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International Trade Drives Global Resource Use: A Structural Decomposition Analysis of Raw Material Consumption from 1990–2010

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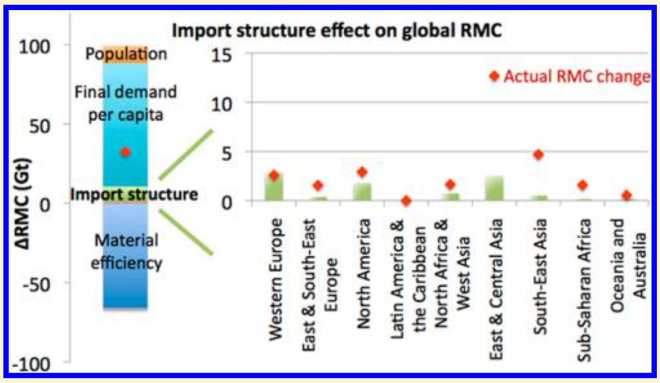
Supporting Information

ABSTRACT: Globalization led to an immense increase of international trade and the emergence of complex global value chains. At the same time, global resource use and pressures on the environment are increasing steadily. With these two processes in parallel, the question arises whether trade contributes positively to resource efficiency, or to the contrary is further driving resource use? In this article, the socio-economic driving forces of increasing global raw material consumption (RMC) are investigated to assess the role of changing trade relations, extended supply chains and increasing consumption. We apply a structural decomposition analysis of changes in RMC from 1990 to 2010, utilizing the Eora multi-regional input-output (MRIO) model. We find that changes in international trade patterns significantly contributed to an increase of global RMC. Wealthy developed countries play a major role in driving global RMC growth through changes in their trade structures, as they shifted production processes increasingly to less material-efficient input suppliers. Even the dramatic increase in material consumption in the emerging economies has not diminished the role of industrialized countries as drivers of global RMC growth.



1. INTRODUCTION

Over the last century, human societies have extensively increased resource extraction and use.[1] Environmental impacts, such as depletion of limited resources, degradation of ecosystems, pollution through waste flows and anthropogenic climate change, are increasing in direct relation to resource use.[2,3] International cooperation and the establishment of a global economy, specialization, and international trade lead to a global division of labor.[4,5] With trade and cost-efficient transport technology, production and consumption are no longer necessarily located in close proximity but are spatially disconnect.[6,7] International trade patterns changed from early trade between industrial cores and peripheral colonies to intensive trade activities among industrialized nations and then expanded toward deliveries from emerging countries to industrial nations.[8,9] Primary production stages in particular were relocated from high-wage to low-wage countries.[5,10] What follows is the increasing spatial disconnect between the consumption of a final product and the environmental pressures due to its production process.[11−13]

Trade is widely considered to contribute to an economically efficient distribution of production processes.[5] In recent years, an increasing body of literature has investigated the effects of changing international trade patterns on resource use and other environmental concerns.[7,11,14−16] However, the question whether trade also contributes to an environmentally sound distribution of materials extraction and production is not yet answered. In the light of the current discourse on green growth, decoupling and sustainable development, implications of trade on the indicator resource efficiency (GDP/resource use) have to be further investigated.[17,18] Does trade contribute to a global increase in resource efficiency? Or do economic considerations such as production costs overrule environmental interests and lead to a shift of production processes to places where environmental pressure associated with resource use is relatively high?

Most developed countries report a relative decoupling of economic growth from material consumption, that is, GDP increases faster than apparent domestic material consumption.[2,19] In a few cases, even an absolute decoupling has been observed, which means that material consumption is actually declining, despite continued economic growth.[14,20] However, developed economies are only decoupling from their *domestic* material consumption.[2,14] A consideration of upstream material requirements associated with trade flows reveals no decoupling due to increased sourcing of material-intensive production stages from other world regions.[7,21,22] Since the 2000s, a recoupling of global material consumption with global GDP has even been reported.[19] Besides the national perspective on

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distribution patterns of production and consumption, the question, whether trade leads to higher resource efficiency on the global level, is still unanswered.

