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The global metabolic transition: Regional patterns and trends of global material flows, 1950–2010

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ABSTRACT

Since the World War II, many economies have transitioned from an agrarian, biomass-based to an industrial, minerals-based metabolic regime. Since 1950, world population grew by factor 2.7 and global material consumption by factor 3.7–71 Gigatonnes per year in 2010. The expansion of the resource base required by human societies is associated with growing pressure on the environment and infringement on the habitats of other species. In order to achieve a sustainability transition, we require a better understanding of the currently ongoing metabolic transition and its potential inertia. In this article, we present a long-term global material flow dataset covering material extraction, trade, and consumption of 177 individual countries between 1950 and 2010. We trace patterns and trends in material flows for six major geographic and economic country groupings and world regions (Western Industrial, the (Former) Soviet Union and its allies, Asia, the Middle East and Northern Africa, Latin America and the Caribbean, and Sub-Saharan Africa) as well as their contribution to the emergence of a global metabolic profile during a period of rapid industrialization and globalization. Global average material use increased from 5.0 to 10.3 tons per capita and year (t/cap/a) between 1950 and 2010. Regional metabolic rates range from 4.5 t/cap/a in Sub-Saharan Africa to 14.8 t/cap/a in the Western Industrial grouping. While we can observe a stabilization of the industrial metabolic profile composed of relatively equal shares of biomass, fossil energy carriers, and construction minerals, we note differences in the degree to which other regions are gravitating toward a similar form of material use. Since 2000, Asia has overtaken the Western Industrial grouping in terms of its share in global resource use although not in terms of its per capita material consumption. We find that at a sub-global level, the roles of the world regions have changed. There are, however, no signs yet that this will lead to stabilization or even a reduction of global resource use.

1. Introduction

The global transition from agrarian to industrial regimes is linked to an explosion of resource use: Early in the 21st century, humanity used approximately 68 Gigatonnes (Gt) of materials each year, 10 times as much as 100 years earlier, with resource use continuing to grow at a rate of 3.4% per year (Krausmann et al., 2009). The high and growing level of resource use poses a major threat to local and global sustainability and is likely to move humanity beyond the planetary boundaries within which it may safely operate (Rockström et al., 2009). At the same time, resource use is distributed unequally and linked to poverty in many world regions (Griggs et al., 2013). Policy responses to the multiple ecological, economic, and social crises have included measures to promote a transition to sustainability, frequently defining resource efficiency and decoupling of resource use and economic growth as targets (European Commission, 2011; UNEP, 2011; Zhijuan and Nailing, 2007). So far, neither the reduction nor stabilization of global resource use has been attained.

In this article, we present a new, international long-term database of material flows exploring global patterns of material use during the past 60 years. We find that we are currently in the midst of a global metabolic transition such that any attempt to achieve a new transition toward sustainability will face the inertia of this trajectory. Material flow accounting provides both detailed

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information and aggregate headline indicators on the extraction, trade, and use of materials, making it an important tool in the development of effective sustainability strategies (OECD, 2008b; Fischer-Kowalski et al., 2011; UNEP, 2011). In recent years, an increasing body of research on economy-wide material flows has been published. Krausmann et al. (2008b) analyzed global material flow patterns, describing the metabolic transition expressed by the growing magnitude and changing composition of these flows. Internationally, the transition from an agrarian to an industrial metabolism is still underway (Krausmann et al., 2009). Several regional and national case studies identify an accelerated growth of material use in the emerging economies during recent decades (cf. Schandl and West, 2010; Singh et al., 2012). The dynamics of global resource consumption in the context of trade and environmental conflicts were explored by Muradian et al. (2012) who focused on the shift in the hegemonic center of capitalism to China and its impact on the scale and spatial distribution of resource extraction and consumption. The authors make a strong argument for considering various associated shifts in the global resource base including the extension of commodity frontiers to new regions in Latin America and Africa. Due to lack of a consistent data set, their analysis is based on studies employing differing methods and monetary (rather than physical) primary data.

While multinational material flow data sets do exist, they typically cover only a shorter period of time: The Sustainable Europe Research Institute (SERI) maintains an online database of material extraction, use, and trade in 200 individual countries in annual resolution for the time period from 1980 to 2009 (Behrens et al., 2007; SERI, 2013). Based on this data, Dittrich and Bringezu (2010) discussed global patterns in material use since 1980. Eurostat compiles material flow accounts of the European Union member states annually starting in 2000 (Eurostat, 2013). Schandl and West (2010) have analyzed material flow data for the Asia-Pacific region for 1970–2008 and West and Schandl (2013) provide a similar analysis for Latin America and the Caribbean. Only a few studies on individual countries cover longer periods of time including the early emergence of the industrial metabolic regime: among these are, for example, the United States (Gierlinger and Krausmann, 2012), the United Kingdom (Schandl and Schulz, 2002), and Japan (Krausmann et al., 2011). For some world regions and key time periods of the metabolic transition, data coverage remains sparse. This applies especially to Africa and the former Soviet Union and its allies and to the decades of rapid changes in growth trends between 1950 and 1980.

In this article, we present a comparative regional assessment of the global metabolic transition in the second half of the 20th century, aiming to fill some of these knowledge gaps. We introduce a new long-term global material flows database covering 177 individual countries in the period from 1950 to 2010 in ten-year intervals. Important stages of the global metabolic transition are covered, from the emergence of global mass production and consumption immediately following the World War II (‘1950s syndrome’: Pfister, 2010), to the deceleration of physical growth after the oil price shocks of the 1970s and 1980s (‘1970s syndrome’: Wiedenhofer et al., 2013), and the recent economic crisis in the early 21st century. Based on this database, we discuss metabolic profiles (patterns of extraction, trade, and consumption of materials) for six country groupings and regions asking whether these profiles converge or if different pathways occur within the global metabolic transition. This assessment contributes to a better understanding not only of the currently ongoing global metabolic transition but also of the dynamics and the inertia of the global metabolic system which we face as we strive toward a sustainability transition.

