How countries' resource use history matters for human well-being – an investigation of global patterns in cumulative material flows from 1950-2010.

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Abstract

Global resource use has been expanding rapidly after 1950 and improved material living conditions and human well-being of large parts of the global population. We here apply a cumulative long-term perspective to gain broader insights into the material requirements of human well-being, the role of trade and the history of environmental pressures than the usual perspective of annual or most recent flows would reveal. Furthermore, we investigate environmental pressures expressed as cumulative extraction per area over the last 60 years. To both ends, we utilize cumulative data on material flows on domestic material inputs (DMI) and domestic extraction (DE) for 148 countries from 1950 -2010 and the Social Progress Index. We find that a high level of well-being required at least 460t/cap of cumulative material inputs from 1950-2010. An analysis of the relation between cumulative flows and current human well-being shows statistically significant that at similar levels of cumulative material inputs, biophysical export-orientation of a country has a weak negative influence on well-being. When the Sustainable Development Goals are to be achieved, the scientific community and policy makers have to consider the history of development of resource use to better understand the future challenges ahead.

Highlights

- We investigate the history of 148 countries' cumulative material use.
- Cumulative extraction indicates different histories of environmental pressures.
- High Social Progress requires a long history of sustained material use.
- Cumulative material flows reveal historic dynamics and trajectories of development.

Introduction

Global resource use has been growing constantly since the beginning of the 20th century, from approximately 8 billion tons (Gt) in 1900 to 71 Gt in 2010, a nearly 9-fold increase (Krausmann et al., 2008; Schaffartzik et al., 2014). The metabolic scale is driven by a range of natural and socio-economic factors such as resource endowment, economic development and population size. Alongside a world population that grew by a factor of 4, the material requirements of sustaining one individual (i.e., the metabolic rate) increased significantly, from 4.6 to 10.3 t/cap/yr (Krausmann et al., 2009). At the same time, unprecedented progress has been made in terms of human well-being, which is reflected in rising living standards, a reduction in the rate of extreme poverty, and rising life expectancy (United Nations Development Programme, 2016). The Millennium development goals have been declared a success in hindsight, yet a considerable part of the global population still lives in poverty, while the excessive resource consumption of the global North has led to numerous global environmental problems (Sachs, 2015).

In 2016, the Sustainable Development Goals (SDGs) officially came into force (United Nations, 2016). The 17 different SDGs entwine economic, social and environmental targets such as ending extreme poverty or sustained, inclusive and sustainable economic growth (economic dimension), reducing inequality and promoting peaceful, inclusive and just societies (social dimension), and tackling global environmental change (environmental dimension). The SDGs thus recognize that the stable functioning of the Earth's systems is a prerequisite for a prosperous society and that a certain level of material wealth is also indispensable to ending poverty and hunger and satisfying basic human needs. If the Sustainable Development Goals are to be achieved, addressing the growing affluence of developed countries and the need for development in poor countries demands drastic measures in all countries. Based on different levels of resource use within and between countries, equity-based questions of distribution and re-distribution come into play and raise the question of how available resources should be distributed (Hajer et al., 2015).

Numerous empirical studies have found that, following rapid gains in human development with increasing resource and energy use, saturation occurs (Martínez and Ebenhack, 2008). At this point, human development no longer improves substantially, although resource and energy use still grows (Easterlin, 1974; Easterlin et al., 2010; Lamb et al., 2014; Sachs, 2015; Steinberger et al., 2012; Steinberger and Roberts, 2010). The SDGs further acknowledge economic growth as an important factor in achieving sustainable development (United Nations, 2016). For example, in poor countries, income growth enables people to purchase material goods and services that satisfy their basic human needs (Howarth, 2012). However, at a certain point, human well-being does not grow along with income, while resource use does (Steinberger and Roberts, 2010). Hence, Herman Daly stated in an

essay published in (2015), reprising an argument he first made 40 years ago, that *"The prevailing obsession with economic growth puts us on the path to ecological collapse, scarifying the very sustenance of our well-being and survival"*, The close coupling between economic growth and resource use (Ayres, 1996; Brundtland et al., 1987; Daly, 2015; Fischer-Kowalski, 1998; Fischer-Kowalski and Hüttler, 1998; Georgescu-Roegen, 1986) has continued to raise concerns about sustainability, mostly because of scarce evidence that absolute decoupling between economic growth and resource use has taken place (Akenji and Bengtsson, 2014; Steinberger et al., 2013; UNEP, 2011).

