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Institute of Social Ecology
IFF - Faculty for Interdisciplinary Studies (Klagenfurt, Graz, Vienna)
Alpen-Adria Universitaet
Schottenfeldgasse 29
A-1070 Vienna
+43-(0)1-522 40 00-403

www.aau.at/socec
workingpaper@aau.at

The socio-metabolic transition. Long term historical trends and patterns in global material and energy use

Edited
by

Fridolin Krausmann

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Introduction

Human beings, like all other organisms, depend on a continuous throughput of materials. Water and food are the most essential of these material requirements. Food, a specific mix of digestible biomass, provides humans with nutritional energy and with the organic and mineral components necessary to build up and maintain the body and its functioning. After being used or stored in the human metabolic system, all intakes leave body in the form of excrements or through the respiratory system. The same applies to human society. It requires a permanent input of materials and energy for the production and reproduction of its physical stocks: But the material needs of a particular society are generally much larger and more diverse than the basic metabolic needs of the sum of the individuals forming its population. Next to population, the physical stock of any socio-economic system comprises domesticated livestock and a vast number of artefacts, from simple tools and shelters in traditional agrarian communities to machinery, durable goods, infrastructure and buildings in modern industrial societies. To build up these stocks, to maintain, renew and operate them, industrial societies extract vast amounts biotic and mineral materials from their natural environment. These materials are processed and transformed, some are consumed within a short period of time, while others are stored for centuries, some are discarded after use and some recycled. At some point, however, all materials leave the socioeconomic system in the form of wastes or emissions. In analogy to the metabolism of biological organisms the term *social* or *industrial metabolism* has been coined (Baccini and Brunner, 1991, Fischer-Kowalski and Hüttler, 1998, Ayres and Simonis, 1994). Many of the regional to global environmental problems that human society faces at the beginning of the 21st century are directly related to its metabolism: From the extraction of raw materials in agriculture and mining and their processing in industry to the consumption of the supplied goods and services and the inevitable formation of wastes and emissions, our metabolism causes a huge variety of environmental pressures including the most serious threats to global sustainability.
In this context, the concept of social metabolism has not only proven a useful metaphor to stress the biophysical foundation of social systems and their economy, but it has emerged as a key analytical concept in sustainability science. In new interdisciplinary fields like industrial ecology or ecological economics sophisticated methods and tools have been developed to study material and energy flows in socio-economic systems in order to contribute to the design and implementation of more sustainable types of industrial metabolism (Bringezu et al., 2009).

The notion of (socio-) *metabolic transition* has been introduced to describe fundamental changes in socio-economic energy and material use that occur in the course of human history from prehistoric hunter and gatherers towards present day industrial societies (Fischer-Kowalski and Haberl, 2007). It has been shown that the transition from an agrarian towards an industrial society, for example, implies a multiplication of both metabolic rates (material and energy flows per capita and year) and population and consequently also metabolic scale (the overall size of resource flows) (Krausmann et al., 2008). Not only the size of material and energy flows, but also their composition changes, and a shift from biomass towards mineral and fossil materials occurs. Growth in material use typically is accompanied by a considerable decline in resource use per unit of GDP (resource intensity) (Krausmann et al., 2009). The transition from a solar energy system tapping into renewable flows of biomass towards a fossil fuel powered energy system based on the exploitation of large stocks of energy resources allowed for an emancipation of the energy system from land use and abolished traditional limits of growth (Sieferle, 2001). Along with resource consumption also the production of wastes and emissions and pressures on the environment increased. It has been argued that humans have entered an entirely new era, the anthropocene (Steffen et al., 2007).

Empirical research so far has focussed on the energy side of the metabolic transition, and only limited evidence from material flow analysis (MFA) exists. Most existing MFA studies are limited to a few decades and, with a few exceptions, time series begin in the 1970s only (e.g. Russi et al., 2008). These studies allow for the analysis of a specific phase of industrialisation which was marked by the oil price shocks of the 1970s and the subsequent deceleration of growth in energy and material use in most countries, but they miss important phases of industrial development which were of key importance for the emergence of the metabolic patterns of modern industrial societies.

This volume explores the long term historical dynamics of changes in social metabolism during the last one and a half centuries from a material flow perspective. Three national case studies investigate the evolution of material use in two fully industrialized and a newly industrializing economy. Chapter one and two present material flow accounts covering a 135 year period for two leading economies of the world: Japan and the United States of America. While the USA overtook the United Kingdom as the world's leading economy in the early 20th century, Japan is a typical late comer and was characterized by a very rapid process of industrialisation after World War II. At the beginning of the 21st century, the US economy still dominates both the global economy and global metabolism. It consumes roughly one quarter of all primary energy and raw materials and has one of the highest levels of per capita material consumption. Japan, in contrast is one of the few economies which has implemented a consequent policy aiming at an absolute reduction in material use and indeed has shown absolute dematerialisation for a period of more than a decade. Its current per capita material use amounts to only half of that of the US. Despite the differences in their current patterns of material use, both economies show similarities in terms of their metabolic transition. Both have multiplied the amount of materials used by more than one order of magnitude, despite massive increases in resource productivity. Chapter three focuses on India, one of the worlds most populated economies and a rapidly developing economy. India, comprising almost a fifth of the world's population, but consumes only 6% of global energy, and 10% of global material supply. But India's resource demand is growing rapidly which is of high relevance for sustainable development both for India and at the global scale.
The last paper provides a long term perspective of the evolution of global material use. It investigates changes in the structure of human resource use from hunter gatherer societies to modern industrial societies and puts the findings from the three country case studies in a larger context.

Fridolin Krausmann, May 2011

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The metabolic transition in Japan: A material flow account for the period 1878 to 2005

Fridolin Krausmann, Simone Gingrich and Reza Nourbakhch-Sabet

1. Abstract

The notion of a (socio) *metabolic transition* has been used to describe fundamental changes in socio-economic energy and material use during industrialization. During the last century, Japan developed from a largely agrarian economy towards one of the world's leading industrial nations. It is one of the few industrial countries which experienced prolonged dematerialization and recently has adopted a rigorous resource policy. This paper investigates changes in Japan's metabolism during industrialization on the basis of a material flow account for the period 1878 to 2005. It presents annual data for material extraction, trade and domestic consumption by major material groups and explores the relation between population growth, economic development and material (and energy) use. In the observed period, the size of Japan's metabolism grew by a factor of 40 and the share of mineral and fossil materials in DMC grew to over 90%. Much of the growth in the Japanese metabolism was based on imported materials and occurred in a very short period of only 20 years after WWII, when Japan rapidly built up large stocks of built infrastructure, developed heavy industry and adopted patterns of mass production and consumption. But the surge in material use came to an abrupt halt with the first oil crisis. Material use stabilized and the economy eventually began to dematerialize. Although GDP grew much faster than material use, improvements in material intensity are a relatively recent phenomenon. Japan appears as a role model for the metabolic transition, but is also exceptional in many ways.

2. Introduction

The notion of (socio-) *metabolic transition* has been introduced to describe fundamental changes in socio-economic energy and material use during industrialization (Fischer-Kowalski and Haberl 2007; Haberl et al. 2009). It has been argued that the transition from an agrarian towards an industrial society typically implies a multiplication of both metabolic rates (material and energy flows per capita and year) and population and consequently also metabolic scale (the overall size of extraction and trade flows). Not only the size of material and energy flows, but also their composition changes, and a shift from biomass towards mineral and fossil materials occurs (Krausmann et al. 2008b). It has also been shown, that growth in material use typically is accompanied by a considerable decline in resource intensity (resource use per unit of GDP) (Krausmann et al. 2009). Research so far has focused on the energy side of the metabolic transition (Gales et al. 2007, Warr et al. 2010, Krausmann et al. 2008c), and only limited empirical evidence from material flow analysis (MFA) exists. Most existing MFA studies are limited to a few decades and, at best time series at best begin in the 1970s (e.g. Schandl and West 2010; Russi et al. 2008). These datasets allow for the analysis of a specific phase of industrialization which was marked by the oil price shocks of the 1970s and the subsequent deceleration of growth in energy and material use in most countries (Krausmann et al. 2008c; Bringezu et al. 2004). These studies thus miss important phases of industrial development and the metabolic transition, such as the decades after WWII, and the emergence of a society of mass production and mass consumption, during which tremendous increases in per capita resource use in industrial countries occurred (cf. also Grübler 1998; Steffen et al. 2007). To our knowledge, only two comprehensive long term material flow datasets consistent with current conceptual and methodological standards in material flow accounting exist: Material use in the United Kingdom for the period 1850 to

1998 has been analyzed by Schandl and Schulz (2002) and Krausmann et al. (2009) recently published a global time series of material extraction for the last century. Long term data have also been published for selected material flows, for example, for the USA (Rogich and Matos 2002).

This paper presents a time series of material flow data for the Japanese economy for the period 1878 to 2005.[1] With this study, we significantly extend the period for which material flows in the Japanese economy have been compiled so far: a first material flow account for Japan, covering the period 1975 to 1993 has been included in the seminal multinational MFA study by the World Resources Institute (Adriaanse et al. 1997) and Japan's Ministry of the Environment (e.g. 2007) has compiled annual time series data beginning in 1980.[2]

The time period observed in this paper begins right after the Meiji restoration and covers Japan's transformation from an agrarian country to one of the leading economies in the world, then the so-called lost decade after the Japanese bubble economy burst in the late 1980s, and economic recovery in the 1990s (Allen 1981, Hentschel 1986). It also includes important incidents at the global scale such as the world economic crisis in the 1930s, World Wars I and II and the oil price shocks following the initial incident in 1973.

After a brief description of methods and data sources, we present annual times series data for the period 1870 to 2005 for extraction, imports and exports of materials by main material groups and for aggregate material flow indicators such as domestic material consumption and material intensity. Based on these data we investigate the path of the metabolic transition in Japan. We identify changes in material input and use during Japan's industrialization and discuss the significance of socio-economic factors underlying the observed changes in the physical economy of Japan. Finally, we explore changes in the material intensity of the Japanese economy and the issue of dematerialization.

3. Methods and data

We followed the basic principles and current international standards of economy wide material flow accounting (MFA) as proposed e.g. by the European Statistical Office (Eurostat 2009, see also OECD 2008) to account for used extraction, and direct imports and exports of materials. Unused extraction or indirect flows associated with imports and exports were not accounted for (see e.g. Bringezu et al. 2009). We applied standard estimation procedures for the extraction of flows not reported in statistical sources and adapted them for long term historical application. Our data are thus consistent with the current state of the art methods of MFA and are comparable to other existing material flow accounts for Japan covering more recent periods (section 4). Our database provides material flow data at a medium level of aggregation discerning a maximum of 61 different material groups. For this paper we use aggregate information and present data on the level of four main material groups: biomass, fossil energy carriers, metal ores and non-metallic minerals (including construction minerals).

[1] Data will be made publicly available and can be downloaded from the web page of the Institute of Social Ecology: http://www.uni-klu.ac.at/socec/inhalt/1088.htm

[2] See also Moriguchi 2001; Moriguchi 2002 for a discussion of early Material Flow data of the Japanese economy.

Data on fossil energy carriers, metal ores and non-metallic minerals are also subsumed under mineral and fossil materials (as opposed to biomass).

We calculated the following material flow indicators (see Fischer-Kowalski et al. 2010): Domestic extraction (DE), imports and exports; domestic material consumption (DMC, defined as DE plus imports minus exports); physical trade balance (PTB, defined as imports minus exports); trade dependency (defined as PTB per DMC); material intensity (MI, defined as DMC per unit of GDP; MI is the inverse of material productivity). We refer to per capita values of domestic material (and energy) consumption as metabolic rates.

We quantified material extraction and use for Japan proper as defined by the statistical sources we have used for the respective period. We did not include material extraction in Japanese colonies (e.g. Formosa (Taiwan), Chosen (Korea) or Manchuria), but trade between Japan proper and its colonies was accounted for as foreign trade. In practical terms, this means, that the observed territorial system roughly resembles that of Japan in its current boundaries throughout the observed period.[3] Our main data source was the excellent Japanese historical statistics database maintained by the Statistics Bureau Japan (2008) which provides among others comprehensive physical information on agriculture, forestry, fishing and mining, the production of related industries and trade. It contains annual time series data beginning as early as 1868 to the most recent years. However, some of the series are shorter and several cover the period after WWII only. Other important publications on Japanese historical statistics include a comprehensive data collection by The Bank of Japan (1966) and early data on foreign trade by Ishibashi (1935). Additionally we used international data compilations and sources to complete and crosscheck our data series. These data compilations include Mitchell (2003), FAOSTAT (2010), UN (2007), IEA (2007), USGS (2008), United Nations Statistical Division (2008) and more specific literature. Data on population and GDP (in international Geary-Khamis Dollars) were taken from Maddison (2008).

3.1. Biomass

We combined information on crop harvest and fish catch from Statistics Bureau Japan (2008) and FAOSTAT (2010). Complete and comparable data were available for the whole period. Crop residues were estimated using region-specific information on corn-straw rations (harvest indices) from Krausmann et al. (2008a) for which we assumed changes over time (i.e. a 20 to 80% increase in harvest indices during the last 130 years, depending on crop species). Grazed biomass was estimated on the basis of data on livestock numbers (Statistics Bureau Japan 2008; FAOSTAT 2010) and average feed intake per head and day. Feed intake data were calculated on the basis of ruminant production (milk yield per cow, average live weight) and assumptions on productivity changes. To arrive at the amount of grazed biomass and other roughage harvested to feed livestock we subtracted information on available feed (market feed, fodder crops and crop residues used as feed) from total demand. Data on feed supply were derived from Statistics Bureau Japan (2008) and FAO (2010). For the period from 1878 to 1961 only limited information on the volume of available market feed was available and we assumed that grazed biomass and harvest from grassland covered 70% of the feed demand

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[3] Minor deviations from these territorial system boundaries are possible; often, sources are not explicit about their reference system and in some cases not all prefectures or islands have been included in the surveys (see Statistics Bureau of Japan 2008).

of grazers. The feed balance was performed in dry matter; results were converted into MFA relevant mass assuming an average moisture content of 15% (Eurostat 2009).

Statistics Bureau Japan (2008) covers fuel wood extraction beginning in 1929 and lumber harvest beginning in 1954. This information (which includes some statistical breaks and implausibilities most likely due to unit confusions in the sources) was completed with data from the Bank of Japan (1966) and FAOSTAT (2010) and crosschecked with information in Mitchell (2003). For the period prior to 1929 fuel wood harvest was extrapolated from the average per capita consumption of the early 1930s and population numbers. We assume that official fuel wood data underestimate actual use in early periods, particularly in the period prior to WWII, for which we arrive at a per capita DMC of fuel wood of comparatively low 0.2 t/cap/yr. Information on the extraction non timber and fuel-wood products from forests was scarce; however, the involved mass flows are typically very low.

3.2. Fossil energy carriers

Extraction of fossil fuels is covered completely in Statistics Bureau Japan (2008). Additionally we used data from The Bank of Japan (1966), IEA (2007) and Mitchell (2003) to crosscheck data and eliminate minor flaws.

3.3. Ores and non metallic minerals

Data on mineral extraction provided by Statistics Bureau Japan (2008) begin in 1874, however, for many mineral materials data series only begin in the early 20th century. To complement data for the years prior to WWII we used data provided by The Bank of Japan (1966) and Torgasheff (1930). For the period 1960 to present, we also used data from USGS (2008) and UN (2007) to crosscheck and amend the data base. We calculated the amount of extracted gross ores using information on metal content, ore grades and coupled production derived from USGS (2008) and Torgasheff (1930). The applied extrapolation coefficients were kept constant over time.

Data on construction minerals were not reported in available statistical sources, except for some years and some specific items. In particular flows of natural aggregates used in construction and limestone for cement production had to be estimated. We used the procedure proposed in Krausmann et al. (2009) (and applied in a slightly modified form in a recent study on material flows in the Asia-Pacific region by Schandl and West (2010)) and estimated the demand for sand and gravel used for concrete and asphalt production on the basis of data on cement and bitumen consumption. We assumed a ratio of sand and gravel to cement in concrete of 6.1 and of gravel to bitumen in asphalt of 20. Furthermore we assumed that 1.15 tonnes of limestone are required to produce one ton of cement (Krausmann et al. 2009). Data on cement production and consumption were derived from Cembureau (1998), Statistics Bureau Japan (2008) and Bank of Japan (1966); bitumen consumption was derived from data in IEA (2007) and Statistics Bureau Japan (2008). Additionally we calculated sand and gravel demand for the construction of railroads assuming 10,000 t of sand and gravel per km of newly built railroad tracks (Bank of Japan 1966, Statistics Bureau Japan 2008) in order to cover important construction activities in earlier periods. In general the applied coefficients are conservative and it can be assumed that the procedure has a tendency towards underestimating the overall amount of natural aggregate use: Our estimate emphasizes on natural aggregates which in most countries account for more than 90% of construction minerals, but we neglect other materials such as clay for bricks. Also filling materials are not fully accounted for (Krausmann et al. 2009).

3.4. Trade

For the period 1960/61 to 2005 we used data from FAO (2010) for trade with agricultural and forestry products, IEA (2007) for trade with fossil energy carriers and trade data from United Nations Statistical Devision (2008) at the three digit level of SITC rev.1 (approximately 300 items) for trade with all other products. Data for the period 1946 to 1960 were derived from Statistics Bureau Japan (2008) and are presumably incomplete (we assume that we do not account for some 20-40% of total trade flows in mass in that period). Data for the period 1870-1933 are based on Ishibashi (1935) and include trade with Japanese colonies. Trade between Japan proper and its colonies was significant and accounted for 23% of total imports and 26% of total exports in 1933. For the period 1934 to 1945 no trade data were available. Although trade flows in that period may have increased, we assume that the overall mass of trade flows remained small compared to DE; after WWII trade volumes (in monetary terms) reached the level of the middle of the 1930s only in the late 1950s (Allen 1981).

3.5. Primary Energy

Data on material flows were used to calculate total primary energy supply (TPES). We converted fuel wood and fossil fuel DMC into energy units using material specific coefficients for gross calorific values. Energy flow data derived from MFA were supplemented with energy inputs from hydropower, nuclear heat and geothermal sources. Data on electricity output from hydro and nuclear power plants were converted into primary energy input by applying coefficients for average conversion efficiency (Warr et al. 2010).[4]

4. Data quality and reliability

One of the reasons why most MFA studies hardly go back in time beyond the 1970s is that it is a difficult and laborious process to compile long term time series data of sufficient robustness and comparability. International data compilations and digitally available data get increasingly scarce for periods prior to the 1970s. In the case of Japan the compilation of a time series covering 135 years was feasible because Japan has a long tradition of statistical records and comprehensive sources for historical statistics (e.g. Statistics Bureau Japan 2008) provided a reliable empirical backbone for the material flow account. However, long term data do have their weaknesses and uncertainty tends to increase, the further time series are extended to historic periods as underreporting, data gaps and flaws become more frequent.

Japan has a long tradition in statistics and the quality of the used sources must be regarded as very high. Nevertheless, we assume that we slightly underestimate material extraction, in particular for the early years. As has been outlined in the methods section, our estimates for

[4] While most of the electricity produced in Japan comes from thermal power plants, this is already accounted for in the consumption of fossil energy carriers. In contrast, the primary power and heat used to produce electricity in hydro- and nuclear power needs to be extrapolated from electricity output (Haberl 2001).

construction minerals and some biomass flows, in particular the extraction of wood and other forest products have to be considered conservative. Furthermore, the data coverage is insufficient for the period 1934 to 1945 for which only data on DE but no trade data were available. Also for the years 1946 to 1960 trade data were incomplete and net imports have to be considered too low (roughly by 20-40%). Hence, aggregate indicators for this period have to be interpreted cautiously. Despite these caveats, it can be assumed that our data represent the size of material flows for the four material groups and their development over time fairly well, even in the time period from 1878 to 1960. We assume that possible underestimations of some flows are not significant enough to distort the overall picture of trends in material use over time.

The reliability of our data is further corroborated when compared with official Japanese MFA data: For the period 1980 to 2004 MFA accounts published by the Japanese Ministry of the Environment (2007) are available. For most flows and material groups our data match very well with the Japanese data set; this is in particular encouraging for domestic extraction, where large material flows were estimated (e.g. grazed biomass, sand and gravel and gross ores). For the extraction of gross ores (which is a very small flow compared to the other main material groups in Japan) we arrive at considerably higher figures than those reported in the official Japanese dataset; however, an in-depth review showed that Japanese data most likely refer to metal content rather than gross ore. Figure 1 shows that our results are very similar to official Japanese MFA data both with respect to the overall amount of DMC and its development over time. In terms of trends over time, our data also match well with the Japan data published recently in a multinational material flow database for the Asia-Pacific covering the period 1970 to 2005 (Schandl and West 2010). The Schandl and West data are, however, not based on national statistical sources or country specific coefficients used in estimates, which explains differences in metabolic scale (Figure 1).

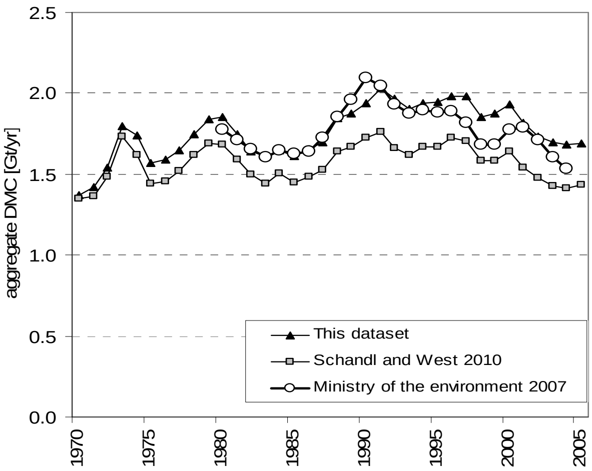

***Figure 1**: Comparison of aggregate DMC from available MFA datasets for Japan for the period 1970/80 to 2005: The official Japanese MFA data published by the Ministry of Environment (2007), the Asia-Pacific data set of Schandl and West (2010) and this dataset.*

5. Domestic extraction, trade and domestic material consumption

Figure 2 shows the development of domestic material extraction (DE), trade flows and domestic material consumption (DMC) by the four main material groups. In 1878, biomass accounted for almost 90% of DE, but the extraction of fossil energy carriers and mineral materials increased continuously, and by 1923 surpassed biomass in terms of mass. Between 1878 and the 1940s total extraction multiplied almost 7 fold from 0.03 Gigatonnes (Gt, billion tonnes) to 0.2 Gt. At the end of WWII, DE slumped to only half of the pre-war value, in particular the extraction of mineral materials. After 1947 DE quickly recovered: It surpassed the pre-war peak already in 1951 and then experienced a sheer explosion in the period until 1973. The steep increase in overall DE was caused by a surge in non-metallic minerals, mostly natural aggregates for construction, which dwarfed all other material flows. The steep rise of non-metallic minerals DE was interrupted by the oil price shock in 1973, but DE continued to rise to reach its maximum in 1991. The development of the extraction of all material groups shows an inverted U shape and declines after early peaks: DE of fossil energy carriers already peaked in 1943, not quite reaching this level again in a second peak after WWII in 1962. DE of biomass peaked in 1960 and DE of ores in 1967. During the observed period, aggregate extraction grew 36 fold and reached a peak in 1991 at 1.4 Gt (i.e. 3% of global DE at that time). Biomass was the material group with the lowest growth; it quadrupled between 1878 and 1960. After 1960, DE of biomass declined from 0.13 to 0.08 Gt or by 40 %.

Trade flows exhibit an even more extreme growth pattern (Figure 2). Mass flows entering or leaving Japan via trade were very small in the decades before World War II: Total imports only reached 1/10 of DE in the 1930s and exports never exceeded 5% of DE. The most relevant trade flows in this period were imports of biomass, above all food items and cotton, and, in later years, also of ores. On the export side, coal and increasingly manufactured products were the dominating mass flows. Unfortunately, no trade data for the period 1934 to 1955 are available, although it can be assumed, that imports of wood and minerals from Manchuria and other colonies have been considerable. After the war both imports and exports experienced steep growth: Imports grew at average annual rates of 21% and exports at 26% during the period 1955 to 1971. The surge of imports was interrupted in 1973 (oil price shock), but continued in the 1980s, while the growth of exports slumped between 1985 and 1990. By 2005, exports had reached 15% of DE and imports more than 80%. During the whole period after WWII, imports were much larger than exports and Japan remained a massive net importer of all four material groups. It imported large amounts of biomass and fossil energy carriers, but also ores and minerals. Exports mostly consisted of products from metals and non-metallic minerals.