2. Materials and methods

By considering a society’s metabolism (Fischer-Kowalski and Haberl, 1998) or measuring the “Weight of Nations” (Matthews and Hutter, 2000), sustainability science set an important counterpoint to the prevalent fixation on the gross domestic product (GDP) or the “Wealth of Nations” (Smith, 2009(1776)) as the measure of all things. The fact that many economies now account not only for their monetary wealth but also for their resource use (in physical units) can be considered one of the fruits of the work of those who first criticized the dominant paradigm of boundless economic growth (Ayres and Kneese, 1969; Daly, 1973; Meadows et al., 1972). Based on the standardized methodological framework of economy-wide material flow accounting (Eurostat, 2007; OECD, 2008a; Fischer-Kowalski et al., 2011), we have compiled data on used extraction and on imports and exports of materials. All materials processed in an economy, except water and air, are accounted for, irrespective of whether or not they have measurable monetary value. Therefore, biomass grazed by livestock, used crop residues, and waste rock removed from the lithosphere during mining of metal ores are also included. Our database distinguishes 65 materials or material types which are aggregated into six main material groups: biomass, fossil energy carriers, metals, industrial minerals, construction minerals, and traded products which cannot be allocated to one of the main raw material groups. We compiled data on domestic extraction, imports, and exports for the years 1950, 1960 (1962), 1970, 1980, 1990, 2000, 2005, and 2010 for 177 countries mostly based on international statistical sources; in some cases national data were used to fill gaps. We followed the conventions of material flow accounting as described by Eurostat (2007) but made adaptations where necessary for non-European countries, the application to historical time periods, and the use of international databases. Material flows not covered by statistical sources were estimated based on standardized procedures and bio-physical data. Time and region- and/or country-specific data and estimation coefficients were used whenever possible. From our database, we calculated standard indicators of material flow accounting: domestic extraction (DE), domestic material consumption (DMC), and the physical trade balance (PTB). We used population data to calculate per capita flows and GDP in constant 1990 international Geary-Khamis dollars to calculate material intensities (material flows per unit GDP), both from Maddison (2008).

2.1. Biomass

Data on agricultural and forestry harvest were extracted from the UN Food and Agricultural Organization’s (FAO) statistical database (FAOSTAT, 2013). Harvest and use of crop residues were estimated using specific harvest factors and data for each region and year, respectively (Krausmann et al., 2013). We estimated grazed biomass by calculating the feed demand of ruminants based on livestock and production data and comparing this demand to the available market feed and forage (data source: FAOSTAT, 2013). The difference between the two is the so-called grazing gap and corresponds to the amount of grazed biomass and grassland harvest. Data on fish capture were extracted from the FAO’s Fisheries and Aquaculture database (FAO Fisheries and Aquaculture Department, 2013). More specific documentation on the methods used is provided by Krausmann et al. (2008a, 2013).

2.2. Fossil energy carriers

Data on the extraction of fossil energy carriers (lignite and hard coal, petroleum, natural gas, peat) was derived from the energy statistics of the UN Statistics Division (UNSD, 2013). Because it covers a larger number of countries and a longer period of time beginning in 1950, preference was given to the UNSD data rather than to the data of International Energy Agency (IEA) frequently used in material flow accounts.

2.3. Metals and industrial minerals

Data on the extraction of metals and non-metallic industrial minerals was obtained from the United States Geological Survey (USGS, 2013). Because reporting conventions changed several times during our reference period, we had to limit our accounting to 17 metals and 17 non-metallic minerals. In order to ensure both the consistency and the representativeness of our data, we based our selection on the following hierarchical criteria: (1) size of flows in terms of mass at the country level, (2) criticality of minerals for industrial economies (European Commission Enterprise and Industry, 2010), and (3) strategic importance of minerals according to expert consultation (Weber, 2011). Our selection of metals covers more than 98% of the total global flows (measured in tons) in each year (except for 1950, where missing data for iron extraction in some countries reduces our coverage to 86%). For non-metallic industrial minerals, coverage is even better at over 99%. For the decades from 1970 to 2000, we used USGS mineral yearbook data digitalized by Rogich et al. (2009). For cross-checks and the correction of missing or erroneous data, we additionally consulted the data provided by the British Geological Survey (2013). Material flow accounting conventions require that metals be included in terms of their gross ore, i.e. metal and the surrounding waste rock (Eurostat, 2007). Both the USGS and the BGS report most metals in metal content (important exceptions are iron ore, bauxite, and manganese commonly reported as gross ore). We used USGS data on ore grades as well as on the structure of the mining industry in order to calculate gross ore while taking the occurrence of coupled production (more than one metal extracted from the same ore, e.g. lead and zinc as by-products of nickel mining) into account. Where country-specific ore grades were not available, we used regional coefficients based on data reported by Schandl and Eisenmenger (2006) and expert consultation (Weber, 2011). As a last resort, global average ore grades were applied. While ore grades seem to have declined during the last century for several major metals (cf. Mudd, 2010), no consistent information is available at the country-level yet. We therefore maintained constant ore grades referring to the period between 1995 and 2005 over the whole time period. This procedure is likely to result in an overestimation of gross ore extraction for some ores in the earlier years. In this article (and in contrast to most existing material flow accounts), we report metal and waste rock extraction separately.

2.4. Construction minerals

Data on non-metallic minerals used primarily for construction (sand, gravel, and crushed stone) are not readily available from statistical sources and therefore have been estimated. We used the procedure outlined by Krausmann et al. (2009) and widely applied in material flow accounting. The sand, gravel, and crushed stone used for the production of cement, concrete, asphalt and in rural non-cement related construction was estimated using average global coefficients presented by Krausmann and colleagues and was based on data on cement production and consumption (Cembureau, 1998, 2013) and bitumen consumption (IEA, 2013) as well as on rural and urban population (FAOSTAT, 2013). The result is a conservative estimate which (as it does not fully consider minerals used as fillings and base material) is likely to underestimate the overall extraction of sand, gravel and crushed stone for construction by 20–40%.

2.5. Trade

Trade data was extracted from the UN Comtrade database (United Nations Statistical Division, 2013) which provides import and export data for individual countries in physical and monetary units from 1962 onwards. We used data at the product groups (three-digit codes) level of the Standard International Trade Classification (SITC), Revision 1 and checked these data for errors and gaps. Wherever possible, gaps were filled using information on monetary flows (usually available and of better quality than physical data) and calculated global average prices. However, as Dittrich and Bringezu (2010) point out, Comtrade's coverage is not complete and for approximately 20% of all records, physical values are missing. Therefore, we used data sources with more complete coverage for trade in agriculture and forestry products (FAOSTAT (2013) covers imports and exports in physical units for around 500 agriculture and forestry products providing better coverage of total global biomass flows than Comtrade) and fossil energy carriers (IEA, 2013). For 1950, no physical trade data were available. We therefore assumed that aggregate physical trade flows changed with the same growth rate as monetary trade flows between 1950 and 1960. For these two years, aggregate monetary data on imports and exports in US dollars at constant prices are available from the World Trade Organization (WTO, 2013). Detailed information on data and methods used to account for trade flows are provided by Loy (2014).