Mainly based on empirical observations, there has been widespread concern that since the great acceleration of the 1950s ecosystems are threatened to a very dangerous extent by the ever-increasing economic mobilization of natural resources (Rockström et al., 2009; Steffen et al., 2015, 2007). The regional and qualitative proliferation of global social metabolism has been associated with a wide range of environmental and social pressures. These pressures occur throughout the whole life cycle, from resource extraction to consumption to disposal or recycling. Martinez-Alier et al. (2016) found that most socio-environmental conflicts – in their database of more than 1,000 conflicts – are caused by resource extraction and its adverse side effects, while carbon emissions or other forms of pollution also occur during the consumption and disposal of material products and the services they provide. Yet, different environmental pressures also depend on the resource that is extracted, with the most significant differences being between biomass (a renewable resource) and non-renewable resources such as minerals and fossil fuels (Bunker and Ciccantell, 2005; Foley et al., 2011, 2005; Griggs et al., 2013; Kastner et al., 2012; Martinez-Alier, 2002; Temper and Martinez-Alier, 2012; UNEP, 2011). The conversion of natural to agricultural lands for the production of biomass has continuously altered the landscape (Erb et al., 2016; Sanderson et al., 2002) and resulted in a massive change in bio-geochemical flows, biodiversity loss and deforestation, and social changes such as rural migration. The extraction of non-renewable resources such as fossil fuels and metal ores has led to scarcities on the input side and to overstressing of the sink capacities of the atmosphere (IPCC Climate Change, 2013; Schaffartzik et al., 2016).

Such changes in the environment have a strong feedback into societal relations. French anthropologist Maurice Godelier has established the link between culture and history in the introduction to *"The Mental and the Material"* (1986, p.1): *Human beings have a history because they transform nature*. Based on this argument that the human appropriation of nature modifies nature and that this modified nature in turn stimulates social change, Fischer-Kowalski and Weisz (1999, p. 27) define human societies as *hybrids between a natural, material world and a cultural world of recursive communication, whose material elements are structurally coupled to the autopoietic communication system*. In this case, everything that affects these material elements of a society affects society itself.

In this manuscript, we investigate how social progress is linked to a history of resource use, thus providing a comparative assessment of whether improvements in the social dimension of sustainable development have been achieved without a quantitative increase in society's resource bases and subsequent pressures on the environment. To estimate society's resource base, we make use of material flow accounting, which provides indicators that quantify the annual resource flows to a socio-economic system, i.e., countries. We here measure the cumulative material flows over the period from 1950 to 2010 and thus extend the temporal boundary from one year – which is common in material flow accounting – to 60 years for our cross-country comparison of 148 countries. Cumulative material flows are different from societal in-use stocks like buildings and infrastructure. Pauliuk and Mueller (2013) describe social in-use stocks as determinants of the long-term dynamics of social metabolism, as they remain in use for a relatively long time and shape the future flows of materials and energy. Societal in-use stocks are usually processed materials (i.e., from ores to steel bars), are accumulated in built structures within societies, and provide services, for example as roads or buildings (Fishman et al., 2015; Lin et al., 2016; Pauliuk et al., 2013; Wiedenhofer et al., 2015). In contrast to in-use stocks, cumulative material flows are flows and not stocks, but parts of these flows are stock-building and used to build up and maintain infrastructure and large machinery, while other parts of these flows are used for direct consumption such as human nutrition and energy provision and get converted into gaseous emissions (mainly carbon dioxide [CO₂]) and other residues, normally in a period shorter than one year. Based on such an understanding of cumulative material flows, we assume that social progress requires sufficient resource use over an extended period of time, be it for direct consumption or stock-building. Therefore, in this work we do not explicitly estimate the dynamics of in-use stocks; rather, we are interested in the cumulative history of resource use of biomass, fossil fuels, metal ores, and construction minerals and their relationship to human well-being and social development.

The following sections begin with a comparison of current and cumulative material use between world regions in relation to the cumulative and current populations of countries and country groups. We then continue with an analysis of cumulative material extraction in relation to land area and investigate disparities in extracted renewable and non-renewable resources among countries during the last six decades. We further cluster countries based on their physical trade balances – whether they are net consumers or net suppliers, and finally, we investigate the link between social progress and resource input at the country level to better understand which resource use patterns are associated with higher and lower levels of human well-being. We do so by applying a cross-country comparison of a country's material base and trade patterns, the Social progress indicator (SPI), and indicators of social and environmental performance (Porter et al. 2015).

Materials and Methods

We here present cumulative material flows for 148 individual countries and world regions for the period from 1950 to 2010. Economy-wide Material flow accounting (EW-MFA) compiles annual inflows of physical matter (except water and air) into socioeconomic systems, thus quantifying economy-wide resource use in tons (EUROSTAT, 2012; Fischer-Kowalski et al., 2011). We base our analysis on a MFA dataset by Schaffartzik et al. (2014), which comprises annual flows of 65 material types and aggregates them into five main material groups, i.e., biomass, fossil energy carriers, metal ores, industrial and construction minerals (i.e., non-metallic minerals), and traded products that cannot be allocated to one of the main raw material groups. These data include material flows that were extracted from the domestic environment of a country (domestic extraction, DE), and all physical imports (Im) and physical exports (Ex) for the years 1950, 1960 (1962), 1970, 1980, 1990, 2000, 2005, and 2010, mostly based on international statistical sources. The indicators that are used in the following chapters are all calculated based on these three types of flows. Further details on data gathering, aggregation procedures, and necessary methodological adaptations are described in Krausmann (2009) and Schaffartzik et al. (2014).

