Growth in global materials use, GDP and population during the 20th century.

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Abstract

The growing industrial metabolism is a major driver of global environmental change. We present an assessment of the global use of materials since the beginning of the 20th century based on the conceptual and methodological principles of material flow accounting (MFA). On the grounds of published statistical data, data compilations and estimation procedures for material flows not covered by international statistical sources, we compiled a quantitative estimate of annual global extraction of biomass, fossil energy carriers, metal ores, industrial minerals and construction minerals for the period 1900 to 2005. This period covers important phases of global industrialisation and economic growth. The paper analyses the observed changes in the overall size and composition of global material flows in relation to the global economy, population growth and primary energy consumption. We show that during the last century, global materials use increased 8-fold. Humanity currently uses almost 60 billion tons (Gt) of materials per year. In particular, the period after WWII was characterized by rapid physical growth, driven by both population and economic growth. Within this period there was a shift from the dominance of renewable biomass towards mineral materials. Materials use increased at a slower pace than the global economy, but faster than world population. As a consequence, material intensity (i.e. the amount of materials required per unit of GDP) declined, while materials use per capita doubled from 4.6 to 10.3 t/cap/yr. The main material groups show different trajectories. While biomass use hardly keeps up with population growth, the mineral fractions grow at a rapid pace. We show that increases in material productivity are mostly due to the slow growth of biomass use, while they are much less pronounced for the mineral fractions. So far there is no evidence that growth of global materials use is slowing down or might eventually decline and our results indicate that an increase in material productivity is a general feature of economic development.

Introduction

The 20th century was characterised by an unprecedented growth in population and in the size of the global economy: During the last one hundred years, global population quadrupled to 6.4 billion and global economic output as measured by GDP grew more than 20-fold (Maddison, 2001). This expansion of the global socio-economic system was accompanied by fundamental changes in society-nature-relations and by a massive transformation of natural systems (MEA 2005; Hibbard et al. 2007; Steffen et al., 2007). Although humans have altered their physical environment throughout their 4 million year history, *there has never been anything like the 20th century*, as John McNeill (2000, p.3) has put it in his seminal book on the environmental history of the 20th century, entitled *something new under the sun*. One of the main drivers of human induced environmental change has been the growing social or industrial metabolism, i.e. the inputs of materials and energy into socio-economic systems and the corresponding outflows of wastes and emissions (Ayres and Simonis, 1994, Fischer-Kowalski and Haberl, 2007). Changes in the structure and size of social metabolism are directly and indirectly linked to a wide range of environmental pressures, to resource scarcity and corresponding conflicts and are key to sustainable development. A better understanding of the patterns and trends of changes in the global social metabolism helps to understand the dynamics of human environment relations (Wagner, 2002; National Research Council of the National Academies, 2003).

While global time series data for the long-term historical development of important socio-economic indicators such as GDP and population (Maddison, 2008) and a number of biophysical indicators such as primary energy supply (Etemad and Luciani, 1991, Grübler, 1998, Podobnik, 1999), CO_2 emissions (Marland et al., 2007) or the use of specific substances

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(e.g. Kelly and Matos, 2008) have been compiled in the last decade, a comprehensive account of global materials extraction and use is still missing.

Economy-wide material flow accounts for historical periods have been compiled for a growing number of individual countries.[1] Most of these country-level case studies document historical trends ranging from several years up to several decades. Only very few studies include time periods before 1970 (see e.g. Matos and Wagner, 1998, Schandl and Schulz, 2002, Petrovic, 2007). Several attempts have been made to compile global country-by-country material flow accounts for recent years (Schandl and Eisenmenger, 2006, Behrens et al., 2007, Krausmann et al., 2008b). According to these studies, global materials extraction was estimated to range between 47 and 59 billion metric tons (Gt) per year at the beginning of the 21st century. Up to date, only one dataset presenting time-series data on global materials extraction has been published: The SERI (2008) dataset provides a quantitative estimate of global resource extraction for the period 1980 to 2005. Time series data for the material extraction during earlier periods of industrial development is scarce.

This paper presents a first quantification of global materials extraction for the past century, based on the conceptual and methodological principles of economy-wide material flow accounting (MFA). On the global level, the amount of resources extracted is equal to the amount of resources used. On the individual country level, domestic extraction of resources (DE) differs from domestic resource use (DMC), as trade has to be taken into account.[2] In the first section, we describe accounting principles, data sources, estimation procedures used to quantify material flows not covered in statistical records, and the general structure of the database. We then present an overview of the development of global materials extraction in the period 1900 to 2005, structured according to the four major material categories (biomass, fossil fuels, industrial minerals and metallic ores and construction minerals).[3] In the discussion section, we explore the interrelations between the trajectory of global materials use and population, GDP and primary energy supply. We also discuss changes in the volume of materials used per capita and per unit of GDP. We conclude with an outlook on the possible future development of global materials use and implications for sustainable development.

Methods and data

According to broadly accepted principles of economy wide material flow accounting (MFA) (Eurostat, 2007b), we accounted for the extraction (domestic extraction, DE) of all types of biomass, fossil energy carriers, ores and industrial minerals as well as for bulk minerals used for construction. Extraction by definition also includes the biomass grazed by domesticated livestock, used crop residues and the tailings which accrue during the processing of extracted ores. Resources extracted but not used, that is, materials that are moved by human activities but are not subject to any further economic use (e.g. overburden in mining, excavated soil, burnt crop residues etc.) have not been accounted for. As on an aggregate global level, total net trade is zero and consequently, total amount of resources extracted (DE) equals total amount of resources used (DMC), resource extraction and resource use are synonyms, and we employ these terms interchangeably. The following section briefly describes the data sources used and the estimation procedures applied.

[1] See, for example, Adriaanse et al., 1997, Rogich et al., 2008, Eurostat 2007a, Gonzalez-Martinez and Schandl, 2008 and Russi et al., 2008.