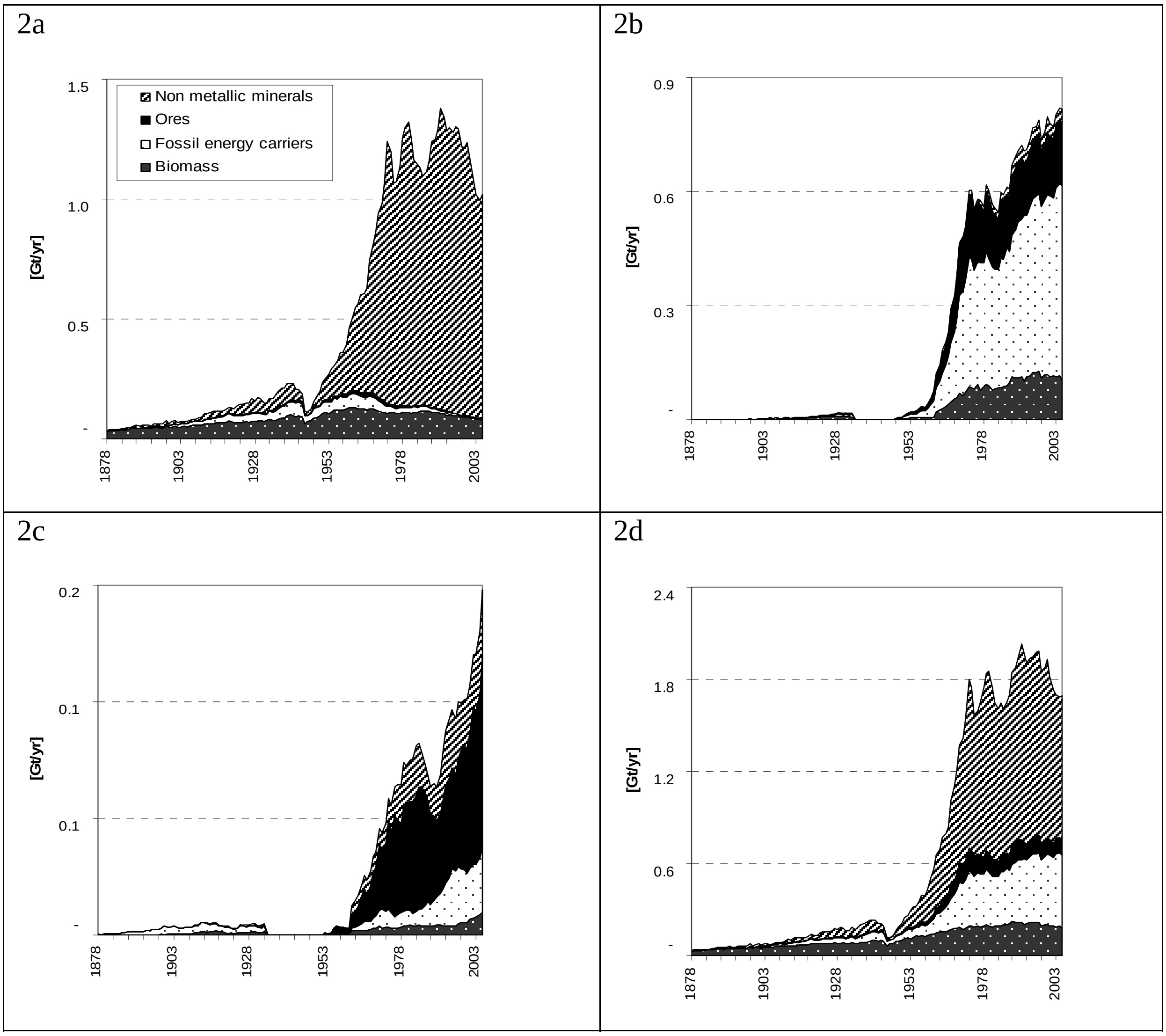

Figure 2*: Material flows in Japan 1878 to 2005: Domestic extraction (DE) of raw materials (2a); imports (2b), exports (2c) and domestic material consumption (DMC) (2d) of raw materials and manufactured products. Manufactured products have been allocated to one of the four main material groups based on the dominating material. Note the different scales of figures 2a to 2d*

As a result of the development of DE and trade flows, domestic material consumption (DMC) (Figure 2d) grew slowly in the period before WWII, from 0.04 Gt in 1878 to 0.23 Gt in the 1940s but surged in the 1950s and 60s to 1.8 Gt in 1973. The effect of the oil price shocks on DE and imports is clearly reflected in material consumption which dropped considerably in 1973. After 1973, the previous growth dynamic came to a halt. DMC experienced major ups and downs and reached its peak at 2 Gt in 1990. Since, Japan's economy has been dematerializing and DMC decreased by 15% to 1.7 Gt in 2005.

6. The dynamics of growth

Japan presents itself as a show case of the metabolic transition from an agrarian to an industrial metabolic regime. During the observed 130 year period, population grew by a factor of four, but metabolic rates surged by more than an order of magnitude: Material use (DMC/cap/yr) grew by a factor of 14 and primary energy supply (TPES/cap/yr) by a factor of 50 (Table 1 and Figure 3). While biomass dominated material and energy use in the late 19th century, its contribution to DMC and TPES was dwarfed to less than 10% a century later (Table 2). This transition was by no means a steady process. Three periods with distinct patterns of change in material and energy use can be identified: A period of moderate physical growth from 1878 to the outbreak of WWII (interrupted by the World Economic Crises of the 1930s), a period of radical growth beginning shortly after WWII and lasting until the early 1970s and finally a period of stagnation beginning in 1973, which is characterized by strong fluctuations and eventually dematerialization. Table 1 shows average annual growth rates for major physical and economic headline indicators for these three periods. Growth rates for all resource use indicators are moderate in phase one, increase by a factor 3 to 5 during the second phase and are low or even negative during the third phase.

	Moderate growth* 1878-1930	Rapid growth 1948-1973	Stagnation 1973-2005	Growth factor 2005/1878
Population	1.1%	1.2%	0.5%	4
GDP in intl. $	2.8%	9.2%	2.6%	97
DMC in t	3.2%	10.2%	-0.2%	49
Income in $/cap/yr	1.6%	7.9%	2.1%	28
DMC in t/cap/yr	2.1%	8.9%	-0.7%	14
DMCminerals/fossils in t/cap/yr	5.1%	12.0%	-0.7%	104
TPES in GJ/cap/yr	3.4%	7.9%	1.3%	50

Table 1*: Average annual growth rates of population, GDP and material and energy use during periods of development. Sources: own calculations.*

*we calculated growth rates only for the period 1878 to 1930 in order to avoid distortions from the world economic crisis and incomplete data (see section 2).

In the 1880s, during the Meiji period, the metabolism of the Japanese economy resembled the metabolic profile of a typical agrarian regime (Krausmann et al. 2008b). Four fifths of the population was making their living in agriculture (Table 2); material consumption amounted to merely 1.1 t/cap/yr with biomass accounting for almost 90% of DMC. Nearly all material resources were met from domestic extraction; imports and exports were insignificantly small. But the shift from an organic to a mineral economy (Wrigley 1988) was already under way. The so-called Meiji restoration at the end of the 1860s led to the abolishment of feudal traditions and institutions and opened the country to the West. Japan began to industrialize and engaged in international trade. Much of this early industrialization was in the silk and textile industry in small scale factories and based on biomass as primary raw material. The expansion of metal manufacturing and chemical industries in the late 1930s resulted in a more material intensive development and an increase in the per capita consumption of mineral and fossil materials (Figure 3b). In this period, the merchant fleet and the railway system were expanded and exports in monetary terms surged (Allen 1969). Japan's (military) expansion in the Far East, culminating in the Sino-Japanese war in 1937, significantly contributed to rapid industrialization in this period (Allen 1981). The corresponding material flows, however, remained comparatively low (Figure 2). Japan was exporting considerable amounts of ores and later also coal and imported predominantly food and cotton. But overall, imperial Japan rather followed a policy of economic self-sufficiency and trade dependency (net imports as share of DMC) remained low at only 8% in 1930 (Figure 4). In the first decades of the 20th century also heavy industry gained significance and contributed to physical growth, but its per capita output in physical terms remained rather low.[5] Industrial growth is reflected in increasing but overall still low values of material and energy use per capita (Figure 3). But even in this period of moderate physical growth, material and energy use increased faster than population and GDP (Table 1). All in all per capita material use tripled and the share of biomass in DMC declined to less than 50% in the years prior to Japans involvement in WWII.

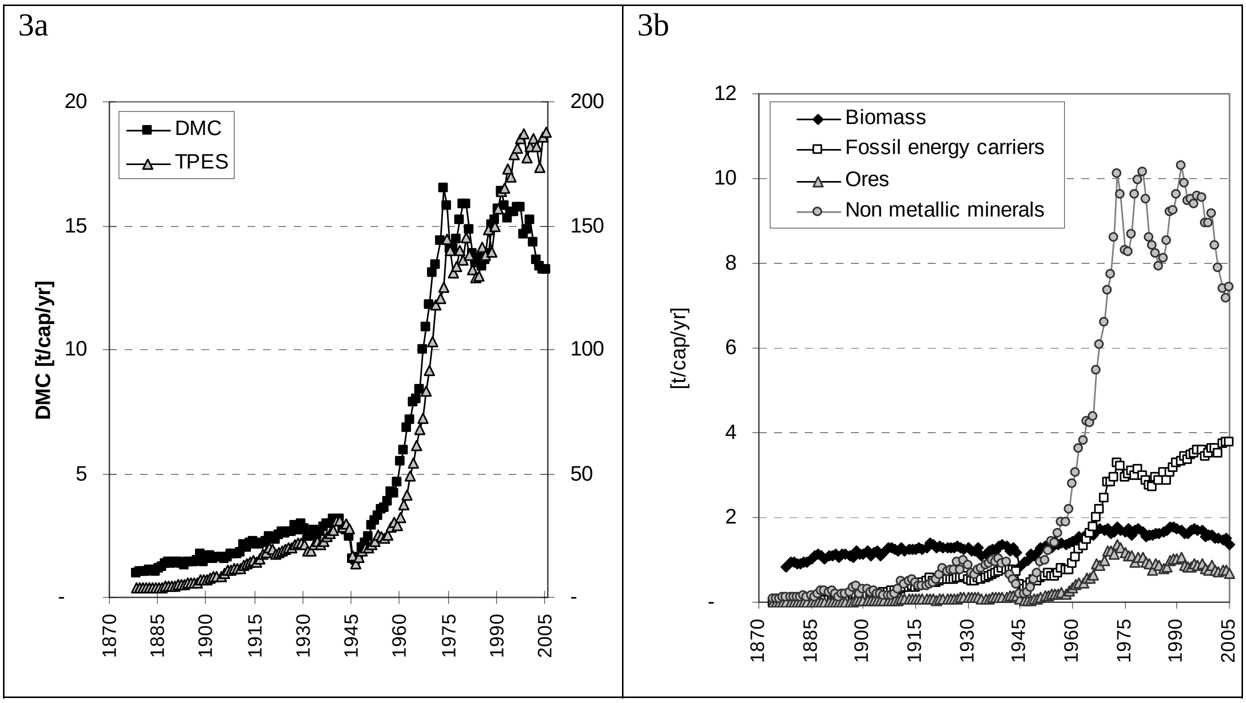

***Figure 3**: Metabolic rates: Material use (DMC) and total primary energy supply (TPES) per capita and year (3a) and DMC per capita by main material groups.*

World War II left Japan with massive destruction. Most cities, industrial buildings and plants were devastated.[6] Raw materials were scarce and food and other necessities of life were lacking (Allen 1981). In the 1950s, pushed by economic, social and institutional reforms of the Occupational Authorities and demand increases induced by the Korean War, Japan's economy recovered quickly. In the two decades that followed Japan's independence in 1952, the Japanese economy grew faster than any other large economy in the world (Allen 1981).

[5] Per capita output of Japanese heavy industries remained low: Steel production, for example, barely reached 100 kg/cap/yr in the years prior to WWII, compared to around 350 kg/cap/yr in Germany or the USA (based on Mitchell 2003). Similarly, Japanese cement production (per capita) amounted to less than half the value typical for European industrializing countries (Cembureau 1998).

[6] The amount of physical destruction has been estimated at twice the national income of the fiscal year of 1948/49 (Allen 1981)

This period saw the building of great trunk roads and elevated highways, the modernization of the rail system and a massive expansion of heavy industry and manufacturing.[7] Concrete rapidly replaced the traditional building material wood and stocks of built infrastructures increased to several hundred tons per capita (Hashimoto et al. 2007; Tanikawa and Hashimoto 2009). Japan experienced a consumption revolution and material benefits of economic development now also reached rural areas. This triggered rapid physical growth and radical changes in Japan's metabolism. Material and energy use grew much faster than population and even faster than GDP. Per capita material and energy use saw average annual growth rates of 8.5 and 12 % (Table 1, Figure 3) and the share of biomass in DMC declined rapidly (Figure 2d). Under US occupation, Japan dismissed its autarky policy and sought integration into international markets. Japan began to import most raw materials and energy carriers. Within less than 20 years, trade dependency for fossil energy carriers and ores surged from almost zero to more than 90% (Figure 4). Domestic extraction of these materials, in contrast, peaked and began to decline in the 1960s (see section 4). In 1973 material consumption reached an all time high of 16.5 t/cap/yr, which was 6 times the pre-WWII level. The share of biomass had declined to less than 10%.

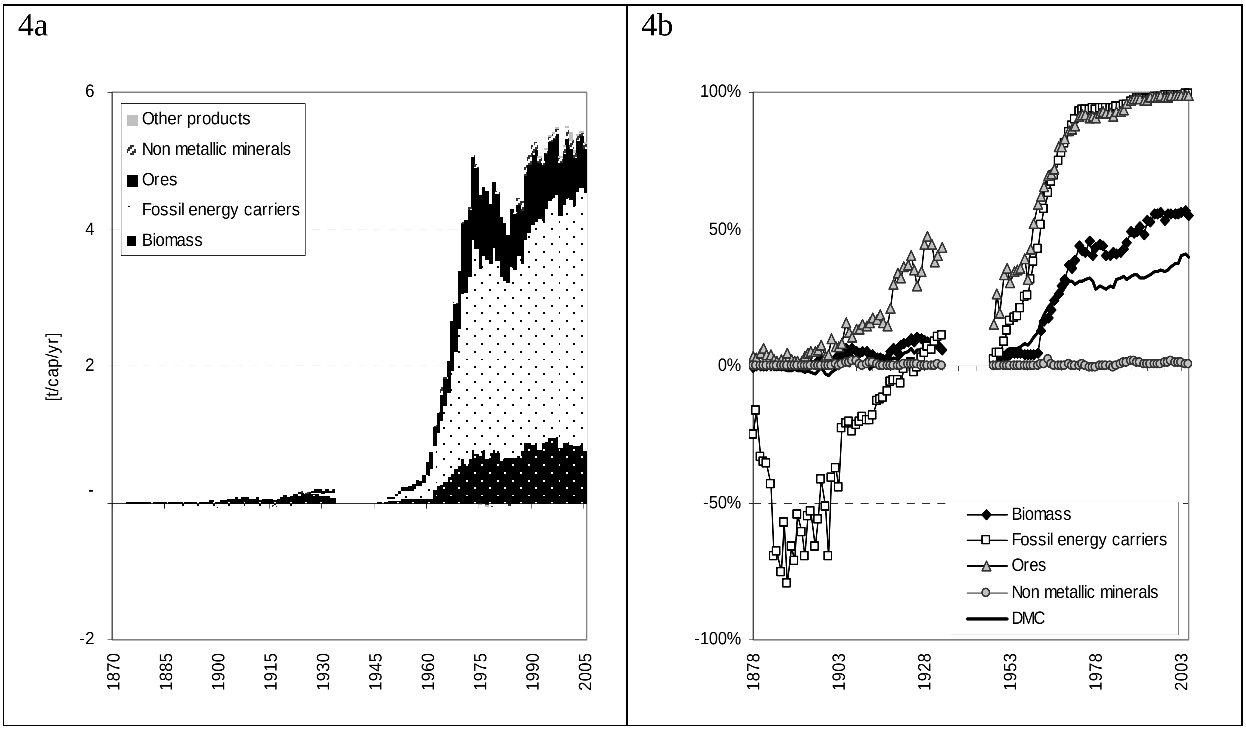

***Figure 4**: Physical trade balance: PTB per capita (4a) and trade dependency (PTB per DMC) (4b) by main material groups. Note: Physical trade balance (PTB) is calculated as physical imports minus exports. Negative values designate net exports. Trade dependency is defined as net trade (PTB) per DMC.*

[7] Per capita steel output of the Japanese economy surpassed that of USA, UK, and Germany in the 1960s and peaked at 1,100 kg/cap/yr in 1974. With 700-800 kg/cap/yr at the beginning of the 21st century it was still higher than in most industrialized countries.

Things changed in 1973. Japan, who was depending massively on oil imports for its industrial development felt the oil price shock sharply; the drastic increase in industrial costs cut short the boom. While income (GDP/cap/yr) quickly recovered after 1973, the impact of this event on the physical economy was longer lasting. After a period of strong fluctuations in the 1970s, per capita DMC began a continuous decline following the economic crisis of the 1990s (Figure 3). In 2005 it reached 13.3 t/cap/yr or the level of the early 1970s. Energy use, however, shows a different pattern: TPES recovered in the mid 1980s and grew significantly until the late 1990s, but the composition of energy use changed. Per capita consumption of petroleum declined and energy provision shifted towards coal and nuclear power. The import dependency of the Japanese economy was not lastingly affected either. Even imports of fossil energy carriers soon began to rise again (Figure 4). In 2005 import dependency amounted to almost 100% for ores and fossil energy carriers and to 55% for biomass, higher values than those observed for the economies of Belgium and the Netherlands which have the highest trade dependency in the European Union (Weisz et al. 2006).

7. Material intensity and dematerialization

Since the late 19th century, the Japanese economy experienced tremendous growth, both in physical and monetary terms. This section explores the links between growth in GDP and material use. Between 1878 and 2005, GDP grew significantly faster than DMC and aggregate material intensity declined by more than 50% to 0.6 kg/$ in 2005. Figure 5a shows that aggregate material intensity remained at a high level until the early 1970s, oscillating between 1.2 and 1.7 kg/$. Only after the first oil price shock (1973) did a rapid decline of material intensity set in. The contribution of individual material groups to this aggregate trend differed largely: While the material intensity of biomass DMC declined continuously since the late 19th century, the use of mineral and fossil materials grew much faster than GDP. Material intensity for this group grew from 0.1 kg/$ in 1880 to 1.3 kg/$ in 1974. Only then did the trend reverse itself and the following sharp decline characterized the development of aggregate material intensity in the period 1974 to 2005.

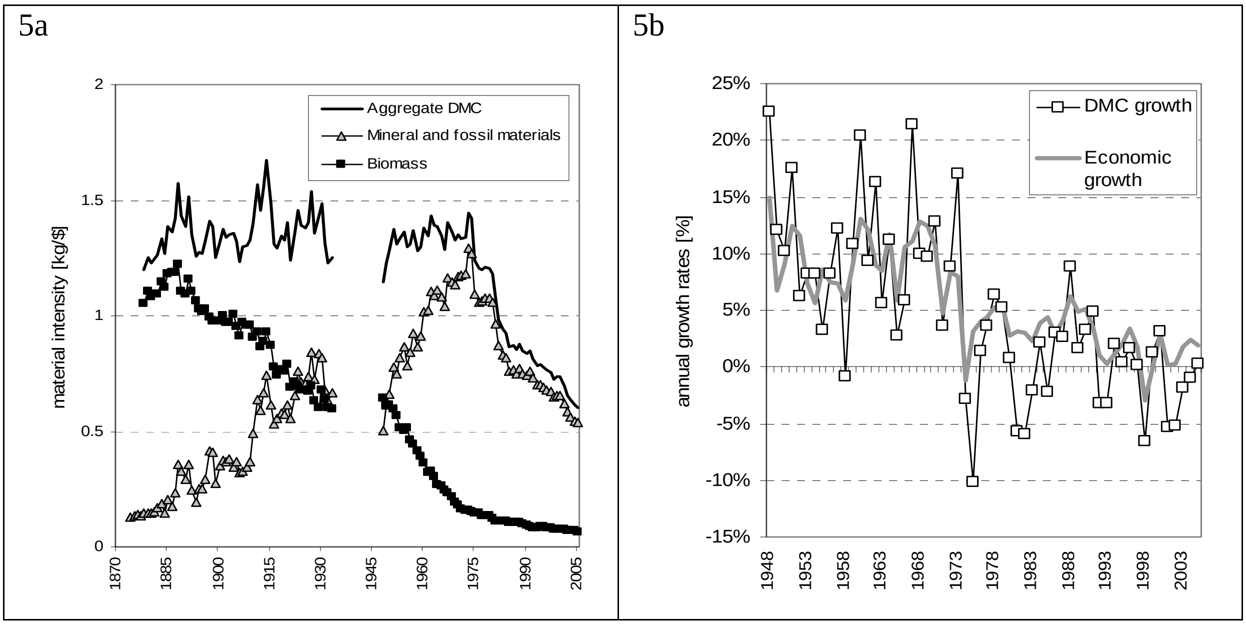

***Figure 5**: Material use and economic development: Material intensity (DMC per GDP) (5a) and average annual growth rates of DMC and GDP (5b). Source: Own calculations using GDP in international Geary-Khamis $ from Maddison (2008).*

The case of Japan shows that significant increases in material productivity (i.e. a declining material intensity) are a comparatively recent phenomenon. Biomass is a resource which is scarcely related to economic development, and much more to population growth (Steinberger et al. 2010), while mineral and fossil materials, key resources of industrial development, seem to grow faster than GDP throughout large periods of industrialization. Similar long term trends have also been observed for material intensity at the global scale (Krausmann et al. 2009) and for the ratio of useful work and GDP in several industrialized countries including Japan (Warr et al. 2010).

Since the 1970s (when empirical evidence becomes available), most industrialized countries show increases in material productivity. But any improvements are usually outgrown by GDP and despite a considerable decline in material intensity only relative decoupling of economic growth and material use is achieved (Steger and Bleischwitz 2009; Bringezu et al. 2004). Japan is one of the rare exceptions showing a significant and long lasting decline in aggregate material use or, in other words, absolute dematerialization.[8] After a period of strong fluctuations following the oil price shocks of the 1970s, aggregate DMC peaked in 1991 (Figure 2d). Since, a lasting decline began which resulted in a 17% reduction by 2005.[9] Energy use showed a different development. TPES per capita did recover in the 1980s and continued to rise, with changes in composition (see above). Our data show that much of the observed decline in DMC was due to reduced consumption of construction minerals, although

[8] In contrast to absolute dematerialization, relative dematerialization occurs, when DMC is growing, but at a slower pace than GDP. As a consequence material intensity of the economy is declining, while material use continues to rise.

[9] According to the official Japanese MFA data (Ministry of the environment 2007), the peak in material use was already reached in 1990 and from then on DMC declined by 29% until 2004.

DMC of biomass and ores declined also. In contrast, the consumption of fossil energy carriers continued to increase, contributing to the observed growth in TPES. The reductions in material use can predominantly be attributed to reductions in domestic extraction, while imports of most materials continued to grow (Figure 2). Hashimoto et al. 2008 found that in the period 1995 to 2002 changes in the demand structure, above all a shift from construction towards machinery and services, contributed the largest share improvements in material productivity and dematerialization (in spite of an increase in material input per unit of constructed buildings and infrastructures due to more restrictive building codes, which were implemented after the Kobe earth quake in 1995 (see Tanikawa and Hashimoto 2009)). Which activities or measures were actually driving the remarkable decline in material use is still largely obscure and requires further research.

Figure 5b shows annual growth rates of GDP and DMC and exhibits a high correlation between economic and physical growth. The oil price shock of 1973 obviously brought an abrupt end to high economic growth rates, which from then on rarely exceeded 4% per year. DMC very much followed the trend of GDP; growth rates of DMC declined markedly after 1973 and even became negative in many years.

We see that the decline in growth rates of DMC in Japan coincides with a long lasting reduction of GDP growth, which corroborates previous findings that a stabilization or a decline of DMC in many cases only occurred during periods of low economic growth or recession (Mudgal et al. 2010) and vice versa: high economic growth usually goes hand in hand with physical growth. Since 2000, Japan is officially pursuing the goal of establishing a *sound material cycle society* (*Junkangata Shakai*) and to reduce material consumption by pursuing the so called 3R policy (reduction, reuse and recycling). As one of very few countries Japan has adopted a resource policy with clear targets aiming at an overall reduction of material use (Takiguchi and Takemoto 2008). It is generally assumed that this policy has further enhanced a trend of absolute dematerialization in Japan which has its roots in economic restructuring after the Asian economic crisis (see e.g. Hashimoto et al. 2008). However, detailed knowledge about the actual effect of the Japanese resource policy and its specific measures on the observed trends is still lacking.

		1880	**1930**	**1970**	**2005**	**Factor 2005/1880**
Population density	[cap/km²]	97	170	276	337	3.5
Share of agricultural population	[% of total]	80%	50%	15%	4%	
Income	[intl $/cap/yr]	863	1,850	9,714	21,999	25.5
DMC per capita	[t/cap/yr]	1.1	2.8	13.1	13.3	12.5
Trade dependency	PTB as % of DMC	0%	5%	31%	40%	
Share of biomass in DMC	% of total DMC	88%	45%	12%	8%	0.1
TPES per capita	GJ/cap/yr	4	21	122	187	48.0
Share of biomass in TPES	% of total DMC	85%	15%	1%	1%	0.0
Electricity per capita	MWh/cap/yr	0	0.25	3.45	8.65	
Power density (DEC per unit area)	GJ/ha/yr	13	58	389	678	50.5
Material load (DMC per unit area)	t/ha/yr	1	5	36	45	43.3

Table 2*: Japan’s metabolic transition: Key indicators for selected years. Sources: Rural population (Allen 1981); Population density and income based on data from Maddison (2008); all others: own calculations based on the MFA database.*

8. The metabolic transition in Japan – role model or special case?

Japan was a late comer of the industrial revolution, but it caught up with the leading economies in an unprecedented speed. During Japan's development from a largely agrarian economy towards one of the world's leading industrial nations, its material turnover grew 49 fold, and the share of mineral and fossil materials in DMC surged to more than 90% (Table 2). Despite considerable population growth, growth in DMC was rather driven by increases in metabolic rates than by the growing number of inhabitants. Over the whole period the 14 fold increase in per capita material use accounted for three quarters of the total increase in DMC. These profound changes in size and composition of material use are typical for the metabolic transition from an agrarian to an industrial metabolic regime (Fischer-Kowalski et al. 2007).

But the Japanese case appears exceptional in several ways: For one thing, the speed of the transition is remarkable. After WWII, Japan's metabolism experienced sheer explosive growth and a considerable part of per capita growth in material and energy use occurred during a time span of merely 20 years in which Japan developed a massive heavy industry, built up large physical stocks in buildings and infrastructure and adopted mass production and consumption. But in the 1970s, coinciding with the first oil price shock, growth came to an abrupt halt.

Another remarkable feature is Japan's high dependency on trade: Very early on, the metabolic transition in Japan was based on imported raw materials, rather than on domestic resources. As a result, the Japanese physical economy today depends to a degree on net imports, which is usually only seen in small countries with a very specialized economy.