EW-MFA commonly uses annual time-steps, which is consistent with most statistical databases (e.g., FAO statistics) and allows comparison with socio-economic indicators such as GDP and population statistics. For this study, however, we have used the annual data and summed it up for the period from 1950 to 2010 to derive the total values for DE, imports and exports (except for Figure 2b, where we have added biomass only, and 2c for all other materials). Whenever we refer to cumulative flows in this manuscript, we add the acronym $_{1950-2010}$ to the respective indicator.

$$(1) \quad DE_{1950-2010} = DE_{1950} + DE_{1951} + \dots + DE_{2010}$$

$DE_{1950-2010}$ comprises all materials that were extracted from the domestic environment during the period from 1950 to 2010, calculated as the sum of cumulative annual domestic extraction.

Primary data were gathered at 10-year intervals (as an exception we added 2005 to increase accuracy in recent years), and we had to estimate the data for the intermediate data-gaps. We assumed linear development between the years for which we had data. A comparison between interpolated and annual data for the countries included in our analysis shows that in 91% of all countries ($n=144$) interpolated flows are lower than when annual flows are used ($r^2 = 99.9\%$, see SI). Given that the material flow dataset we have used for this study is the only data set that has a) global coverage and b) temporal coverage from 1950 to 2010, we have favored this dataset against others that are currently available (Institute of Ecological Economics, 2016; Schandl and West, 2010; UNEP, 2016; West et al., 2014; West and Schandl, 2013). Data published by Schandl and West has only limited

world-regional coverage, the materialflows.net database only has coverage from 1980-2010, and not all flows are reported at the level of the 4 main material categories, while a global MFA database published by UNEP only covers the period from 1970 to 2013.

The estimation of different material flows entails a moderate level of uncertainty, yet for metal ores, fossil energy carriers, and biomass, both a broad knowledge of the material system and solid data do exist. Data for non-metallic minerals shows the highest level of uncertainty (mainly due to construction minerals and poorer data quality and estimation procedures (Miatto et al., 2016) and is thus responsible for most of the discrepancy between different material flow data sets. The dataset used for this study shows that global totals are within a 5% range of other global datasets available (Institute of Ecological Economics, 2016; Krausmann et al., 2009), while a comparison with national MFA studies reveals that the figures were approximately 15 to 20% lower. This underestimation is mainly due to the conservative approach applied to the estimation of construction minerals (Fischer-Kowalski et al., 2011; González de Molina and Toledo, 2014; Schaffartzik et al., 2014).

We use the following extensive indicators in our study:

$$DMI_{1950-2010} = DE_{1950-2010} + Im_{1950-2010}$$

$$(2) \quad DMC_{1950-2010} = DE_{1950-2010} + Im_{1950-2010} - Ex_{1950-2010}$$

$$PTB_{1950-2010} = Im_{1950-2010} - Ex_{1950-2010}$$

DMI = Direct material input, DMC = Domestic material consumption, DE = Domestic extraction, Im = Imports, Ex = Exports, PTB = Physical trade balance. For a detailed description see (EUROSTAT, 2012)

Standard material flow accounting comprises direct biophysical flows only, while the methodology for indirect or embodied flows is still being developed and requires harmonization (Eisenmenger et al. 2016). The difference between both accounting methods is based on different system boundaries for trade flows. In direct accounting, these flows ($Im_{1950-2010}$, $Ex_{1950-2010}$) are measured based on their weights when they cross the border of a socio-economic system, which provides information about the global redistribution of materials as direct inputs to these socio-economic systems (i.e., a country or a region). This methodology is referred to as production-based assessment, while consumption-based assessments (often referred to as material footprints) include upstream material requirements along international supply chains attributed to final consumption but exclude domestic material requirements for exports (Bringezu et al., 2004; Galli et al., 2012; Peters, 2008; Schandl and West, 2012; Wiedmann et al., 2015). We here use the direct accounting method to quantify trade flows between countries, while it is important to acknowledge that when we analyze country groupings we only include inter-, not intra-, trade flows of country groupings.

In addition to the extensive indicators above, we use per area and per capita values for country-to-country comparisons. As far as material flow data for 2010 are concerned, we simply divide total flows by 2010 population numbers to arrive at metabolic rates. The extension of the temporal boundary to six decades entails the problem that population numbers are not additive over several years because the majority of the population of one year equals next year's population and thus cannot be counted twice. We thus added life years (i.e., one life year equals one person per year) instead of population for figure 1. We relate cumulative material flows to the country's land area in 2010 or the population living there in 2010. We use the first indicator to show the cumulative environmental pressures that have been exerted through resource extraction ($DE_{1950-2010}/ha$). We further split this indicator into renewable (i.e., biomass) and non-renewable (i.e., metal ores, non-metallic minerals, fossil fuels) materials, as the environmental pressures are fundamentally different.