In recent years, the conceptual and methodological basis to investigate resource use and emissions embodied in international trade have been advanced substantially.[23−25] Robust data on material use is gathered in the economy-wide material flow accounting (EW-MFA) framework,[26−28] based on the social metabolism concept.[29] The most commonly used EW-MFA indicator is domestic material consumption (DMC), which accounts for materials domestically extracted plus imports minus exports; trade flows are considered with their mass upon crossing the administrative border of a nation state. This so-called production-based indicator therefore allocates material consumption for the production of traded goods and services to the country where the production occurs.[24,26]

To capture resource use—no matter where in the world it occurs—induced by national final demand, consumption-based indicators have been developed, which allocate resource use along supply chains of traded goods and services to their final consumption.[30] Studies on consumption-based indicators have been published for a range of environmental issues like land use,[31,32] water,[33,34] biodiversity loss[11,35,36] or emissions.[37−39] For materials, the main consumption-based indicator is raw material consumption (RMC), which is also referred to as material footprint.[7] RMC encompasses all materials extracted and used along the full supply chain to satisfy final demand. Thus, consumption-based indicators can be interpreted to reflect the increasing spatial disconnect of production and consumption as well as the international relocation of material extraction and associated environmental pressures.[21]

At present, several RMC accounting methodologies are being developed and tested.[24,25,40] The method currently considered most promising and strongly promoted is the multi-regional input−output (MRIO) approach.[24,25] MRIO models are able to reflect the material intensities of different industries in different countries or regions and allocate material extraction by monetary intersectoral and trade flows to the final consumption. Several global MRIO models have been developed[15,41−45] and were successfully applied to quantify the disconnect between production and consumption, using the RMC indicator.[7,13,22,46]

Empirical data on global material use as related to final consumption provides the groundwork for further analysis. One of the directions of analysis is the identification of drivers of resource use to identify possible entry points for sustainability interventions. The majority of studies so far have investigated drivers from a production-based perspective.[20,47−50] Consumption-based approaches to investigate drivers of resource use were conducted for a number of countries.[50−54] Studies including trade as a driver of material use exist on a national level;[48,51] studies on a global level do not specifically test for trade.[50,54] However, to the best of our knowledge, it has not yet been assessed whether the changes in international trade patterns have resulted in change in global material use, that is, if international trade is a driver of material use or contributes to more efficient production globally.

This study addresses an important knowledge gap by analyzing driving factors of the change of RMC for all countries worldwide, in particular by explicitly identifying the effect of changes of international trade patterns on global change in material use. For this purpose, a structural decomposition analysis (SDA) of RMC for 186 countries between the years 1990 and 2010 has been conducted using the Eora MRIO model in constant prices.[55] The analysis differentiates 7 driving factors: material efficiency, production recipe, import structure of intermediate demand, import structure of final demand, final demand composition, final demand per capita, and population. The driving factor material efficiency describes the materials extracted per total economic output per sector (often also referred to as material intensity). Production recipe represents the monetary direct and indirect input requirements of economic production. Two of the drivers address trade relations (import structure of intermediate demand and import structure of final demand) both representing changes in the composition and origin of imports and the relation of domestically produced versus imported goods and services. On the basis of these definitions, we then seek to answer the question: Are changing international trade structures contributing or counteracting growth in global raw material consumption?

2. METHODS AND MATERIALS

We conducted a structural decomposition analysis (SDA) to decompose the annual change of RMC between 1990 and 2010 using information from the global MRIO model Eora-26. Decomposition analysis, in general, is a method that helps to understand the underlying constituent factors determining the development of a certain endogenous variable (e.g., RMC).[56] If the decomposition is conducted using input-output models for a detailed analysis of changes in the economic structure of a country, it is called SDA.[57] The typical results of an SDA show by how much an endogenous variable would have changed if only one specific underlying factor had changed as it actually did while all other factors are held constant (ceteris paribus).[58]

We followed the application of the SDA method developed by Arto and Dietzenbacher,[59] who investigated the drivers of global carbon emissions using the WIOD MRIO model. The decomposition was conducted in two stages using the approximate Dietzenbacher and Los (D&L) method,[56] as it is recommended by Su and Ang[57] for a large number of constituent factors. A full description of the methodology can be found in the Supporting Information (S2−S6). The specific methods (MRIO modeling, SDA) clearly have certain limitations, which potentially affect the results, due to dependency problems, issues related to sector and spatial aggregation and IO assumptions, which are well elaborated in literature.[60−65] For this study, we decomposed the annual change in RMC of each country in our global sample (ΔRMC) into seven explicit determinants. The final decomposition equation applied can be represented as

$$\begin{aligned}\Delta \text{RMC} = & \underbrace{\Delta f brtcyp}_{\text{material efficiency}} + \underbrace{f \Delta brtcyp}_{\text{production recipe}} \\ & + \underbrace{fb \Delta rtcyp}_{\text{import structure of intermediate demand}} \\ & + \underbrace{fbr \Delta tcyp}_{\text{import structure of final demand}} \\ & + \underbrace{fbrt \Delta cyp}_{\text{final demand composition}} + \underbrace{fbrtc \Delta yp}_{\text{final demand per capita}} \\ & + \underbrace{fbrtcy \Delta p}_{\text{population}}\end{aligned}$$