2.6. Robustness of results

We compiled our database in accordance with internationally harmonized material flow accounting methodology and the most reliable international data sources (Fischer-Kowalski et al., 2011). We applied conservative estimation procedures wherever possible so that our results represent an under- rather than an overestimation of the actual physical flows. We compared our results to existing national studies with coinciding time frames as well as with existing global material flow accounts. In general, our results represent an underestimation compared to national material flow accounts and are highly consistent with global totals from other studies; the comparison is presented in the supplementary material.

2.7. World regions

Our database covers 177 individual countries which, for the purposes of this article, we have clustered into two country groupings and four world regions according to politico-economic and geographic criteria. A list of the countries by grouping or region can be found in the supplementary material. We use the country groupings to distinguish two different economic and political pathways of industrialization followed after the World War II. The *Former Soviet Union and Allies* (*FSU-A*) comprises the Soviet Union until 1990 (and the 15 independent countries which emerged from its disintegration thereafter) and the 6 satellite states of the Soviet Union after the World War II while the *Western Industrial (W-Ind)* grouping encompasses North America, Australia, New Zealand, Japan, and the Western aligned countries in Europe. The *Asia* region includes 28 countries in Asia and Oceania but not Japan or the Asian countries which were part of the Soviet Union. The *Middle East and North Africa* (*MENA*) region encompasses 18 countries. 30 countries in *Latin America and the Caribbean* make up the *LACA* region. The 47 countries of the *Sub-Saharan Africa (SSA)* region extend from Mauritania in the North-West and Sudan in the North-East to South Africa in the South. Although such a macro-regional perspective obscures existing differences within the groupings, it allows us to analytically highlight important biogeographic and economic features as well as the metabolic trajectories which these countries share. Based on our country-by-country data, we will also point out differences within the regions whenever necessary in the interpretation of our results.

3. The metabolic profiles of world regions

We present data on extraction, trade, and apparent consumption of materials for all six world regions and country groupings in Gigatonnes per year (Gt/a) and in per capita values (t/cap/a). Domestic material consumption per capita is also denoted as metabolic rate (Fischer-Kowalski et al., 2011). Two panels (Figs. 1 and 2) illustrate the data. Background data on the regions as well as on their metabolic profiles are also available in the supplementary material.

3.1. Western industrial

With a share of 44% of the global GDP and 15% of the world population in 2010, this grouping had a higher average per capita income than any other region, surpassing the global average by a factor of over 3 in 2010. Between 1950 and 1970, the countries in this grouping were responsible for almost half of global material use. An impending saturation with industrial stocks (buildings, infrastructures) coupled with intensified industrialization processes in other world regions, especially Asia, caused the Western Industrial share in global material use to decrease to 21% by 2010.

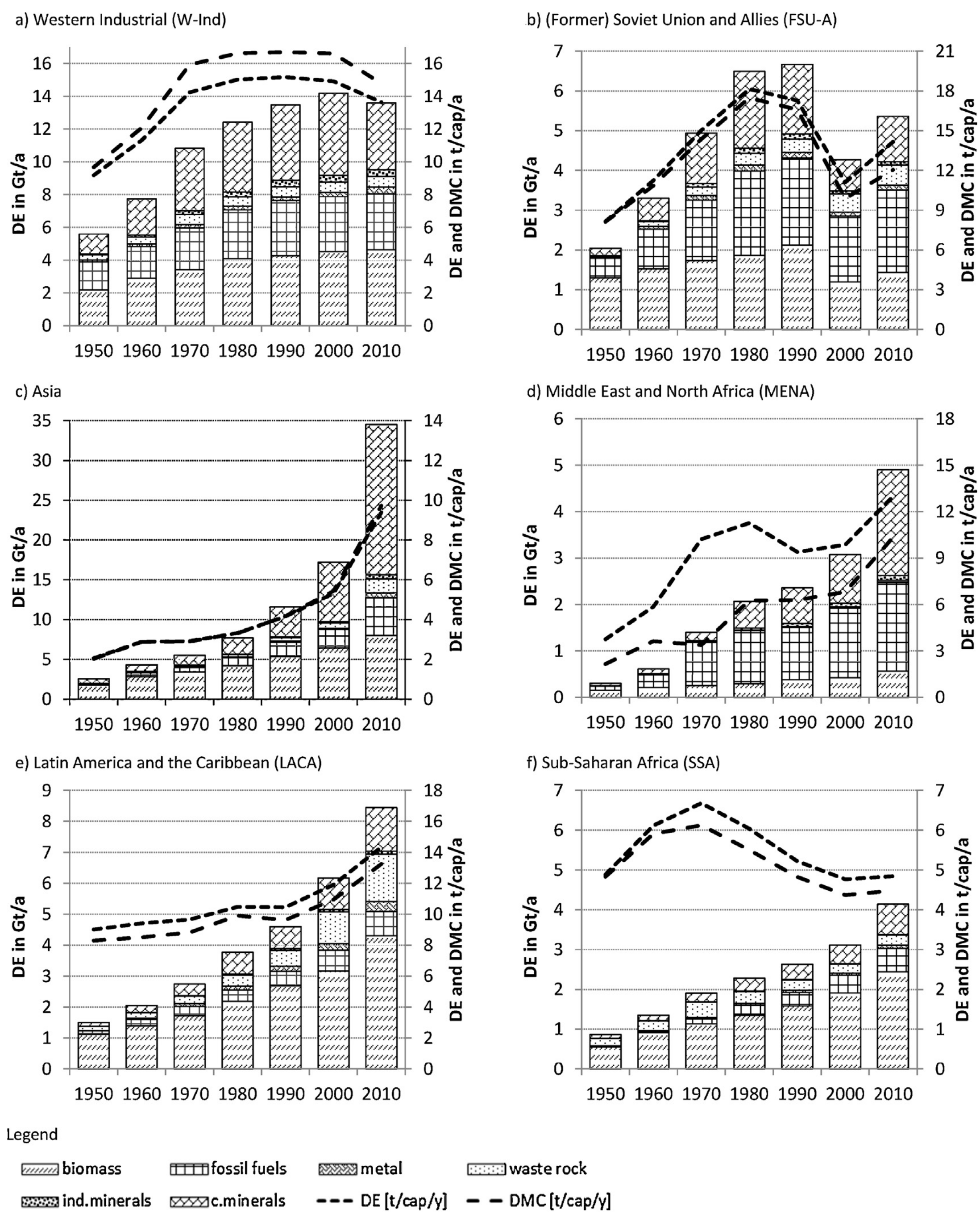

Fig. 1. Domestic extraction (DE) in Gigatonnes per year (Gt/a) by main material groups in columns on the primary vertical axis and per capita DE and domestic material consumption (DMC) in tons per capita and year (t/cap/a) in lines on the secondary vertical axis. Please note that different scales are used on both vertical axes in Fig. 1a–f.