And finally, the fact that Japan experienced absolute dematerialization over an extended period (and not only during recession or induced by massive deindustrialization) deserves special attention: Japan's DMC peaked at 16.5 t/cap/yr in 1973 and in 2005 was as low as 13 t/cap/yr. This is far below average material use in the OECD (20t/cap/yr) and in the European Union (15 t/cap/yr) and one of the lowest of all high income countries.[10] But caveats are warranted: the high significance of net imports which amount to more than 5 t/cap/yr or almost 50% of DMC may be one important cause for low metabolic rates and low material intensity. Net importing countries externalize a good part of material intensive production processes, and several studies conclude that high import dependency can contribute to high embodied consumption and emissions (see e.g. Stromman et al. 2009, Hertwich and Peters 2009 for CO_2). For countries like Austria, Germany and Czech Republic, (import dependency of less than 20%), it has been shown that DMC would be roughly 30% higher if upstream flows of net imports would be accounted for (see e.g. Mudgal et al. 2010).

The study of long-term trends in socio-economic material use helps to better understand the dimensions of changes in social metabolism occurring with industrialization and highlights the significance of the metabolic transition for sustainable development. The case of Japan

[10] The UK and Switzerland are the only fully industrialized countries which have a similarly low per capita DMC.

shows very clearly that while severe (and successful) efforts have been made to reduce materials use and increase resource efficiency, laying a path towards sustainable levels of resource use still remains a major political challenge.

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The physical economy of the United States of America: Extraction, trade and consumption of materials from 1870 to 2005

Sylvia Gierlinger and Fridolin Krausmann

1. Abstract

The USA is not only the world's largest economy, but they are also one of the world's largest consumers of natural resources. The country, which is inhabited by some 5% of the world's population, uses roughly one fifth of the global primary energy supply and 15% of all extracted materials. The paper explores long term trends and patterns of material use in the USA. Based on a material flow account which is fully consistent with current standards of economy wide MFA and covers domestic extraction, imports and exports of materials for a 135 years period, we investigate the evolution of the United States industrial metabolism. This process was characterized by a 19fold increase in material consumption, entailed a multiplication of material use per capita and a shift from renewable biomass towards mineral and fossil resources. In spite of considerable improvements in material intensity, no dematerialization happened so far; in contrast to other high income countries, material use has not stabilized in the 1970s but continued to grow. The paper analyses the factors underlying the over proportionally high level of per capita resource consumption and explores the role of the physical economy of the USA for global resource use.

Keywords: MFA, material flows, resource productivity, dematerialization, social metabolism

2. Introduction

In the late 19th century the USA challenged the UK as the leading economic power and since occupies a predominant role in the world economy; at the turn of the 21st century the USA produced almost 30% of the global GDP. The USA is not only the world's largest economy but it is also the world's largest consumers of natural resources. In the year 2005 the country, which inhabited merely 5% of the global population, used roughly one fifth of the global primary energy supply and 15% of all extracted materials. On the output side the US emitted 21% of the global CO_2 emissions from fossil fuels and cement (Marland et al. 2007). This paper explores the long term historical development of the physical economy of the USA and the evolution of its industrial metabolism. It presents a material flow account for the period 1870 to 2005 and investigates the extraction, trade and consumption of materials for main material groups.

Several previous studies have explored historical trends of energy and material use in the USA. Schurr and Netschert (1960) presented a first analysis of the development of (technical) primary energy use in the US since the mid 19th century. More recently Ayres et al. (2003) have investigated primary energy inputs and useful work supply (exergy use) for the USA for the period 1900 to 1998 (see also Warr et al. 2010). Also material inputs into the U.S. economy have been studied: An initial database compiled by Matos and Wagner (1998) focused on raw materials for industrial use and presented yearly data for the period 1900 to 1995. It was later updated and currently includes 2006 as the most recent year (see Rogich et al. 2008; Rogich and Matos 2002; Matos 2009). Although covering important parts of social metabolism, these data are not fully consistent with current MFA system boundaries and accounting principles: Important materials, for example the largest part of all biomass flows and most fossil energy carriers are not considered while others, such as recycled materials are, in deviation from MFA standards, accounted for as inputs. Ayres et al. (2004) used their database on long term exergy and material use to analyze if the U.S. economy was dematerializing in the 20th century. Both datasets focus on apparent consumption and do not distinguish between extraction, imports and exports. Finally, the USA was one case in the seminal comparative MFA study initiated by the World Resources Institute (Adriaanse et al. 1997). From this study detailed MFA data exist, but only for the period 1975 to 1993; this dataset was later updated to the year 2000 (Rogich et al. 2008).

We compiled a long term historical data base for material flows in the U.S. economy which is fully consistent with current standards of economy wide MFA. Compared to previous studies, our dataset considerably expands the observed time period and the flows and materials covered. It provides detailed data for domestic extraction, imports and exports in annual resolution for a 135 year period and distinguishes up to 60 material groups. MFA data and the derived indicators such as domestic material consumption or physical trade balance are comparable to other long term MFA studies (Schandl and Schulz 2002, Krausmann et al. 2009, Krausmann et al. 2011) and are publicly available from http://www.uni-klu.ac.at/socec/inhalt/1088.htm

The paper explores the metabolic transition in the USA and the emergence of its industrial metabolism, a process which is characterized by an overall growth in material use, far above the pace of population growth and by fundamental changes in the composition of material use. We analyze how material input and use is changing in relation to economic development, population growth and energy consumption. Furthermore, we compare the material throughput of the USA to that of other countries and discuss the significance of the U.S. economy for global material use.

After a brief description of methods and data sources used to compile the database in section 2, the paper presents time series data on extraction, trade and material consumption for the period 1870 to 2005 (section 3). Section 4 discusses the different phases of the metabolic transition in the USA in relation to economic and political developments. In section 5 we analyze the relation between material flows and economic development and finally discuss US resource use patterns in a global context (section 6).

3. Methods and data

For compiling a comprehensive database on the long-term development of material and energy flows in the U.S. economy[11], standard methods of economy wide material flow accounting were applied (Eurostat 2009). The study quantifies used extraction, imports and exports of materials and uses data from a range of national and international statistical sources. Estimation procedures were applied for materials which were not reported in statistical sources. The MFA data base follows the materials classification used by Eurostat (2009) and distinguishes between 50 and 60 material groups for (used) domestic extraction,

[11] The territorial system boundary used in this MFA refers to the current territory of the United States of America (USA), including Alaska which was purchase from Russia in 1867 and, since its annexation in 1898, also Hawaii.

imports and exports. Unused extraction or indirect flows (upstream material flows of traded products) were not considered. In this paper, data and indicators are presented for four main material groups: biomass, fossil energy carriers, ores and non metallic minerals. Furthermore a distinction between biomass (renewable) and mineral and fossil (non-renewable) materials was made.

We have calculated the following material flow indicators (see Fischer-Kowalski et al. 2010): Domestic extraction (DE); import and export; domestic material consumption (DMC) which is defined as DE plus import minus export; physical trade balance (PTB) which is defined as import minus export; trade dependency, which is defined as PTB per DMC; material intensity (MI) which is defined as DMC per unit of GDP; MI is the inverse of material productivity. We refer to per capita values of domestic material (and energy) consumption also as metabolic rates.

3.1. Data sources

We based our long term historical reconstruction of material flows in the USA on three major sources: The Historical Statistics of the United States (HSUS 1975)[12] provides a comprehensive collection of statistical time series data covering a wide range of socio-economic variables including resource extraction from colonial times to present. In the 1960s and 1970s Resources for the Future[13] commissioned a number of studies on historical resource trends in the USA. These yielded two comprehensive data compilations: Potter and Christy (1962) and Manthy (1978) provide annual data on production of and trade for a large number of raw materials and commodities since the late 19th century. Finally, the United States Geological Survey (USGS) maintains a material flow database and provides time series data for most mineral materials for the period 1900 to the most recent years (Kelly and Matos 2008). In addition to these national sources, we used a range of international databases providing data for the more recent decades. As a general rule, international data were crosschecked with national sources for selected overlapping years in order to ensure consistency between sources and to avoid statistical breaks. Crosschecks have shown that while the pre 1960 sources in general cover a smaller number of materials, the difference in overall mass flows covered is negligibly small.

Crop harvest was fully covered in national and international statistical sources. We used HSUS (1975), Potter et al. (1962), Manthy (1978), FAO (2005 and 2009) to compile data on crops.

The extraction of used crop residues was estimated on the basis of time dependent harvest factors and recovery rates for major crops based on information derived from Wirsenius (2000) and Cunfer and Krausmann (2009). Grazed biomass was estimated on the basis of a simplified feed balance (Krausmann et al. 2008a). Data on livestock, livestock production and feed availability were taken from the HSUS (1975) and FAO (2009). Feed demand (kg dry matter per head per day) for cattle was calculated on the basis of ruminant production (milk,

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[12] For reasons of accessibility we used the 1975 edition of the Historical Statistics of the United States. The most recent edition has been published in 2006. The data we have used are identical in those in more recent versions.
[13] http://www.rff.org

meat) and assumptions on changes in livestock productivity derived from Krausmann et al. (2008a) and Cunfer and Krausmann (2009). Feed demand factors for all other grazers were kept constant over time. In order to arrive at the amount of grazed biomass, available fodder crops, market feed and crop residues were subtracted from the calculated total dry matter feed demand. For early years no information on market feed was available. Based on information available for the 1960s (FAO 2009) we assumed a share of 15% of market feed in total dry matter feed demand. Data on fish catch (excluding aquaculture, which in MFA is considered an internal transfer) was taken from HSUS (1975), Manthy (1978) and FAO (2006).

Data on the extraction of industrial round wood were derived from HSUS for years prior to 1960 and from FAO 2009 for the period 1961 to 2005. For the years 1870 to 1900 HSUS reports lumber and pulpwood only. The inclusion of other wood items in statistical reporting after 1900 results in a statistical break; industrial roundwood production increases by 25%. For fuel wood data are available from energy statistics (Schurr and Netschert 1960, IEA 2007) and production statistics (Manthy 1978, Howard 2007). While both sources show a very similar development of fuel wood use over time, the values derived from energy statistics are up to 40% higher than those from production statistic. To avoid double counting due to re-use of wood, we followed a conservative approach and used the lower values from the production statistics.

Data on the extraction of fossil energy carriers are well covered in statistical sources. For the period 1870 until 1960 data on the extraction of coal, oil and natural gas were taken from HSUS (1975) and for the more recent years (1961 to 2005) they are from IEA (2007). Data on peat extraction were taken from Kelly and Matos (2008).

Data on the extraction of ores are very well documented by the USGS (Kelly and Matos 2008) from 1900 on. Data for the years prior to 1900 are from the HSUS and were complemented with data from Manthy (1978). Only for iron and bauxite statistical sources report production in terms of gross ore. All other metals are reported in terms of metal content. To arrive at gross ore production, as required in MFA, we used information on coupled production and metal content derived from USGS (e.g. United States Bureau of Mines 1987). For copper, which is the largest mass flow of non-iron ores, we assumed that ore grades declined from 2.5% in 1880 to 0.5% in 1975 based on ore grades given in Ayres et al. (2004). For all other metals, current ore grades were used, which results in a slight overestimation of gross ores in earlier periods, when grades of some domestic ores were higher (cf. Mudd 2009).

We used data on the extraction of non-metallic minerals from HSUS (1975) and Kelly and Matos (2008). Data on the extraction of natural aggregates (sand, gravel, crushed stone) reported in HSUS are not consistent with numbers provided in Kelly and Matos (2008) which are much lower. Therefore we estimated the demand for sand, gravel and crushed stone based on the production and use of cement, concrete and asphalt (see Krausmann et al. 2009, Eurostat 2009, Schandl and West 2010). We applied standard coefficients on the ratio of sand and gravel to cement and bitumen in concrete and asphalt to extrapolate natural aggregates use. Data on the production and consumption of cement and bitumen were taken from HSUS (1975), Kelly and Matos (2008), IEA (2007) and Abraham (1945). The results of this estimate match well with data reported in the HSUS (1975) and those estimated by Kelly (2009);

trends over time are similar in both estimates (see supporting online material (SOM) for details).

Comprehensive trade data are difficult to obtain. Most sources only cover trade with raw materials and semi-manufactured products, but mass flows of manufactured products are rare. Trade with biomass, fossil energy carriers and products thereof has been derived from Potter et al. (1962) and Manthy (1978) for the years 1870 until 1960. From 1961 on we use FAO (2009) for trade with agricultural and forestry products and IEA (2007) for trade with fossil energy carriers and petrochemical products. For wood only data on net-trade were available for the years 1870 to 1950. Trade with non-metallic minerals and ores and semi-manufactured metal products was taken from Potter et al. (1962) for the period 1870 to 1899 and from Matos and Kelly (2008) for the period 1900 to 2005.
We used data from UN's comtrade data base (United Nations Statistical Division 2008) to crosscheck our results and to quantify underestimations due to incomplete coverage of trade with manufactured products like furniture, textiles, machinery or vehicles. Comtrade data are available for the period 1962 to present, but for most years data on physical trade flows are fragmentary. Comprehensive data on imports and exports are available only for the years 1978, 1985-1988 and 2005. An analysis of comtrade data for the years 1978 and 2005 reveals that manufactured products not considered in our account amount to 10-20% of total imports and 4-11% of exports (see SOM for details). In terms of net trade underestimation is much smaller. Underestimation is highest for imports and exports of metal products (vehicles, machinery), petrochemical products (organic chemicals, plastics) and so called other products (that is, products which can not be assigned to a specific material group).

Data on material flows were used to calculate the supply with primary energy (TPES). We converted flows of fuel wood and fossil energy carriers into energy units using material specific gross calorific values. Energy flow data derived from MFA were supplemented with energy inputs from hydropower, nuclear heat and geothermal sources. Data on electricity output from hydro and nuclear power plants (HSUS (1975) and IEA (2007)) were converted into primary energy input by applying coefficients derived from information on average conversion efficiency (Warr et al. 2010).

4. Results

Figure 1 shows the development of domestic extraction (DE), domestic material consumption (DMC), physical imports and exports of materials in the USA from 1870 to 2005 by four main material groups.[14]

DE of materials rose from 0.4 Gt (Gigatons, 10^9 tons) in 1870 to 7.4 Gt in 2005 corresponding to a 17-fold increase. Extraction was growing almost throughout the whole period; decline during consecutive year was a rare exception. The most significant slumps in DE occurred during the Great Depression in the early 1930s and in the aftermath of oil price spikes of 1973 and 1979, but basically all periods of recession (e.g. in 1990 and in 2000) were mirrored in

[14] A comparison of the results of our estimate of U.S. material extraction and use with results from previous studies is presented in the supporting online material.

declining rates of resource extraction. At the beginning of the observed period DE was dominated by biomass. The fraction of biomass declined rapidly from 85% in 1870 to below 50% in 1910 and 25% in the early 1960s and remained at level since. Even though the relative contribution of biomass to DE declined continuously, the total mass flow multiplied: DE of biomass grew five fold from 0.37 Gt/yr in 1870 to 1.76 Gt/yr in 2005. Since the beginning of the 20th century, mineral and fossil materials are dominating domestic extraction; their share increased from 15% to roughly three quarters of total DE. In 2005 non metallic minerals, mostly natural aggregates, accounted for 3.6. Gt or almost 50% of DE, fossil energy carriers for 1.7 Gt. Extraction of metal ores was growing at the same rate as DE of non-metallic minerals until the end of the 1920s. From then on, DE of metal ores stabilized and remained between 0.3 and 0.4 Gt/yr.

Prior to WWII trade flows were small compared to DE, only than trade began to soar. In 2005 the size of imports had grown to 15% compared to DE and that of exports to 5%. The USA has been a net exporter of materials for most of the observed 135 year period. Only after WWII imports outgrew exports and the physical trade balance turned positive, indicating net imports. Since, net imports increased to almost 0.8 Gt per year or 9% of DMC. Net trade is dominated by fossil energy carriers which accounted for over 90% of net imports in 2005. Trade dependency of this material group amounted to 29%. On closer examination it shows that the USA have been self sufficient with respect to fossil fuels for most of the observed period and even exported large amounts of coal and oil. Exports peaked at 70 Mt (million tons, 10^6 tons) in 1947. After WWII imports grew rapidly and in 1957 the USA became a net importer of fossil fuels. Since, net imports of oil and natural gas have been growing, and only slumped for a few years when oil prices multiplied in the 1970s. The USA is a major exporter of biomass. Net exports of biomass have been growing in the 19th century and reached a first peak of 13 Mt around 1900, then they began to decline. For several decades after WWI imports of biomass exceeded exports. Only after 1960 exports surged and net exports increased rapidly to a peak of 135 Mt in 1981. During the last years net biomass exports have stabilized around 80 Mt per year. Physical trade for ores and non metallic minerals was roughly balanced for most of the observed period. Net imports of ores began to surge after WWII and for non metallic minerals only in the 1970s.

Throughout the observed period, net trade was small compared to domestic extraction. Consequently, the difference between DE and DMC in terms of size, composition and development over time is small with the exception of fossil fuels, where DMC became considerably larger than DE (Figure 1). The share of fossil fuels in DMC in 2005 was 33% (compared to 23% in DE). Total DMC increased steadily over the whole period and rose from 0.4 Gt in 1870 to 8.1 Gt in 2005. Similar to DE, all periods of economic disruptions or recession materialized in the form of a temporary decline in DMC.

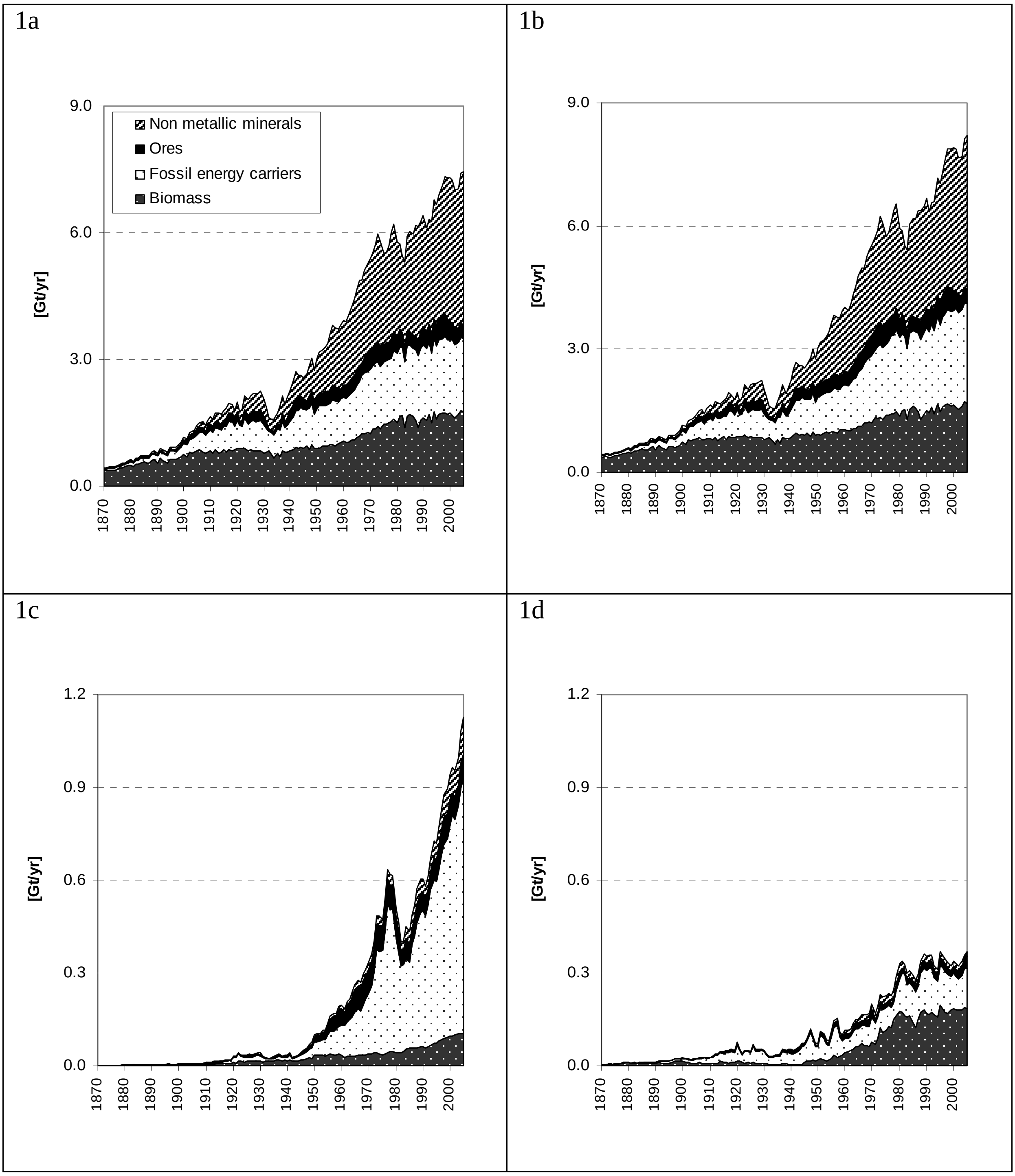

Figure 1*: Material flows in the USA 1870 - 2005: Domestic extraction of raw materials (1a), imports (1c) and exports (1d) of raw materials and semi-manufactured products and domestic material consumption (1b).*

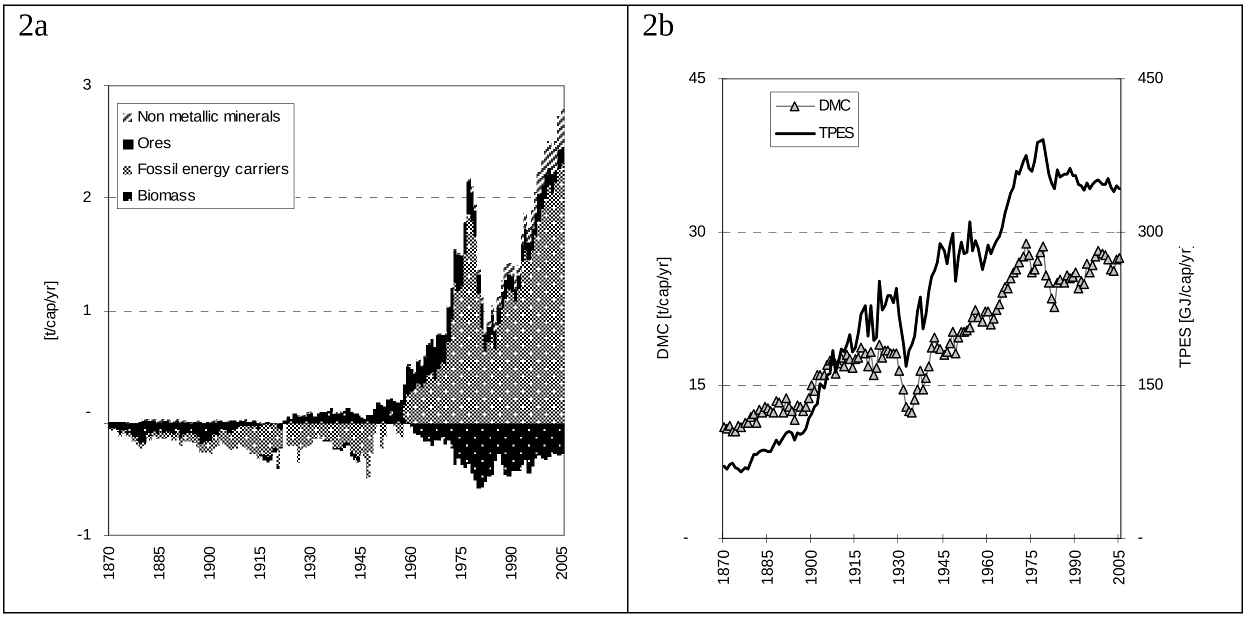

Figure 2*: Physical trade balance (2a) and metabolic rates (2b) (material use (DMC) and energy use (TPES) per capita and year). PTB is calculated as physical imports minus exports. Negative values designate net exports. Trade dependency is defined as net trade (PTB) per DMC.*

5. Socio-metabolic transitions

This section discusses the USA's transition from an agrarian to an industrial socio-metabolic regime (Haberl et al. 2011, Krausmann et al. 2008b). In line with observations from other case studies (Krausmann et al. 2009, Krausmann et al. 2011) we distinguish phases, which differ with respect to the composition and growth rates of material and energy use and the level of per capita consumption (see also Table 1).

5.1. The coal phase of the metabolic transition

We begin to observe the physical economy of the US in a period of economic and metabolic transition. After the Civil War (1861-1866) the USA moved rapidly from an agrarian to an industrial regime and followed a pathway of coal based industrialization much like the United Kingdom (UK) had started several decades earlier (Schandl and Schulz 2002; Krausmann et al. 2008c). In the 50 years from 1870 to the World Economic Crisis, coal extraction and consumption increased 15 fold (Fig. 3). By 1929 domestic consumption of coal had soared to 4.3 t per capita and year, outpacing the UK. A considerable amount of coal was even exported. In association with coal, iron and steel production surged. Production grew from less than 2 kg/cap/yr in 1870 to 408 kg/cap/yr in 1929 and the USA's share in global production reached 50%. The railroad network expanded from 85000 to 410000 km[15], opening up the resource rich continent. Settlement and cultivation expanded westward and the homesteading program resulted in the cultivation of 440000 km² of fertile soils were

[15] own calculation based on HSUS (1975)

cultivated in the Great Plains region between 1870 and 1930 (Cunfer 2005). Agricultural production multiplied and the railway delivered Midwestern grain and meat to the growing domestic urban and international markets (Cronon 1992). Agricultural output by far exceeded domestic demand and the US emerged as a major exporter of agricultural products. At the turn of the century, around 15 Mt of crops and animal products were exported, alone 5.5 Mt of grain was exported to the UK (K.K.Ackerbauministerium 1900). But the heydays of exports did not last. Cropland expansion reached its limits and could not keep up with high population growth and the fast rising demand for animal products. Net exports peaked already in 1898 and eventually the USA turned into a net importer of biomass in the 1920s.

In this period the USA gained its position as dominant economic world power. In 1901 GDP per capita[16] overtook that of the UK (Maddison 2008) and immigration contributed to rapid population growth. The USA exploited its rich natural resource base and emerged as a major net exporter of natural resources, providing the industrializing economies in Europe with food and fuel (coal, petroleum). The coal phase of the metabolic transition was characterized by a rapid decline of the share of renewable biomass in DMC. Already in 1910 it fell below 50% and continued to decline, despite domestic consumption of biomass more than doubled. DMC and in particular the consumption of mineral and fossil materials grew fast and growth rates exceeded that of population (Table 1). Physical growth even accelerated around 1900. Overall DMC grew from 10 to 18 t/cap/yr during the coal phase of the metabolic transition.