[2] According to standard MFA methods, DMC is defined as follows: DMC=DE + imports – exports. On the global level, trade equals out, and thus DE = DMC.

[3] The data discussed in this paper can be downloaded from http://www.uni-klu.ac.at/socec/inhalt/1088.htm

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Biomass

In order to quantify global biomass extraction, we use a novel method employed to account for biomass extraction on a country by country level for the year 2000 (Krausmann et al., 2008a). We adapted the method for time series application and adjusted some of the estimation procedures to account for technological change (e.g. changes in harvest indices and recovery rates needed to estimate the extraction of crop residues). Total biomass extraction includes the amount of harvested primary crops (up to 165 items); used extraction of crop residues (up to 50 items); harvest of fodder crops, grasses and grazed biomass (12 items) and wood extraction (2 items). Crop residues were estimated using harvest indices and recovery rates for the most important crops (Krausmann et al. 2008). Based on regional estimates, it was assumed that harvest indices improved by 10 to 70% since 1900 – most of this growth took place in industrialised countries since the 1950s (Evans, 1993, Krausmann, 2001). Grazed biomass was estimated on the basis of livestock numbers and daily roughage requirements of different livestock species. Figures for daily roughage intake were estimated using data on the development of live-weight and milk output based on data provided by FAO (2006) (see Krausmann et al., 2008a). To quantify wood harvest, we used data reported by FAO (1955 and 2006) and Zon & Sparhawk (1923) (see also Fernandes et al., 2007). All biomass flows are reported in fresh weight at the time of harvest (ranging from 14% for cereals to over 90% for fruits and vegetables), with the exception of the biomass harvested from grassland, grazed biomass and grass-type fodder crops, which have been standardized to air-dry mass at 15% moisture content.

Annual data were available from FAO (2006) for the period 1961 to 2005. For 1910, 1930 and 1950 data from various statistical yearbooks of FAO and the Institut International d'Agriculture (e.g. 1931) were used. Data for countries not reported in the data compilations of the Institut International d'Agriculture were estimated by using regional per-capita data derived from reporting countries and weighted by population numbers. Although global biomass harvest grows continuously and shows little annual fluctuations during the period from 1961 to 2005, it has to be assumed that we underestimate slumps in biomass harvest which are likely to have occurred during and shortly after the World Wars I and II.

Relative to other estimates of biomass extraction in the MFA tradition, we feel we have achieved a higher degree of consistency and comprehensiveness, particularly by careful and region specific estimates of (the substantial) amounts grazed – a fraction chronically hard to quantify (see Haberl et al., 2007).

Fossil energy carriers

Material flow accounts distinguish brown and hard coal, petroleum, natural gas and peat. The extraction of fossil energy carriers is well documented in statistical sources and data compilations. Underestimations may occur, because production statistics sometimes excludes the amount of energy carriers used immediately at the site of extraction (in particular for petroleum resources). Since the 1920s, annual data on the production of fossil energy carriers have been published by the United Nations (1952) and later also by the International Energy Agency (IEA, 2007b). Comprehensive data compilations have been provided for example by Etemad & Luciani (1991). We used data series based compiled by Podobnik (1999) on the basis of official energy statistics and reconverted numbers given in energy units into mass using standard calorific values, and then updated the series on the basis of IEA (2007) and data provided by Kelly and Matos (2008) for global peat extraction. Data from Podobnik (1999) and IEA (2007b), complemented with data on primary solid biomass used as fuel from

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Fernandes et al. (2007), were also used to calculate global total primary energy supply (TPES).

Metal ores and industrial minerals

We used data on the global extraction of mineral commodities compiled by the United States Geological Survey (Kelly and Matos, 2008) and distinguish 44 types of ores and 33 types of industrial minerals. With the exception of iron ore and bauxite, Kelly and Matos (2008) report data in terms of metal content (excluding tailings). In order to arrive at the amount of gross ore extracted (as required by the MFA conventions), we used average global ore grades derived from country-by-country information on ore mining from USGS (2008) for the year 2000. Information on coupled production of ores was considered in order to avoid double counting. The question if and to what extent the average ore grades declined during the last century is contested (Martin and Jen, 1988). Consistent information on the development of ore grades is limited, but for several ores there is evidence that average ore grades have been declining. We used a recently published study (Mudd, 2007a) on the long-term historical development of ore grades in Australian mining and other literature (Mudd, 2007b; Gerst, 2008) in order to derive conservative estimates of changes of ore grades for lead, zinc, nickel, copper, gold, silver and uranium over time (assuming linear development between 1900 and 2005). However, the effect of changing ore grades on the trends of the total extraction of metal ores is small: Our assumptions on historic ore grades result in a reduction of total extraction of ores in 1900 by less than 20% as compared to keeping ore grades constant at the present level. This difference is diminishing over time.

Bulk minerals for construction

Reliable data on the extraction of crushed tone, sand and gravel used for construction are only reported for a number of industrial countries and for recent years. No global data on the extraction of construction minerals exist. In the MFA literature, different approaches are discussed to estimate bulk materials used in construction. Several authors proposed to base estimates on an assumed relation between income (as a proxy for industrialisation) and per capita DMC of construction minerals (Schandl and Eisenmenger, 2006; SERI, 2008, Krausmann et al. 2008b). This procedure, however, is problematic for two reasons: first, the relation between income and the use of construction minerals still lacks solid empirical testing, neglects other influencing factors and the factors applied have to be considered as being very rough. Second, the use of GDP data to estimate the size of material flows has the disadvantage of constraining the analysis of the relation between materials use and economic development by generating a priori methodological interdependencies and circular arguments. In its compilation guide for economy wide MFA Eurostat (2007b) proposes an estimation procedure based on the combination of data on concrete production, and changes in road length, employing factors for average demand of sand and gravel associated with concrete production and road building. We based our account on a modified version of this approach: We used data on cement production to estimate the total amount of limestone extracted and the amount of sand and gravel used for concrete production by assuming a ratio of cement to limestone of 1 to 1.4 and of cement to concrete of 1: 6.5 (Eurostat 2007b; Rubli and Jungbluth, 2005); Additionally, data on bitumen production allowed to extrapolate the amount of sand and gravel used for asphalt production, assuming a ratio of 1:20. In order to account for other construction materials (bricks, dimension stone), sand and gravel used for other purposes than concrete and asphalt production, we proceeded as follows: We assumed an