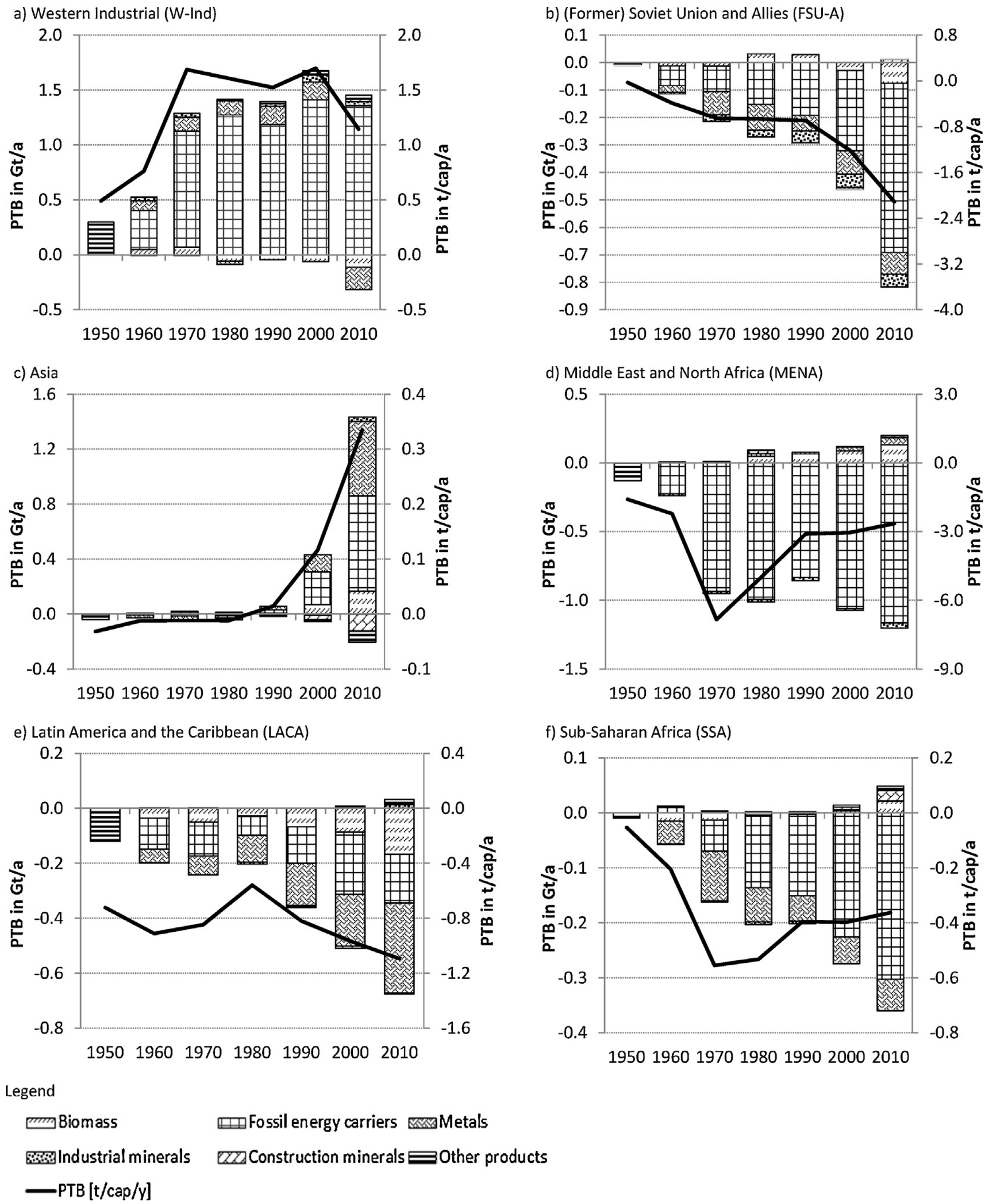

Fig. 2. Physical trade balance (PTB = imports minus exports) in Gigatonnes per year (Gt/a) by main material groups in columns on the primary vertical axis and PTB in tons per capita and year (t/cap/a) as a line on the secondary vertical axis. In 1950, all trade is classified as other products because no detailed data on material composition are available. Please note that different scales are used on both vertical axes in Fig. 1a–f.

Current resource endowment varies across countries: many densely populated European countries and Japan have a long history of industrial development and their domestic resource base, especially for fossil energy carriers and metals, is largely depleted while the sparsely populated new world countries continue to extract large amounts of resources. Located mostly in the temperate zone, with climate favorable to agriculture, most of the Western Industrial countries have a highly productive and intensive agricultural production system and are net global suppliers of biomass (see Fig. 2a). Total domestic extraction (DE, see Fig. 1a) amounted to 13.6 Gt/a in 2010.

The decades after the WW II were a period of rapid metabolic transition characterized by strong growth. Domestic material consumption increased from 10 to almost 17 t/cap/a in 1990 (Fig. 1a). By 1970, the transition that occurred in the composition of material consumption led to a metabolic profile which can be considered typical for fully industrialized economies (Krausmann et al., 2008b): The minerals required to build, maintain, and use large infrastructures and durable goods account for more than two thirds of domestic material consumption while the share of biomass, most of which is still used directly and indirectly in human nutrition, has declined to below 30%. The sparsely populated countries in this group typically have a significantly higher metabolic rate than the densely populated countries (Krausmann et al., 2008b).

Imports play an important role in meeting Western Industrial resource requirements: net-imports multiplied from 0.3 Gt/a in 1950 to 1.1 Gt/a in 2010 (see Fig. 2a). Driven by a 3-fold rise in oil net-imports, the biggest surge in trade volume occurred in the 1960s, a decade characterized by rapid growth of GDP in virtually all Industrial economies. Fossil energy carriers consistently dominate the physical trade balance shown in Fig. 2a. Following the oil price shocks of the 1970s, a slowing of imports and a return to the domestic resource base can be observed in some Western Industrial countries (notably the United Kingdom, Norway, Australia, and Canada) lasting until 1990, when the expansion of domestic extraction ceased and net imports of fossils regained higher significance. Major global raw material exporters such as Australia and Canada are the exception among the Western Industrial countries, however, these countries provided 10% of total global exports (and 20% of global biomass exports) in 2010.