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ΔRMC can be understood as the amount of materials ultimately associated with final demand in one country, that is, private and government consumption, investments, and changes in inventories. The 7 determinants are defined as follows: (1) Δf represents the change in material efficiency, that is, material input per unit of total economic output per resource extracting sector (t/$), and (2) Δb represents the change in production recipe (often also referred to as sectoral productivity), that is, the total monetary input requirements of each sector to produce one additional unit of output to final demand ($/$). Components 1 and 2 together can be interpreted as changes in the technological preconditions in a country. (3) Δr represents the change in the import structure of intermediate demand, that is, fraction of the input requirements of each sector's production that is imported from some other country or produced domestically ($/$), and (4) Δt represents the change in the import structure of final demand, that is, fraction of each sector's final demand that is imported from some other country or produced domestically ($/$). Throughout most parts of this paper, those two components (3 and 4) are added up to the total change in import structure of the respective country. (5) Δc represents changes in final demand composition, that is, share of total final demand of a country that is spent on each sector's products ($/$), and (6) Δy represents the change in total final demand per capita ($/cap). Components 5 and 6 can be interpreted as changes in the consumption patterns of a country. (7) Δp shows the change in population size of the respective country (cap).

Data for this analysis was taken from the MRIO model Eora-26 in constant prices valuated in purchaser prices.[41,55,66] The Eora model distinguishes between 186 countries and covers the time period 1990−2010.[41,66] The Eora-26 model has 26 economic sectors for each country and is available in constant 1990 prices.[55] It is an aggregated version of the full Eora model, for which the national resolution ranges from 26 to 511 sectors. It has been shown that the aggregated Eora-26 and the full Eora-MRIO agree well.[67] The full Eora model is not available in constant prices.[41,66] However, for a temporal SDA, it is crucial to use IO data in constant rather than current prices, as price changes solely due to inflation would distort the time series changes.[68]

Data on material flows for the environmental extension of the MRIO were sourced from the "CSIRO Global Material Flow Database".[7,69] This database provides data on domestic extraction for 191 countries and was compiled using harmonized economy-wide material flow accounting principles.[27] For the structural decomposition analysis of the RMC, four main material aggregates were distinguished: biomass, metals, non-metallic minerals, and fossil fuels.

3. RESULTS

3.1. Drivers of Global RMC: Consumption, Population, Trade, and Technology. From 1990 to 2010, global material use nearly doubled (+87%) from 37 to 70 Gt, increasing by 32 Gt. The major driver for this increase is growing final demand per capita (Figure 1). If only final demand per capita would have increased while everything else remained constant, global RMC would have increased by 240% (78 Gt). Growing global population is the second main driving factor, adding 33% (11 Gt) to the increase of global RMC. Interestingly, changing import structures contribute positively to RMC growth and led to a 30% increase (10 Gt). Thus, changing import structures,

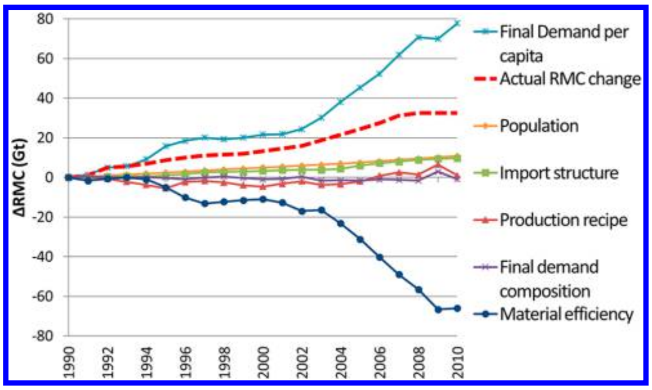

Figure 1. Contribution of each driving factor to changing global raw material consumption (RMC) from 1990 to 2010. Summing up the effects of all factors resulted in the total observed global RMC growth (32 Gt).

which indicate changes in the origin of economic inputs, are almost as important as population growth in driving global material use.