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average use of alternative construction materials of 0.3 tons per capita of rural, and of 0.9 tons per capita of urban population. These figures are based on information on the amount of construction materials used in railroad construction and the expansion of the global railway system, the urban use of bricks and dimension stone in the city of Vienna and other sporadic evidence. They have to be considered rough estimates, but they allow in particular to account for systematic underestimation in the first half of the 20th century, when cement and asphalt were only beginning to substitute for other construction minerals. All factors chosen are conservative; Based on comparison of our results with reliable data for the use of sand and gravel which exist for a number of industrialized countries, we assume that we underestimate the use of bulk materials in construction by 20 to 40%, in particular because the use of sand, gravel or crushed stone used for fillings and as base material are not accounted for.
Data on cement production were derived from Schmid (1948) and Kelly and Matos (2008); data on bitumen from IEA (2007a), UN (2007a) and Abraham (1945), population data from Maddison (2008) and FAO (2006) (rural and urban population).

Data Reliability

The core of the time series of all four main material categories is based on statistical data which have been collected by national statistical offices and compiled by international organisations. As far as MFA data are based on these statistics, their calculation is relatively straightforward, and data quality matches the international statistics. A limited number of (large) flows (including, for example, grazed biomass, harvested crop residues, tailings of ore mining and construction minerals), though, is not reported in statistical sources and had to be estimated. The backbone of the estimation procedures applied was in all cases statistical data such as livestock numbers, data on animal production, primary crop harvest, net ore production or cement and bitumen production. These have been used in acknowledged procedures to account for the associated material flows. Hence, our estimate is to a very large extent based on annually reported data in physical units.

Statistical reporting of data on resource extraction has a long tradition, and many countries adopted annual accounting and reporting schemes already in the 19th century. By the beginning of the 20th century, many nations were publishing annual data on agriculture, mining and industrial production. These data were then collected by international bodies (e.g. the League of Nations or the Institut International d'Agriculture). These data are considered reliable, although, for various reasons, there is some underreporting, in particular in the early periods, which had to be taken into account: For the case of biomass use, underestimations are largest because a significant number of countries in the first half of the 20th century had no data reported. We accounted for these underestimations by applying population-based corrections. The best data are probably available for fossil energy carriers, for ores and industrial minerals. Minor underestimations (probably less than 3%) are possible, because in earlier years only the most important producers were included in the reporting or because fossil energy carriers consumed at the site of extraction are not adequately reported (see also Kelly and Matos, 2008). Construction minerals make up a large flow. The estimate is based on data of high quality, but we assume a systematic underestimation resulting from the fact that bulk flows used in fillings and as base materials are not adequately considered in our estimate. On the level of aggregate materials use, we assume our estimate to be conservative and systematically under-represent material extraction for the whole period by something between 10% and 20%. This underestimation may be somewhat larger during the early periods of the observed time period. In general, we assume that our data provide a consistent picture of the overall size and composition of global materials use and their change over time.

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Our data also match well with another estimate of global material flows covering the period 1980 to 2005 (SERI, 2008): According to our estimate, we observe a steeper trend of growth in material extraction (2.28% as compared to 1.55% average annual growth 1980 to 2005), which is predominantly due to differences in the approach used to account for construction minerals.

Findings

Trends in global materials use

Figure 1 shows global material extraction for the period 1900 to 2005 in a break down by four major material types. Total material extraction during this century has increased by a factor of 8. In 2005, roughly 59 Gt/yr of materials were extracted and used worldwide. The strongest increase during this period can be observed for construction minerals, which grew by a factor 34, ores/industrial minerals by a factor 27. Biomass extraction grew only 3.6-fold. For most of the 20^{th} century, biomass was the most significant of the four material types in terms of mass and only in the 1990s it was overtaken by construction minerals. The share of biomass in total DMC declined continuously throughout the observed period. In 1900, biomass accounted for almost three quarters of total DMC. One century later, its share had declined to only one third. In particular, the period between WWII and the first and second oil price peak in the early 1970s saw a rapid shift from renewable biomass towards mineral materials. The relative biomass peaks of the years 1920, 1933 and 1946 (Figure 1d) do not really represent peaks in biomass extraction but a reduction in the use of the other materials. It is also no surprise that the slumps in overall materials use induced by WWI and WWII and the world economic crisis were less pronounced for biomass than for the other material categories. Quite understandably, it is of highest priority that people and domestic animals continue to be nourished.

Throughout the observation period, DMC increased continuously with annual growth rates between 1% and 4%. Periods with declining or stagnating DMC were rare, and never lasted for more than a few years. All periods of absolute dematerialization (i.e. declining DMC) coincided with economic recession: Declining DMC was observed in some years during and shortly after WWI, during the world economic crisis (1930-32), during several years during and after WWII and in 1992. The years following the oil price peaks (1973, 1979 and 1988) were characterised by sharply reduced growth of GDP and stagnation in materials use.