While the Western Industrial region experienced strong growth of its metabolic rate during the first decades under observation, per capita material consumption stagnated from the 1970s onwards. The decade between 2000 and 2010 even saw a considerable drop in domestic material consumption in both per capita and absolute terms (see Fig. 1a); it remains to be seen if this trend is one of a beginning dematerialization or rather reflects the impact of the economic crisis of 2008. Stabilization of material use can be observed in most industrialized countries and may be the result of a beginning saturation with material-intensive stocks (Wiedenhofer et al., 2013).

3.2. Former Soviet Union and allies

The countries in this grouping account for 6% of global population on 17% of the global land area. In spite of the very specific political and economic framework conditions in these centrally planned economies after the World War II, the grouping's metabolic trajectory was remarkably similar to that of the Western Industrial countries. Following the dissolution of the Soviet Union and the Council for Mutual Economic Assistance (COMECON) in 1991, however, both industrial and agricultural output declined drastically, not showing signs of recovery until the late 1990s. The grouping offers a unique insight into the behavior of a 'collapsing' and 'regenerating' industrial metabolism.

The period from 1950 to 1980 was characterized by rapid expansion of the physical economy, the transition from a biomass-to a minerals-based metabolism, and the emergence of a metabolic profile very similar to that of those Western Industrial countries with high resource endowment and low population density (Krausmann et al., 2008b). By 1980, at 17.5 t/cap/a, material consumption had reached a higher level than in the Western Industrial grouping (Fig. 1b). Extraction and use of construction and other non-metallic minerals had grown by one order of magnitude and consumption of metals and fossil energy carriers, core resources of industrialization, multiplied 4- to 6-fold. In contrast, the share of biomass in domestic material consumption was down to 30% by 1980. A large share of these resources was extracted on the territory of the Soviet Union and its allies which is abundant in many resources like coal, natural gas, metals, and other minerals. The grouping is also rich in forests and agricultural areas and a major producer of biomass: Between 1950 and 1990, biomass extraction roughly doubled based on land expansion and intensification. Nonetheless, extraction could not keep pace with growing demand and in the 1970s and 1980s, the grouping became dependent on net imports of food and feed.

The dissolution of the Soviet Union in 1991 caused a dramatic a slump in material extraction and use (Fig. 1b). In 2000, total domestic extraction was down to 64% of the 1990 value, mostly due to a radical drop in the extraction of construction minerals and biomass to 45% and 56% of their 1990 values, respectively. In contrast, the extraction of fossil energy carriers, ores and industrial minerals was less affected and the exports of these materials even increased (Figs. 1b and 2b). The high and rising rates of exports of these strategic materials after 1990, paired with low consumption of construction minerals and biomass, reflects that domestic infrastructures were neglected, often at the expense of rural areas and that the collectivized agricultural system did not recover. In particular, the output of the heavily subsidized and biomass-intensive livestock industries could not compete with imported goods (cf. Ioffe and Nefedova, 1997; Petersona and Bielkeb, 2002). Economic development was largely based on raw material exports. After 1990, the Soviet Union's former allies all opted for a pathway of economic and political development orientated toward attaining membership in the European Union. In metabolic terms, this move resulted in a slightly faster recovery of the physical economy and a comparatively high level of net-imports, especially of fossil energy carriers and other minerals. Between 1990 and 2010 net exports from the region more than tripled and amounted to over 2 t/cap/a in 2010. The grouping emerged as one of the most important global suppliers of a broad range of raw materials, in particular oil and gas. Between 2000 and 2010, domestic material consumption grew by 21% and reached 12 t/cap/a. During the last decades, growth in material extraction was faster than in material consumption (Fig. 1b), reflecting that the restructuring and recovery of the economy was largely based on the exploitation of natural resources for export.

3.3. Asia

Driven by its "growing giants" (Hashimoto et al., 2012), Asia, home to half the world's population, dominated global material flows at the end of our period of observation: Following a growth spurt between 2000 and 2010 during which material extraction and consumption doubled (Fig. 1c), half of global resource consumption occurred here. Per capita material consumption rose to 9.7 t/cap/a in 2010, almost reaching the global average. The major share (97%) of this consumption stemmed from domestic resources and only in 2000 did Asia become a net-importer, most notably of fossil energy carriers and metals (Fig. 1c).

Material flow data indicate that the region is in a rapid transition from a largely agrarian toward an industrial metabolic profile. Biomass, which accounted for more than 70% of material use in 1950, drastically lost significance by 2010. Due to the low significance of biomass-intensive livestock products in many Asian diets and of fuel wood in energy supply (FAOSTAT, 2013), per capita consumption of biomass is small by international comparison (Krausmann et al., 2013). Rapid industrialization of the region is reflected in explosive growth, especially during the last decade, in the domestic extraction of fossil and mineral materials. In 2010, mineral and fossil materials amounted to 77% of domestic material consumption. In the last decade, the region began to dominate global resource use, consuming 40–65% of mineral and fossil materials and 38% of all biomass.

In spite of its soaring resource consumption, Asia was a net-supplier of resources within the global economy for most of the observed period (Fig. 2c). But with growing demand, the region's role in global trade also changed: By 2000, the region's imports of biomass, fossil energy carriers, and metals began to exceed exports, albeit at a low level compared to the Western Industrial grouping. This changed between 2000 and 2010, when net imports grew by a factor of 7 to a total volume corresponding to over half of the net imports of the Western Industrial grouping, making Asia the only other net-importing region, although with a still low physical trade balance of only 0.3 t/cap/a.

Material use in Asia is dominated by the growing giants India and China which, in 2010, were home to 72% of the region's population, accounting for 79% of its GDP and 84% of its domestic material consumption. While similar in terms of population size, India and China exhibit different metabolic profiles. China's DMC grew by a factor of 11 between 1950 and 2010 and material consumption reached 17.4 t/cap/a in 2010. China's share in global material consumption surged from only 7% in 1950 to 34% in 2010. In the process of industrialization, China began to build up large infrastructure stocks, simultaneously driving demand for construction minerals and other industrial resources such as steel, copper, and fossil energy carriers. In 2010, China alone accounted for the vast majority of the region's consumption of metals (75%), construction minerals (78%), fossil energy carriers (72%), and industrial minerals (80%). In contrast, India's metabolic rate is, at 4.5 t/cap/y in 2010, still at a much lower level. Nonetheless, India also seems to be undergoing a metabolic transition: Since 1980, its metabolic rate has grown by 55% and the share of biomass in domestic material consumption decreased from 72% to 42% (cf. Singh et al., 2012). During the last decade, the other countries in Asia exhibited a similar development, albeit at a much lower level of material consumption: After a long period of stagnation, material use in the rest of the region increased by 33% between 2000 and 2010.