Improvements in material efficiency only partially offset these increases and by themselves would have reduced global RMC by −203% (−66 Gt). Interestingly, the production recipe shows a completely different trend than the material efficiency. Over time, its role changes from slightly reducing RMC growth (−6% from 1990 to 2005), to contributing to increasing RMC (9% from 2005 to 2010). Cumulatively, the changing production recipe slightly contributed to global RMC growth, by 3% (1 Gt) between 1990 and 2010. Changes in the composition of final demand had a relatively small effect and contributed to a reduction of global RMC growth of only −3% (−1 Gt). For the input structure of consumption and production (production recipe and final demand composition) no significant effect was found, although this could be affected by relatively high sector aggregation of the EORA-26 model.[65]

3.2. How Did Changes Across Countries and World Regions Contribute to Global RMC Growth? The analysis in section 3.1 identified the following three main positive drivers of global material use: final demand growth, population, and import structure, whereas material efficiency acts as a negative driver. The importance of these factors differs greatly across countries and world regions. We therefore present results for nine world regions following the regional groups defined by Krausmann and colleagues,[70] which were aggregated from the country results. A list of the countries included in each region is provided in the SI.

Increases in final demand—an indication for growing affluence—was the most important driver of resource use on the regional level, similarly to the global results. Highest contributions to RMC change due to increases in final demand per capita can be found in North America (409%), as well as in Western Europe (329%) and East and South-East Europe (303%); the lowest in Sub-Saharan Africa (170%) and North Africa and West Asia (179%) (Figure 2). Increases in material efficiency somewhat counteracted this development in all regions, most pronounced in Western Europe (372%) and in North America (311%). The lowest material efficiency gains were found for Latin America and the Caribbean (137%) and Sub-Saharan Africa (157%). Changes in the production recipe contributed to an RMC increase in East and Central Asia (30%) and in South-East Asia (17%) and contributed to an RMC decrease in East and South-East Europe (−33%). The by

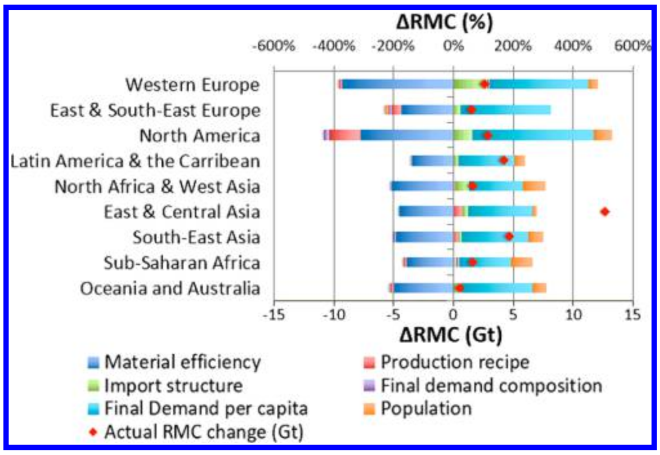

Figure 2. Driving factors of changing raw material consumption (RMC) by region, expressed as percentage of total RMC change for each major world region from 1990 to 2010. The percentage values of all driving factors per region sum up to a total RMC change of 100%. The red dots additionally indicate the total observed RMC growth for each region in Gt on the lower secondary x-axis.

far highest effect due to production recipe changes was found in North America, where it contributed to a decrease of RMC by 103%. Population contributed positively to RMC change in each world region with the exception of East and South-East Europe where countries experience very low population growth or even decline.

The contribution of changing import structures is positive throughout all regions. Highest contributions to RMC change are observed in Western Europe (115%), North America (62%), and North Africa and West Asia (44%). Trade seems to play a minor role in Sub-Saharan Africa (10%), South-East Asia (11%), and Latin America and the Caribbean (12%). Thus, it seems that industrialized countries to a large extent expand their supply chains toward less material-efficient countries and world regions, thereby contributing significantly to global RMC growth.