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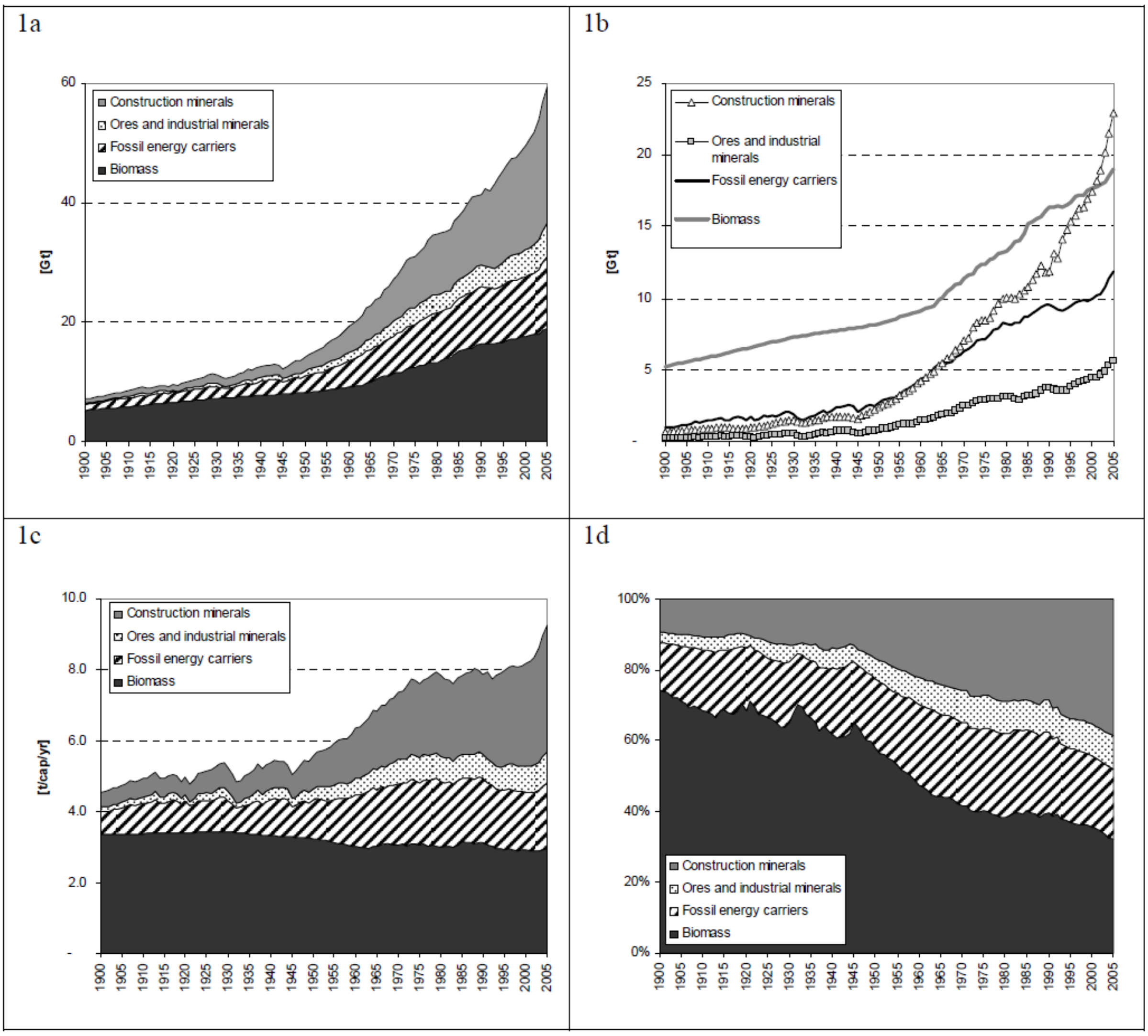

Figure 1: Materials use (DMC=DE) by material types in the period 1900 to 2005. 1a and b) total materials use in Giga tons (Gt) per yr; 1c) metabolic rate (materials use in t/cap/year); 1d) share of material types of total materials use.
Sources: See text

Changes in the composition of materials use over time

Table 1 shows changes in the composition of total materials use on a more detailed level. The share of primary crops in total biomass extraction increased from 21% to 35%, the share of roughage (fodder crops, grazed biomass) declined from 47% to 30% and that of wood from 15 to 11%. Tailings accounted for roughly 75 to 80% of total extraction of metal ores throughout the observed period. Iron is the most important metal throughout the period. It accounted for 95% of all extracted metals (metal content only) in 1900 and its share declines gradually to slightly over 80% in 2000 and has increased since to 85%. Other metals of significance are copper and alumina with a share of several per cent of total metal extraction in 1900; in 2005, alumina accounted for 7%, copper for 2% and all other metals for 7% of all extracted metals. With respect to fossil energy carriers, we observe the well known shift from the dominance of coal to petroleum and natural gas. Coal accounts for more than 98% of all extracted fossil energy carriers in 1900 and its share declined continuously to somewhat less than 50% in the 1970s and remained at this level since. Changes in the composition of construction materials have to be interpreted with care, because of the built-in assumptions

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used in the estimation procedure of these bulk materials. According to our estimate, the share of construction minerals associated with the production and use of cement increases continuously throughout the period. Accounting for merely 15% of total construction minerals in 1900, its share increased steeply after World War 2 to more than 60% at the beginning of the 1970s and amounted to 74% in 2005. Sand and gravel used for the production of asphalt accounted to only 8% of all construction materials after WWII. This share increased to 14% in 1973 and since remained between 10 and 15%. All other construction minerals still dominate in 1900 (making up 85% of all construction materials) but decline rapidly to an intermediate low in the 1930ies and then again after WWII from 50% in 1950 to finally 17% in 2005.

Table 1: Changes in the composition of global material extraction.