To test whether there is a relationship between cumulative material flows (expressed as $DMI_{1950-2010}/Pop_{2010}$) and current wellbeing of the population (expressed as SPI_{2015}), we use a sample of 110 countries where MFA and SPI data were available (measured as t/cap). We use a multiple linear model for our regression analysis, which is in line with other studies on the interrelations between material or energy use and human development (Lamb et al., 2014; Steinberger and Roberts, 2010). The Social Progress Index – SPI (Porter et al., 2015) ranks countries by an aggregated score of non-economic output indicators and alludes to three dimensions of social progress: basic human needs, foundations of well-being, and opportunity, and each of these dimensions is further broken down into four underlying components. The SPI is based on the following four principles: 1) it uses exclusively social and environmental indicators; 2) it measures outcomes, not inputs (e.g., the level of public health, and not the amount of money that a country invests into healthcare); 3) it is holistic and relevant to both developing and developed countries; and 4) it provides a detailed level of individual measures that can be transformed into policy action. The SPI scores are all based on a 0-100 scale, and this scale is determined by identifying the best and worst absolute global performance on each indicator recorded by any country since 2004. These actual performance levels are used to set the maximum (100) and minimum (0) bounds (Stern et al., 2015). Thus, the Social Progress Index scores reflect realistic performance, which links very well to the material flow data this indicator is compared with. Overall, the close linkage of the SPI to the SDGs was the main argument for choosing this indicator instead of the others mentioned above. In fact, 15 of the proposed 17 SDGs are closely aligned to the SPI, with 7 goals linked to the dimension “basic human needs”, 10 goals to “foundations of well-being”, and 4 goals to “opportunity” (Porter et al., 2016).

We have tested both samples for outliers and removed the DR Congo and Kuwait from our sample as their $DMI_{1950-2010}/Pop_{2010}$ values were beyond the IQR3 (i.e. 3x interquartile range $Q_{75}-Q_{25}$, see e.g.

(Timischl, 2000). We use the DMI instead of DMC, as we are interested in the total amount of resources that flows into one country's economy. This includes all materials of economic value that are used in production and consumption activities. We thus consider DMI a better proxy for a society's material base than if exports are subtracted (DMC). Yet, this indicator has two major shortcomings. First, the DMI of all countries cannot be added, as this would lead to double counting (i.e., one country's exports are another country's imports). Second, MFA data are only available until 2010, while the indicator we use as a proxy for human well-being is only available beginning in 2014 as a beta version and underwent major revisions and an expansion of country coverage in 2015. Excluding material flows from 2011 to 2015 leads, by trend, to an underestimation of the total materials used, while the strength of the correlation is less affected. Notwithstanding this weakness, we have preferred the Social Progress Index (SPI, see Porter et al., 2015) over other mainstream indicators of wealth and social progress such as the HDI (United Nations Development Programme, 2016), GPI or ISEW (Daly et al., 1989; Lawn, 2003; Stockhammer et al., 1997) because the SPI is a non-economic indicator. While the HDI is simply a composite index that captures two concrete dimensions beyond GDP (life expectancy and education), and while the GPI and ISEW are indeed more complex but still based on economic indicators, the SPI is a comprehensive framework for measuring social progress that *is independent of GDP and complementary to it* (Porter et al., 2015, p. 13).

Results – Resource extraction, trade, and the material base of current societies

A historical perspective on cumulative resource use matters for disparities

Most existing research and policy formulation focuses only on annual resource use patterns and thereby substantially underestimates the importance of the history of development. In the first step of our analysis, we explore the extent to which the cumulative material flows from 1950-2010 (which we use in the subsequent sections of this paper) and population levels differ from present (i.e., 2010) flows. We present regions' or countries' shares of global totals for domestic extraction (DE₂₀₁₀ and DE₁₉₅₀₋₂₀₁₀), imports (Im₂₀₁₀ and Im₁₉₅₀₋₂₀₁₀) and exports (Ex₂₀₁₀ and Ex₁₉₅₀₋₂₀₁₀) and compare them to the population shares of 2010 and total life years from 1950-2010 by world region, which adds an equity dimension to this comparison (figure 1).

Figure 1: Graphical comparison between the shares of DE, imports, exports and Population in 2010 and from 1950-2010, in global totals for selected countries, world regions, and the rest of the world category (ROW), with underneath table providing detailed numbers. Please note that the population from 1950-2010 is expressed as the sum of life years. For definitions of country groupings, see SI.

In 2010, 7% of the global population lived in Western Europe and 5% in North America. For this 12% of global population the share of material extraction out of global totals, however, was 16% in 2010, and it is considerably higher when cumulative material extraction (DE) over six decades is considered.

Nearly 29% of global materials from 1950-2010 were extracted in Western Europe and North America,

sustaining 15% of total life years. Yet, these world regions have also had considerable inflows from other world regions, with 59% of cumulative imports, compared to 44% in 2010. In Southern Asia and Sub-Saharan Africa, on the other hand, 36% of the global population only extracted 16% of the DE_{2010} , with the same share for cumulative extraction ($DE_{1950-2010}$), yet for a lower share of total life years (31%), indicating a lower per capita material extraction when the historical period is included. The shares of global trade are both relatively low, for current and for cumulative flows. In Latin America and the Caribbean, a similar dynamic to Southern Asia persists, albeit resource extraction per capita was higher; 9% of the global population were living in Latin America and the Caribbean in 2010 (8% of total life years), and approximately 12% of global materials in 2010 were extracted there, with similar results for the cumulative history. In China, the difference between annual and cumulative flows is the largest. With 20% of the world's population, China extracted 32% of global resources in 2010, while the share of cumulative material extraction is considerably lower at only 17%. China was the second-largest importer in 2010, with 15% of global flows, while its share of cumulative imports was considerably lower, with only 5% of global totals. In terms of the share of total life years, China is at 22%. Detailed results for the rest of the world (ROW), which is a very heterogeneous grouping, can be found in the SI.