Country-level results are illustrated as maps in Figure 3, with each map representing one of the driving factors in percentage of total national RMC. Material efficiency contributed to a strong decrease in RMC in all countries, except for Uzbekistan and Ethiopia. Changes in final demand per capita led to a high increase of RMC across all countries in the world, with the lowest relative contributions found in the African and Latin American countries. Only in the Democratic Republic of Congo and in North Korea, did consumption level changes contribute to an RMC decrease between 1990 and 2010. This seems plausible, as both countries experienced a decrease in GDP per capita in the respective period. Changes in population numbers mostly contributed to an RMC increase. The highest positive contributions can be found in Sub-Saharan Africa (coinciding with very high rates of population growth), especially in South Africa, the Democratic Republic of Congo and Zambia. Exceptions to these patterns are many post-Soviet Union and post-Yugoslavian nations in Eastern Europe, where

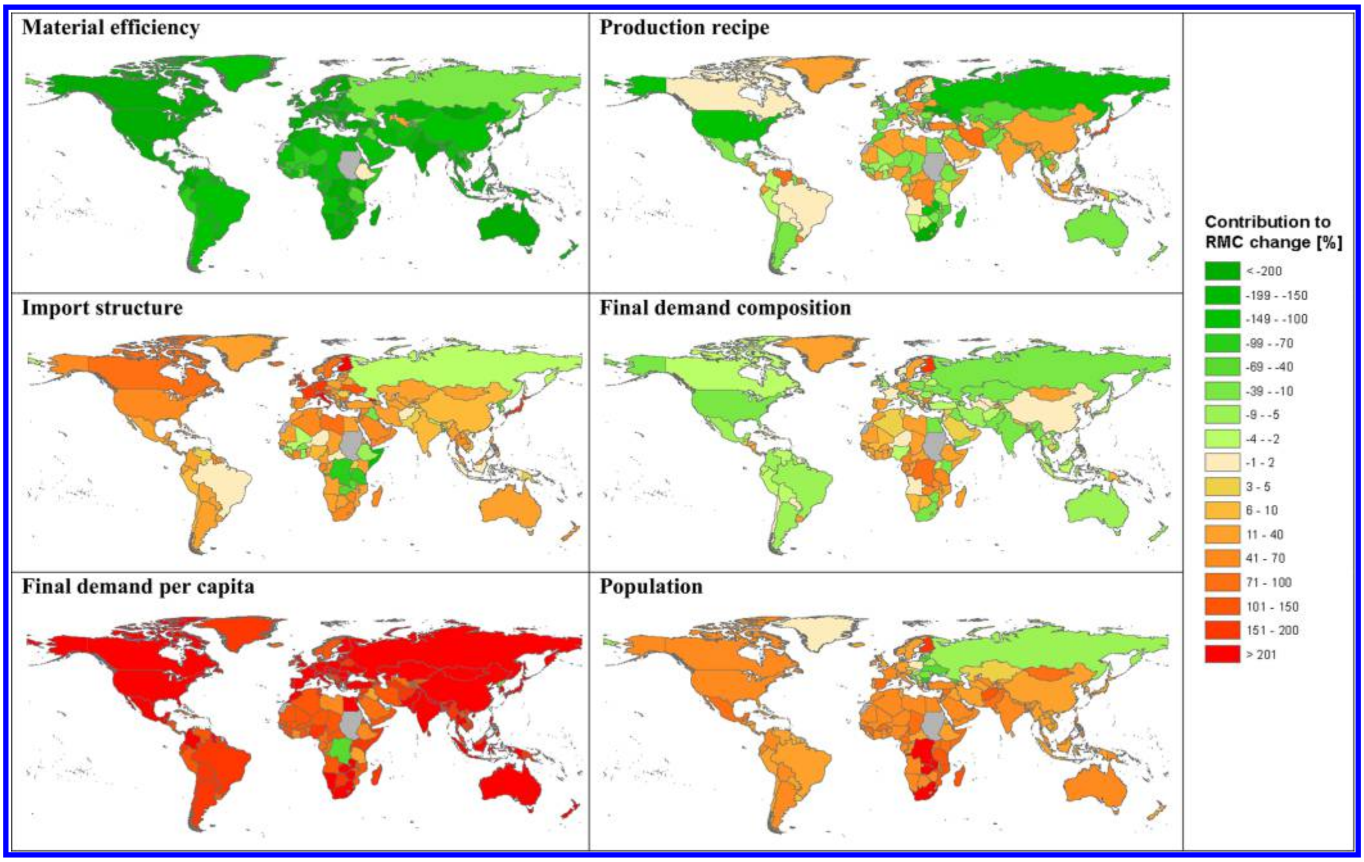

Figure 3. Driving factors of changing raw material consumption (RMC) from 1990 to 2010, in percent of total RMC change per country. Shades of red indicate a contribution to RMC increase, shades of green a contribution to RMC decrease and gray no data available. Summing up the contribution of all six driving factors resulted in each country's RMC growth (100%). Data: own calculations based on the Eora-26 model in constant prices.[55] Software used: ArcGIS by ESRI.