		1900	1925	1950	1975	2005
Biomass	**[mio t]**	5,272	6,942	8,193	12,402	19,061
Primary crops		21,4%	23,3%	24,1%	29,4%	35,4%
Crop residues		16,1%	15,6%	17,9%	21,0%	23,1%
Roughage		47,1%	44,9%	40,6%	36,4%	30,2%
Wood		15,4%	16,2%	17,4%	13,2%	11,3%
Fossil energy carriers	**[mio t]**	968	1,787	2,754	7,171	11,846
Coal (incl. peat)		97,5%	90,9%	75,5%	48,6%	48,6%
Petroleum		1,9%	7,5%	18,5%	38,2%	32,8%
Natural Gas		0,6%	1,6%	6,0%	13,2%	18,6%
Metal ores (metal content only)	**[mio t]**	51	87	149	552	961
Iron		95,1%	92,0%	89,2%	86,6%	85,0%
Copper		1,0%	1,8%	1,6%	1,2%	1,6%
Alumina		0,1%	0,6%	2,0%	4,7%	6,6%
All other metal ores		3,8%	5,6%	7,2%	7,5%	6,8%
Tailings (metal ores)	**[mio t]**	142	330	538	1,681	3,521
Industrial minerals	**[mio t]**	17	57	125	655	1,154
Construction minerals (cm)	**[mio t]**	667	1,269	2,389	8,445	22,931
Cement-related cm		15,2%	32,3%	40,4%	60,3%	74,3%
Asphalt-related cm		0,0%	0,9%	9,5%	14,5%	9,0%
All other cm		84,8%	66,8%	50,1%	25,2%	16,7%

Source: See text

Distinguishing phases of resource use over time

Global materials use is a complex process driven by population growth and economic prosperity as reflected in GDP. Based on the rates of materials use per capita, we are able to discern three periods with distinct growth dynamics (Figure 1 and Table 2): During the first half of the 20th century, materials use grew only modestly, partly because two World Wars and the economic crisis in the 1930s caused major disruptions even on a global scale (cf. McNeill, 2005). On the one hand, these crises interrupted periods of growth, on the other hand, restructuring and reconstruction during post-war periods induced phases of accelerated growth. This is particularly obvious from the dynamics of per capita materials use in Figure 1c. Overall DMC in the first half of the 20th century grew by just 1.2% per year, that is, at a considerably slower pace than GDP (2.13% per year), only slightly faster than the world population (0.98% per year). Thus materials use per capita had no more than an average

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annual growth rate of 0.2%. We observe very low average annual growth rates for biomass and construction minerals, and modest growth for fossil energy carriers and ores/industrial minerals.[4]

After WWII, physical growth accelerated and kicked off a period of uninterrupted and rapid growth of materials use which lasted for three decades. In this period, annual growth rates exceeded 4% in several years. The average annual growth rate of DMC was 3.3%, fossils use grew by 4.5% yearly, and the use of ores, industrial and construction minerals even around 6% per year. Even biomass use rose faster (1.52% per year) than ever before or after. In this period, growth rates of materials use by far exceeded population growth and led to an unprecedented increase in the rate of materials used per capita.[5]

Table 2: Average annual growth rates of major materials, population, GDP and total primary energy supply (TPES) for different periods

	Biomass	Fossil energy carriers	Ores/ ind. minerals	Constr. minerals	Total DMC	DMC/ cap	Populati on	GDP	GDP/ cap	TPES
1900 to 1945	0.92%	1.70%	2.30%	1.98%	1.21%	0.23%	0.98%	2.13%	1,13%	1.33%
1945 to 1973	1.52%	4.48%	5.74%	6.05%	3.30%	1.55%	1.72%	4.18%	2,42%	4.39%
1973 to 2005	1.42%	1.63%	2.21%	3.22%	2.13%	0.56%	1.56%	3.27%	1,69%	1.90%
1900-2005	1.23%	2.41%	3.18%	3.43%	2.04%	0.68%	1.35%	3.02%	1,64%	2.31%
1900-2005 (factor)	3.6	12.2	26.7	34.4	8.4	2.0	4.1	22.8	5,5	11.0

Sources: See text; own calculations based on Maddison 2008 (GDP in 1990international Geary Khamis Dollars and Population); Podobnik 1999, IEA 2007b and Fernandes et al. 2007 (TPES).

Then the oil price peaks of the early 1970s set an abrupt end to these heydays and growth slowed down markedly. With the exception of biomass use, which continued to rise at a moderate pace, average annual growth rates declined by 50% or more. The annual growth rate of DMC slumped to 2.13%, and the distance to population growth was significantly reduced, so that materials use per capita stabilized (with annual growth rates down to 0.56%). Towards the turn of the new millennium, though, growth of materials use accelerated again; global growth rates of all materials as well as per capita materials use increased markedly since the year 2000 (see Figure 1c).

Across the whole period, global DMC grew significantly faster than population but much less than GDP. Consequently, per capita DMC doubled, while material intensity (measured as DMC per unit of GDP) declined continuously and in 2005 amounted to only 40% of the value of 1900.

[4] It is interesting to note that the preparation and equipment for the two World Wars has contributed less to an increase in overall energy and metals use than the reconstruction and welfare period after WWII.
[5] In an environmental history context, this period has also been described as “great acceleration” (Hibbard et al. 2005) or the “1950s syndrome” C. Pfister (1994)

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Discussion

The global metabolic transition

The outstanding role the 20th century played in the transformation of societies' natural relations which John McNeill (2001) has outlined so impressively is also reflected in the development of global material extraction. According to our data the global size of social metabolism has multiplied several times during the last century. Global material extraction reached the enormous amount of 59 billion tons in the year 2005 and continues to rise at a very high rate. The size of social metabolism has been approaching a magnitude that is comparable with major global material flows in ecosystems. For example, global human materials use is in the same order of magnitude as the amount of global terrestrial net primary production, that is the amount of biomass produced annually by green plants through photosynthesis (120 Gt, Haberl et al., 2007). Throughout the century, the physical economy grew faster than population[6], and average per capita use of materials (i.e. metabolic rates) increased considerably. In particular, the years between 1945 and the first oil price shock, which have been described as the period of the emergence of a society of mass production and mass consumption (Ayres, 1990, Grübler, 1998, Pfister 1994), appear as a period of major metabolic change. Rapid industrialization processes in Western industrial economies and in Japan drove global change and left their imprint on the global metabolic system. In these 28 years alone, per-capita use of materials increased by more than 50%, and the use of non-renewable minerals by 340%. Still, the current global level of per capita materials use is low compared to that of fully industrialized regions: It amounts to just under 60% of the average per capita DMC of Western Europe and less than one third of that of North America (Krausmann et al., 2008b).