The comparison between cumulative material extraction, trade and life years versus most recent (2010) material flows and population shares highlights the differential history of development across the globe. For the old industrialized world, their share of global resource use over the last 5 decades is almost double compared to their part in only the most recent year. At the same time, China's share of resources used is halved when we explicitly consider the long history of the metabolic transition.

Spatial provenance of cumulative resource extraction and environmental pressures

In the following section we present three global maps of cumulative material extraction over six decades. Figure 2a shows a global map of total cumulative material extraction per ha for 148 countries and three country aggregates (Former USSR, former Czechoslovakia, and former Yugoslavia SFR). Figures 2b and 2c show the same maps for biomass and non-organic materials (i.e., renewable and non-renewable materials). We relate the environmental pressures through resource extraction to the land area of a country, which we consider a proxy for its socio-ecological capacity (Krausmann et al., 2009; Mayer et al., 2016; Schaffartzik et al., 2016). This socio-ecological capacity is, certainly, shaped by environmental conditions, technological capacity of the extractive sectors and many other factors. A detailed analysis of environmental impacts thus has to consider these factors, whereas given the regional and temporal scale of our analysis, we have to reduce complexity of our indicator. For such a comparative global analysis, we consider $DE_{1950-2010}/\text{area}$ an appropriate proxy for a discussion of

cumulative environmental pressures on the country-wide level.

Figures 2a – 2c: Global maps of cumulative extraction per area ($DE_{1950-2010}/area$) in t/ha for total materials (2a), renewable (2b) and non-renewable materials (2c).

The area-related environmental pressures exerted through material extraction vary widely across all countries, as the map in figure 2a shows. While nearly one third of countries ($n = 56$) extracted fewer than 100 t/ha between 1950 and 2010, 19 countries exerted aggregated environmental pressures that were an order of magnitude higher, with an average rate of nearly 3000 t/ha. African countries dominate the group with the lowest area-related environmental pressures, while most of the Andean states are also in this group. Both world regions are important resource frontiers, where the recent expansion of resource extraction is not reflected in our long-term perspective, yet social and

environmental pressures have been deepening in recent years (Hall, 2011; Martinez-Alier and Walter, 2016). The list of countries with the highest environmental pressures consists of high population-density Western European countries with a long history of intensive agricultural colonization and industrialization (Krausmann et al., 2008), as well as small Arab countries that provide fossil fuels for the social metabolism of industrialized countries. The majority of Western European countries extracted at rates between 500 t/ha and 1000 t/ha, which is well above the global average of 460 t/ha. Important global resource providers such as Brazil, Argentina, Australia, the USSR and South Africa have cumulative environmental pressure rates that are below the global average.

Figures 2b and 2c show the area-related environmental pressures for renewable and non-renewable materials. Highly industrialized countries such as those in Western Europe, Island states in the Caribbean, as well as Bangladesh and India exerted the highest environmental pressures through the extraction of biomass (250 – 900 t/ha). Intensive agricultural systems dominate in all countries that also have high population densities. However, while the highly industrialized countries have low population shares employed in the agricultural sector, the remaining countries are still dominated by agricultural populations, making them more vulnerable to the negative environmental pressures of their agricultural systems and potentially required expansions of food production (Strzepek and Boehlert, 2010; Turner and Ali, 1996). A total of 100 countries are below the average of 133 t/ha; this category includes countries that have hot and arid climate conditions and are rarely suitable for agriculture and most of the Sub-Saharan countries, which, despite the fact that their metabolisms mostly depend on biomass, have low-input low-output agricultural systems, leading to comparably low area-related environmental pressures. Figure 2c shows a distinct pattern, yet the Western European countries are again among the countries with the highest rates, with an average value of 590 t/ha. Such a pattern is the result of a long period of high industrialization, during which a dense infrastructure was built up, fueled and maintained. In these countries, non-renewable resource extraction is dominated by construction minerals, where the main environmental pressures are associated to land take (Gardi et al., 2015), and the amount of waste when the infrastructure is out of use (Miatto et al., 2016). These rates are only surpassed by the Northern African and Western Asian regions, with 1057t/ha, where, fossil fuel extraction accounts for the majority of extracted resources, and the main environmental pressures are associated to local pollution during extraction and processing. The extraction of metal ores contributed in 14 countries to more than 50% of all non-renewable materials. Most of these countries were important exporters, such as Chile (copper), South Africa (Iron ores and several other metal ores), Liberia (Iron ores), or Jamaica (bauxite). Metal ore mining is generally considered one of the most environmentally and socially disruptive activities undertaken by business (Jenkins and Yakovleva, 2006).

Global net-suppliers and net-consumers in the long-term perspective

International trade connects places of extraction, production, and consumption and plays a pivotal role for point resources. Point resources occur in highly concentrated form only in certain places on earth, such as fossil energy carriers and metal ores. Here we explore the involvement of individual countries in global trade, either as cumulative net- importers or net-exporters of natural resources and manufactured products. The cumulative overall trade pattern (PTB₁₉₅₀₋₂₀₁₀) of a country can be positive when imports exceed exports, negative when more resources are exported than imported, or balanced. The balanced trade pattern is the result either of no trade or of a high, two-sided world market integration.