	1870-1929	1932-1973	1984-2005	Factor 2005/1870
Population	1.9%	1.3%	1.0%	7.5
GDP in intl. $	3.7%	4.4%	3.1%	91.6
DMC in kg	2.8%	3.3%	1.5%	19.0
TPES in J	4.1%	3.3%	0.8%	36.5
Income (GDP per capita) in intl.$/cap/yr	1.7%	3.0%	2.0%	12.2
DMC in t/cap/yr	0.9%	2.0%	0.4%	2.5
DMCminerals & fossils per in t/cap/yr	3.3%	3.2%	0.7%	13.4
TPES in GJ/cap/yr	2.1%	2.0%	-0.3%	4.9

***Table 1**: Average annual growth rates of population, GDP and resource use during different periods of the metabolic transition. Sources: HSUS (1975), FAO (2009) (population); Maddison (2008) (GDP); all other data: own calculations based on MFA database.*

5.2. Oil and the emergence of mass production and consumption

The Wall Street Crash of 1929 and the following World Economic Crisis had a severe impact on the U.S. economy. With GDP, also the physical economy plummeted. Material and energy use slumped by roughly 30% in the years after 1929 (Figure 2b). After only four years the physical economy recovered and material and energy use started to grow at unprecedented rates (Table 1). The 1929 level of resource use was surpassed around 1940. Recovery of the physical economy was supported by New Deal measures. As a response to the economic crisis, several economic and social programs were initiated. Large construction projects were launched, electrification of peripheral areas was pushed forward, structural adjustment in agriculture was promoted and the Social Security Act was created (Adams 2008). These

16 GDP in international Geary-Khamis Dollar

measures and the beginning of WWII accelerated the transition from coal to oil and boosted the consumption of mineral and fossil materials, a process which, which began already before the crisis with the emergence of a new technological cluster consisting of oil, automobile, chemical industry and electricity (Grübler 1998). Combined with a new socio-economic order shaped by New Deal it formed the basis for a new pattern of material and energy use driven by mass production and mass consumption (Cohen 2003). Oil and later natural gas from domestic deposits increasingly supplemented coal in the energy system and overtook coal as dominating energy carrier already in the 1930s. Similar to biomass, coal was, however, not replaced by oil and natural gas, but the overall amount of coal used continued to increase (Figure 3).

The period between the Great Depression and the oil price shocks in the 1970s was a period of unprecedented physical growth. DMC grew at an average rate of 3.3% per year (Table 1). Declining resource prices and fast rising wealth paired with motorization, suburbanization and electrification of households in driving resource use. Material and energy use grew much faster than population: DMC per capita more than doubled from 13t/cap/yr in 1932 to 29t/cap/yr in 1973, and TPES per capita grew from 169 GJ/cap/yr to 375 GJ/cap/yr in the same period (Figure 2b). The use of non-metallic minerals for construction multiplied 6 fold to 12 t/cap/yr and from 1951 onwards non-metallic minerals had the highest share in total DMC. Major infrastructure projects, such as the development of the Interstate Highway System beginning in 1950, contributed to the growth of resource use. Construction is a major driver of demand for mineral materials and ores. It has been shown for the US that a large fraction of steel and copper is used in infrastructures and buildings (Gordon et al. 2006; Müller et al. 2006). The USGS (Sullivan 2006) estimates that the current 73,000 km of Interstate Highways alone (of a total road network of more than 6.5 million km) correspond to a stock of 1.5 Gt of natural aggregates, 48 Mt of asphalt and 6 Mt of steel. Also the massive diffusion of motor vehicles contributed to the rising resource use: Between 1945 and 1973 the number of registered cars rose from 182 to over 600 vehicles per 1000 inhabitants (HSUS 1975, RITA 2010), containing 7% of all steel stocks in the USA (USGS 2006).

With this fast growing resource demand, the U.S. economy became a net importing economy. In 1958, the USA turned from a net exporter of fossil energy carriers to a net importing country, and in 1973 import dependency for petroleum and natural gas reached 20%. Net imports of ores and metals already began to increase in the late 1940s and that of non-metallic minerals in the 1970s (Figures 1c and 2a). Only biomass exhibited a different trend: After four decades of net imports, the industrialization of agriculture boosted crop production and the USA became a net exporter of crops and agricultural products. The green revolution once again made the USA one of the worlds largest exporters of agricultural products, in particular of wheat, corn and soy beans.

This phase of the metabolic transition was characterized by the rapid expansion of physical stocks and fast growth of per capita use of all material groups. The typical pattern of an industrial metabolism emerged in close association with the establishment of the American way of live and patterns of mass production and consumption.

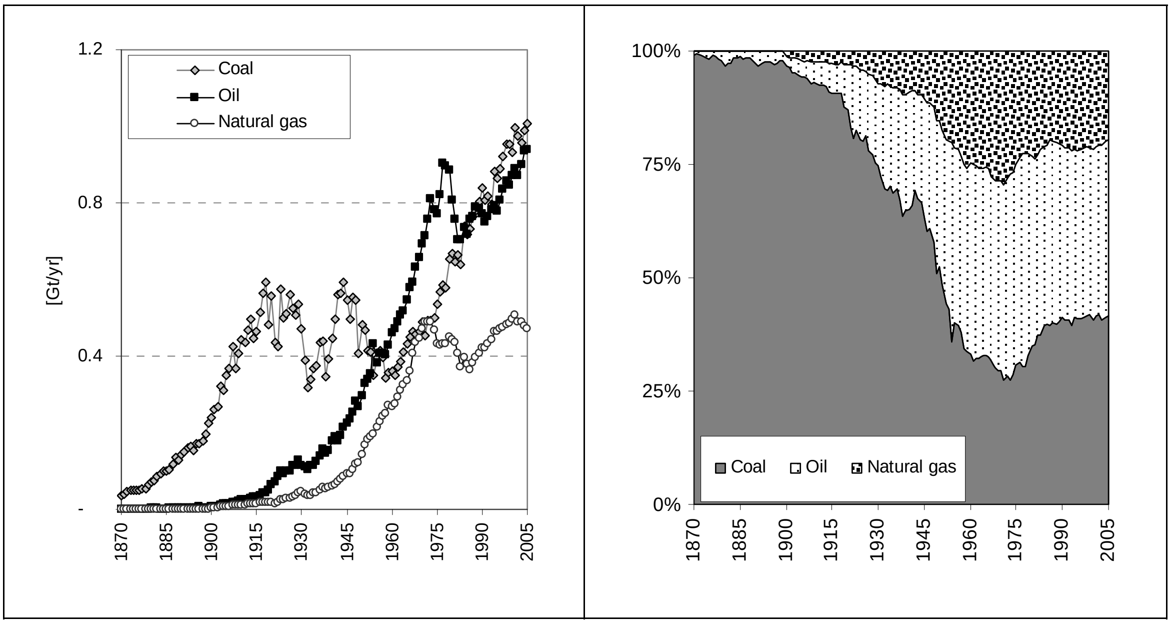

***Figure 3**: DMC of fossil energy carriers in Gt/yr (3a) and as share of total fossil energy carrier DMC (3b)*

5.3. Consolidation of the industrial metabolism after the oil price shocks

The two oil price shocks in 1973 and in 1979 ended a period of three decades of fast and continuous physical growth and contributed to a severe recession in the early 1980s. Oil imports plummeted, and in 1970 also domestic extraction of petroleum reached its peak and began to decline. With energy consumption, also growth in all other materials came to a halt. As with the World Economic Crisis, the physical economy recovered after a few years, though. Oil imports began to rise again, but in the aftermath of the high oil prices and peak extraction also domestic coal was rediscovered as an energy carrier and gained significance in the energy system (Figure 3). Coal extraction and use increased continuously and in 2005 exceeded the peak values of the coal phase by 60%; in contrast, domestic extraction of oil was 43% below the 1970 peak. After several ups and downs, DMC began to increase again in 1984, but at considerably lower rates than before (Table 1). Material and energy use now grew at a similar pace as population and by 2005 metabolic rates had not yet reached the level prior to the first oil price shock. The hitherto peak of per-capita DMC was reached in 1973 at 29 t/cap/yr and that of TPES in 1979 at 391 GJ/cap/yr (Figure 2b). The overall amount of DMC and TPES, however, continued to grow: by 2005 material and energy use was roughly 30% above the 1973 level. Import dependency of fossil fuels reached a new maximum with 29% in 2005. The oil price shocks had a massive short term impact, but they also had some lasting impacts on the structure of the economy and the pace of physical growth and the composition of material and energy use (Ayres 2006). This might be interpreted as a consolidation of the patterns of industrial metabolism, a development observed in most industrialized countries in the last three decades.

6. Material use and economic development

Figure 4a shows the evolution of material and energy use in comparison with GDP and population. During the observed 135 year time period DMC grew by a factor of 19 and TPES by a factor of 37. Population increased only seven fold while the economy increased by almost two orders of magnitude and hence considerably faster than resource use. As a consequence, the amount of materials (and energy) used per unit of GDP (material intensity) declined substantially. The U.S. economy thus exhibits a pattern of relative dematerialization (or relative decoupling) (Swilling et al. 2011). Figure 4a shows that energy consumption had been rising very much in line with GDP for almost a century, and decoupling started only in the 1970s. Material use, in contrast, grew much slower than the economy during the whole 20th century. This resulted in a significant reduction in material intensity (Figure 4b). Material intensity improved by a factor four: In the 1870s more than 4 kg of materials were used per unit of GDP; at the beginning of the 21st century, this ratio was down to less than one kg per $. But Figure 4b also illustrates, that material intensity did not decline equally for all material groups.

While biomass intensity declined throughout the whole period, mineral and fossil materials were much tighter linked to economic development. Material intensity for this group, just like energy intensity, even increased during the first 45 years and only then started to decline. Similar trends have been observed for many key materials of industrialization and also for useful work (Ayres et al. 2004). Most of the improvements in material intensity of key materials and energy carriers have actually only occurred since the 1970s. This further justifies conceiving of the period after the oil shocks of the 1970s as a distinct phase in the industrial metabolism in the USA.

During the last 135 years, resource use only declined during periods of recession or severe economic crisis. Absolute dematerialization has not been achieved, in spite of massive efficiency gains in many industrial processes and in the end uses of material and energy (Ayres et al. 2004). All resource savings have been offset by rising demand induced by declining prices and growing income (Sullivan et al. 2000; Ayres et al. 2003). Also a shift from products towards services in the economy in the last decades has only contributed to relative dematerialization, while overall material and energy use continued to grow. At the turn of the 21st century, each additional dollar of GDP still requires roughly an additional 0.2 kg of renewable biomass, 0.7 kg of mineral and fossil materials and 11 MJ of primary energy.

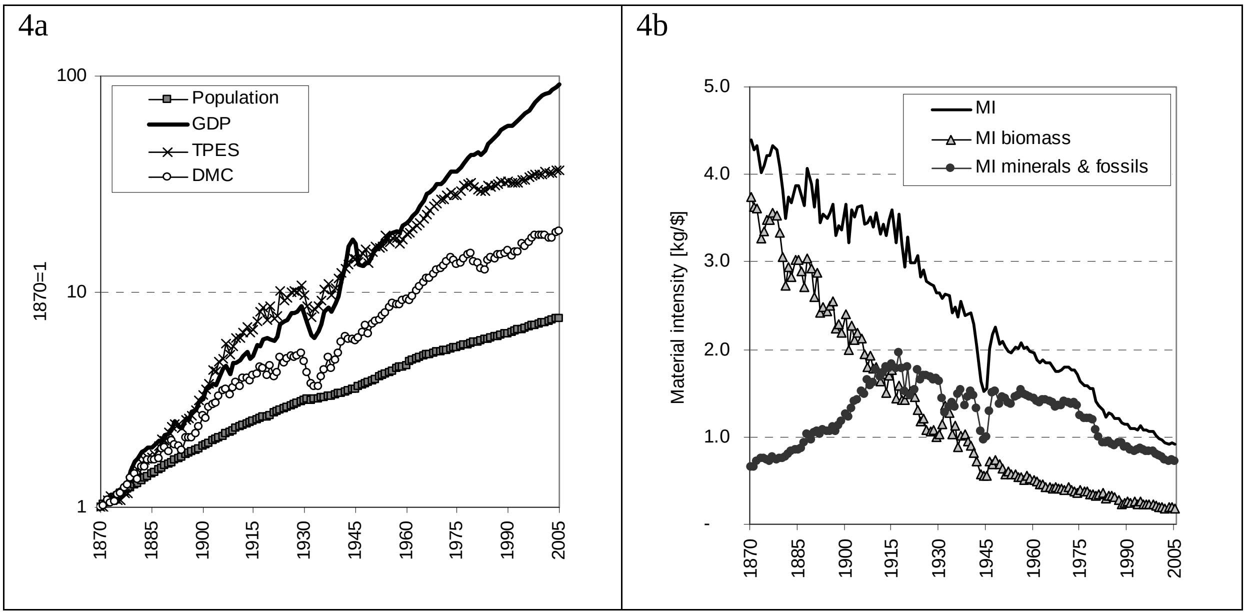

Figure 4: *Material use and economic development in the USA: Development of population, GDP, domestic material consumption (DMC) and primary energy supply (TPES) (4a) and material intensity (MI) (DMC/GDP) (4b). Note the logarithmic scale in Figure 4a. Sources: HSUS (1975), FAO (2009) (population); Maddison (2008) (GDP); all other data: own calculation based on MFA database*

7. The physical economy of the USA in international comparison

The USA has not only dominated the global economy during the 20th century, it also had a considerable impact on global resource use: According to our calculations the contribution of the U.S. economy to global material use (Krausmann et al. 2009) expanded from 16% in 1900 to 22% in the late 1950s. In the last 50 years the contribution of the USA to global material use has been slowly declining but was still around 15% in 2005. The U.S. share in global TPES is even larger. It peaked in 1945 when the USA used half of the global primary energy supply, and it accounted for 21% in 2005. The USA with 5% of the global population consume an over proportionally large share of global resources. In terms of per capita DMC, the USA today rank among the global top 10, surpassed only by extractive economies such as Australia, Chile or Canada (Krausmann et al. 2008b). Per capita DMC of the USA is 27t/yr and higher than that of most industrialized high income countries. It is, for example, roughly twice the size of the average Japanese DMC or that of the UK (Figure 5b); differences with respect to energy use are even larger. Figure 5 shows that this is not a recent phenomenon, but the USA had a high rate of materials use even at the very beginning of our time series and by far exceeded the Japanese or the UK's DMC in 1880.

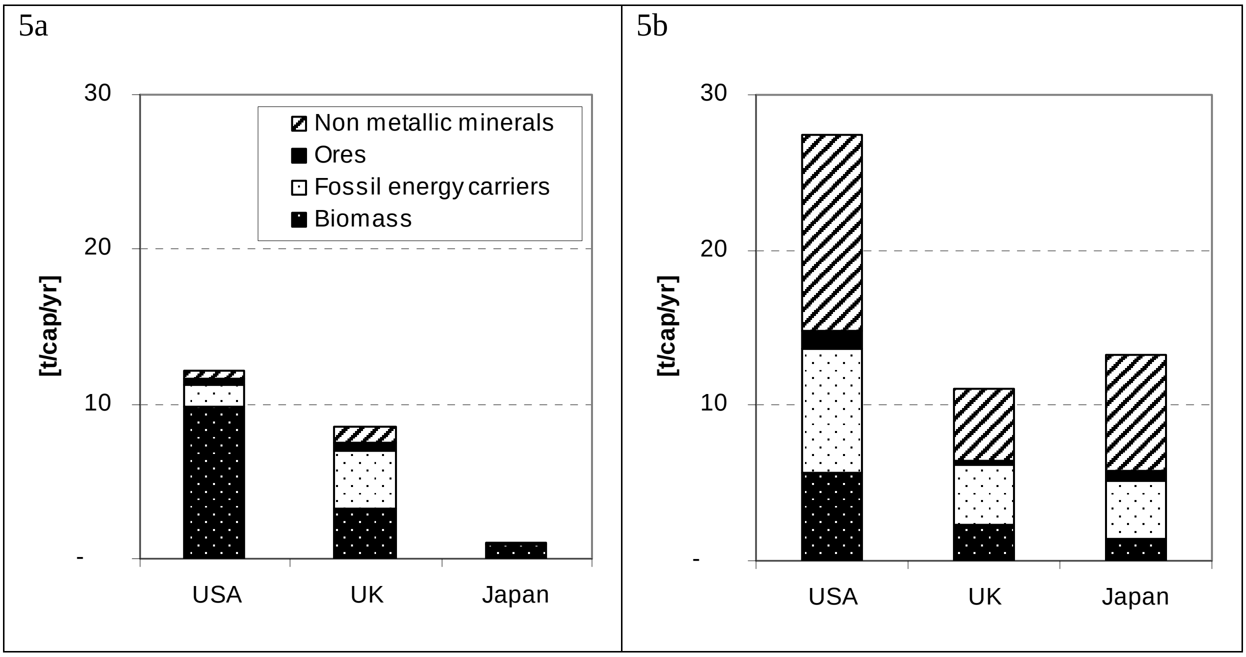

***Figure 5**: DMC per capita in the USA, UK and Japan in 1880 (5a) and 2005 (5b). Sources: Based on Krausmann et al. 2011, Schandl and Schulz 2002 and Eurostat 2007.*

What are the underlying factors for this high level of resource use? The USA is sparsely populated compared to Japan and most European countries, but rich in natural resources. This serves as a rough indication for a high endowment with natural resources in relation to population. Relative abundance in natural resources is at least one factor that has contributed to a high level of per capita material and energy use from the very beginning. In 1870 population density was only 4 persons per km² and fertile land was abundant. This facilitated a very high rate of biomass extraction and use of almost 10 t/cap/yr in the USA in 1880, much higher than in the UK (3.2 t/cap/yr) or Japan (0.9 t/cap/yr). The high number of livestock per capita (780 cattle per 1000 inhabitants in the US compared to 290 in the UK or 30 in Japan) was the single most important cause for the high biomass DMC. But also the generous use of abounding fuel wood and timber in households and industry and the high rate of exports of agriculture and forestry products did have an influence. Large livestock numbers and high per capita meat consumption (Table 3) also today contribute to a much higher rate of biomass use in the USA compared to the other two countries (Figure 5b).

		USA	UK	Japan
Population density	cap/km²	32	249	351
Income (GDP/cap) (const. 2005 $)	$/cap/yr	37,702	27,754	38,972
Household final consumption expenditures	$/cap/yr	26,757	18,626	21,817
Livestock	Cattle/1000 inh.	315	178	35
Meat consumption	kg/cap/yr	124	87	47
Motorization	MVH/1000 inh.	820	478	562
Pump price of gasoline (2000)	US$/l	0.5	1.2	1.1
Passenger road transport	1000 pkm/cap/yr	26	12	7
Electricity consumption	MWh/cap/yr	14.6	6.8	8.7
Residential electricity consumption	MWh/cap/yr	4.5	1.9	2.6

***Table 3**: Drivers of resource use in the USA, the UK and Japan. Data for 2005, excepted when noted differently. Sources: World Bank Group (2010) (road transport, income,*

household final expenditure, gasoline price), IEA (2007) (electricity), FAO (2009) (cattle, meat consumption), Mitchell (2003) and RITA (2010) (motorization).

In the 20th century, increasingly also the large scale extraction of coal, oil and mineral resources and the growing significance of large heavy industries drove high rates of apparent consumption. The USA developed a typical metabolic profile of an extractive and export oriented economy as it is characteristic today for other new world countries such as Canada or Australia (Krausmann et al. 2008b; Schandl and Turner 2009). Figure 5b shows that per capita consumption of each of the four main material groups in the USA in 2005 was much higher than in the UK or Japan; this was the case during most of the 20th century. Low and declining prices for energy and materials and high economic growth facilitated resource intensive industries and consumption patterns and provided little incentives for reduction (Ayres et al. 2004, Sullivan et al. 2000). Mobility and motorization can serve as an example: With more than 800 motor vehicles per capita, the USA has one of the highest rates of motorization (Table 3). In an international comparison of energy use, Schipper (2004) concluded that the U.S. Americans drive higher distances per year, the number of car owners in relation to GDP is higher than in any other country and that the USA have the highest fuel intensity in terms of fuel use per km (see also Table 3). Mobility patterns not only contribute to a high level of fuel use, but building up and maintaining the large vehicle fleet and an extensive road network in a sparsely populated country have contributed to the high consumption of metals, construction minerals and fossil energy carriers in the past and continue to do so. Also low density settlement patterns, suburbanization and energy intensive heating and cooling patterns contribute their share to the high DMC of the USA (Rickwood et al. 2008). Schipper (2004) found that houses in the USA are larger than in other countries and that household appliances are more inefficient and contribute to the high level of residential energy and electricity use in the US (Table 3).

8. Conclusions

The development of the physical economy of the USA during the last century shows the characteristic pattern of the socio-metabolic transition: Massive growth of both extraction and trade of materials, a shift from the dominance of renewable biomass towards fossil and mineral materials and a multiplication of metabolic rates. As for other cases, it is possible to distinguish different phases of growth and stabilization or even slight decline in per capita material and energy use since the 1970s. But unlike most other industrial countries DMC did not stabilize but continued to grow. Our results corroborate the findings by Ayres et al. (2004) that the USA is not dematerializing to any degree that has environmental significance. Our material flow analysis indicates that population growth obviously plays an important role in the U.S. case. Each additional inhabitant with resource intensive consumption patterns adds to overall material use. But if we acknowledge that high economy-wide flows are also a result of general material intensive structures (infrastructures, industry), population growth may also have another effect: In this case, population growth means that high overall flows are divided by a larger number of people contributing to a decline in per capita DMC.

We have shown, that the U.S. economy is contributing an over proportionally high share to global resource use. Per capita rates of material consumption in the US are higher than in other industrial countries. This is a result of different underlying factors and can be attributed to a material intensive lifestyle and consumption patterns of the *American Way of Life*, but also to material intensive infrastructures, settlement and mobility patterns which have evolved in the course of industrialization as a result of bio-geographic factors, abundant resources and declining raw material prices (Rogich et al. 2008). In that sense, our results indicate that high (or low) metabolic rates are not only a result of consumer choices and lifestyle but of historically grown patterns of agricultural and industrial production, infrastructures and settlement patterns. The U.S. example also illustrates that decisions on the spatial organization of the economy and infrastructures have a long lasting effect of resource use and the resource intensity of housing and mobility patterns. The exact interplay of the underlying factors which determine material use is far from fully understood and requires further research. A better understanding of these factors, their interplay and how they materialize in historical legacies which shape future resource use patterns are essential for the question, where measures and policies in support of dematerialization might best be applied.