During the last century, we not only observed an exponential increase in global materials use, but also a fundamental shift in its structure and composition. Between 1900 and 1950 the share of biomass declined from roughly 75%, a value typical for economies at the beginning of the industrial revolution (Schandl and Schulz, 2002), to less than 50%. At the beginning of the new millennium, non-renewable resources accounted for more than 70% of total materials use, and their share is still increasing. The economic historian Anthony Wrigley (1988) has described this shift in the resource base as a typical feature of the industrial revolution in the UK in the 18th and 19th century and has termed it a shift from an *(advanced) organic economy* towards a *mineral economy*. In this process, for the first time in human history, the resources obtained from the exploitation of large but finite mineral stocks gained significance as compared to renewable biomass which prevailed as the key energy and material resource of the organic economy. Minerals use eventually by far outgrew biomass. Our data indicate that, from a social metabolism perspective, the global transition from an agrarian towards an industrial resource base has progressed considerably during the last century. Another aspect of this metabolic transition is a shift from "throughput materials", materials which by and large are consumed within a year or less, towards a high share of "accumulation materials" building up large socioeconomic material stocks. Biomass, which is predominantly used as food for humans and livestock, and fossil energy carriers which are combusted in order to

[6] It is interesting to note that biomass, the material basis for human nutrition, is the only material group that grew at slightly slower pace than population (see Table 2). Above all this can be attributed to considerable efficiency gains in biomass conversion, such as improvements in the harvest index of cultivars and more efficient livestock conversion (see e.g. Smil 2000). Additionally, the substitution of fossil fuels for draft animals and fuel wood has contributed to reductions in per capita biomass extraction.

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produce energy,[7] used to dominate global DMC until WWII. During the period of accelerated growth after WWII, in less than 30 years the share of metallic and non-metallic minerals that accumulate in built infrastructure and durable artefacts increased from 15 to 35%. Although no reliable estimates of global material stocks yet exist, information from case studies indicate that in fully industrialized countries minerals accumulated in built infrastructure and artefacts amount to several hundred tons per capita (Hashimoto et al., 2007; Rubli and Jungbluth, 2005). These material stocks generate a lasting demand for future investment of materials and energy for maintaining and using infrastructure (and eventually for their destruction). On the other hand, parts of these stocks may serve as future “mines” for raw materials (Brunner, 2004, Gordon et al., 2006).

Material and energy use, economic growth and dematerialization

Combining the data on the global use of materials with existing information on GDP and total primary energy supply (TPES) allows highlighting some issues concerning the relation between physical and economic growth at the global scale (Figure 2) and the development of the resource intensity[8] of the global economy. During the 20th century, global population roughly quadrupled while global GDP surged by a factor 24. Average per capita income increased from 1260 US$/cap/yr to currently around 7000 US$/cap/yr. With growing income and population also the physical size of the economy in terms of material and energy use multiplied, but as Figure 2a and b indicate, global material supply grew somewhat slower than primary energy supply. Both indicators for the size of the physical economy grew faster than population; the metabolic rate, that is the amount of materials and energy used per capita and year, more than doubled. It is interesting to see that material and energy use follow a very similar trajectory.[9] Figure 2a shows that the physical size of the economy grew at a much slower pace than its monetary size and during the last century, the material and energy intensity of the global economy continuously declined towards 30% (materials) and 50% (energy) of its value calculated for 1900 (Figure 2c). This trend does not apply to all materials, though, as Figure 2d shows. Most of the reduction in material intensity was due to the declining intensity of biomass use, while the intensity of minerals use even increased during the larger part of the 20th century and began to decline only during and after the 1970s. Biomass, which is among others the material basis for human nutrition, seems to be linked primarily to population growth, but the use of non-renewable minerals is much more closely linked to economic growth. On the centennial scale, overall efficiency (or resource productivity) gains for mineral materials therefore appear to be comparatively small.

Our results indicate that an overall decline in the material intensity of the global economy, or, inversely, the increase in efficiency with which materials (and energy) are used, is a characteristic feature of a period of global industrialisation. The efficiency gains achieved are remarkable: Energy intensity declined by 0.68 % per year, and material intensity even by 1% per year.[10] These efficiency gains did not translate in a reduction of the materials and energy

[7] The material use fraction of biomass (e.g. timber) and fossil energy carriers (e.g. feedstock for the petrochemical industry) is comparatively small and ranges between 5 and 10%.

[8] Material and energy intensity are defined as material (DMC) or energy (TPES) input per unit of GDP and are measured in kg or Joule per unit of GDP.

[9] Both DMC and TPES include fossil energy carriers and primary solid biomass used for energy generation. However, they are aggregated in different units (DMC: mass units, TPES: energy units) which results in considerable differences. Significant flows of material (all non-energy use materials) and energy (hydropower, nuclear heat, geothermal energy) are not overlapping.

[10] It should be noted, that the long term historical development of GDP is difficult to measure and that such a time series is based on many assumptions concerning prices and production. Although the global series which

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used. Both global TPES and DMC continue to grow, and after a phase of relative stabilization this growth rate again accelerated since the year 2000.[11] Throughout the period observed, however, materials use has reacted sensitively to recessions and even to slow down in economic growth: Whenever the global economy experienced decline or stagnation, material and energy use slumped. The only periods of absolute global dematerialization occurred after the two World Wars and during the World economic crisis in the late 1920ies and following the oil-price peaks in the 1970s. This documents the intimate linkage between materials use and economic development.