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changes in population numbers contributed to a decrease in RMC. These countries are characterized by particularly low population growth rates between 1990 and 2010. Some of these states even experience a decreasing population, partly due to emigration.

For changing production recipes, results are more heterogeneous. On the one hand, changes in the input structure of the economy tended to increase RMC in many East and South Asian countries (including China, India, and Japan), East-European, Scandinavian and Arabic countries as well as several African countries. On the other hand, they decreased RMC in the USA, Russia, Australia, most Western-European countries, and several African countries. Reasons for the effect of this driving factor might be quite different from country to country and depend i.a. on economic development, composition of economic production, and economic growth rate of a country.[20] Taking China as an example, rapid industrialization and urbanization resulted in fast growth of the construction industry. An increasing demand for construction materials[51] was associated with this change in the production recipe. In contrast, production recipe changes led to a decrease of RMC in the USA due to the large shift of economic production from industry sectors to service sectors.[62]

At the national level, changes in the composition of final demand did not have a strong effect on RMC change. Slight RMC increases due to changes in final demand composition can be found in several European and African countries. In all other world regions, final demand composition tended to slightly decrease RMC. This unspecific pattern might be a result of the high sectoral aggregation in the Eora-26 model. Further analysis is required using a more detailed model to provide a more elaborate conclusion on the potential contributions of changes in final demand composition.

In general, changes in the import structure tended to contribute to an RMC increase on the national level. This was most pronounced in many European countries (Italy, Finland, France, Germany, and the UK), as well as Japan, Taiwan, Hong Kong, Canada, Georgia, and Libya. However, several countries, mainly located in Sub-Saharan Africa showed negative contributions of changes in import structure to RMC change. A slightly negative contribution is also visible for Russia. Several countries in Asia, Africa, Latin America, and Australia showed only slightly positive effects on RMC growth. These countries act as major resource suppliers in the global trade system.[28] The variation reveals that RMC is not strongly affected by changes in the import structure of many countries worldwide. Just a few countries (especially some key EU members, that is, France, Germany, and the UK), which are highly dependent on imports, are responsible for the overall growth in RMC due to trade structure changes. Results of specific countries previously mentioned cannot easily be explained by one aspect but require further analysis. The following section will especially consider the effects of changes in the import structure on RMC change.

3.3. Is Growing Trade Driving Global Resource Use?

The driving factor import structure, which represents the impacts on RMC from changes in a country's import structure, combines a highly complex bundle of processes that can affect RMC in both directions, that is, increasing or decreasing it. Given a country's intermediate input requirements for the production of goods and services, as well as for consumption and investment purposes, the country may have substituted domestically produced inputs for imported inputs (or vice versa). Additionally, imported inputs from one country could also be substituted for those from another country. If producers and consumers shift to buying goods and services that are produced in a more (or less) material-intensive way, RMC will increase (or decrease).

International trade contributed 9.8 Gt (30%) to global RMC growth between 1990 and 2010 (see Figure 4). However, RMC

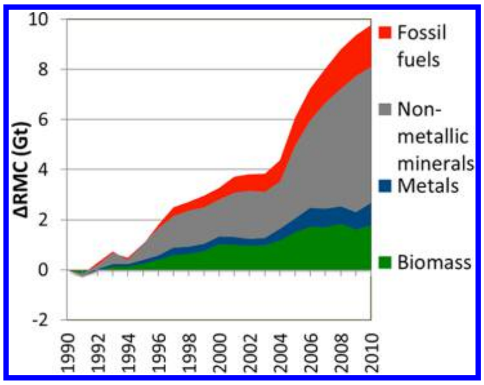

Figure 4. Isolated effect of changing import structures (ceteris paribus) on global RMC change by material categories, 1990−2010. In this case, global RMC would have increased by 9.8 Gt.

growth induced by import structure changes did not show a clear continuous trend throughout the whole time period. In the years 1991 and 1994, the contribution even turned negative, resulting in a decrease of global RMC. After ten years of modest growth or stagnation, RMC experienced a significant increase due to import structure changes since the year 2005. Highest effects occurred in the material group of nonmetallic minerals, which increased by 56% during the 20 years of observation. The use of nonmetallic minerals is strongly related to building and maintaining housing, transportation, and production infrastructure. In terms of total mass, this is a material group of high relevance, which makes up around 50% of global RMC.[28] Impacts from changes in import structure are in the same order of magnitude, that is, 50% of RMC growth is made up of nonmetallic minerals. The trade effect of biomass products was rather constant, ranging between 20% and 30%, whereas the use of fossil fuels increased the trade effect from 10% to 20% throughout the observed period. The contribution of metal use to the trade effect is relatively small (9%); during the 20 years of observation, the induced changes on RMC even decreased in relation to the other material categories.