9. Acknowledgements

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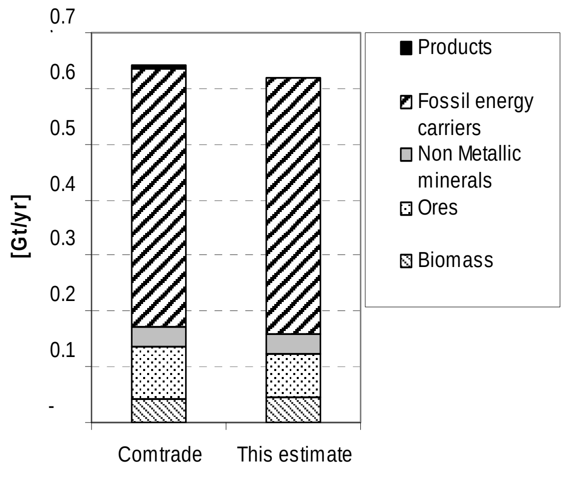
11. Technical Annex

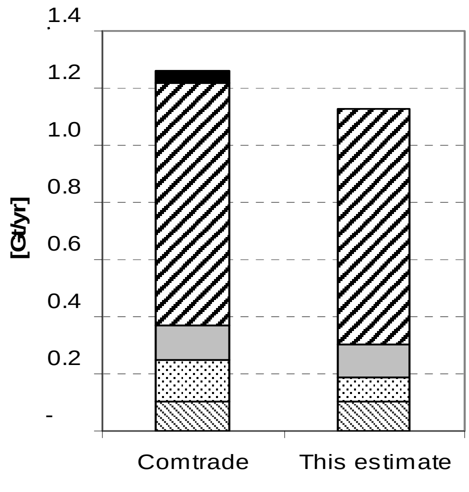
11.1 Trade flows

Due to limited availability of trade data, our series on physical imports and exports includes raw materials and semi-manufactured products only, while trade of many manufactured products, such as vehicles, machinery, chemicals, plastic products or furniture was omitted. In order to get a quantitative understanding of the significance of the omission of these flows, we crosschecked our results with data from the UN's comtrade data base (United Nations Statistical Division, 2008). Comtrade data are available for the period 1962 to present, but also this database reports fragmentary data for physical trade for most years. More or less complete coverage of mass flows of imports and exports exists only for the years 1978, 1985-1988 and 2005. A comparison of trade estimates that include manufactured products from comtrade database and the trade flows covered in our data series for the years 1978 and 2005 is presented in Figure S1. It shows that that manufactured products not considered in our account amount to 10-20% of total imports and 4-11% of total exports. Underestimation is highest for imports and exports of metal products (vehicles, machinery), petrochemical products (organic chemicals, plastics) and so called "products" (products which can not be assigned to a specific material group). However, in terms of net trade (PTB), the underestimation is much lower and amounted to -1% in 1978 and 6% in 2005. Although the omission of manufactured products causes considerable distortions for some material groups, the effect on aggregate flows and indicators of material use is rather insignificant. The impact on the size and time trend of DMC or PTB of the four main material groups is small.

a) Material imports 1978



b) Material imports 2005



c) Material exports 1978

d) Material exports 2005

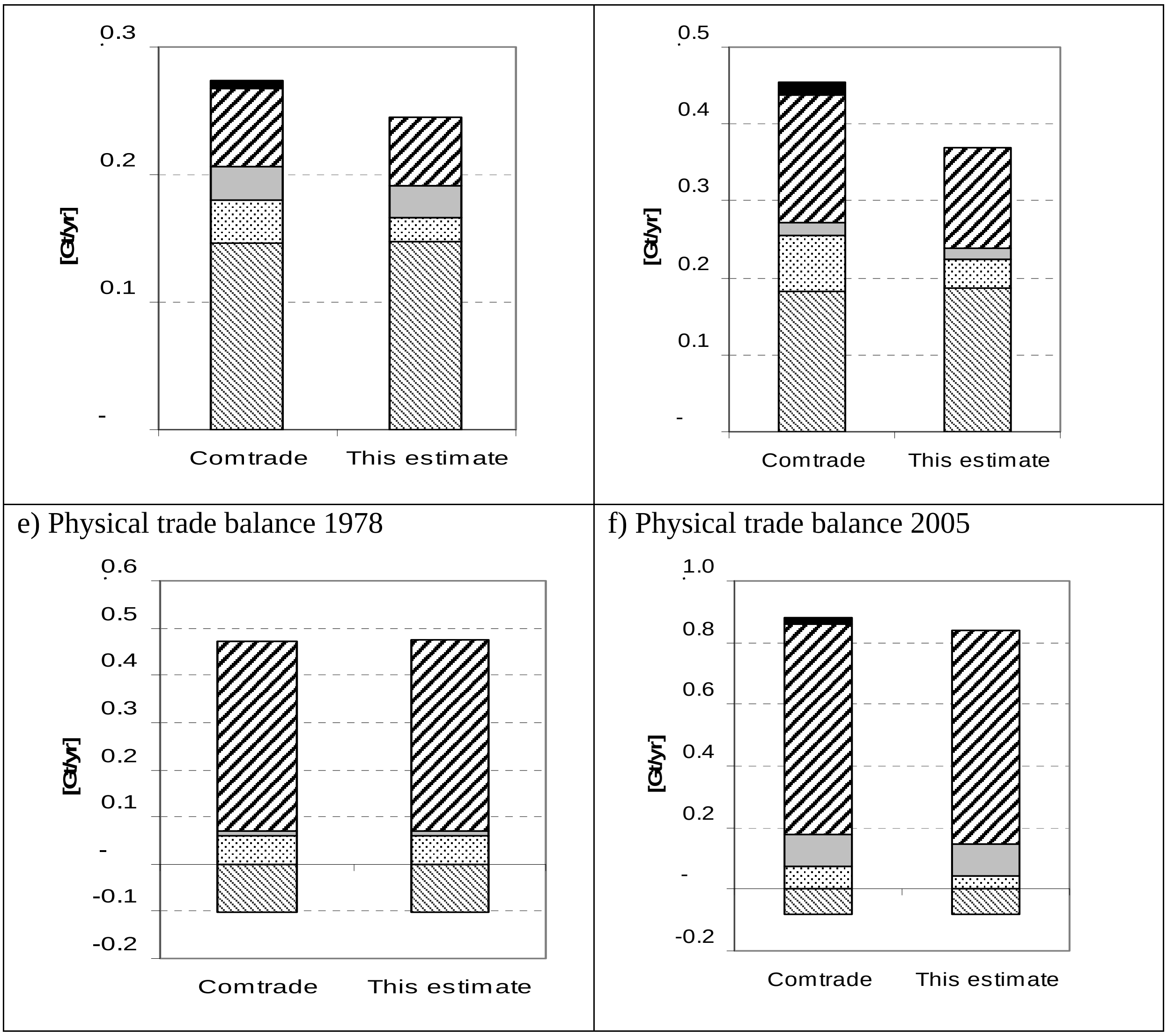


Figure A1: *Comparison of trade data from different sources for the years 1978 and 2005. Estimates of trade flows presented in this paper ("this estimate") are compared to an estimate that includes data on manufactured products from UN's comtrade database ("comtrade"). The classification system used to allocate trade items to material groups follows Eurostat 2009: Manufactured products are attributed to material groups according to their main raw material component; in cases where this was not possible, they were assigned to the group "products". Physical trade balance (Fig. S1e and f) is defined as imports minus exports. Negative values indicate net exports. Sources: "Comtrade" combines raw material trade as reported by FAO, 2009 and IEA, 2007 with trade of manufactured products as reported in comtrade (United Nations Statistical Division, 2008).*

11.2 Extraction of sand, gravel and crushed stone

Although quantitative information on the use of natural aggregates (sand, gravel and crushed stone) is available from statistical sources, we applied an estimation procedure to quantify the extraction of this large fraction of non metallic minerals. On the one hand, data on the extraction of natural aggregates reported in HSUS, 1975 are not consistent with the much lower values provided in Kelly and Matos, 2008. Also results presented by Matos, 2009 indicate significantly higher values. On the other hand, we wanted to ensure the highest possible degree of comparability with other long term MFA studies. We applied an estimation procedure based on the guidelines of material flow accounting of Eurostat, 2009. This procedure is widely used and has been adapted for the application in other world regions (e.g. Schandl and West, 2010, Steinberger et al., 2010) and long term historical studies (Krausmann et al., 2009; Krausmann et al., 2011). In contrast to other available estimation procedures, which use monetary information to quantify the use of so called construction minerals, the estimate applied in this study is based on purely biophysical data. It uses data on the production and use of cement, concrete and asphalt to extrapolate the demand for natural aggregates. We applied standard coefficients on the ratio of sand and gravel to cement in concrete and sand and gravel to bitumen in asphalt to extrapolate natural aggregates use. Based on Krausmann et al. (2009) we assumed a ratio of sand and gravel to cement in concrete of 6.1 and of gravel to bitumen in asphalt of 20. Furthermore we assumed that 1.15 tonnes of limestone are required to produce one ton of cement. In order to account for sand and gravel use as filling material in road construction and in the considerable network of unpaved roads, we increased the asphalt estimate by 50% (cf. Steinberger et al., 2010). Data on the production and consumption of cement and bitumen were taken from HSUS 1975, Kelly and Matos 2008, IEA 2007 and Abraham, 1945.

The results of our estimate, which we regard as conservative, are significantly higher than the values for sand and gravel used for construction reported by Kelly and Matos 2008 and match remarkably well with the more comprehensive figures presented in the USGS estimate of minerals use (Matos 2009). Figure S2 shows that out estimate of non-metallic minerals is roughly 20% above the values reported in Matos (2009), and that trends over time are highly consistent in both estimates.

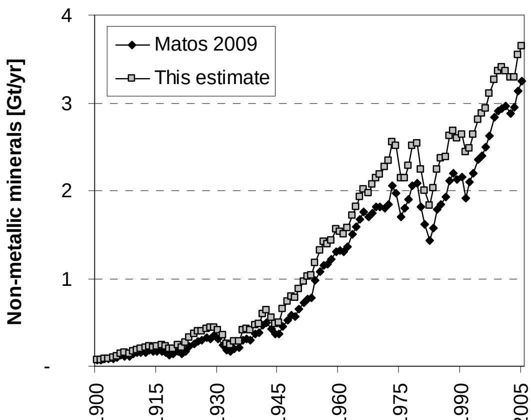


***Figure A2**: Use of non-metallic minerals in the USA 1900 to 2005: Comparison of data provided in Matos (2009) and this estimate.*

11.3 Comparison with previous material flow accounts for the USA

As has been outlined in the introduction of this paper, several previous studies have explored historical trends of energy and material use in the USA. An initial database compiled by Matos and Wagner (1998) focussed on raw materials for industrial use and presented yearly data for the period 1900 to 1995. It was later updated and currently includes 2006 as the most recent year (Matos, 2009, see also Rogich and Matos, 2002); the data is available for download from the USGS webpage. Although covering important parts of social metabolism, these data are not fully consistent with agreed upon MFA system boundaries and accounting principles (Fischer-Kowalski et al., 2011, Eurostat 2009): The estimate focuses on materials use in industrial processes and accounts for materials at the input-to-manufacturing stage, and not for materials extracted from nature. Furthermore it omits the largest part of all biomass fossil energy carriers and only considers biomass used as raw material for industrial processes and fossil energy carriers used as feedstock in the chemical industry. In contrast, recycled materials are, in deviation from MFA standards, accounted for as inputs. Another drawback of this dataset is that it focuses on apparent consumption only and does not distinguish between extraction, imports and exports. Figure S3 shows a comparison of the development of aggregate material use in the USA according to Matos (2009) and results of this study. While the overall trend in material use is remarkably similar in both datasets, the omission of biomass and fossil energy carriers results in much lower values of aggregate material use in the Matos (2009) series. Matos (2009) accounts for 12% of all materials in 1900; this share slowly increases up to 40% in the 1960s and since remained at that level.

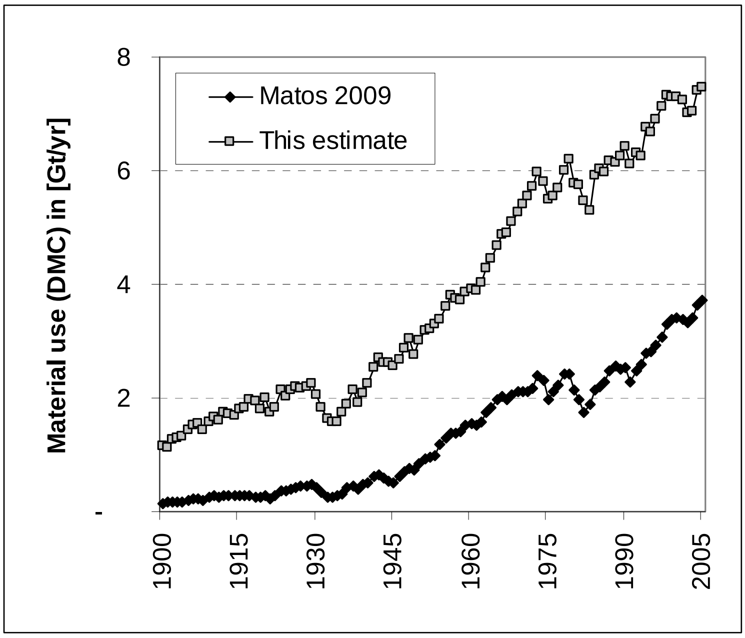


***Figure A3**: Development of aggregate material use in the US from 1900 to 2005. Comparison of data provided in Matos (2009) and this estimate.*

The USA was also one of the case studies in the seminal comparative MFA study initiated by the World Resources Institute (Adriaanse et al., 1997). From this study detailed MFA data exist, but only for the period 1975 to 1993; The material flow account was later updated to the year 2000 (Rogich et al., 2008). Figure S4 compares our estimates of material use with these data: Although the system boundaries and accounting procedures applied in Rogich et al. (2008) are similar to those suggested by Eurostat (2009) which have also been used in this study, some important differences remain, in particular because Rogich et al. (2008) apply a more restrictive definition of what is accounted for as used extraction and what as hidden flow: Rogich an colleagues do not account for gross ores or crop residues as used extraction. Also large flows like biomass grazed by livestock are omitted and instead meat and milk are accounted for as inputs. Figure S4 shows that the overall development of material use is remarkably similar in both material flow accounts, but that Rogich et al (2008) arrive at a roughly 25% lower value for total DMC than we do. This is due to the above mentioned differences in system boundaries and in particular to the less inclusive definition of used extraction applied by Rogich et al. (2008). Accordingly, the differences are largest for biomass (crop residues and grazed biomass) and minerals (mine overburden).

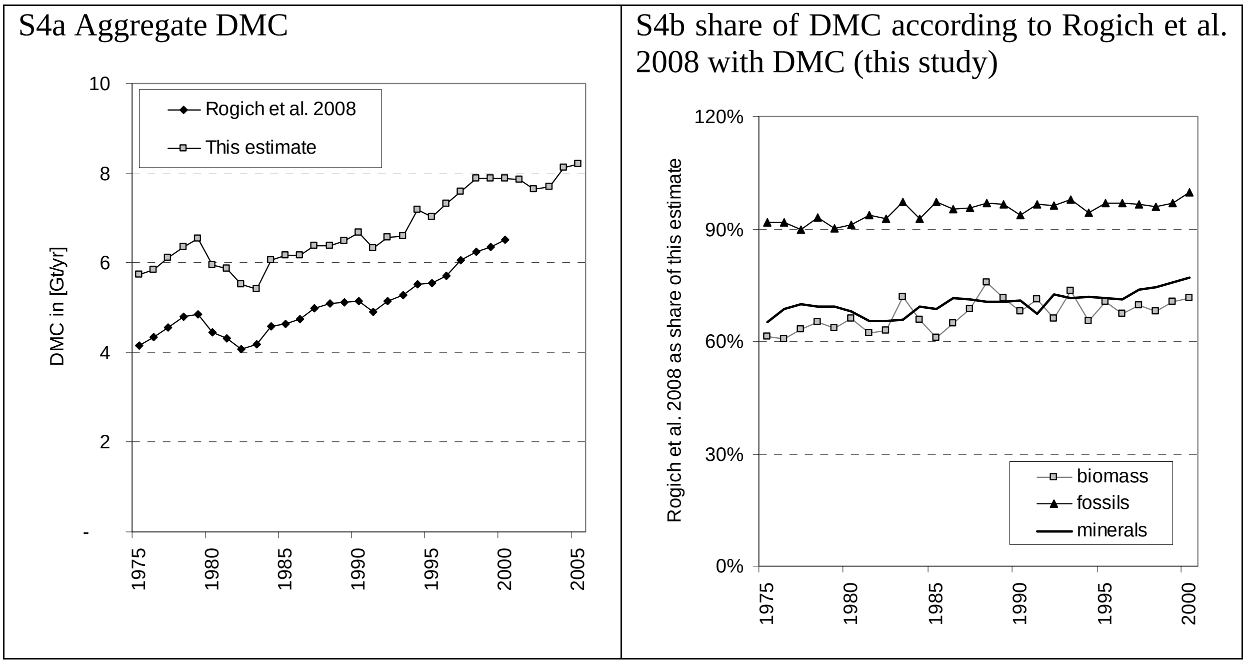


***Figure A4**: Comparison of DMC according to Rogich et al. 2008 this study. S4a compares aggregate DMC; figure 4b presents data on DMC of biomass, fossil energy carriers and minerals according to Rogich et al. 2008 as percentage of the estimate presented in this study.*

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India's biophysical economy, 1961 - 2008 Sustainability in a national and global context

Simron Jit Singh, Fridolin Krausmann, Simone Gingrich, Helmut Haberl, Karl-Heinz Erb and Peter Lanz

1. Summary

India's economic growth in the last decade has raised several concerns in terms of its present and future resource demands for materials and energy. While per capita resource consumption is still extremely modest but on the rise, its sheer population qualifies India as a fast growing giant with material and energy throughput that is exponential and still growing. If such a trend is to continue, the challenges for national as well as global sustainability are immense in terms of future resource availability, pressure on land and ecosystems and atmospheric emissions. Using the concepts of social metabolism and material flow analysis, this paper presents and discusses resource use trajectories for India from 1961 up to 2008 in a national and global context. We argue for India's need to grow in order to be able to provide a reasonable material standard of living for its vast population. To this end, the challenge is in avoiding the precarious path of industrialisation so far followed by industrialised countries in Europe and Asia, but to opt for a regime shift towards sustainability in terms of resource use by building on a host of promising examples and niches to make India a trendsetter.

2. Introduction

Within the ongoing discourse on global sustainability, India has come to feature rather prominently with its unequivocal message of attaining a higher material standard of living for its population by 2025, at par with industrialised nations. There has actually been an increase in industrial activity and income in the last decade. Demanding an increased share of the world's resources by invoking the language of environmental justice, India has leashed forward a development policy that demands more environmental space to grow. Obviously, this has not, and will not come without ecological consequences, both to its domestic as well as to the global environment.

The basis for India's arguments comes from its unequal share in the consumption of the world's resources. With a population that is one-fifth of the global total, India currently uses only 10% of the global supply of material resources (in terms of mass) and 6% of global primary energy supply (Steinberger et al. 2010). Its share in the use of key resources of industrialisation such as petroleum or copper is even smaller. Even though India's per capita level of resource use and emissions is strikingly modest, India's resource requirements are by far not negligible. For example, India is the world's fifth largest energy consumer and is third, after China and the US, when it comes to global carbon emissions (Marland et al. 2007, CDIAC data at http://cdiac.ornl.gov/). The challenge for India, therefore, is to be able to meet its development goals and resource requirements in a sustainable way.

As India is on its way to industrialise, the question remains to what extent this may be possible following the same pattern of industrialisation of the West that had occurred under very different conditions, namely, the benefit of cheap raw materials and labour from colonies and the abundance of fossil energy reserves accessible at low cost. Given the fact that India is still in the early phases of a metabolic transition from an agrarian to an industrial resource regime (Krausmann et al. 2008b), there are reasons for concern on how this process may continue within given biophysical constraints. On the other hand, being a latecomer opens up opportunities for India to learn from past mistakes, experiment with innovative pathways with high sustainability potential and to become a trendsetter for sustainable development.

This paper explores some of the sustainability challenges faced by India and tries to interpret the meaning of its development rhetoric in a biophysical sense. To be able to understand India's future sustainability challenges, we investigate its social or industrial metabolism, using the material and energy flow accounting framework (Ayres and Simonis 1994, Haberl et al. 2004, Fischer-Kowalski and Haberl 2007). Some of the derived indicators are also presented in relation to GDP to better understand the relationship between the economy and biophysical flows. Finally, the paper attempts to evaluate these trends in a global context and what this might means in terms of future global resource extraction and sustainability.

The next section gives a brief description of India's economic development since its independence in 1947 through the neo-liberal decades up to the present. Section 3 introduces the methods, indicators and data sources used in this study. Section 4 presents the main results of the material flow analysis and discusses the development of India's metabolism in detail, followed by a discussion of India's resource use in a global context in section 5. The paper concludes with an outlook, reflecting on possible futures.

3. India's economic policy and development since independence

At the time of independence in 1947, India inherited an economy that was predominantly agrarian with 70% of the workforce in the agriculture sector that contributed half of the country's total national income. Industry was underdeveloped with most goods imported from abroad that provided little impulse for economic growth. As the population grew, pressure on land increased for feeding an increasing number of people. Low levels of industrialisation, low labour productivity and agricultural output and under-employment contributed to a low national income. The Industrial Policy Resolution of 1948 under India's first Prime Minister, Jawaharlal Nehru, was in favour of rapid economic development and aimed to increase national savings with the state playing a key role. Agriculture remained the main instrument for addressing poverty in the rural areas and for improving food security for the infant nation. But most of the industrial production and manufacturing was state owned (such as mining, iron & steel, energy, infrastructure, communication, defence, etc.) and only a small number of industrial categories was left to the private sector.

Even so, up until the early 1980s, private industrial production was state controlled, which imposed severe barriers to the growth of firms with quantitative restrictions in their production levied through heavy taxation and licence fees. A main philosophy behind this was to distinguish between necessities and capital goods. Influenced by the socialist thinking of Russia towards which India was inclined, the ideology was in favour of moderate consumption as against accumulation or the use of "luxury goods". While necessities such as food and textiles were cheaply available, industrial goods such as televisions, cars, scooters, refrigerators, etc. were heavily taxed. The other reason was to reduce reliance on the import of energy and machinery since national savings was a major concern.

A large body of literature exists on the inefficiency of India's industrial policy that gripped the nation until the early 1980s (Ahluwalia 1985, Jalan 1992, Basu 2007). The stagnation of industrial production was attributed to low productivity and quality, high costs, obsolete technology and corruption in the license system. While India debated hesitatingly on its industrial reforms during the 80s, China doubled its GDP between 1978 and 1991. Close to an economic crisis and bankruptcy in 1991, India was forced to opt for a more liberal regime under Prime Minister P.V. Narasimha Rao that led to the dismantling of the license system, reduction of tariffs and dispensing of quantitative controls on imports. All in all, the new policy contributed to opening up more areas for the private sector, foster a competitive environment, uncontrolled production, and opening up to foreign investments, in particular for infrastructure and export-oriented sectors.

Despite such developments, for India, at the turn of the 21st century the primary sectors still plays an important role in contributing to the GDP, and still also is the sector where most of the labour force is employed. In 2005, 56% of the total work force was engaged in agriculture, contributing 19% to the nation's GDP. While the overall percentage of the population employed in the agriculture sector has steadily declined, the absolute number of agricultural workers has remained more or less the same (about 238 million). Industry and services, on the other hand, employ 19% and 25% of the labour force respectively. However, their contribution to GDP is rather significant, with 27.4% for industry and 53.6% for services. This comes in sharp contrast to the fully industrialized countries where typically less than 5% of the population are engaged in food production, contributing only one or two percent to the GDP, while the major share of income comes from services (Asian Development Bank 2007).

4. Concepts, methods and data sources

We use the concept of social or industrial metabolism (Ayres and Simonis 1994) and the corresponding methodology of material flow accounting (MFA) to investigate changes in India's biophysical economy, compatible to standard monetary system of accounts (Fischer-Kowalski et al. 2011). Following this approach, we aim at analysing the ecological "embeddedness" of India's socioeconomic systems (Martinez-Alier 1999). We refer to current standards of economy wide material flow accounting (Eurostat 2009, OECD 2008) to quantify domestic extraction (DE), imports and exports of materials and to derive aggregate headline indicators in physical units (mass and energy):

- *Domestic material consumption* (DMC) measures the apparent consumption of materials in an economy and is defined as the sum of DE and imports minus exports. It has been argued that DMC also equals the waste potential of an economy in the long run.
- The *Physical Trade Balance* (PTB) measures the physical net trade of a country and is defined as imports minus exports in physical units. Negative values indicate net exports.
- *Trade Dependency* (TD) measures the contribution of net imports to material consumption is defined as the share of net imports of DMC
- *Material Intensity* (MI) measures the amount of materials required to produce one unit of GDP and is defined here as DMC per GDP. It is the inverse of material productivity.

In this paper we discuss data and indicators at an aggregate level, distinguishing between the four main material groups: biomass, fossil energy carriers, ores and industrial minerals and construction minerals. Fossil energy carriers, ores, industrial and construction minerals are

also subsumed under mineral and fossil materials as opposed to biomass. In some cases we also refer to a more detailed split of material groups.
The material flow database we established for India follows the structure proposed by Eurostat (2009) and, at the most detailed level, includes data on the yearly mass flows of 50-70 material groups. It covers the time period 1961 to 2008. We used international statistical sources, but cross-checked international data with national statistical sources where possible for some points in time. Main source for these cross-checks were the Indian Statistical Abstracts series (CSO 1966, and other years).

For the domestic extraction of biomass we used data from FAOSTAT (FAO 2005, FAO 2009) for harvest of crops, fuelwood and timber, as well as fish capture. The amount of used crop residues was estimated by using region specific harvest indices and recovery rates for major crops (Krausmann et al. 2008a). We calculated dry matter feed balances to estimate grazed biomass and roughage extraction by applying a "grazing gap" method, i.e. assuming the difference between total feed demand and market feed supply being covered by grazing (Krausmann et al. 2008a; Eurostat 2009). Livestock numbers were drawn from the FAO (2009). Feed demand was estimated by using livestock numbers from FAO (2009) and species-specific feed intake factors reflecting changes in livestock productivity over time (changes in milk yield, live weight; see Wirsenius 2003, Krausmann et al. 2008a). Market feed supply was calculated based on statistical data (FAOSTAT 2010).

Data on the domestic extraction of fossil energy carriers was obtained from the International Energy Agency (IEA 2007, IEA 2010) for the extraction of coal, petroleum and natural gas for the period 1970 to 2008 and UN statistics (UN 2007) for the period 1961 to 1970. For the domestic extraction of ores and industrial minerals the main sources were the United States Geological Survey (USGS 2008 and other years) and the United Nations (UN 2007). We used region specific information on coupled production and ore grades derived from US databases (USGS 2008, United States Bureau of Mines 1987) to extrapolate the amount of extracted gross ore from reported metal/mineral content.

Construction minerals comprise mostly of sand, gravel and crushed stone. None of these materials are reported in national or international production statistics. We estimated the use of natural aggregates by applying a procedure discussed and applied in recent MFA studies (Krausmann et al. 2009, Schandl and West 2010). This method allows a quantification of sand and gravel used for concrete and asphalt production on the basis of data on cement and bitumen consumption. Data on cement production and consumption were taken from the literature (Cembureau 1998); bitumen consumption was derived from IEA (2010). The applied coefficients are conservative and it can be assumed that the procedure has a tendency towards underestimating the overall amount of natural aggregate use: Our estimate emphasises on natural aggregates which in most countries account for more than 90% of construction minerals, but we neglect other materials such as clay for bricks. Also filling materials are not fully accounted for (Krausmann et al. 2009).
Trade in biomass (products from agriculture and forestry) was derived from FAO databases (FAO 2006, FAOSTAT 2010). Trade in fossil energy carriers and derived products was taken from IEA databases (IEA 2007, 2010) and the UN energy statistics yearbook (UN 1984 and other years). Trade in minerals and other manufactured products was taken from the United Nations COMTRADE database (United Nations Statistical Division 2008). We extracted data at the three digit level of SITC rev.1 classification and used Eurostat (2009) correspondence tables to allocate trade items to material groups. Gaps and flaws in primary data were

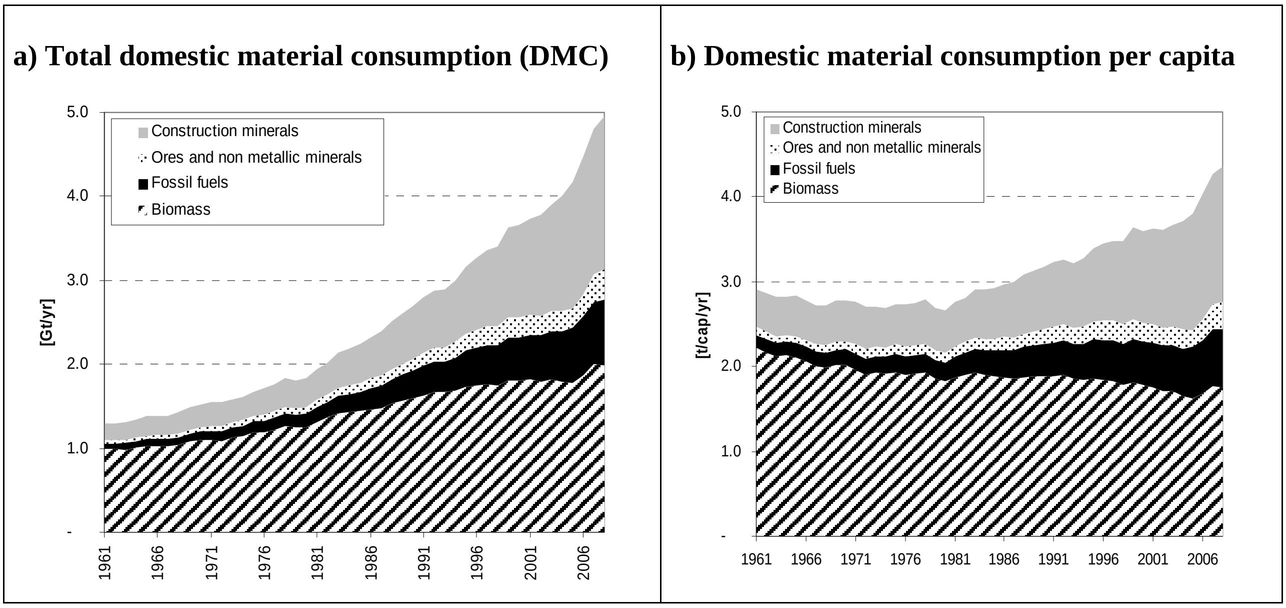
identified via examination of monetary trade data which are more reliable than physical data. Detected flaws and data gaps were corrected by using average unit prices of neighbouring years and monetary information. Data on population and GDP (in constant USD of 2000) were taken from published statistics (The World Bank Group 2010).