3.4. Middle East and North Africa

The smallest region in terms of land area is home to 5% of the world's population with almost proportional shares in global GDP (4%) and material consumption (6%). Due to arid climate and the prevalence of largely unpopulated (semi)deserts, possibilities for agriculture and forestry are limited and biomass extraction is low. The resource base for metals and non-metallic minerals is poor or undeveloped in many countries. The region is, however, endowed with highly significant occurrences of petroleum and natural gas. Since 1950, a transition from a biomass- to a minerals-based metabolism can also be observed with the region's specific resource endowment strongly influencing its metabolic profile: While per capita extraction of fossil energy carriers is far above global average, biomass consumption is low and largely depends on material imports.

In 1950, half of the material extracted in the Middle East and North Africa was biomass (Fig. 1d). Agriculture and in particular pastoralism were important economic activities and grazing accounted for the lion's share of biomass extraction. Even though crop output was significantly increased through the expansion of irrigation after 1980, per capita biomass extraction at 1.5 t/cap/a was lower in 2010 than in any other region. Most countries in the region have been able to compensate the lacking domestic availability of biomass resources required by their growing population with income generated through export of fossil energy carriers (Fig. 2d). Large scale petroleum extraction began in the 1940s and was still developing in 1950, when it already had a share of 30% in domestic extraction (Fig. 1d). In the following decades, and in particular after the foundation of the Organization of Petroleum Exporting Countries (OPEC) in 1960, the region emerged as the major supplier of petroleum for the USA and the industrializing European economies. Between 1960 and 1970, fossil energy carrier extraction tripled to an absolute level higher than that of the Western Industrial grouping. In 2010, 1.4 Gt of petroleum, the equivalent to 36% of the global total, were extracted, approximately half of which occurred in two countries: Saudi Arabia (34%) and Iran (16%). Nonetheless, petroleum exports drove economic growth in the whole region, where GDP (in 1990 GK$) grew by a factor of 17.6 between 1950 and 2010. Increasing levels of petroleum extraction and consumption also coincided with strong growth in the use of other minerals required for the rapid urbanization and development of infrastructure. Overall, material consumption grew by a factor of 22 in the region and metabolic rate multiplied by a factor 5–10.3 t/cap/y, with growth accelerating in the last decade.

The gap between material extraction and consumption remains larger than in any other region (Fig. 1d), reflecting the role of the region as a global supplier of fossil energy carriers. At the same time, the Middle East and North Africa depends on large imports of most other materials, especially biomass. At 0.3 t/cap/a in 2010, net biomass imports were much higher than in any other world region. These imports are crucial in meeting the region's food demand and are thus of strategic importance. Approximately 50% of the domestic food consumption is imported, making the region highly vulnerable to international food price volatility (Ianchovichina et al., 2012). Recently, the exchange of 'fuel for food' via international trade has therefore been complemented with national-level investments in agricultural production in other world regions, in particular Sub-Saharan Africa, aimed at securing long-term access to food. These land investments, that can trigger negative social effects, are often critically referred to as "land grabbing" (cf. Borras and Franco, 2012; Woertz, 2013).

3.5. Latin America and the Caribbean

This region is home to 9% of the world population, generates an almost proportional share of global GDP (8%), 12% of all materials are extracted here, and metabolic rates are above global average: at 13.2 t/cap/a in 2010, material consumption is second only to the Western Industrial grouping. Domestic extraction was even higher (14.3 t/cap/a) and comparable only to the level in the resource-rich and sparsely populated grouping of the (Former) Soviet Union and its allies. The material flow data on Latin America and the Caribbean provide us with the opportunity to trace the impact of heavy reliance on the extraction and export of primary resources (cf. West and Schandl, 2013) on the development of a metabolic profile.

The region stretches across 16% of the global land area, is sparsely populated, and endowed with vast woodlands and agricultural areas and is rich in mineral deposits. The high level of biomass as well as of metal and waste rock extraction is eye-catching (Fig. 1e): the region is the largest net-exporter of biomass and metals and also an important international supplier of petroleum. Although the share of biomass in domestic extraction decreased in this region as well – from 80% in 1950 to slightly over 50% in 2010 – it remained very high by international comparison. Livestock production continues to be an important source of economic income; in 2010, grazed biomass contributed more to total biomass extraction (38%) than in any other region. The availability of biomass also plays a pivotal role in consumption patterns and trade flows: In Argentina, Brazil, and Chile, the level of meat consumption per capita is comparable to the Western Industrial countries while the region simultaneously remains a major exporter of biomass, in particular crops and resource-intensive livestock products (Fig. 2e). Next to biomass, Latin America and the Caribbean is also an important global supplier of metals. In 2010, almost half of global copper extraction occurred in the region, a third of global silver extraction, and one quarter and one fifth of global tin and iron extraction, respectively. While metal concentrates or metal-based products are exported, the waste rock and often hazardous tailings associated with their production remain in the region, resulting in a high apparent consumption of metals (cf. Giljum, 2004). However, between 1950 and 2010, a shift toward the extraction of metals with higher ore grades (mainly iron and bauxite) occurred, making the extraction of metal grow faster (factor 41) than the production of associated waste rock (factor 13). The region was also a net-exporter of fossil energy carriers and in 2010, one quarter of all extracted fossil energy carriers were exported so that consumption remained very low within the region (1.0 t/cap/a). Only the Sub-Saharan Africa region had a lower rate of fossil fuel use. Until 1980, Venezuela was by far the largest material exporter. In the following decades, however, the combined effect of the nationalization of the Venezuelan oil industry, the temporary slumps in international and especially US demand, and the introduction of OPEC allocation quotas caused its petroleum production and exports to decrease drastically. At the same time, this region's 'growing giant', Brazil, was expanding its exports and accounted for 48% of total exports in 2010.

Overall, the focus of the region on exports prevails and the slight decline in the physical trade balance between 2005 and 2008 described by West and Schandl (2013) was reversed by 2010 (see Fig. 2e) and seems to have been a reflection of the economic crisis rather than of structural change in demand. Primary commodity export-orientation shapes the region's metabolic profile with high apparent consumption of biomass and ores. The low level of material investments into infrastructure is reflected in a level of per capita consumption of construction minerals which, at 2.3 t/cap/a, is much lower than in the emerging economies of Asia.