Figure 3: Cumulative physical trade balance (PTB) for the largest net-exporters (left) and net-importers (right) by material composition of net trade, 1950-2010, in billion tons (Gigatons, Gt). For country abbreviations see SI.

Figure 3 shows PTB₁₉₅₀₋₂₀₁₀ for the ten largest net-importing and net-exporting countries and country aggregates. The former Soviet Union, Saudi Arabia, and Australia had a negative PTB₁₉₅₀₋₂₀₁₀, exceeding 10 Gt. The former two countries were also the largest net-exporters of fossil fuels, the largest single material group in Figure 3; this is followed by metal ores, albeit at a much lower level for many countries. Only Australia and Brazil have cumulative net-exports of metal ores. While the net-export pattern in Australia, as well as in Canada and to a lesser degree, the FSU and Brazil, is diversified, in all other countries PTB₁₉₅₀₋₂₀₁₀ is dominated by fossil fuels.

Countries identified as cumulative net-exporters can be described as extractive economies that generate income through the exploitation and export of their natural resources (Figure 3). Yet, there is an extensive literature about this strategy's negative societal impacts, such as the Dutch disease, dependency on world-market prices, or unpleasant social change for local communities from mining and large-scale agriculture (Bebbington et al., 2008; Bebbington and Williams, 2008; Bunker, 1985;

Bunker and Ciccantell, 2005; Dunning, 2005; Eisenmenger and Giljum, 2007). These negative socio-economic impacts contradict the long-term stability of development paths based on the export of primary resources. The strong concentration of countries with large net-exports of fossil fuel exports has also had considerable geo-political impacts since WW II. Billon and Khatib (2004) and Barnes and Jaffe (2006) identified oil as a major driving force behind foreign interests, regional and domestic balances of power, and territorial conflicts in the Persian Gulf, while Byman (2016) underlines the importance of oil resources for the Islamic State.

Western European countries, the United States, Japan, and South Korea, all of which have been highly industrialized over a longer period, show the highest positive $PTB_{1950-2010}$, ranging from 5 - 30 Gt. All of these countries were mainly import-dependent on fossil energy carriers, accounting for 60% or more of the overall $PTB_{1950-2010}$. The only exceptions are the United Kingdom and China, with the former being equally import-dependent on biomass as on fossil energy carriers, and the latter being heavily dependent on metal ore imports. The latter was significantly driven by the export-oriented manufacturing sector in China (Roberts and Rush, 2012), which is also reflected in the negative $PTB_{1950-2010}$ of manufactured products (Figure 3).

Population density is a decisive factor for the trade patterns of a country (Krausmann et al., 2008). Countries with the largest positive $PTB_{1950-2010}$ all had high population densities in 2010, except the United States. Conversely, eight of the ten largest net-exporters had population densities below 50 cap/km². Indonesia and Kuwait are exception, as they had population densities above 200 cap/km² in 2010, which is far beyond the threshold of 50 cap/km² for high population density, as defined by Krausmann et al. (2008). Given that both countries mainly exported point resources, the influence of population density in these countries is lower than the availability of and accessibility to these resources.

Resource use and human well-being

After presenting patterns of cumulative flows of material extraction and trade, we now focus on the intersection between cumulative material flows and present human well-being. We thus quantify, using multiple regression statistics, how cumulative material input is related to the Social Progress Index of 2015 and whether trade has a statistically significant impact on this relationship. To arrive at robust and unbiased estimates, and to test for saturation effects, we transform the predictor to In-scale (Steinberger and Roberts, 2010). This procedure necessitates that we transform our PTB indicator, which can be negative as well, into a dummy variable that indicates if a country is a cumulative net-importer (zero) or net-exporter (one) over the entire time period.

Figure 4: $\ln_DMI_{1950-2010}/Pop_{2010}$ on the x-axis plotted against SPI_{2015} on the y-axis. Cumulative net-exporters are marked in red, cumulative net-importers in blue. The colored labeling on the y-axis shows a classification of low, medium, and high SPI following the classification of Porter et al. (2015). We tested the linear regression model for heteroscedasticity with the Breusch-Pagan test (see SI). Country abbreviations and ANOVA tables see SI. Data sources: see methods section.

We find that human well-being, as measured in the SPI, is closely correlated to cumulative material inputs ($r^2 = 0.77$, for detailed ANOVA tables see SI) and that this relationship has a saturation effect. Additionally, we found a statistically significant influence of the history of physical trade (PTB-dummy). From our statistical model we can derive that, on average, a one percent increase in cumulative DMI increases SPI_{2015} about 0.15 points. Additionally, if a country is a cumulative net-exporter of materials, then the regression model shows that, at the same level of cumulative material inputs, a significantly lower SPI_{2015} of 7.6 points can be expected. This means that while more cumulative material use leads to higher human well-being, those countries with export-focused economies have statistically significantly lower human well-being than those countries with a history of physical net-imports.