5. Material flows through the Indian economy (1961 – 2008)

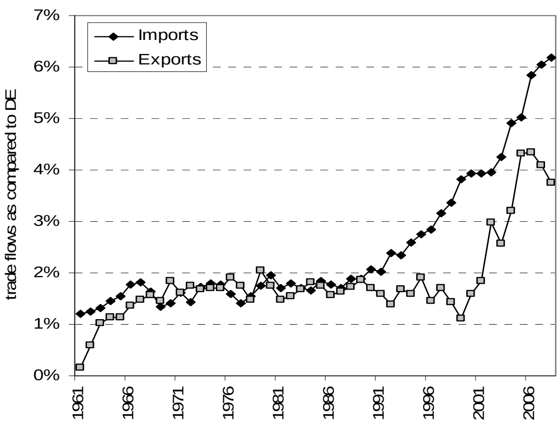
5.1. Overall trends

In this section we report results of our calculations of material flows in India to examine the ongoing metabolic transition in India since the 1960s. Figure 1 provides an overview of the yearly Domestic Material Consumption (DMC) between 1961 and 2008, both in absolute (Figure 1a) and per capita (Figure 1b) units. In the 1960s, about three quarters of the total material consumption consisted of biomass while construction materials were second in importance. Fossil fuels and industrial minerals and ores were insignificant in relation to the total flows. In the course of the 47 year period, this has changed considerably, not only in the quantity of total resource flows per year, but also in the composition. The use of biomass doubled, but compared to other materials this growth was almost insignificant. Fossil fuel consumption multiplied by a factor of 12.2, industrial minerals and ores by a factor of 8.6, and construction materials by a factor of 9.1.

Total material flows have almost quadrupled (factor 3.8) since the 1960s, with an increasing share of resources coming from non-renewable geological stocks: The share of biomass in total DMC declined from 75% in 1961 to ca. 40% in 2008. On the other hand, the share of mineral and fossil materials in India's DMC increased steadily from only 25% in 1961 to 60% in 2008. The growth period corresponds to the period of India's liberalisation and structural adjustment in the early 1990s, where heavy emphasis for the development of infrastructure and industry was laid on attracting foreign corporations and investments.



c) Trade flows as compared to domestic extraction (DE)



d) Material intensity of the Indian economy

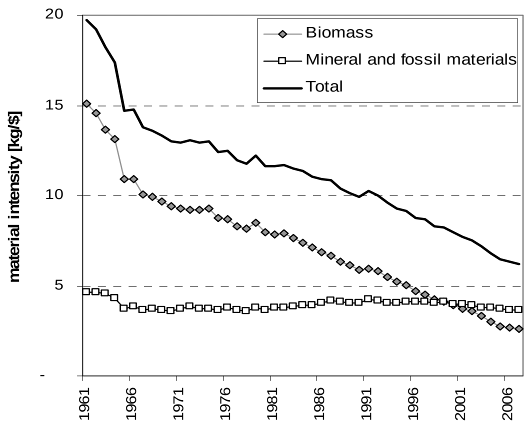


Figure 1: *Trends in material use and material intensity*

Until the 1980s the population grew at a slightly faster pace as material throughput. Throughout the 1960s and 1970s, material use remained at a low and slowly declining level of less than 3 t/cap/yr (Figure 1b). Only since the early 1980s a sustained growth in per capita material consumption set in and during the last three decades per capita material use grew by over 60% to 4.3 t/cap/yr, with growth accelerating in the last five years. India’s societal metabolism is largely dominated by domestically extracted materials. Both imports and exports are small compared to domestic extraction, but the significance of trade for India’s societal metabolism is increasing rapidly. Until the late 1980s the size of material imports amounted to 1-2% of the size of DE and since has tripled to over 6%. Export flows remained in the 1-2% range as compared to DE until the late 1990s and since have grown to around 4% (Figure 1c). In 2008 India was mostly importing fossil fuels, timber and ores and derived products, while exports were dominated by ores, non metallic minerals and crop products.

Although trade flows are small compared to DE, India is an important player in global trade relations because of the overall size of these flows.

India achieved considerable economic growth during the observed period. Its GDP (in constant 2000 USD) increased by more than an order of magnitude (factor 12.4). That is, the monetary economy grew much faster than the physical economy. As a consequence, the material intensity of the Indian economy, measured as the ratio of DMC per GDP, declined by 69%, from almost 20 kg of DMC per $ GDP to only 6 kg per $ (Figure 1d). This decline can be attributed mainly to the slow growth of biomass consumption. In contrast, the use of mineral and fossil materials grew at exactly the same pace as GDP, resulting in a fixed material intensity of these materials of slightly less than 4 kg per $. This indicates that resource use efficiency did not improve despite technological developments during this period.

5.2. India’s biomass system

Due to its role in human and animal nutrition, biomass is an essential component of social metabolism in all economies (Ayres 2007). Biomass is an area-based resource and, at least potentially, renewable. Its production is directly related to land use and entails specific environmental pressures on terrestrial ecosystems. In contrast to all mineral resources, the size of biomass metabolism is connected more to bio-geographic factors such as population numbers, the size and composition of livestock, and land productivity rather than to economic development (Krausmann et al. 2009, Steinberger et al. 2010, Steinberger and Krausmann 2011). While fossil fuels replaces biomass as source of technical energy (such as fuelwood or animal traction) in the course of a socioecological transition (Erb et al. 2008), biomass in food is non-replaceable, and its per-capita consumption varies much less over time than that of any other resource. However, the composition of biomass in food may considerably alter depending on changing food habits.

India’s biomass system has undergone fundamental changes in the past decades. Domestic consumption of biomass doubled from around 1 Gigaton (or 1 billion = 10^9 tonnes) per year in 1961 to 2 Gt/yr in 2008 (Figure 2a), showing a steady increase which accelerated in the late 1960s. Agricultural biomass makes up the lions share (85%) of all extracted biomass throughout the entire period. Wood, the largest part of which is used as fuel wood, accounts for only 15% of total biomass extraction. In the year 2004, the share of biomass in India’s technical primary energy consumption (excluding human and livestock nutrition) was 32%, a substantial part of which was used in the residential sector for cooking and heating (Planning Commission 2006, Pachauri and Jiang 2008).

Aggregate imports and exports range in the level of only 1% of domestic consumption of biomass throughout the time period. Nevertheless, trade in biomass is important for India’s physical economy and a strong change in trend in India’s biomass foreign trade relations can be observed (Figure 2b). From the 1960s until the late 1970s, India was a net importer of crops. From the late 1970s to the late 1980s, net trade with biomass was negligibly small. Since then, India has exported increasing amounts of primary crops, peaking at 0.017 Gt/yr (i.e. 17 million tonnes per year) in 2008, while at the same time importing more and more wood. Even though domestic extraction of wood more than doubled from 1961 to 2008, India increasingly depended on wood imports to meet the population’s demand for timber.

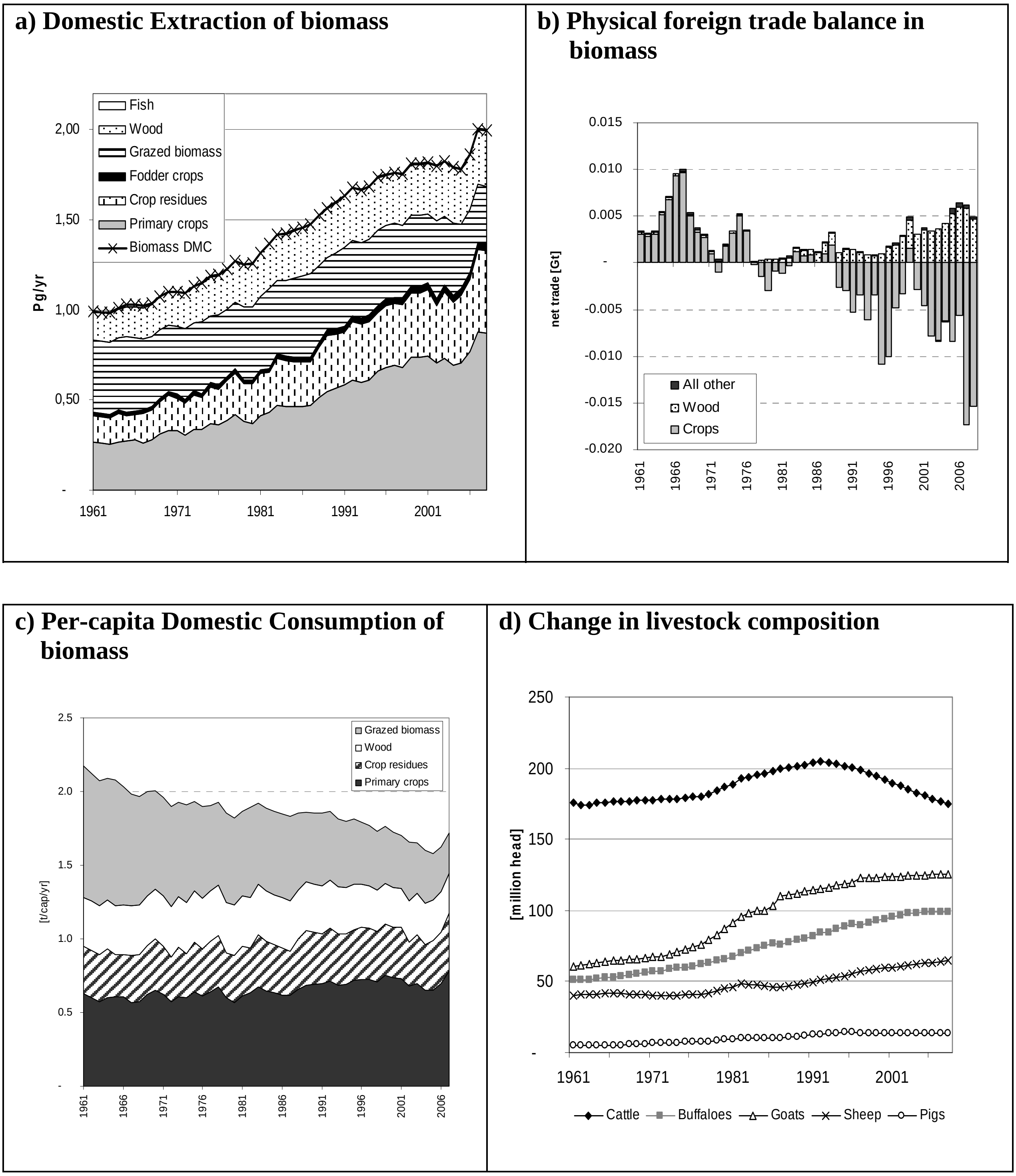


***Figure 2**: Trends in biomass use and livestock*

Primary crop production grew by a factor of 3.3 between 1961 and 2008. This increase was even steeper than population growth in the same period and crop production per capita went up by more than 20%. Agricultural production can grow due to agricultural area expansion or yield increase. In India, yield increase was the dominant factor for the rise in agricultural production in the observed period as a consequence of the green revolution rapidly adopted in the mid-1960s after a series of food crises following two wars and two consecutive droughts

(Gupta 2008).[17] Average cereal yields rose by a factor of almost 2.8 between 1961 and 2008, from 0.8t/ha/yr in 1961 to 2.2 t/ha/yr in 2008. Arable land experienced its last significant expansion in the 1950s when 25 million hectares were cultivated, corresponding to a 25% increase in cropland (Gupta 2008). Since then, arable land has stayed relatively constant around 160 million hectares (increasing by 2%). However, with 54% of the total land area used to grow crops, India is currently the country with the fifth highest share of arable land worldwide (FAO 2009).

Besides a shift from traditionally grown crops towards high-yielding varieties of wheat, corn and rice, two types of agricultural modernisation were fostered in the course of the green revolution through a liberal subsidy policy: the use of agrochemicals, above all fertilizers, and the improvement of irrigation technology (Gupta 2008, Birner et al. 2009). Between 1981 and 2005 national fertilizer consumption went up from 6 to 20 million tonnes, with more than 60% of the gross cropped area under fertilizer use.[18] Most of the fertilizers are domestically produced and India is now the fifth largest producer of fertilizer in the world (Birner et al. 2009). Since the 1960s, the total irrigated area has tripled and now about 40% of all cropland is irrigated. The expansion of irrigated area was an important variable in increasing agricultural yields. Subsidy in the form of cheap electricity has raised the share of groundwater as a source of irrigation considerably, from 30% in the 1950s to nearly 60% in 2000. Today, nearly half of the total irrigated area uses electric pumps for its water supply (Kapila 2008).

Despite increased production and comparatively small exports, total domestic consumption of biomass did not keep pace with population growth, as shown in Figure 2c. Per-capita availability of biomass declined from 2.2 t/cap/yr in 1961 to 1.7 t/cap/yr in 2008. While primary crop production even outpaced population growth and all other biomass categories including wood grew at a similar pace as population, the only material group which actually did decline in relation to population growth was grazed biomass (Figure 2c). Its share in total DMC went down from 40% to 16% and also the absolute amount of grazed biomass decreased considerably since the late 1980s when the number of cattle, which are responsible for the lion's share of grazed biomass, began to decline (Figure 2d). So to say, while the overall per capita consumption of biomass declined, it was not at the cost of per capita availability of food crops that actually increased. At the same time, the decline in livestock and grazed biomass did not, however, result in a decline in the output of animal products. On the contrary, the total output of milk increased five fold and that of meat even 16 fold in the observed period (FAO 2009). This indicates considerable efficiency improvements in livestock production related to the green revolution.[19]

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[17] The war with China was in 1962, and the one with Pakistan in 1965. The two droughts were in 1965-66, that lead to a massive food crisis. Food grains had to be imported from the United States, but on one occasion, against the backdrop of the Cold War, a U.S shipment was stopped on the way to ensure compliance from India.

[18] However, there exists strong variation between the various states of India. For example, more than half of the fertilizer use is concentrated in the states of Punjab, Haryana, Uttar Pradesh, and Andhra Pradesh. The average kg/ha in these states double that of the Indian mean (Birner et al. 2010).

[19] Our data show that the output of animal products per unit of feed input (both in tons dry matter) increased from 0.04 to 0.14 t/t; total output per unit of grazed biomass even surged from 0.05 to 0.32 t/t. This is a result of changes in livestock management; among the most important factors driving these increases in feeding efficiency were a shift towards more productive livestock species like chicken and poultry, improvements in the quality of feed (from crop residues towards market feed) and also a shift from multifunctional livestock

The data presented above shows that per capita primary crop availability increased in India from the 1960s up to today. FAO (2009) reports that cereals used for food increased between 1961 and 2007 from 139 kg/cap/yr to 153 kg/cap/yr; the importance of non-grain food such as sugar crops or fruit increased even more strongly. Milk consumption almost doubled to 69 kg/cap/yr. This indicates that India not only managed to supply a growing population with sufficient food, but also achieved improvements in dietary patterns (more and higher quality food availability per capita). The only exception here is meat consumption; in spite of considerable increases in output, per capita meat consumption in 2008 was 12% lower than in 1961 and much lower as compared to other Asian countries.[20] Meat is the most biomass-intensive food product and the low significance of meat in Indian dietary patterns is one important factor contributing to the comparatively efficient biomass system in India. Overall, food production per unit of agricultural biomass DMC went up from 0.14 to 0.23 t/t between 1961 to 2008. This ratio is still relatively low as compared to other Asian countries: China produced 0.34 tonnes of food per ton of agricultural biomass DMC in 2000, Japan 0.45 t/t and the Republic of Korea 0.46 t/t.

India's demand for biomass will further increase. While the expected growth is primarily related to continuing population growth, changes in income and dietary patterns as well as the demand for biotic energy carriers and raw materials might also drive demand upwards. How can the growing demand be met? Next to importing biomass, there are potentials to further increase domestic supply: Despite the achievements of the green revolution, India's crop yields still appear to be rather low. With the exception of sugarcane, potatoes and tea, the potential for increasing production is considerable (Birner et al. 2010). For example, the yield of rice, the most important cereal in India, was at 3.4 t/ha/yr in 2008, only about half of the value of China (6.6 t/ha/yr) or Japan (6.4 t/ha/yr) (FAO 2009). Further improvements of yields could be accomplished through the adoption of more efficient breeds, but also through better management. While fertilizer use in some regions may already cause ecological problems (Kapila 2008), average fertilizer use in India is at 100 kg/ha/yr still far below many countries in the region, such as China (276 kg/ha/yr), Bangladesh (155 kg/ha/yr) or Pakistan (135 kg/ha/yr) (Planning Commission 2006, FAO 2009). Also, the irrigation system could be further improved (Planning Commission 2006, Birner et al. 2010) to approach the full potential of irrigation (estimated at 85 million hectares). An indication of this potential is that the current productivity of the vegetation is only 78% of the productivity of the potential vegetation;[21] this difference is even larger on cropland where it is 69% (Haberl et al. 2007a). The world average, in contrast, is at 90% (on cropland 65%), but in industrialized countries this share is substantially larger: The vegetation of the EU-15, for example, is at 93% of the potential productivity, for the sum of ecosystems as well as on cropland. (Haberl et al. 2007a). Soil degradation, on croplands well as on grazing lands, plays a substantial role in this context (Zika and Erb 2009). In the last decades, the reduction of productivity resulting from land use has been reduced (see Table 3 below).

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providing labour, manure and milk in subsistence agriculture towards the mono-functional production of meat and milk.

[20] While per capita meat consumption in China and Japan was at a similar level as in India in 1961, consumption in these countries multiplied and in 2008 was drastically higher than in India (53 and 46 kg/cap/yr, respectively, as compared to 3.3 in India).

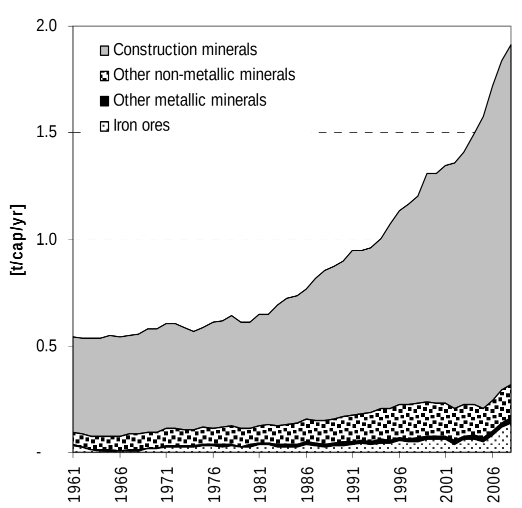
[21] Potential productivity denotes the productivity of the potential vegetation, i.e. the vegetation that is assumed to prevail in the absence of human activities (pristine ecosystems).

Improvements in the livestock system could be another source for increasing biomass output. India maintains a very a large livestock, both in terms of livestock units per capita and per unit of area, with a very high share of ruminants. In 2008, India hosted twice as many cows as China and four times as many buffaloes. In contrast to the large number of animals, output of animal products and overall feed conversion efficiency of the livestock system are, despite improvements in the past, still very low (see also Birner et al. 2010). In 2005 roughly 60% of all extracted biomass was used to feed animals, while the contribution of animal products to total food output was only 7% (measured in tons dry matter). To some degree, the low efficiency of the livestock system is due to the fact, that Indian cattle not only provide milk and meat, but also labour and manure for subsistence farmers and put value to crop residues and land not suitable for cropping. But also the considerable number of unproductive animals might play a role here, as has been argued in the extensive debates on India's livestock system by anthropologists since the 1960s (Harris 1966).[22] Considerable efficiency increases in livestock production thus seem possible.

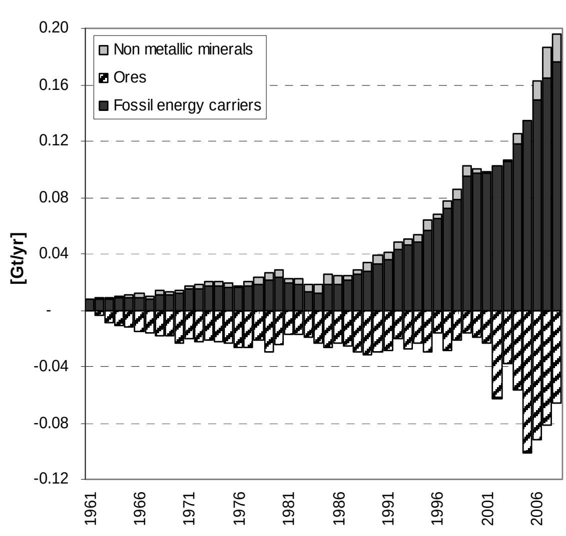
5.3. Mineral and fossil materials

Mineral and fossil materials show a fundamentally different pattern of development over time as compared to biomass (Steinberger et al. 2010). Fossil energy carriers, ores and non-metallic minerals are the key resources for industrial development and their use is closely intertwined. The shift from the dominance of renewable biomass towards a high share of mineral and fossil materials in aggregate material use is a characteristic feature of industrialisation (Krausmann et al. 2008b). This process of a metabolic transition can also be observed for the Indian case: In the early 1960s, still three quarters of all materials used in India were biomass; mineral and fossil materials have only been used at a rate of 0.7 t/cap/yr. By 2008 per capita consumption has almost quadrupled to 2.6 t/cap/yr and the share in aggregate material use rose to 60%. In this section we explore the flows of mineral and fossil materials in the Indian economy and their growth over time.

a) DMC/cap of ores and non metallic minerals

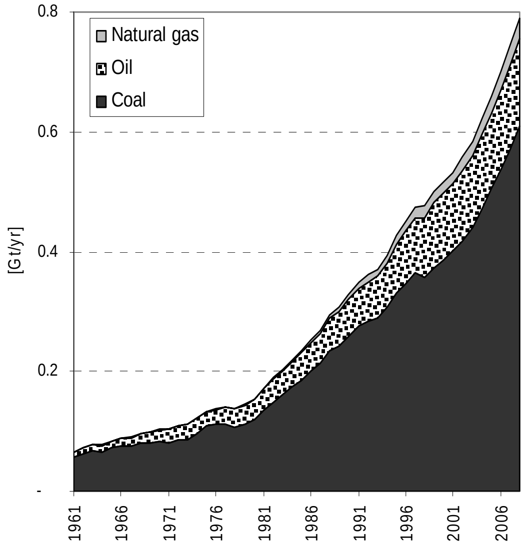


b) Physical net trade with mineral materials



[22] The so called "Holy cow debate" was concerned with the question if the size and sex ratio of cattle stocks in India was more determined by ecological or religious reasons.

c) DMC of fossil energy carriers.



d) Per capita DMC and import dependency of fossil energy carriers.

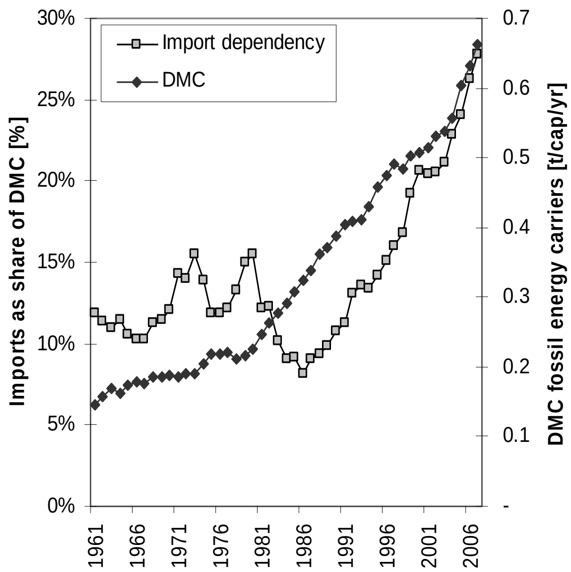


Figure 3: *Development of flows of mineral materials and their trade dependency*

Non-metallic minerals used for construction, most of them natural aggregates (sand, gravel, crushed stone) occupy the lion's share of the mineral materials fraction. During the 1960s and 1970s construction minerals roughly grew in line with population, but in the early 1980s a shift in the dynamic of growth occurred and per capita consumption began to increase (see Figure 3a). Since, DMC of construction minerals tripled and reached 1.6 t/cap/yr in 2008 (Table 1). This increase indicates that India is building up physical stocks as a result of rapid urbanisation and the expansion and modernization of infrastructures. In the observed period, urban population grew from 77 to 314 million people and in 2004 already 28% of the total population lived in cities as compared to 17% in 1961 (The World Bank Group 2007). The Indian government has made considerable efforts to modernize the country's rail and road infrastructure. Improving the country's 3.3 million km road network contributes to a growing demand of construction minerals. Although motorization has been speeding up in the 1980s and the amount of vehicles in use has been growing at an annual rate of almost 10%, still 14 vehicles per 1000 inhabitants is extremely low (Mitchell 2003).