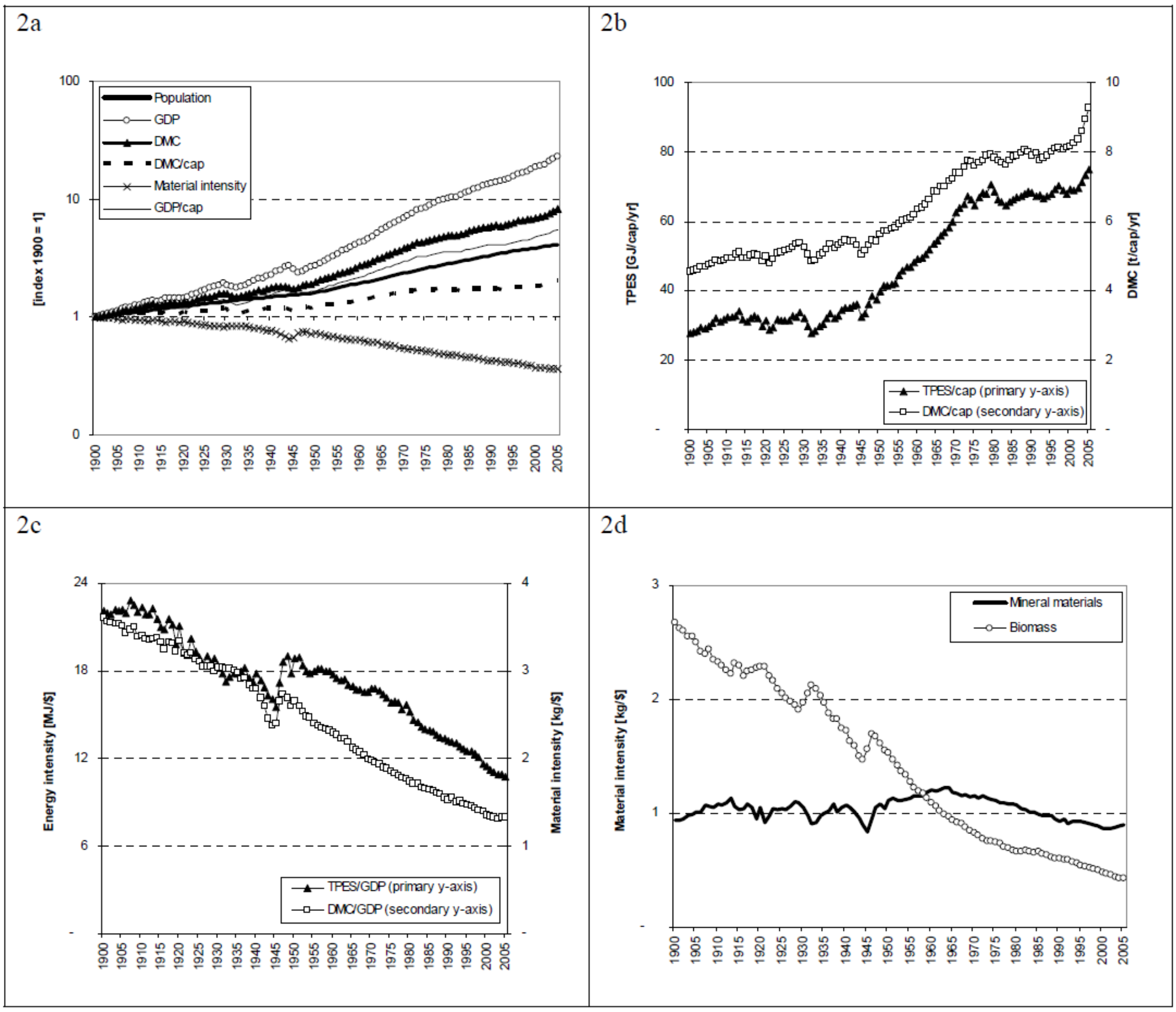

Figure 2: (a) Development of materials use (DMC), total primary energy supply (TPES), population and GDP; (b) Metabolic rates (materials use and TPES per capita and year); (c) material and energy intensity; (d) material intensity for biomass and mineral materials
Sources: TPES derived from Podobnik (1999), IEA (2007) and Fernandes et al. (2007); Population and GDP (1990 international Geary-Khamis Dollars) from Maddison (2008). All other data: see text.

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we have used (Maddison 2008) can be considered the most reliable estimate currently available, considerable uncertainties remain. Despite of these uncertainties, we assume, that the overall level of GDP growth in the observed period (more than 20fold) is robust and that the finding that GDP grows at a much faster rate than DMC during the 20th century is solid. The global trend is corroborated by data for individual countries for which more solid data for the historical development of both material/energy use and GDP exist (e.g. Gales et al. 2007, Bartoletto and Rubio 2008, Matos and Wagner 1998; unpublished calculations for Austria, UK, USA and Japan by the authors).

[11] In the period 2000 to 2005 DMC grew at an average annual growth rate of 3.7% (TPES: 2.7%) as compared to 1.8% (TPES: 1.4%) in the preceding decade.

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Which countries or regions drive global growth in materials use?

Unfortunately, no country- or region-specific data on global materials use are available yet for the observed period which constrains a more in-depth discussion of the contribution of different world regions or country groups to the trends observed at the global level. Nevertheless, some basic issues can be pointed out. Total global materials use in a given year can be expressed as the product of population and metabolic rates (materials use per capita). Thus, for a given material standard of life, population growth drives materials use: Population increased considerably and continuously throughout the last century in all regions of the world, but it grew by a factor of two faster in the so called "developing world" than in the industrialized countries.[12] In contrast, the metabolic rate increased much faster in the industrialized countries. Available case studies for the long term development of material and energy use in industrialized countries such as the USA (Matos and Wagner, 1998) and various European countries (Schandl and Schulz, 2002; Krausmann et al., 2008c; Kuskova et al., 2008; Gales et al., 2007; Bartoletto and Rubio, 2008) show that in the post WWII period per capita resource use has been rapidly growing. After the oil price peaks in the 1970ies, growth slowed down markedly and materials use in industrialized nations stabilized at a high per-capita level (see e.g. Eurostat, 2007a). In contrast, in developing countries such as India (Lanz, 2008), the Philippines (Kastner, 2007), China (Eisenmenger et al., 2009) and many Latin American countries (Russi et al., 2008, Gonzalez-Martinez and Schandl, 2008), during most of the 20th century growth in materials use was predominantly driven by population increase. Only in the last one to two decades a more pronounced growth of the metabolic rate can be observed. Even today, the use of fossil fuels and minerals per capita and year is very low in many countries of the South (Krausmann et al., 2008b).