If we now analyze countries based on low to high social progress, we see that those countries at the lower range of SPI_{2015} (from 30-60) have $DMI_{1950-2010}/Pop_{2010}$ rates of 79 - 500 t/cap (mean = 166 t/cap) and are thus also in the lower range of cumulative material use. Reasons are that in these countries, weak governance, inefficient policy making and corruption often lead to low utilization and extraction of resources (resulting in a low DMI), highly unequal distribution of the gains from exporting resources, and strong negative environmental and social impacts resulting from existing extraction (Stürmer, 2010). In these countries, most of them located in Sub-Saharan Africa and Southern Asia, $DE_{1950-2010}$ mainly consisted of biomass and none of the typical industrial materials, which – if any – were imported. Most of the countries that rank at the lower end of $DMI_{1950-2010}$ were net importers of physical resources, although these net imports are related to little trade overall. However, there are

also countries with similarly low rates of SPI that were net-exporters. Yet, there are also countries that had considerable amounts of exports. Those countries have mostly specialized in very few export goods, and oil exports made up the largest part of the negative $PTB_{1950-2010}$ in Nigeria, Angola, Indonesia, Yemen, and Cameroon.

Most countries that have a SPI between 60 and 70 had $DMI_{1950-2010}/Pop_{2010}$ from 200 t/cap up to 1200 t/cap (mean = 417), showing a broader range of cumulative material use than the first group discussed above. In this group, the countries with the highest $DMI_{1950-2010}/Pop_{2010}$ were again low population density countries where the export portfolio was specialized in a few materials, such as the USSR, Saudi Arabia, Venezuela and Mongolia (fossil fuels). Guyana has a broader export portfolio (raw bauxite, gold, sugar, and rice), yet mostly exports these goods as raw materials, thereby accruing little added value. Again, cumulative net-exporters tend to have a higher cumulative material input than import-dependent countries.

The last group of countries with a SPI above 70 exhibits a number of commonalities. First, countries scoring high in the SPI ranking have a mean $DMI_{1950-2010}/Pop_{2010}$ value of 885 t/cap (range of 460t/cap to 2199 t/cap), which is double the mean value for the countries with an SPI between 60 and 70. Second, countries with a positive $PTB_{1950-2010}$ dominate this group ($n = 24$ cumulative net-importers versus 12 cumulative net-exporters), and within these countries are mostly Western European countries, as well as Japan and South Korea. These countries have considerable amounts of cumulative imports ($Im_{1950-2010}/Pop_{2010}$) of at least 130 t/cap, with a mean value of 340 t/cap.

The group of countries with a very high SPI (larger than 80; $n = 20$, thereof 14 cumulative net-importers) have had a mean of 1100 t/cap of cumulative material inputs and includes countries with both trade patterns (966 t/cap for cumulative net-importers, against 1544 t/cap for cumulative net-exporters). The net-exporting countries in this group, i.e., Australia, Norway, Canada, New Zealand, Sweden, and Iceland (in declining order of $DMI_{1950-2010}/Pop_{2010}$) thus had considerably higher levels of cumulative material use than the net-importers. These countries might have benefitted from vast fertile and resource-rich land and low population density.

Sustainable development goals require tackling long-standing disparities

Our assessment of cumulative material flows from 1950 to 2010 changes the role countries have on the global social metabolism as if 2010 as a single year is analyzed. While a 2010 snapshot indicates that 16% of global materials were extracted in Northern America and Western Europe and 32% in China, a cumulative view of the period 1950 to 2010 shows 29% for Northern America and Western Europe and 17% for China, almost turning the relation upside down. Northern America and Western Europe also dominated import flows, with 44% in 2010 and 59% in a cumulative view. Our focus on

cumulative material flows reveals heterogeneous patterns for extraction and trade, which vary by an order of magnitude between countries and world regions. Furthermore, we could show that cumulative extraction flows in most Sub-Saharan African countries mainly were biomass (64%), with low shares for non-renewable materials (36%) related to low levels of industrialization. On the other end of the range of countries, the early industrializers of Western Europe and North America, as well as Japan and South Korea, have had considerably larger cumulative inputs of non-renewable materials and thereby reached a high level of human well-being for their populations. Yet, there are also countries that had cumulative material inputs far beyond the global average, while they have failed to score high at the Social Progress Index. In approximately one fourth of these countries, high material inputs to their socio-economic systems did not lead to high human well-being of their respective populations. As most existing research and policy formulations focus only on annual and recent resource use patterns, they substantially underestimate disparities due to their long standing nature and path dependencies on material use trajectories and societal factors such as human well-being. Cumulative material flows thus allow for a more extensive comparison of individual countries material use over an extended historic period.

We have quantified the cumulative environmental pressures that were exerted by material extraction. High rates of material extraction over a period of 60 years have caused substantial impacts on ecosystems, the natural environment and reserves of non-renewable resources. The increasing exhaustion of resources and overstressing of sinks has already pushed the Earth's systems beyond the thresholds of 4 of the 9 planetary boundaries (Bringezu et al., 2016; Rockström et al., 2009; Steffen et al., 2015). By analyzing cumulative – rather than annual – material flows, we could better trace the environmental pressures that were generated through resource extraction.