Most construction minerals are abundant and scarcity is usually only a regional phenomenon (Habert et al. 2010). However, constructing large stocks of built infrastructure in general goes hand in hand with the use of ores and fossil energy carriers, not only for building, but also for running and maintaining these structures. Due to the long life time of these structures and their significance for economic development, everything that is built now will influence material and energy requirements for the coming decades. Decisions on infrastructure and their design – and hence the use of construction minerals – are important for sustainable development.

	1961	1980	2008	1961-1980	1980-2008
GDP [bio USD at const. 2000]	66	156	812	3.5%	6.0%
Population [mio]	444	687	1140	2.3%	1.8%
Fossil energy carriers [DMC t/cap/yr]	0.1	0.2	0.6	4.7%	6.0%
Ores and industrial minerals [DMC t/cap/yr]	0.1	0.1	0.3	3.4%	5.6%
Construction minerals [DMC t/cap/yr]	0.4	0.5	1.6	2.0%	6.2%

Table 1*: DMC [t/cap/yr] of the three main groups of mineral and fossil materials and their average annual growth rates (%) in comparison to population and GDP.*
Sources: Material and energy flows: own calculations; GDP and Population: The World Bank Group 2009

Ores and industrial minerals are a very large and heterogeneous group of materials with a broad range of applications. Only few ores and industrial minerals are of quantitative importance in terms of their mass flows in India, above all iron, bauxite and copper ore. India is a major producer and exporter of iron ore (Figure 3b). According to USGS (2008), India was the world’s third ranked supplier of iron ore and exports currently more than 70 million tons, mostly to China but also to Europe, Japan, and the Republic of Korea. Although domestic consumption of ores and industrial minerals has been growing, again at an accelerated pace since the 1980s, DMC amounted to only 0.3 t/cap/yr in 2008, a very low value in international comparison (Figure 3a).

Fossil energy carriers are the key resource of industrial energy systems. They were the fastest growing of the four material groups and DMC increased 12 fold to 790 million tons in 2008 (Figure 3c). The use of fossil energy carriers is tightly linked to economic growth. Throughout the observed period, the DMC of fossils was growing faster than GDP, accelerating considerably in the 1980s (Table 1). Since, fossil energy carriers have outgrown fuel wood and other renewables as major sources of primary energy. Their contribution to India’s energy supply has been rising from less than one third in the 1960s to roughly two thirds in 2004 (IEA 2007). Table 1 shows that between 1980 and 2008 the per capita consumption of fossil energy carriers more than tripled from 0.2 to 0.7 t/cap and year. This level, however, is still extremely low in international comparison. China, for example uses already twice this amount (1.2 t/cap/yr) and Korea and Japan around four tons per capita and year (Krausmann et al. 2008b). This is also reflected in the low overall per capita consumption of energy in India[23]. Lagging somewhat behind consumption, also imports of fossil energy carriers, mostly petroleum, have soared (Figure 3d). Import dependency is by far highest for this group of materials and surged from only 8% in 1986 to 28% in 2008. India’s net imports of fossil energy carriers have risen to 176 million tons in 2008 and are growing at an annual rate of 9% (Figure 3b and 3d).

At the beginning of the 21st century, India’s DMC of fossil energy carriers is still dominated by coal (Figure 3c) and is likely to remain so for a while given its abundant occurrence in India. Coal accounts for two thirds of DMC. Most of the coal is used to produce electricity in thermal power stations: India is now the third largest producer of coal in the world and has major coal reserves in the eastern part of the country that are estimated to last for another 140 years at current rates of extraction. But if domestic coal production continues to grow at 5%

[23] Total Primary Energy Supply (TPES) in the year 2005 amounted to 20 GJ/cap/yr for India as compared to 55 GJ/cap/yr in China. Electricity use in India was at 2 GJ/cap/yr in 2000, as compared to 3.8 GJ/cap/yr in China, 20.4 GJ/cap/yr in Korea, and 30.9 GJ/cap/yr in Japan (IEA 2007a).

annually, the total extractable coal reserves would run out in around 40 years (Planning Commission 2005).

Oil is second in importance as an energy source, contributing roughly one fifth to the DMC of fossil energy carriers of which 73% is imported, mainly from Saudi Arabia, Kuwait, Iran and Nigeria (Planning Commission 2005).According to recent statistics (U.S.Energy Information Administration 2010), oil reserves in India as of January 2010 are estimated to be 700 million tons (or 5.6 billion barrels) and growing only very slowly. These reserves amount to five times the annual consumption at current rates. Since consumption is growing faster than domestic production, import dependency for oil is increasing.[24] Natural gas is an extremely sought after energy source since the 1980s, but limited in supply. Natural gas presently has a share of 4% in the total fossil use and is estimated to go up to 20% by 2025 in combination with India's policy on restricting air pollution. The natural gas reserves in India were estimated to be 923 billion cubic metres in 2005, with new ones constantly being discovered (Planning Commission 2005). Still, India's domestic production is unlikely to keep up with the demand, which according to the government will increase at a rate of 4.8% annually until 2025. Hence, the planned pipelines from Iran and/or Turkmenistan have appeared as attractive options to mitigate continued environmental degradation but seem unrealistic given political controversies around energy security (Kiesow and Norling 2007). In general, there is a gradual shift away from low efficiency solid fuels (biomass and coal) to higher efficiency liquid and gas fuels for generating electric power and for transport as motorisation and number of vehicles per capita increases. In the future, however, the draw on cheap domestic coal is likely to increase.

Mineral and fossil materials exhibit a characteristic pattern of growth; the DMC of all subgroups increased several fold in the observed period. This growth was not continuous but accelerated at the beginning of the 1980s. Since then growth rates of mineral materials began to considerably exceed the rate of population growth and per capita consumption, which has been more or less stable throughout the 1960s and 70s, began to rise. This is a strong indication that the changes in the economic policy in favour of liberalisation and the subsequent shift towards a more market driven economy left their imprint also on India's physical economy. With accelerating economic development, India took a distinct step towards a metabolic transition. The use of all mineral and fossil materials grew at a similar pace as GDP and material productivity and the amount of mineral materials used per unit of GDP did not improve for these materials (Figure 1d).

The strong linkage between economic growth and the use of mineral and fossil materials, which has also been observed in international comparisons (Steinberger et al. 2010) suggests, that if India's economy continues to grow as expected, this will drive a surge in the demand in the coming decades – despite the fact, that a large part of India's economic growth is due to a rapidly growing service industry which is less material intensive than traditional industries. While this might contribute to improvements in material productivity beyond those observed in other countries with a higher significance of material and energy intensive heavy industries like China, it is unlikely that this alone can prevent growth of material use or even result in

[24] The demand for oil in India is increasing at the rate of about 4-5% each year, as compared to the global average of 1.6% (Kiesow and Norling 2007).

dematerialisation. India is only beginning to build up large networks of built infrastructure, material intensive patterns of settlements and mobility and with rising income typically material intensive consumption patterns increase. In a business-as-usual development, this will lead to a surge in India's demand for mineral materials and fossil energy carriers.

Although the scarcity of minerals in India is not of immediate concern – reserves for iron ore are estimated to last for 97 years, 200 years for copper and 166 years for Bauxite at 2006 production rates (Planning Commission 2006) –, the environmental and social consequences for such mining are reported to be severe (Padel and Das 2010). Moreover, production rates are on the rise which will result in the early exhaustion of these mineral reserves. The concern over future energy supply to sustain the 8% economic growth led policy makers to come up with a report on India's integrated energy policy envisioned for 2030. Among the several recommendations put forth is to achieve an increase in energy efficiency by 25% through a variety of measures as well as increasing the share of non-fossil based energy sources in the total energy mix for India to become 'energy independent'. However, realizing the full potential of hydropower and a 20-fold increase in nuclear and solar will only augment their share to 5-6% for each of them, while more than 80% of energy needs will still have to be met from fossil energy by 2030 (Planning Commission 2005).

6. Socio-metabolic transitions and the sustainability challenge: India and the global context

India shows key features of a sociometabolic transition from agrarian to industrial society (Fischer-Kowalski and Haberl 2007, Krausmann et al. 2008b, Haberl et al. 2011). In the 1980s a shift from biomass towards mineral and fossil resources was observed as well as an overall increase in per capita material use, in particular that of minerals and fossils. The size of trade flows concerning these materials too is growing rapidly as compared to domestic extraction. Overall, these developments have significantly accelerated in the past five years. From these trends we can say that India has already started its transition from an agrarian to an industrial resource regime, but still far behind industrialised nations where the dependency on geological stocks (mineral and fossil materials) is about six times higher and nearly three times in case of newly industrialising countries such as China (Table 2).

Also, the overall per capita consumption of all materials for an average Indian is significantly low at 3.6 tons per year in the year 2000, as compared to the world average of 8 t/cap/yr, and far below Europe's 14.1 t/cap/yr. Comparing the same with other highly populated countries in the region, India represents a profile of an agrarian economy while Korea and Japan are clearly industrial, in close proximity with the EU-15.

	Unit	India	China	Korea	Japan	EU-15	World
Population density	cap/km²	307	134	471	336	116	45
Resource use							
DMC	t/cap/yr	3.6	7.5	15.2	11.9	14.1	8.0
DMC biomass	t/cap/yr	1.8	1.9	1.6	1.4	4.3	2.9
DMC mineral and fossil fuels	t/cap/yr	1.8	5.7	13.4	11.5	9.4	5.1
Electricity use	GJ/cap/yr	2.0	3.8	20.4	30.9	25.2	9.0
Sustainability indicators							
Carbon emissions	tC/cap/yr	0.31	0.59	2.5	2.54	2.23	1.03
Ecological footprint	ha/cap/yr	0.8	1.6	4.05	4.35	5.0	2.2
Environmental pressures							
DMC per area	t/ha/yr	17	10	71	40	16	3.6
Biomass extraction per area	t/ha/yr	6.8	2.6	7.7	5.0	5.7	1.4
Human appropriation of net primary production (HANPP)	%	73%	38%	26%	24%	43%	22%
Productivity changes due to land conversions	%	-21%	-5%	+1%	-7%	-7%	-10%

Table 2*: Comparing metabolic profiles and sustainability indicators, 2000.*
Sources: Krausmann et al. 2008b, online dataset version 1.1 (DMC); Marland et al. 2007 (Carbon emissions); Loh and Wackernagel(eds.) 2004 (Ecological footprint); Haberl et al. 2007a (HANPP)

In this sense, the sustainability indicators for an average Indian seem rather favourable: per capita carbon emissions (from fossil fuels and cement manufacturing) and the ecological footprint, i.e. the area that would be required to sustainably support India's metabolism on the global average (Monfreda et al. 2004, WWF 2010), amount to only a third of the global mean, and about an eighth of industrialised economies, including Japan and Korea. These figures reflect a metabolic profile of a still highly agrarian society. While parts of India are rapidly industrialising, a large section of the population still live on subsistence and semi-subsistence agriculture (selling their surplus) with a modest material standard of living and lack of access to modern infrastructure such as electricity,[25] transport and roads.

However, owing to its vast population of 1.2 billion (current estimates) and high population density of more than 300 persons/km², the modest per-capita numbers become problematic while discussing overall sustainability of the Indian biophysical economy. India is the third largest emitter of carbon to the atmosphere from fossil fuel combustion, despite the below-per-capita-average of 1.4 tCO_2-equivalents/cap/yr, which is rank 142 in the global national comparison (the global average is at 4.6 tCO_2-equivalents/cap/yr; Marland et al. 2007).

Even with such modest per capita consumption of materials and energy, in an absolute sense they cause significant pressure on domestic resources. The amount of materials used in relation per unit of land area, a proxy for aggregate pressures on the domestic environment, is considerable. India has a DMC of approximately 17 t/ha/yr and year, 70% above the Chinese level and almost at par with the European Union. Of this, an increasing proportion is mineral

[25] About 46% of the households in rural India do not have access to electricity, while in urban it is 9%; those that do have access are characterised by intermittent power cuts (Pachauri and Jiang 2008).

and fossil materials from limited geological reserves but eventually deposited onto the biosphere and cannot be absorbed leading to pollution problems.

More than the use of mineral and fossil materials, the biomass system in India is affected by high population and shrinking per capita land availability. Despite relatively modest per capita consumption values, the overall amount of biomass extracted (and used) per unit of land area has doubled since the 1960s and amounted to 6.8 t/ha/yr, which is almost three times the land use intensity of China or Japan (Table 2). Environmental pressures related to such land use intensity and biomass production are considerable and are reflected in an extraordinary high level of Human Appropriation of Net Primary Production (HANPP). HANPP measures the aggregate effect of biomass harvest and land use intensity and denotes the amount of biomass appropriated by human activities compared to the potential productivity of the corresponding ecosystems (Haberl et al. 2007b). With a national average of 73% as compared to a global average of 25%, India's HANPP is extremely high and ranks fifth worldwide (Table 2). The figure tells us, that by land use humans harvest, destroy or lose 73% of the potentially available annual biomass flow and leave only 27% for all other species. Around one third (29%) of overall HANPP is due to productivity changes owing to replacements of pristine ecosystems and land degradation (Kapila 2008). The ecological impacts of India's HANPP in terms of biodiversity loss or deterioration of ecosystem services (Haberl et al. 2007b) can only be guessed.

Also footprint analysis indicates significant pressures resulting from India's overall resource use: India's footprint, despite the low per-capita values, is exceeding its own territory extension. This circumstance, denoted as ecological deficit (WWF 2010, Global Footprint Network and Confederation of Indian Industry 2008) is mainly explained by the combination of land use related ecosystem pressures and large total green house gas emissions. Net imports of biomass, or "net-imports of ecological capacity" (Wackernagel and Giljum 2001, Moran et al. 2009), do not play a prominent role for this "overshoot"). The difference between HANPP on India's territory and the global HANPP associated with the domestic consumption of biomass in India is almost negligible, indicating that India's biomass demand is predominantly covered by domestic sources, despite substantial sub-national biomass flows (Erb et al. 2009).

		India 2000	**India 2050**	**Increase in global DE**
Population	[billion]	1.01	1.53	
Biomass	[Gt/yr]	2.0	2.2	1%
Fossil fuels	[Gt/yr]	0.5	5.6	52%
Industrial minerals and ores	[Gt/yr]	0.1	1.7	31%
Construction minerals	[Gt/yr]	1.4	10.3	44%
Total DMC	[Gt/yr]	4.0	19.9	30%

Table 3*: A projection of India's DMC in 2050 under the assumption of the current Japanese metabolic profile.*
Source: Using population projections of the UN and per capita DMC of Japan from Krausmann et al. 2008.

Our analysis has shown that India's share of global resource use is over proportionally low and average per capita levels of material use are far below the global average, while pressures

on the national and global environment caused by India’s metabolism are already now considerable.
At the same time, India’s metabolism, and above all the use of mineral and fossil materials, is growing with its economy and is likely to continue to do so. A simple back of the envelope calculation illustrates the impossibility of such a business as usual development. If India with a projected population of 1.6 billion in 2050 would accomplish the per capita material use of Japan this would boost its demand for fossil energy carriers, ores and industrial minerals by a factor of 10 to 15 (Table 3). Globally, this would add 50% to the current levels of global extraction of fossil energy carriers, and 30% in case of minerals. India’s total DMC would increase from currently 4 Gigatons per year to roughly 20 Gigaton, which is almost a third of the current levels of global resource use annually. In other words, India’s development alone would lead to an increase of global material use by 30% (Table 3).

Thus, even if India would adopt the metabolic profile of Japan, currently one of the best performing industrial countries, this would result in enormous pressures on India’s and on the global environment. Such a path is, however, also questionable from economic reasons where prices for some key materials are likely to surge. Hope lies in the fact that for India, still in the early stages of a metabolic transition, the directions of change may be less path-dependent as compared to other booming Asia-Pacific countries such as China that are already far ahead with a resource intensive strategy of industrialisation (Schandl and West 2010).

7. Outlook

In the last three decades, the Indian economy has exhibited a new pattern of physical growth shifting from a biomass towards a mineral and fossil resource base, and towards a growing per capita resource use. In the past, the green revolution has drastically increased land and labour productivity of Indian agriculture and made it possible for India to provide a rapidly growing population with more and better food from domestic agriculture. Considering the high level of biomass extraction per unit of area and the high level of HANPP, potential for improvement can be achieved only through further efficiency increase in biomass production. But increasingly it is not population and biomass use that drive overall growth of material use but economic growth linked to the extraction of geological stocks and their per capita consumption. This trend is likely to continue if not to accelerate in the coming decades.

There is no doubt that India’s metabolism will grow in the coming decades. Just as it is imperative that the fully industrial economies will need to reduce their metabolism, India needs to be able to increase its currently extremely low level of resource consumption to improve the quality of life of its population. India needs access to energy and key raw materials, but it is extremely doubtful that India can adopt metabolic patterns typical for industrial economies. The big question that arises is, how India, which will be inhabited by 1.6 billion people in 2050, will be able to supply its growing economy with sufficient natural resources either from domestic or international sources and to do so in a sustainable way, without increasing pressures on its domestic and the global environment.

India will need a new resource revolution. But unlike the green revolution, which boosted the output of plant based raw materials, the next revolution must reduce the amount of mineral materials required. Part of this can probably be reached with efficiency gains and progress in prevailing technologies, but solving this puzzle will also require more fundamental changes. There is a host of extremely promising examples and initiatives in India that need to be recognised, rather than imitating western capitalism and industrialisation. For example, introducing different patterns of mobility (such as urban mass transport, freight movement by railways and energy efficient vehicles) and resource efficient settlement patterns and infrastructure design that are less environmentally damaging (such as in the use of compressed earth block technology, decentralised rural energy system, solar refrigeration in dairy, and the use of wind power) should be widely considered. Policies establishing benchmarks in energy use for all energy intensive sectors, as well as offering incentives for meeting energy efficiency targets might be useful.

The experience from TERI (The Energy and Resource Institute, Delhi) reveals great potential in targeting Small and Medium Enterprises (SME) that contribute to 45% of India's manufacturing output and 40% of exports. Material and energy throughput among SMEs is substantial but they have remained highly isolated from modern technological developments and continue to depend on obsolete inefficient technologies. In collaboration with Indian and international partners, TERI demonstrated a reduction between 25 and 65 percent energy use in foundries making cast iron in West Bengal. TERI has identified 178 SME clusters that are material and energy intensive but with high potential to bring about technological revolutions that will not only be environmentally friendly but also profitable (Sethi 2009).

New regimes are being created in terms of food, energy and infrastructure and opportunities for new niches are abundant (Wiskerke and Van der Ploeg 2004, van den Bergh and Bruinsma 2008). India is not to expect a meta-level transition but to focus on multi-level transitions based on socio-technological innovations compatible with culture, markets, organisation, regulation and infrastructures (Smith et al. 2010, Geels 2010). Markets, entrepreneurship, and innovation should play an important role. Clearly, the priority is growth and reduction of poverty along with a minimum standard of living for India's population. The challenge, however, is that capacities in terms of science and technology institutions, markets and governance system needs considerable improvement. To find ways is not only imperative for India but also for the global community, by burden sharing, technological transfer and by using a host of integrated and interdisciplinary approaches to make India a trendsetter. Above all, in seeking a new definition of quality of life and human well-being in line with a healthy environment would indeed be rewarding.

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The global metabolic transition: a historical overview

Fridolin Krausmann

1. Socio-metabolic regimes and transitions

The metabolism of human society is dynamic. It underwent major changes during the course of human history and is in a transition process now. Since the time of Palaeolithic hunter-gatherers the amount of materials extracted and used by humans has grown by several orders of magnitude. Quite obviously, a major driver behind this growth was population growth, but it also grew because per capita material consumption has multiplied. Next to the sheer size of the global metabolism also the composition of the used materials and the way in which they are used has been transformed. Through most of human history, the endosomatic metabolism of human organisms coined their material needs and renewable biomass was by far the most important material. In contrast, the metabolism of industrial societies is dominated by the exosomatic metabolism and the use of mineral resources. With these changes also the environmental impacts of our metabolism have changed and many of the sustainability problems human society is facing today are a direct consequence of its metabolism. Maintaining the functioning of society's metabolism without destroying the resource base and without deteriorating the natural environment by exceeding its capacity to absorb the outflows of our metabolism is a basic requirement for sustainability. This struggle is by no means a modern phenomenon or limited to the industrial age but has accompanied humans throughout their history. And it is one of the major challenges that humans are facing at the beginning of the 21st century.

This article recalls major stages in history through the lens of societal use of materials and energy. There is one important lesson to be learned here. Unlike the endosomatic metabolism of the human organism the extrasomatic metabolism of human societies varies by orders of magnitude. When analysing the constituents and sources of these variations, we recognize that historical variations in the social metabolism did not occur arbitrarily. Instead, certain socio-metabolic types (modes of production or subsistence of human societies) can be distinguished for historical and for contemporary societies, that share, at whatever point in time and irrespective of bio-geographical conditions, certain fundamental systemic characteristics derived from the way they utilize and thereby modify nature. This justifies speaking of socio-metabolic regimes which are above all distinguished by their type of energy system and the energy density it allows for. In general, socio-metabolic regimes have in common a main source of energy and the main technologies of energy conversion and accordingly share many other basic characteristics such as patterns and levels of resource use (*metabolic profile*), demographic and settlement patterns, patterns of use of human time and labor (*time allocation profile*, cf. Ausubel and Grübler 1995), institutional characteristics, and communication patterns (Sieferle 2001).

From a global history perspective, three major socio-metabolic regimes have been discerned (cf. Sieferle 1997; de Vries and Goudsblom 2002, Simmons 2008): the regime of hunters and gatherers, the agrarian regime and the industrial regime.[26] The regime character of the current industrial society is, however, to be contested, as neither its reliance on exhaustible resources

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[26] Some authors, such as Boyden 1992 further differentiate between simple agrarian societies (early farming) and advanced agrarian societies (early urban phase) and thus distinguish four regimes. With respect to the basic characteristics of their energy system and the energy density it allows for, however, there is no fundamental difference between these different agrarian societies.

nor its huge outflows which exceed the sink capacity of the earth system allow for long term existence (Sieferle 1997), an issue which will be discussed later on.
Although the most fundamental differences exist among metabolic regimes, there is also significant variation within them. We use *metabolic profiles*, which comprise a set of key metabolic indicators (Singh et al. 2010), to characterise the three socio-metabolic regimes, their subtypes and the differences between them. In our analysis of metabolic regimes we will not restrict ourselves to a discussion of material use, but rather focus on energy. The energy system is a key constituent of metabolic regimes. It is the characteristic of the energy system, which sets the boundary conditions for the material system, as the main purpose of socio-economic energy use is to reproduce and move materials structures. Therefore the use of energy and materials is closely intertwined, a relation which is fundamentally effected by the metabolic transition.

2. Foraging societies and the regime of hunter-gatherers

2.1. The uncontrolled solar energy system of foraging societies

Hunter-gatherers live off the land. They extract roots and fruits and hunt various types of animals much like other large mammals. The distinguishing element of the hunter and gatherer metabolism, as compared to other animals, is the use of fire and the corresponding use of considerable amounts of fuel wood (Goudsblom 1992). It is assumed, that humans began to use fire for cooking, for the provision of heat and for hunting at least since 800.000 years (e.g. Goren-Inbar et al. 2004). Hunter-gatherers use solely recent biomass as energy source. Unlike agriculturalists, though, they do not systematically manage ecosystems in order to increase the availability of usable biomass. The basic metabolic characteristic of hunter-gatherers (or foraging societies) thus has been called an *uncontrolled solar energy system* (Sieferle 2001).

Their lifestyle is often mobile: local resource exhaustion, which may be induced by temporal variations in bio-geographic conditions (climate) but also by the local exploitation and depletion of edible biomass, causes humans to move and prevents them from establishing permanent settlements. The frequency of movement, however, may differ largely (Simmons 2008).

2.2. The metabolic profile of hunter-gatherers

Although little is known about the specific metabolic characteristics of foraging societies, plausible ranges of metabolic profiles can be estimated based on available technologies and the key characteristics of the energy supply system. Quantitative information in the literature suggests that the metabolism of hunter-gatherers is by a factor 2 to 4 larger than the endosomatic metabolism of human beings (Simmons 2008, Fischer-Kowalski and Haberl 1997, Sieferle 2001, Boyden 1992). To meet their needs in terms of food and fuel, hunter-gatherers may extract around 0.5 and 1 ton of biomass per capita and year. This biomass corresponds to an annual metabolic rate of 7-15 GJ/cap/yr. Fuel wood makes up for the lions share of material and energy throughput while food often comprises of smaller share (around 200 kg or 3 GJ per capita and year). Biomass used for clothing and shelter contributes a minor part to material use. Biomass is the dominating resource and accounts for far more than 99% of both material and energy use. Almost all of the extracted materials are used as sources for primary energy; the non energy use of materials including biomass remains very low.

Therefore, the energy metabolism and the material metabolism are practically identical in the regime of hunters and gatherers. In other words, almost all materials are used for energetic purposes, as fire wood or food. In contrast to what common text-book classification of paleo- and neolithic societies into stone- iron- or bronze-age societies might indicate, the mineral component of material use was negligibly small during these periods of human history. Non renewable materials which are used by hunter-gatherers include little more than flint to light fire and stones used to manufacture artefacts like arrow heads or blades. The per capita use of metals such as iron or copper did not exceed a long term average of several grams per capita and year.[27] Taken together, all mineral materials comprise far less than one percent of the total material turn over in hunter and gatherer societies. The mobile life style and the limited availability of energy prohibit the accumulation of artefacts. Almost all materials are consumed shortly after extraction. Physical stocks maintained by humans did not amount to more than a few kg per capita. Although the direct use of materials and energy per capita which is accounted for in DMC and DEC appears to be very small, unused extraction[28], caused by fires used to support hunting, may have been considerable (Simmons, Boyden). Sieferle et al. 2006 estimate that in some cases human induced fires may have destroyed several 100 t of biomass for a few kilograms of hunted game per capita.

Like all human societies hunter and gatherers must match their energy demand density with the available energy supply density. The supply system for both the endosomatic energy (food) and the exosomatic energy (fire wood) is the natural vegetation. The energy supply density of biomass, defined as the continuous supply of power over one year ranges between 0.1 and 1 W/m2, or between 3,2 and 31,6 MJ/m^2 and year (Smil, 1991)[29]. This is the potentially available energy. However, only a very small share of the naturally available biomass in an ecosystem is edible for humans.