3.6. Sub-Saharan Africa

On 18% of the global land area, this region is home to 12% of world's population which grew more strongly than in any other region during the last 60 years. Nonetheless, density remains comparatively low. Sub-Saharan Africa produces only 2% of the global GDP and average income amounts to less than 1/5 of the global average. The region is mainly composed of tropical savanna, rain forest, and areas characterized by arid climate in the Sahara and around the Horn of Africa. Agriculture, often subsistence-oriented and less industrialized than in other regions, is an important economic sector in terms of employment and GDP. The region is endowed with deposits of fossil energy carriers, metals, and other minerals of global significance. Nonetheless, it is also the 'poorest' of all six regions in terms of material consumption which, at 4.5 t/cap/a in 2010, corresponded to less than half the global average.

The transition from a biomass- to a minerals-dominated metabolic profile which is typical of the industrialization process has not occurred in the region. Biomass continues to be the most important material extracted; its share in extraction hardly declined from 64% in 1950 to 59% in 2010 (Fig. 1f) and is mainly made up of grazed biomass indicating the prevalence of extensive agricultural systems. Simultaneously, high rates of soil erosion and land degradation in the region which recent research suggests may be due to biophysical rather than human-induced factors (Kiage, 2013), threaten the future development potential for agricultural production. At 0.9 t/cap/a in 2010, the consumption of construction minerals was lower than in any other region reflecting a low level of infrastructure development. This element of the region's metabolic profile is strongly linked to the slowing of urbanization in spite of high population growth due to the lack of employment opportunities and the increasing poverty rates in urban areas (Potts, 2012, 2009).

In spite of its low metabolic rates, the region is a net-exporter of fossil energy carriers and metals (Fig. 2f). Export flows are, however, dominated by individual countries so that the impact on regional economic development is low: In 2010, South Africa, the region's richest country, and Nigeria, the region's most populous country, accounted for 33% and 29% of exports, respectively. South Africa extracts 60% of all metals in the region and is a major exporter of metals. Fossil fuel extraction, mainly of petroleum and hard coal, was similarly concentrated: In 2010, 98% of the region's hard coal was extracted in South Africa while 73% of petroleum was extracted in Nigeria and Angola. 66% of all fossil energy carriers extracted in Sub-Saharan Africa were exported in 2010 and per capita consumption for this material type was extremely low at 0.3 t/cap/a.

Overall, the metabolic profile is dominated by throughput materials (grazed biomass and crops) rather than by materials used to build up stocks (construction minerals, metals, timber). While in the Western Industrial countries past investments into infrastructure are at least partially linked to current high levels of material consumption, the lack of infrastructure development in Sub-Saharan Africa also translates into comparatively low resource use. The latter, in so far as it coincides with widespread poverty, lack of employment opportunities, and conflict, is not to the benefit of the population. Sub-Saharan Africa not only has the lowest level of income and metabolic rate of all regions, it is also the only region in which per capita material extraction and consumption declined during the last 60 years. Population growth was more pronounced than material growth and the metabolic rate sank by 25% since 1970.

4. Regional patterns of the global metabolic transition

The period after the World War II was characterized by unprecedented growth of the global economy and of population, by the emergence of mass production and mass consumption and, as a consequence, by a dramatic increase in the size of socio-economic metabolism: Since 1950, global material extraction and use grew 5.6-fold, much faster than population. Global physical exports grew 12-fold, faster even than GDP. Our results show that for the longer part of the last 60 years, global development of material flows was dominated by the now mature industrial countries in the Western Industrial grouping and by the planned economies of the Former Soviet Union and its allies. Up to 1990, these countries consumed over 50% of all globally extracted materials (Fig. 3) and drove the 50% increase in global per capita material use observed during this period. In spite of fundamentally

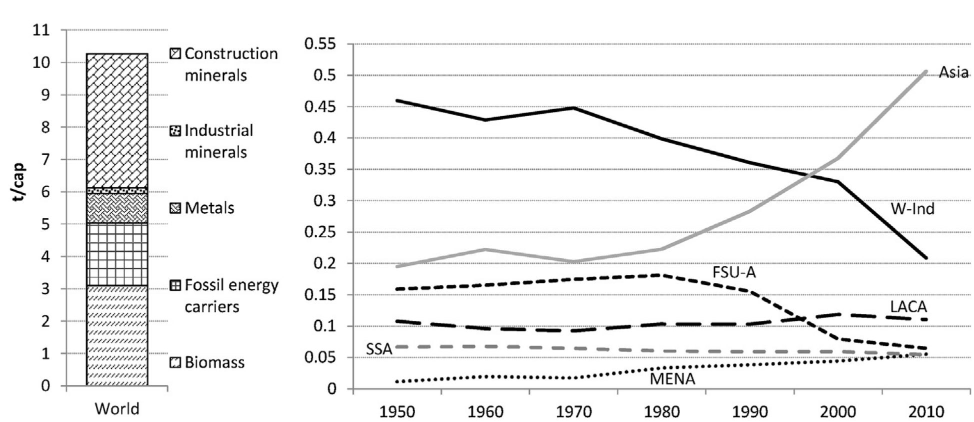

Fig. 3. Global domestic material consumption (DMC) in tons per capita and year (t/cap/a) by material category in 2010 (left) and share in global DMC by region (right).

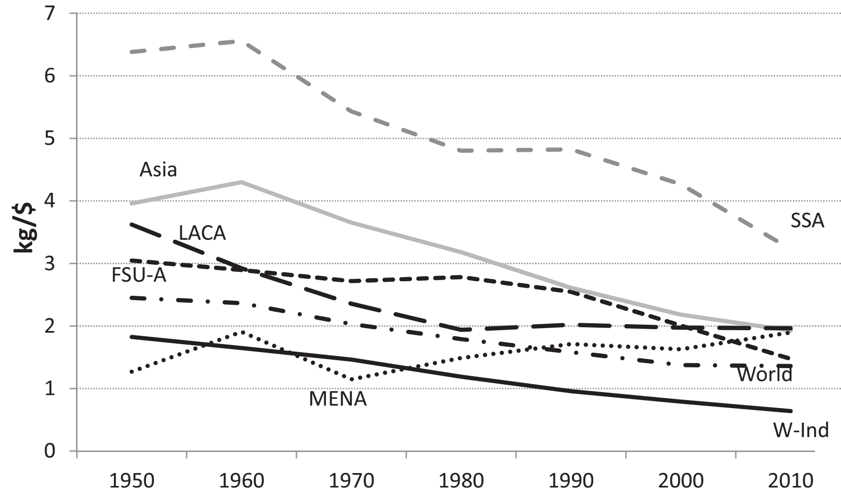

Fig. 4. Material intensity (domestic material consumption per gross domestic product) for the world and by world region 1950–2010 in kilograms per US dollar (kg/$).