These substantial conflicts among resource use, human well-being, and the natural environment substantially limit the opportunities for the global poor to follow a trajectory similar to that of the already established economies. The introduction of the Sustainable Development Goals aims to overcome these three conflicting dimensions of sustainable development. The main difference compared to the millennium development goals is that the SDGs not only focus on the countries of the global South but also on the rich industrialized countries of the global North, which are called upon to change their patterns of economic and social development (Sachs, 2015). Our indicators, therefore, can contribute to linking SDG goals 10 and 12 on sustainable production and consumption (12) and reduced inequality (10). Especially for SDG goal 12, which is based on the 10-Year Framework of Programmes on Sustainable Consumption and Production (10YFP), our indicators contribute to a more detailed stock-taking of the past resource use of individual countries.

By using indicators of cumulative material use we change the common temporal boundary of economy-wide material flow accounting from one year to a longer period, in this case 60 years. While our results are very highly aggregated, they nevertheless provide information on distinct patterns characterizing those resources that were used to build up and maintain the stocks that deliver the physical services necessary for human well-being (Pauliuk and Müller, 2014). Analyzing cumulative material flows over six decades, rather than single annual flows, changes countries' roles in global social metabolism, as we integrate different dynamics of material use over time and thus allow for a different type of comparison of long-industrialized nations with the new growing giants (Hashimoto et al., 2012). Such an analysis eliminates effects of whether only recent years (where e.g. the new emerging economies have the highest growth rates), or past years are compared, as in the period after WW II the early industrializing countries dominated global material flows through the creation and expansion of the consumer society (Brand and Wissen, 2013; Pfister, 1995). Our analysis also has implications for a possible transition towards a low-carbon society (UNDP, 2011). For example, oil and gas were the dominant trade flows for both the largest net-exporters and the largest net-importers. Yet, to combat climate change, a massive reduction in the use of fossil fuels is inevitable, and this would imply negative (economic) consequences for those countries where fossil fuels exports have been essential to their economic model over the last decades.

Understanding the interrelations between resource use and social factors is important when societies must change long-established patterns of unsustainable resource use and societal inequality. Therefore, we have conducted an analysis of the relation between resource use and human well-being using a new approach. Based on the socio-ecological approach of co-evolution between natural and social systems, we explored whether cumulative resource use is linked to current human well-being, measured by the Social Progress Index. The results show that to join the club of countries with a very high Social Progress Index (i.e., > 80), countries needed cumulative material inputs higher than 600 t/cap, with a median of over 1100 t/cap, and the majority of these countries have also been cumulative net-importers. However, 5 of 6 countries with the highest SPI have been cumulative net-exporters. Our regression shows that these countries have been using an over-proportional amount of cumulative resources per capita to achieve their high SPI. This may indicate that beyond a certain point, the adverse social and environmental impacts of their resource exploitation increase. Those countries that rank at the lower range of the SPI – up to a value of 60 – do not show a significant correlation between cumulative resource flows and social progress. In these countries, unfavorable socio-political and economic conditions, as well as a lack of infrastructure, are the main obstacles to an expansion of resource extraction. Overall, 72 countries out of 90 that have Social Progress lower than 80 have cumulative material inputs below 600t/cap. Oil and gas resources have been important inputs for the socio-economic systems of high SPI countries. If these countries adapt the current

material pattern to reach high Social Progress, the resource requirements are likely to surpass the earth's source and sink capacities, cause irreversible environmental impacts, and undermine efforts to combat climate change. Yet the question arises whether countries with high Social Progress are able to significantly reduce their material inputs without compromising the human well-being they provide for their population. The fact that high human well-being required a certain amount of resource input in the past and that it is beneficial to displace resource extraction to other countries through resource imports is important for studies on the decoupling of aggregated resource use and societal dynamics (UNEP, 2011), while certain aspects of human well-being can be improved with minimal environmental impact (Dietz et al. (2007).

These insights are of high relevance for global environmental justice. Many countries still lack the material base necessary for decent living standards. Some of these countries are indeed global suppliers of metal ores or fossil fuels and could also use those resources to fuel domestic industrialization, while others do not own sources of strategic raw materials for industrialization. These countries did not acquire raw materials when they were more abundant and more cheaply available to improve their material bases. In a future of increasing resource scarcity and the necessity to curb GHG emissions, these latecomers will have limited capacity to acquire these strategic resources, while industrialized countries that have incorporated strategic metal ores into their own in-use stocks will have a second chance thanks to the mining of their rich stocks.

The United Nations Sustainable Development Goals pursue a vision of a global transition towards a society where all members enjoy high human well-being without overstressing the limits of the planet. Under the current patterns of resource use, a large number of countries require considerable increases of material inputs to reach high human well-being. Such an increase in the use of fossil fuels is, however, not possible if we want to combat climate change. Furthermore, trade-offs between the expansion of social metabolism and negative impacts for human well-being have to be solved, as those countries which are in the midst of transitioning from an agrarian to an industrialized metabolism are often the same countries where most of the evidence of socio-environmental conflicts from resource extraction and waste dumping is found. Policies that pursue progressing human development while not overstressing biophysical capacities have to consider these constraints, and an efficient tackling of the SDGs will not be possible without considering a historical perspective on these underlying challenges.

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