This indicates that over the whole period, the contribution of the developing world to the growth of global materials use was mostly due to rapidly growing population numbers. In particular, this has driven global biomass extraction, but was much less responsible for the observed surge in the use of non renewable materials. In contrast, industrial development and post-war prosperity multiplied per-capita material and energy use in Europe, North America, Japan and the USSR. In combination with the growing number of people in the industrialized world, this has contributed disproportionately to the observed changes in the metabolic rate and to the changes of composition of materials use at the global scale. Thus the steep increase of metabolic rates and total volume of materials use after WWII as well as the relative stabilization since the early 1970s – mainly reflect the trends within the industrial world. The marked upturn of materials use since the year 2000, though, can be mainly attributed to a rise in metabolic rates in China, India and several Latin American countries. Nevertheless, at the beginning of the new millennium, the industrialized countries still dominate the global pattern of materials use: In the year 2000, fully industrialized countries (inhabited by 15% of the world population) were directly responsible for one third of global resource extraction[13]; this imbalance is even more pronounced for key materials such as fossil energy carriers, industrial minerals and metallic ores, where the share of the industrial countries is above 50% (Krausmann et al., 2008b; SERI, 2008).

[12] The population of industrial countries (here OECD countries plus Eastern European countries and the Soviet Union and successor states) grew by a factor of 3 while that of all other countries by a factor of 6 (Maddison, 2008). Consequently, the share of the industrial countries in world population declined from 25% in 1900 to 15% in 2005.

[13] Indirectly, their share may have been even larger, as many materially and energetically intensive production processes have been externalized to developing countries but result in commodities used in industrial countries (Fischer-Kowalski and Amann, 2001; Giljum and Eisenmenger, 2004).

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Global materials use and environmental impacts

In the past century, the expansion of the global social metabolism has resulted in a significant increase in human pressure on natural systems. The amount of materials used per unit of global land area[14] and year has increased from 0.5 t/ha/yr in 1900 to currently more than 4.5 t/ha/yr. Many local and global environmental problems that emerged in the 20th century are directly or indirectly related to the extraction and use of materials and changes in the size and structure of social metabolism. The expansion of biomass extraction has driven large-scale deforestation, a reduction of wilderness areas and biodiversity loss and an increase in land use intensity which is related to soil degradation, groundwater contamination and groundwater depletion. Mining activities and ore processing are associated with considerable toxic releases and the use of ores and other industrial minerals in consumer goods produces large amounts of often hazardous wastes. The total combustion of 500 Gt of fossil energy carriers in course of the 20th century was a major contributor to global green house gas emissions and climate change. The environmental effect of the extraction and use of bulk construction minerals is mostly indirect. Their movement, processing and use require considerable amounts of energy. The built infrastructure for which these materials are used contributes to soil sealing and requires materials and energy for operation and maintenance. In this case qualitative characteristics of the built infrastructure are more important than the sheer size of the associated flow of materials. Last but not least, the growth in materials use leads to the accelerated exploitation of unevenly distributed and limited stocks of mineral resources. This contributes to increasing production costs and eventually physical scarcity and often causes conflicts about access to resources and about resource prices within and between countries (Martinez-Alier, 2002; Bunker and Ciccantell 2005). In most cases, the ones who suffer from these conflicts are countries of the global south and the poorest fractions of society.
Clearly, the environmental pressures and sustainability problems associated with the extraction and use of materials are extremely heterogeneous. They differ largely by material and vary over time with technological change. Aggregate materials use indicators as those discussed in this paper can not capture the full environmental effect of shifts in the composition of materials use or of technological fixes. But even though there is no simple one to one relation between aggregate materials use and environmental deterioration, the size and composition of materials use serves as a proxy for environmental pressures resulting from human activities.

Conclusions

The last century witnessed an eightfold multiplication of the size of the global social metabolism and a transition from the dominance of renewable biomass towards mineral materials. Materials use has reached a size which matches material flows in ecosystems and continues to grow. In the past century, materials use grew at a smaller rate than GDP, and material productivity continuously improved at an average rate of 1% per year. By the centennial perspective, it is evident that relative dematerialization is a standard feature of economic development. Nevertheless, this dematerialization and these productivity gains did not translate into reductions of materials use. What can we expect for the future of global materials use? During the last century, it has been a combination of global population growth and first rising and then stabilizing per-capita materials use of industrial countries that has driven global materials use. In the most recent past, per-capita resource use in newly

[14] Global land area excluding Greenland and Antarctica (Haberl et al. 2007).

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industrializing country like China, India, Mexico or Brazil started to rise, while the world's least developed countries are only now beginning the transition towards an industrial type social metabolism. With global economic development continuing in a business-as-usual mode and a projected population growth of 30-40% until 2050 (UN, 2007b; Lutz et al., 2004), we should expect another sharp rise in global material extraction. A reduction of global materials use or at least stabilization at the current level will require major reductions in metabolic rates, above all in industrialized countries. Gains in the efficiency of materials use could contribute to a decoupling of economic growth and materials and energy use but this requires effective strategies to avoid rebound effects (Herring 2004), which in the past century have counterbalanced the effect of efficiency gains on material use.

In view of the need to substantially de-carbonize social metabolism (or else face major threats from climate change), an alarming decline of global remains of wilderness and biodiversity, and with multiple scarcities coming into vision (available cropland, fish stocks, freshwater, fossil oil and gas, various metal ores), it does not seem so likely that by the end of the current economic crisis there will be a return to an economic business-as-usual mode. Even if everybody would strive for an American way of life for themselves or their children in the future, it is hard to believe that this is going to succeed. So may be the current economic crisis, willingly or not, provides with an opportunity for a strategic withdrawal from overconsumption instead of taking the risk, that finally humanity has to accept a full defeat.

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