different economic and political paths of industrialization, both groupings exhibit a remarkably similar trajectory of material use and metabolic profile development. However, the high levels of resource use in the planned economies of the (Former) Soviet Union and its allies did not lead to the same levels of economic wealth and material productivity as in the Western Industrial grouping (Fig. 4). While domestic material consumption stabilized at a high level in the Western Industrial grouping in the 1970s, stabilization in the (Former) Soviet Union and its allies did not occur until the 1980s and was followed by a strong decline after the dissolution of the Soviet Union. Between 1980 and 2000, global metabolic rates remained stable just under 8 t/cap/a indicating that growth in material use kept pace with population growth. During the last decade, however, the global metabolic rate surged by 30%, the highest growth rate of the last 60 years and comparable to growth in global income. Although this dynamic is dominated by Asia and above all by China, it is important to note that a rise in material use after a long stretch of stagnation can also be observed in Latin America and the Caribbean and the Middle East and North Africa.

Overall, material use grew more slowly than GDP during the last 60 years. The average amount of material required to generate one unit of GDP (material intensity measured as domestic material consumption per GDP) decreased from 2.5 kg per dollar (kg/$) in 1950 to 1.4 kg/$ in 2010 (Fig. 4). The comparison by world regions shows, however, that the relatively low material intensity at the global level is the effect of high GDP rather than of low resource use: Sub-Saharan Africa, the poorest region with the lowest per capita domestic material consumption, has by far the highest material intensity while the Western Industrial grouping with its high metabolic rate had the lowest material intensity in 2010. While material intensity decreased continuously in all other world regions, the two resource-exporting regions, the Middle East and Northern Africa and Latin America and the Caribbean, stand out in that their material intensity stagnated or even increased during the last three decades: Here, material use, much of it related to the production of exports as we have shown, grows with GDP and there is no sign of decoupling.

We have been able to identify some heterogeneity in the regional material flow patterns related to a broad range of factors including resource endowment, economic development, and integration into the global economy. Nonetheless, a remarkable global convergence toward an industrial metabolic profile can also be observed and gained considerable momentum during the last decade. With the exception of regions of Latin America and the Caribbean and Sub-Saharan Africa, all world regions had completed or were on the brink of completing the transition from a biomass- to a minerals-based metabolism by 2010. Next to the prevalence of mineral flows within a metabolism to which biomass contributed 30% or less, the industrial metabolic profile is also intrinsically linked to large standing stocks in infrastructure, buildings, and durable goods which amount to several 100 t/cap (Fishman et al., 2014). Building and maintaining these stocks and the energy demand associated with their use (e.g., in housing and transport) are major drivers of both economic and material use development: In the industrial metabolic profile, bulk minerals such as sand and gravel, iron, copper, aluminum, or timber tend to play dominant roles. We have found evidence that suggests emerging economies are following a similar path and rapidly building up stocks: In 2010, materials that can be integrated into stocks accounted for two thirds of material use in Asia and the Middle East and North Africa. This development illustrates that stocks will be decisive for future resource use, adding inertia to the ongoing metabolic transition. Out of the six regions and country groupings under investigation, only the important resource frontiers (Muradian et al., 2012) Sub-Saharan Africa and, to a lesser degree, Latin America and the Caribbean do not exhibit the industrial metabolic profile: Instead, the share of biomass in domestic material consumption is above 50% and per capita use of fossil energy carriers and construction minerals is extremely low. So far, these regions have profited little from their role as global suppliers of key materials for industrialization.

5. Conclusions and outlook

The explosion in global resource use around the turn of the century is the combined result of stagnation followed by degrowth in the Industrial countries and immense growth in all other regions - with the notable exception of Sub-Saharan Africa. Massive growth of resource use in the highly populated Asia region has dominated global material consumption during the last decade and left the region with a metabolic rate which is similar in composition to the Industrial region's yet smaller in size. If development policies were to imply that other regions "catch up" to the average Industrial metabolic rate, Asia would have to increase its material consumption to approximately 51 Gt/a, assuming zero population growth. That is an amount of materials corresponding to 71% of all materials globally extracted in 2010. If all regions were to have an Industrial metabolic profile, global material consumption would rise to just below 100 Gt and to twice its 2000 level, again assuming zero population growth. Even if we simply assume that the 2000–2010 development of global resource use, including the slight decrease in the Industrial countries, continues in the next decade (''business as usual''), we would reach a global material consumption of more than 100 Gt/a by 2020.

In 2010, the Western Industrial grouping and the Asian region were the only physical net-importers while the four other regions, home to 30% of the world population, supplied resources to the global economy. Here, significant shares of resource consumption are in fact waste generated or material dissipated in producing exported goods. As was illustrated for the export-orientation of Latin America and the Caribbean, this may result in high levels of apparent material consumption. Since material flow accounting follows a production- (rather than a consumption-) based perspective, materials or energy embodied in traded goods are not specifically traced so that environmental burdens associated with the production for export cannot be allocated to final consumption (cf. Giljum and Eisenmenger, 2004; Giljum, 2004). Recent studies on upstream resource requirements embodied in traded products also suggest that the apparent stabilization of resource use may be the result of offshoring resource intensive production (Muñoz et al., 2009; Bruckner et al., 2012; Wiedmann et al., 2013). Such accounts have the potential to provide an important additional perspective on regional patterns of global resource use as we have discussed them here but further research and methodological advancements are still required (cf. Kastner et al., 2013).

Our analysis of regional trends in resource use highlights what may turn out to be decisive issues in the future of our global social metabolism. The tremendous growth in global resource use across the past 60 years has been closely associated with increasing environmental pressures, both at the local and the global level. The potential doubling of global domestic material consumption by 2020 compared to its 2000 level would cause further infringement on the habitats of other species leading to biodiversity loss as well as land degradation and simultaneously contribute to global environmental change, especially with regard to climate. At the same time, the trends observable between 1950 and 2010 do not indicate a development toward greater resource equality. Instead, we have illustrated how some regions have increasingly focused on the production for export and that this has often occurred at the expense of domestic infrastructures. Population growth, urbanization, and unevenly distributed resources are bound to cause inequality in resource use and so that the spatial disconnect between production and consumption will continue to require the attention of policy makers and scientists alike. If a transition toward a more sustainable resource use is to be made, it must be made globally and it must overcome the potential of inertia of the Industrial metabolic regime and the development trajectory of other regions toward such a regime.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.gloenvcha.2014.03.013.

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