with lax environmental standards (e.g. under globally disparate carbon taxes). In the literature, this has been discussed as the Pollution Haven Hypothesis (Copeland and Taylor 2004). This is clearly an issue for the governance of global environmental impacts, but whilst we cannot directly test this hypothesis (there are many methodological challenges in empirically testing using MRIO analysis (Zhang et al. 2017)) our results do not suggest a strong case for this happening thus far. In the period analysed, clearly a great deal of "environmental leakage" occurred, in that impacts displaced through trade generally grew in the order of 50%. However, we saw the greatest growth in *unregulated* environmental pressures, rather than in greenhouse gas emissions that have come under climate regulation in Europe. Material use and gross energy use showed the greatest increase over time – two pressures that relate to the increasing secondary and tertiary nature of our economies. The growth of materials and energy embodied in internationally traded products was thus more a result of other drivers, such as restructuring in the international division of labour, than of the implementation of specific climate policies (compare (Liu et al. 2016)). At the regional level, the industrialization and increasing role of China and other Asian countries in international supply chains contributed to an increase of environmental pressures displaced through trade (Dietzenbacher et al. 2012). Their highly carbonized energy mix resulted in increased emissions embodied in exported products, while for material indicators, there is an even more significant increase (doubling) of material use embodied in clothing and footwear and in electronics.

The role of infrastructure in shaping global developments. Both at the global level and notably for many emerging economies, such as China, a huge increase in material use and related footprints could be observed over the past 20 years (Table 1, Figure 1), leading to an increasing material intensity of the global economy over our period of analysis. The main underlying driver for this huge increase is the significant investment in infrastructure, which emerging economies such as China are currently undertaking (Wang et al. 2014; Giljum et al. 2015; UNEP 2016; Minx et al. 2011). This infrastructure, serving both domestic and foreign consumption, relates to housing and manufacturing infrastructure (buildings, factories), transport infrastructure (roads, railways, harbors, etc.) as well as energy infrastructure (such as power plants). On the one hand, these infrastructure-related activities slow down the reduction in pollution intensity in emerging countries, such as China (Guan et al. 2014) (Guan et al., 2014). On the other hand, the fast growth in material consumption due to infrastructure activities in emerging economies is consequently transferred to developed regions, such as the EU, via rapidly increasing levels of materials and emissions embodied in imports (see Giljum et al., 2016). This infrastructure not only determines the material patterns of today but will also influence other environmental performances heavily in the future, e.g. regarding energy use and GHG emissions (Feng et al. 2012). Infrastructure thus should receive priority attention when designing strategies to achieve a sustainable economy and sustainable production and consumption patterns (Clarke et al. 2014) as indicated in the Sustainable Development Goals (United Nations 2015).

Footprint trends at the product level. Manufactured goods are the product group with the highest growth rate in environmental impacts. As such, the focus on manufactured goods is becoming increasingly important for European resource efficiency policy, where the consumption of clothing and footwear, mobility (including vehicles) and other manufactured goods represented the greatest growth in environmental pressures. In general, material use is the indicator with the highest growth rates, which is related to the metabolic transition that many emerging economies are currently undergoing (UNEP 2016).

Trade levels. Intensified international trade over the last 20 years has made regions more interdependent on each other's supply of resources. The value chains have become more global (OECD 2013), and an increasing number of products are traded in order to be processed further and exported to the country of final consumption. Whilst the global financial crisis had a significant impact on global trade relations, leading to a sharp drop of the role of imports determining regional footprints, in our results we saw a catch-up of all accounts to levels before the crisis, confirming similar previous reports, specifically for GHG (Peters et al. 2012).

Uncertainty & Variability. Results presented in this paper are based on EXIOBASE3, a top-down model of the global economy with disaggregated agricultural, food, mining and manufacturing sectors. EXIOBASE is the highest resolution global MRIO with harmonised product classifications (compare Eora, with variable product resolution from 25 to over 400 commodities in different countries). However, there is still significant aggregation compared to individual product flows, or compared, to for example the most detailed trade classification of roughly 4000 goods. A significant amount of work has been done to understand the relative variability and uncertainty caused by the use of MRIO approaches, including 1) variability due to choice of model, 2) product level aggregation uncertainty, 3) regional aggregation uncertainty 4) stochastic uncertainty. We do not go into these sources of variability and uncertainty here. For understanding of variability between MRIO results, we refer to the website www.environmentalfootprints.org, where all MRIO results are available in a common classification. This follows up earlier work by Owen and others (Owen et al. 2014; Owen et al. 2016; Wieland et al. 2017) who analyse the sources of differences in MRIO models, and Moran and Wood (2014) who quantity the level of convergence in MRIO results for carbon footprints. The question of aggregation error has been investigated through the work of Steen-Olsen et al. (2014) across multiple models, and in the case of EXIOBASE (de Koning et al. 2015; Wood et al. 2014; Bouwmeester and Oosterhaven 2013; Stadler et al. 2014). Much less work has been done on stochastic uncertainty, although some authors (Lenzen et al. 2010; Lenzen 2011; Lenzen et al. 2013a; Moran and Wood 2014;

Karstensen et al. 2015) address the issue, finding significant cancellation of stochastic errors (assuming no correlation) at the country level, resulting in stochastic errors of carbon footprints in line with stochastic error of production based accounts (roughly 5-15%). A final area of research to point at is showing the differences in using sub-regional production-side models, for example, in the regionalisation of IO tables, or the significant impact on embodied exports with the separation of production-side impacts for processing exports (Dietzenbacher et al. 2012; Su et al. 2013). The summation of this work points to the importance of having high product and regional resolution, particularly for environmental analysis. More work needs to be done in this area, but at the same time, the institutionalisation of MRIO and footprint-based approaches in for example, the OECD (Yamano 2015), will allow for the research frontier to move in this direction (Tukker et al. 2017).

<heading level 1> Conclusion

Achieving absolute decoupling of environmental pressure from economic growth will require strong improvements in resource efficiency. In this paper, we used EXIOBASE3 to look at a range of environmental pressures, the rate of decoupling as well as the impact that growth in international trade has had. We find strongest growth in material use indicators, relatively to population and income. Energy and greenhouse gas emission indicators follow similar but less pronounced trends. Material goods are responsible for a significant portion of the growth, both in absolute levels and as a percentage of traded impacts. Impacts embodied in trade are growing for all indicators, and we confirm the impact that global trade has in the displacement of environmental impacts to developing regions. The results have implications for the realisation of Sustainable Development Goals, and the fact that assessments must take into account the inter-regional displacement of impacts, and the need for proactively addressing the growing material metabolism of our economies.

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