The total effect of changing import structures can be further decomposed into two effects: (1) changes in the import structure of intermediate demand (ISID), that is, changes in the import mix of economic production; and (2) changes in the import structure of final demand (ISFD), that is, changes in the import mix of final consumption. Figure 5 illustrates the results for these two different components and provides the results for the total contribution of import structure changes to RMC growth according to the nine world regions introduced in section 3.2 (for details on the countries' allocation to world regions see SI).

Western Europe, East and Central Asia, and North America showed the highest contribution of import structure changes to RMC growth. Together, these three regions accounted for 75% of the total global contribution of import structure to RMC growth. East and Central Asia (and therein mostly China) played an important role as the region contributes 26% to the total import structure effect. However, as shown in Figure 2

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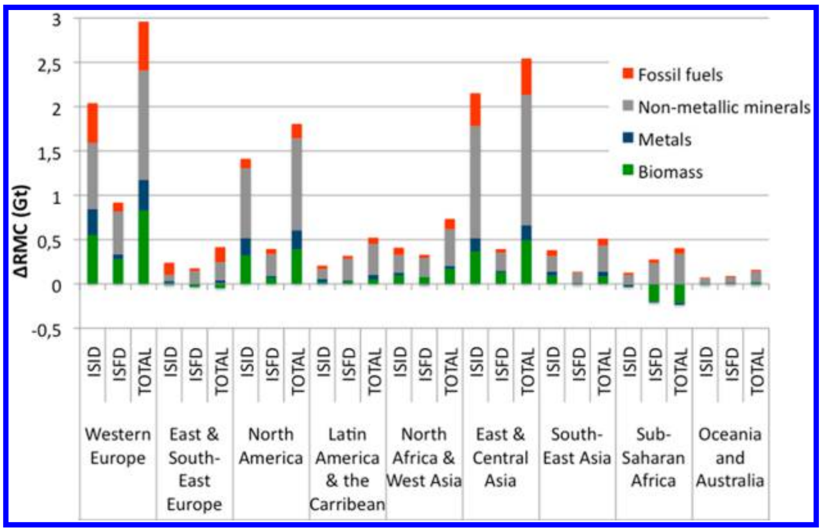

Figure 5. Contribution of import structure changes to RMC change per spatial region from 1990 to 2010. ISID: Import structure of intermediate demand. ISFD: Import structure of final demand. TOTAL: Total contribution of import structure (ISID + ISFD).

(section 3.2), import structure changes are not as relevant as other driving factors for the region; far-reaching economic structural changes took place in East and Central Asia, which induced an increase in RMC highly exceeding the contribution of import structure changes.

Changes in the import structure of intermediate demand had a bigger effect than changes in the import structure of final demand, in particular in the three main contributing regions (Western Europe, East and Central Asia, and North America). It can therefore be assumed that these regions increasingly source the requirements of their economic production from less material-efficient countries. Only in Latin America and the Caribbean, Sub-Saharan Africa, and to some extent in Oceania and Australia, did we find the contribution of the import structure to final demand (ISFD) exceeding the one to intermediate demand (ISID). However, this inverse relation is mainly due to a relatively low effect of ISID on RMC change in those regions. The effect of ISID was also low in East and South-East Europe, North Africa and West Asia and South-East Asia, but still exceeding the effect of ISFD. All the regions with a relatively low effect of ISID did not really change sourcing strategies for their own production; the countries of origin of the intermediate products necessary for their economic production were similar in 2010 as compared to 1990 or changed to countries with similar production patterns.

For the material group biomass, we found a significant negative effect of changing import structures of final demand (ISFD) on RMC change for Sub-Saharan Africa. In this world region, the total import structure effect of biomass reduced RMC by −214 Mt (see Figure 5), that is, the value-mass-ratio of imports is higher and increasing faster as compared to domestic production. This might point to the fact that countries exporting to Sub-Saharan Africa, which is the EU and the US to a large extent, are characterized by higher efficiency in agriculture.[71] However, further analysis is needed to reveal if the trade structure effect occurs because of actual differences in production efficiency or technological preconditions or also due to monetary factors; among those financial instruments like tariffs, subsidies, development aid, and other private and public instruments and their implementation in a MRIO model.[66,72]

4. DISCUSSION: WHAT IS UNDERLYING THE TRADE STRUCTURE EFFECT?

Economic globalization led to an average annual increase of international monetary trade volumes of 6.5% between 1990 and 2010, while global GDP increased by 3.8% per year on average.[73] In almost all countries with GDP growth, additional domestic final demand seems to be overproportionally satisfied by imported goods and services.[74] According to the OECD, during the observed period the main underlying driver for the large increase of international imports from production elsewhere seem to be wage cost differentials rather than environmental regulations or technological requirements.[5] In particular, high-wage countries are increasingly sourcing goods and services from low-wage countries, rather than from domestic production or from other high-wage countries.[4,75] The growth of global trade and changes in trade patterns have had a substantial effect on the growing spatial disconnect between resource use and emissions in production and consumption.[7,15]

With our analysis we showed for the first time that changes in the international trade structure contributed positively to increasing global raw material consumption. We find that between 1990 and especially since around 1995 until the end of our analysis in 2010, increasing international trade by itself would have contributed +30% to the increase of global raw material consumption (Figure 4). This effect is due to the growing contribution of less material-efficient economies to global production.

From our analysis, a counter-factual scenario of "no-trade-expansion" can be calculated. If global final consumption in 2010 would have been produced with the trade structure of 1990, global raw material consumption would have increased by only 22.7 Gt, instead of 32.5 Gt. This means, that if international supply chains would not have expanded any further, global raw material consumption would have only increased by 2/3 of the actual increase.

Changes in the trade structure represent changes in the composition and origin of imports and the relation of domestically produced versus imported goods and services required for intermediate production or to directly satisfy final demand. The impact of trade structure changes on global raw

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material consumption is caused by differences in the material efficiency of economic sectors in different countries. With identical material efficiencies in all countries, changes in trade patterns would have a neutral effect on global material consumption. However, substantial differences among countries persist, which relates to differences in the levels of in-use stocks of manufactured capital and technology.[76,77] Such differences should explicitly be considered as an important factor for differences in the material efficiencies of production.[76,78] Production in a mature economy, with large in-use stocks of infrastructure, will be more efficient than in economies that are just recently expanding their manufactured capital.[20] In the interpretation of raw material use indicators, the impact of linking production and consumption across countries of different economic structure and levels of development must be considered.[20]

The importance of these dynamics of the accumulation of manufactured capital for overall material efficiency is linked to the dominance of non-metallic minerals in the import structure effect (Figure 4) and in global material use. The major fraction of non-metallic minerals are concrete, bricks, asphalt, and sand and gravel, used in construction and only marginally traded.[2,28] As a result, this material category is closely related to national capital investments. Because of the quantitative importance of non-metallic minerals, their allocation can substantially affect results.[7] For example, we found China's investments into construction and infrastructure expansion[51,76] to have a notable global effect, especially from 2005 onward. Trade links countries that differ in their socioeconomic development and in the biophysical stocks that constitute that development's legacy. The impact on global material consumption has yet to be adequately addressed, both methodologically and conceptually.

Our research has shown that the patterns of international trade and national resource efficiencies have contributed to growth in global resource use. Production does not tend to occur exclusively, where it is most material-efficient. Instead, other factors–wage levels and investment costs among them–appear to be more influential.[5] In light of these findings, what can be done to increase global resource efficiency and ultimately curb global resource use? Where resource efficiency does improve, it is important to better understand the drivers of and prerequisites for such development in order to identify possibilities for and obstacles to international replication. To contribute to global resource use reductions, trade relations must—inter alia—be geared toward achieving the highest levels of resource efficiency globally. This will require an unprecedented international political and economic cooperation, including the establishment of institutions capable of fostering cooperation rather than competition.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.7b06133.

Derivation of structural decomposition analysis methodology used for this analysis and list of countries aggregated to world-regions (PDF)

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Author Contributions

B.P. designed the research and conducted the calculations; B.P., N.E., A.S., and D.W. analyzed the data and wrote the paper. All authors have given approval to the final version of the manuscript.

Notes

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