Simmons (2008) assumes an average territorial requirement of at least 25 km² to feed one person, but depending on bio-geographic conditions the area demand may vary widely. Average population densities of foraging societies have been estimated to range between 0.02 and 0.2 cap/km² (Simmons 1989). Low per capita demand for material and energy paired with low population density results in very low extraction rates per unit of area. A per capita material demand of 1 t (equal to 15 GJ) combined with an average population density of 0.2 cap/km² results in an extraction rate of 2 kg or 30 MJ of biomass per ha of land. As Boyden (1992) has pointed out, this means, that foragers use only a very small share of the available biomass of an ecosystem. On average, less than 0.01 % of the annual net primary production (NPP) is extracted by hunters and gatherers. This share, however, would increase considerably, if also biomass burned by human induced fires for hunting (unused extraction) was included in the calculation.

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[27] Based on historical data on global cumulative copper production (Hong et al., 1996) and estimates of pre-historic human population sizes (Biraben J.-N., 2003), copper was likely around 4-5 gram per capita and year in prehistoric times.

[28] Unused extraction is defined as the amount of materials extracted, moved, or transformed without the intention of using them. Large scale burning of the natural vegetation for the purpose of hunting causes a transformation of biomass into CO_2, water and ashes which are released into the atmosphere. It is the quantitatively most important component of unused extraction in hunter and gatherer regimes.

[29] The energy supply density of biomass as defined here is equivalent to the net primary production.

Combining low and high estimates of the metabolic rate (7-15 GJ/cap*year) and low and high estimates of population densities (0,02 to 0,2 persons per km2) with the lower and upper limits of energy supply densities for biomass, foraging societies used between 0,005 and 1% of the annually available biomass energy potential.

In absence of any technologies that would allow increasing the density of usable (edible) biomass, hunter and gather societies are forced to adapt their energy demand density to the available energy supply density. This posed effective biophysical limits to the structure and complexity of these societies, in terms of population size and density[30], accumulation of artefacts, or the establishment of permanent settlements.

It has also been argued, that despite the sparse availability of edible biomass the uncontrolled solar energy system allows for high energy yields of human labour (Boyden 1992). Hunter-gatherers typically invest only a few hours per day to secure their daily requirements of biomass and the energy invested by humans is small compared to the energy output in terms of food and fuel. This leaves them considerable time for activities other than securing food and wood. A characteristic which has been addressed as *affluence without abundance* by Sahlins 1972 (see also Müller-Herold and Sieferle 1998).

2.3. Environmental impacts and sustainability

The absence of purposeful management of ecosystems and low rates of resource extraction do not mean that the impact of foragers on their natural environment is negligible. Large scale fire management to support hunting such as it has been practised for example by the Australian aborigines has led to the establishment of new vegetation types and alterations at the landscape level. There is even an ongoing debate, to what extent hunters have contributed to the extinction of large mammals (e.g. Martin and Klein 1989). Like other mammals, hunters and gatherers are tapping into a flow of renewable biomass. Thus, at a very general level, the mode of subsistence of hunters and gatherers can be considered sustainable. Sustainability was, however, not guaranteed and could be threatened by external factors as well as socio-economic processes. Fluctuations in the natural conditions which have the potential to lower capacity of ecosystems to provide sufficient food for human populations on a supra regional scale imposed an external threat to sustainability. But also population growth could lead to unsustainable situations. In contrast to agriculturalists, hunter-gatherers were not able to deliberately improve the carrying capacity of the ecosystems they inhabited and growth was constrained by the size of the territory and the availability of edible biomass per unit of land. Continued population growth eventually had to result in over exploitation of natural systems. In this context it has been argued, that foragers have established effective social mechanisms to keep population density low and that it remained well under potential capacity in order to buffer the effect of the negative impact of variable natural conditions (Boyden 1992, Simmons 2008). Nevertheless, global population slowly grew. At the beginning of the Neolithic period, some 10.000 years ago, the world population amounted to roughly 4-5 million people (Cohen 1995).

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[30] Both population size and density are decisive preconditions for technological change (Ester Boserup 1965).

3. Agrarian societies and the agrarian socio-metabolic regime

3.1. The controlled solar energy system of the agrarian regime

Just like hunter-gatherers, agrarian societies are fuelled by a solar-based energy system and ultimately rely on the solar energy stored by living plants through the process of photosynthesis in biomass. In contrast to hunter-gatherers, agriculturalists actively manage terrestrial (and in some cases also aquatic) ecosystems. The transition from a hunter and gatherer to an agrarian socio-metabolic regime is commonly referred to as the Neolithic Revolution. Its distinguishing characteristic is the invention of agriculture. Although it is undisputed that agriculture marks a major transition in the history of humans, scholars are still undecided about the reasons for the Neolithic Revolution. There is well established evidence that the Neolithic Revolution occurred in parallel in several world regions of which the Fertile Crescent is probably the best known.

In metabolic terms agricultural techniques of breeding plants, farming and the domestication of animals (colonization of natural systems, Fischer-Kowalski and Haberl 1998) supports first of all a much higher level of useful energy per unit of territory as compared to a hunter and gatherer regime. It is the major characteristic which distinguishes the two regimes and entails fundamental differences in their metabolic profiles and their interactions with their environment. Although the major source of energy is still biomass, and therefore the energy supply system remains to be a land based low energy density system, the proportion of useable energy per unit of land increases by two or three orders of magnitude fold (depending on natural conditions and agricultural techniques, see Table 2). Agricultural techniques enable human societies to increase the output of edible or otherwise useful biomass (above all animal power to perform work and fibres for clothes) and energy resources per area and to systematically modify the carrying capacity of the ecosystems they inhabit. The energy system of agrarian societies has therefore been termed *controlled solar energy system* (Sieferle 2001). Biomass is still the single most important source of energy for socio-economic metabolism and amounts to more than 95% of primary energy supply (Malanima 2002; Smil 2008). The only other energy sources are water and wind power[31]. Wind and water mills provide for specific types of work and the kinetic energy of waterways (floats, riverboats) and wind (sailing ships) were essential for long distance transport. Although wind and water power were of considerable socioeconomic importance on a regional scale, for instance in 17th century Netherlands or 18th century England, they are quantitatively of little significance (Warde 2007). They usually account for no more than a few percent of energy supply. The lack of technological options to convert one form of energy into another imposed a constraint for (historical) agrarian societies. Until the invention of the steam engine, heat could not be converted into work. The provision of certain types of energy was closely related to certain types of land use: Typically, the provision of heat relied on firewood and

[31] In some agrarian societies considerable amounts of fossil fuels have been used. This was for instance the case in the Netherlands, where peat was an important fuel in the 17th and 18th century (De Zeeuw 1978 1978) or in England, where coal was used in considerable quantities already in the 16th century (Warde 2007, Wrigley, 2010). This was, however, quite exceptional and even in these cases, the overall share of fossil materials in DMC or DEC remained low.

woodlands, the provision of food, the energy basis of human work, on cropland and the supply of animal draft power on grassland. Consequently, a certain energy mix required a corresponding land use mix.

The energy system of agrarian societies is intimately connected to land use. The supply of primary energy is limited by the availability of land and the area productivity (yield of useful biomass) which can be achieved in the managed ecosystems. Clearly, there is a range of variation of energy availability, depending on the specific bio-geographical conditions, the type of land use system, available technology and the role of human and animal labour (see below). Although agriculture allows for a larger extraction of useful energy per unit of area and thus a much higher carrying capacity as compared to the uncontrolled solar energy system of hunters and gatherers, the fundamental limitations of a solar based energy system remain in place. A socio-metabolic regime depending on the harvest of solar energy converted by plants sustains itself within narrow limits of available energy and consequently faces limits for biophysical and economic growth (Wrigley 1988, 2010). The land use system and its limited potentials to supply certain types and amounts of primary energy, therefore, constitute a major bottleneck for biophysical growth.

Figure 1 illustrates the basic relations between land, labour and energy which constrain development and growth within the agrarian regime, based on a controlled solar energy system. At the core of this energy system is an agricultural population which invests labor to cultivate terrestrial ecosystems and to produce food, feed, fibre and fuel. Within the agrarian regime, the harvest of biomass products from a given amount of land can be augmented within the limits imposed by natural constraints by intensification, that is, by increasing labor input (Boserup 1965). Under the conditions of low input agriculture[32] biomass output ultimately grows at a slower pace than labor investment and marginal returns gradually diminish (cf. Tainter 1988). At least on a larger scale, the energy output of land use systems (in the form of the desired types of biomass for final use) has to exceed the amount of biomass-based energy which has been invested into the cultivation of the land. The working population has to produce enough food and raw materials to sustain their own living and that of the non-working fraction of the population (small children, old or sick people), otherwise a stable population can not be maintained: The ratio of energy output in the form of biomass for final use and human energy investment in biomass production is termed energy return on investment (EROI) and has to be much larger than one[33]. Its minimum is given by basic demographic requirements, but an agricultural population may even produce a surplus which allows it to sustain a significant non-agricultural population and production; the maximum fraction of non agricultural population is ultimately limited by the physically attainable surplus rate, but in practical terms depends on social arrangements which determine how much the agricultural population is willing or how much it can be forced to give away.

[32] Low input agriculture denotes agricultural production systems which operate in the absence of external energy subsidies or other off-farm resources. In a farming system relying solely on on-farm resources, the maintenance of soil fertility has to be based on a system of either area or labor intensive measures to optimize the utilization of locally available resources. These include the temporal and spatial rotation of different land use types (e.g. shifting cultivation, three field crop rotation with fallow), transfers of biomass and plant nutrients from extensively used woodlands or pastures to intensively used plots (e.g. by litter extraction or grazing in forests), recycling of residues and wastes, the best possible exhaustion of natural regeneration and renewability rates (biological fixation and deposition of nitrogen, soil processes), the establishment and maintenance of irrigation systems and measures to prevent or revert soil erosion (Mazoyer et al. 2006; Kjaergaard 1994, McNetting 1993).

[33] Cleveland assumes a minimum energy return on investment (EROI) of preindustrial agriculture of 5 but also land use systems with a higher EROI have been observed (cf. Leach, 1976; Krausmann, 2004).

High energy costs of transport are another important constraint for the metabolism of agrarian societies and impose severe limits for spatial differentiation and specialization on larger spatial scales: under the conditions of the agrarian regime, only water transport allows for long distance transport of bulk materials. The energy costs of overland transport increase to a prohibitive level after only a few kilometres (Bairoch 1993; Boserup 1981). This implies limitations for the spatial concentration and exchange of staple food, feed and fuel. These are produced at low energy densities (with respect to both energy harvested per unit of land area and energy content per mass unit) and can only be transported over short distances if water transport is not an option. In addition to the surplus limit high transport costs further constrain the sufficient supply of large urban populations and limit urbanisation processes.
Under the conditions of the agrarian regime, the majority of the population lives on the land and off the land. The largest fraction of the population is engaged in agricultural production, the share of non agricultural population and urbanisation is typically lower than 20%. Also the mobility of people is limited which hampers cultural exchange, and by this innovation and diffusion of technologies, but supports local cultural diversity (Sieferle 1997).

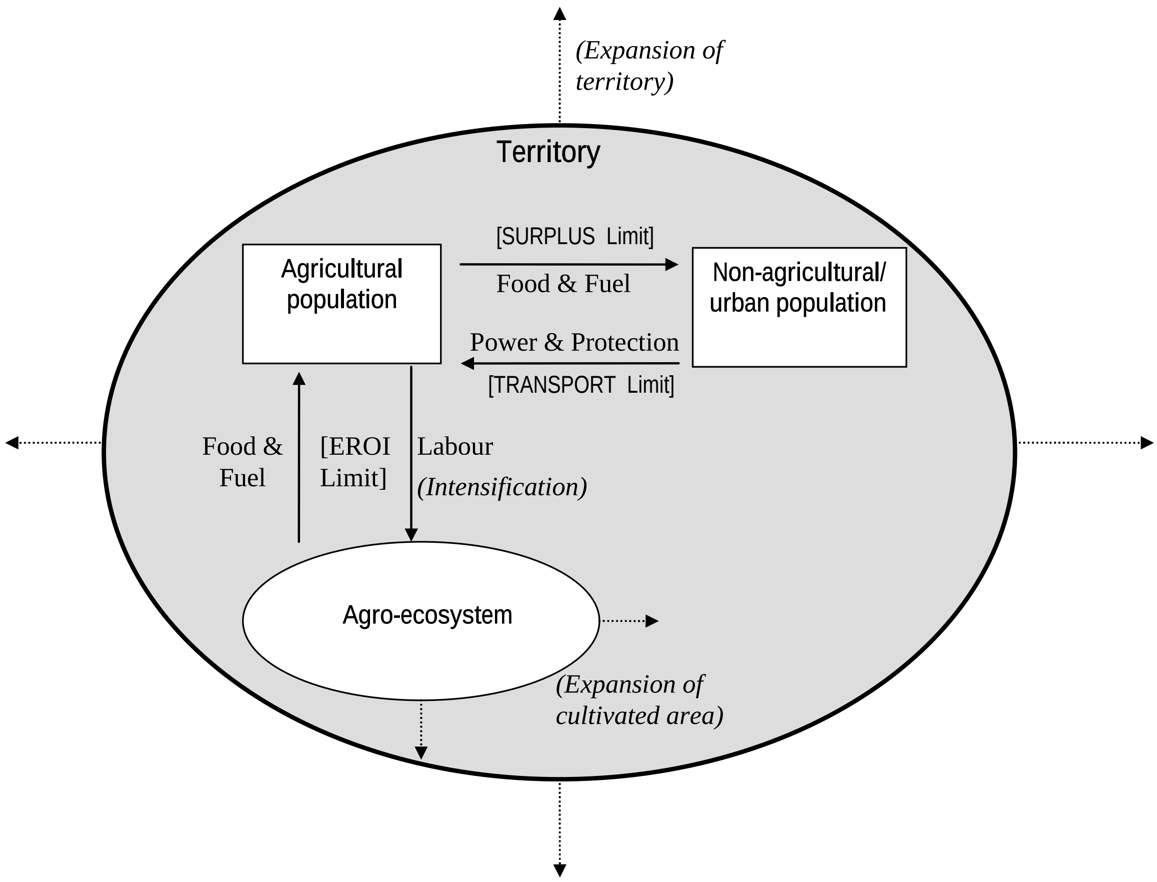

Figure 1: *The energetic constraints of the agrarian regime. An agricultural population invests labour in order to cultivate land and to produce different types of biomass (food, feed, fibre, fuel) sufficient to maintain a stable population. Under given climatic and soil conditions and cultivation technology this may allow to produce a surplus and to provide a certain non agricultural population and its activities with energy and raw materials. Growth of the agricultural population can be based either on the expansion of the cultivated area or on*

intensification. Increasing biomass output per unit of land requires human or animal labour and is limited by diminishing marginal returns. The energetic return of agricultural production (EROI) declines with increasing intensity. The size of the non agricultural subsystem is not only constrained by the surplus rate but also by the energy costs of transportation: Growth of the urban population can be sustained by increasing the surplus rate, that is, by increasing labour efficiency of the land use system in the hinterland (which is possible only within narrow limits) or access to a larger rural hinterland (territorial expansion). Expanding the hinterland, however, increases transport distances and the (energetic) cost of transport, which ultimately constrains urban growth.

3.2. Development paths and subtypes of the agrarian regime

Not only for hunters and gatherers, but also under the conditions of the agrarian regime, the limitations for biophysical growth, whether it is caused by a growth in the size of population or by growing resource demand per capita, are set by bio-geographical conditions, elementary characteristics of biological processes and ecosystem properties: Climate, photosynthesis, decomposition of organic matter or nutrient cycles constrain the theoretically attainable yield of useful biomass per unit of area. However, by deliberately managing properties of ecosystems through cultivation humans can influence and significantly increase (but also decrease) the carrying capacity of the ecosystems they inhabit. This reduces their dependence on naturally given productivity and its fluctuations. Depending on climatic conditions, terrain, the history of population growth and available technology a variety of subtypes of the agrarian metabolic regime with different development paths and considerable differences in structure and level of biomass use and population density have emerged. Both the achievable output of useful biomass per unit of area (energy density) and the apparent consumption of biomass per capita (metabolic rate) are variable within the given ecological limitations. Together energy density and metabolic rate determine the maximum population density which can be sustained in a given subtype of the agrarian regime. The examples of different subtypes of the agrarian regime shown in Table 1 demonstrate the variability of the metabolic characteristics.

		Shifting 50y	Shifting 10y	Temperate mixed farming	Labour intensive tropical cropland	Pastoralism
Cereal yield (real)	[t/ha sown area]	2	0.8	2	4	-
Energy extraction rate (DEC/area)	[GJ/ha/yr]	<2	<10	30	50	2.5
Metabolic rate (DEC/capita)	[GJ/cap/yr]	10-20	10-20	45-75	10-20	250
Metabolic rate (DMC/capita)	[t/cap/yr]	0.7-1.5	0.7-1.5	3-6	1-2	18
Livestock/human	LAU/human	<<1	<<1	Roughly 1	0.1	>>1 (3.5)
Labour intensity		low	moderate	high	very high	very low
Population density	[cap/km²]	<10	<35	<50	Several 100	<2

Table 1: *Examples of the variability of metabolic profiles within the agrarian metabolic regime. DEC…Domestic energy consumption; DMC…Domestic material consumption; LAU…large animal unit. Sources: Based on data from Mazoyer et al. 2006, McNetting 1993*

(shifting cultivation), Sieferle et al. 2006 (temperate mixed farming), Coughenour et al. 1985 (pastoralism). Note: All biomass flows are given in energy units (gross calorific values), but can also be expressed in mass units: 1 GJ roughly equals 70 kg of biomass at 15% moisture content.

Shifting cultivation

In simple types of shifting cultivation or, as it is often called, slash and burn agriculture the exhaustion of soil fertility is prevented by long fallow periods during which essential plant nutrients accumulate in the soil. After several decades of natural succession the biomass regrowth is removed and burnt and for one or two seasons comparatively high crop yields per unit of sown area can be achieved. The overall land requirement for the whole cycle of shifting cultivation is much larger than the area sown in a particular year and so food output divided by the total land area in rotation remains small and only low population densities can be supported. Labour input in long fallow systems is usually low and food output per unit of invested labour can be considerable (cf. McNetting 1993). A simple hypothetical example derived from Mazoyer et al. (2006) illustrates the metabolic characteristics of a production system based on slash and burn agriculture: Energy use per comprises of food for humans and fuel wood and ranges in the order of 10-20 GJ/cap/yr, used extraction of biomass per unit of area is very low (<1 GJ/ha/year), but several hundred GJ of biomass are burnt per capita and year for land clearing; that is, unused extraction is large compared to used extraction. This may be considered a rather wasteful use of the productive capacity of land. By investing more labour in land clearing, the fallow period can be reduced, for example from 50 to 10 years. This reduces the regeneration period of the soils and will lead to a reduction in yields per unit of sown area. But as more area can be cropped per year total territorial yield can be multiplied. Consequently, population density and biomass extraction per unit of area can be increased while the amount of biomass burnt per capita declines. The rate of used to unused extraction improves and area productivity grows but at the expense of labor productivity. Such a long fallow shifting cultivation may support population densities of between 10 and 30 cap/km² at a large scale average, although regional variations can be very large.

Temperate mixed farming

Further reducing the rotation period to less than a year leads to land use systems with permanent cultivation (two or three field rotation with fallow period, crop rotation systems) and allows for further increases in population density at the cost of labour efficiency. Under temperate conditions, mixed farming systems which combine crop production with the multifunctional use of livestock have evolved. Livestock is used in plant nutrient management and to provide farm labour as well as milk, meat and other products. In addition to the land area used to grow crops a significant fraction of the territory is used less intensively (that is with less labour input) as forests or pastures and serves as nutrient reservoir for intensive plots. Studies on mixed farming systems in Austria at the advent of the industrial revolution suggest that up to 30 GJ of primary biomass (food, feed, wood) were extracted at the large scale average and in the long run (Sieferle et al. 2006). As a result of the high demand of forage due to the high livestock to human ratio and high fuel wood demand due to cool climate, average energy use per capita was high and typically ranged between 40 and 70 GJ/cap/yr. In combination with the attainable area productivity a typically population density of 45 to 75 cap/km² was supported (Table 1).

Tropical labour intensive farming

Under tropical climatic conditions (e.g. in South and East Asia) a path towards very labour intensive cropping systems with multiple harvests and irrigation is common. Extensive types of land use are reduced and a large fraction of the land is cultivated and used intensively. Most of the labour is supplied by humans, animals are of less significance and biomass extraction per unit of area can be similar or higher as in mixed farming systems. Less biomass is used per capita and average energy use can be as low as 10 and 20 GJ/cap/yr. This means that carrying capacity can be much higher than in mixed farming systems. For labour intensive rice cultivation of smallholders in South and East Asia local population densities of several hundred people have been recorded (McNetting 1993). It is assumed, that on larger scales average population densities of 150 to 200 persons per km² have be supported by this subtype. (cf. Boserup 1965; de Vries and Goudsblom 2002).

Pastoralism

In contrast, pastoralism is a subtype of the agrarian regime at the other extreme of the range. It prevails under arid or cold climatic conditions which are adverse for cultivation. Pastoralists make use of livestock to concentrate sparse biomass energy from large territories and to increase the output of useful biomass. Only very low population density can be sustained. The average population density of the Ngisonkyoka, a pastoralist community in Kenia, is only 1.3 cap/km² compared to a livestock (mostly cattle and sheep) of 4.5 large anumal units (LAU) per km² (or 3.5 LAU per capita). The large livestock contributes to an extraordinary high rate of biomass extraction per capita. In the case of the Ngisonkyoka energy use amounts to 260 GJ/cap and year, more than 84% of which comprise of biomass grazed by livestock. Woodfuel accounts for most of the reminder. Despite of the high per capita rate, biomass extraction per unit of area remains very low at 2.5 GJ/ha or 7% of the annual net primary productivity (Coughenour et al. 1985, Table 1).

These examples illustrate, that from a long term socio-ecological perspective on agrarian development, growth under the conditions of the agrarian regime is intrinsically related to population growth and leads to higher population densities. Population growth, in turn, usually drives a development towards more labour intensive land use systems (e.g. from long fallow towards permanent crop rotation systems). But also the land and biomass efficiency of land use increases: Intensification means that more useful biomass per unit of land can be produced and the ratio of used to unused biomass extraction increases. But despite considerable increases in the overall output of useful biomass, both labour efficiency and the per capita throughput of biomass decline. This means that, in the long run, continuous agrarian growth tends to result in declining per capita wealth: Food and food quality (e.g. the share of meat in diets) decline with population growth and per capita material and energy use begin to sink (see below).

3.3. Material use in the agrarian regime

The inherent limitations of the biomass-based energy system, namely the low energy density of the supply system, lack of energy conversion technologies, reliance on power delivered by humans and animals and high energy costs of transport shape the patterns of material use. Materials have to be extracted, moved and processed, all of which depends on the availability of power and useful work. Both are scarce in agrarian societies where humans and animals supply most of the useful work and this constrains the movement of large amounts of bulk materials. Biomass continues to be the most important material resource and likewise the most important energy resource. Similar to foraging societies, there is a large overlap between the material and the energy system. From the above examples it becomes clear, that the amount of biomass used per capita largely depends on the significance of livestock[34], on climatic conditions and population density. Locally it can also be influenced by energy requirements of non agricultural production, above all by energy intensive mining and manufacturing. The amount of biomass used can range between one and several tons per capita.[35] Other than biomass, small quantities of metal ores, above all iron, gold, copper and tin, as well as salt, manufacturing (clay, quartz sand) and fertilizer minerals (marls) have been mined and used. The contribution of these non renewable raw materials to material consumption (DMC) did not exceed a few percent (Table 1), although local variations may have been significant: While in mining regions per capita apparent consumption of ores and other minerals may have been considerable, averages at larger spatial scales were low and in the range of 0.01-0.1 t per capita[36]. The extraction and use of construction minerals such as clay for the production of bricks, dimension stone or sand and gravel was highly variable and may have amounted to less than 100 kg in simple agrarian communities and to several 100 kg in more advanced societies with a higher degree of urbanisation and infrastructure networks (e.g. parts of the Roman Empire). But even with considerable stocks of built structures (see below) the annual material flows for construction and maintenance were low, because the lifespan of buildings and infrastructure was long. We estimate that at the eve of industrialization less than 100 kg of gross ores and half a ton of sand, gravel and clay have been extracted in European countries. Reconstructions of the historical metabolism of advanced agrarian regimes such as that of Austria and the United Kingdom at the verge of industrialization (Schandl and Schulz 2002; Sieferle et al. 2006) indicate that the yearly consumption of all materials did not exceed 5 or 6 tonnes per person, of which biomass had a share of 80-90% (Table 1). In less advanced agrarian systems or regions with low population density, the share of biomass may have been considerably higher.

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[34] One livestock unit requires an annual biomass intake of 3-5 t per year, compared to less than 0.5 t of food for human beings. The per capita level of biomass use in agrarian societies is therefore largely determined by the significance of livestock that is by the ratio of livestock to humans: The more livestock per capita, the higher the level of biomass use per capita and consequently overall energy use. Keeping livestock for the provision of draught power, nutrient management or milk production requires large amounts of feed and litter. In European land use systems with a livestock to humans ration larger than one, far more than 80% of all agricultural biomass is used in the livestock subsystem. The highest level of biomass use per capita, therefore, occurs where area intensive herding is linked to very low population density and very low rates of biomass extraction per unit of area. Figures from Coughenour (1985) suggest that pastoralists in Kenia extract some 15t of biomass per capita, grazed biomass accounting for more than 95% of their total material extraction. Contrary, biomass per capita is lowest in labor intensive horticultural production systems with vegetable based diets. Such farming systems typically entail high population density and high biomass harvest per unit of area (Krausmann et al. 2008a; Hayami and Ruttan 1985).

[35] The amount of biomass used per capita in agrarian societies is in general several times larger than in foraging societies, in particular when humans keep livestock. But a large difference in per capita consumption is not necessarily occurring. As outlined above, the major difference between foraging and agrarian societies lies in the level of biomass extraction per unit of area which is always several orders of magnitude above the level of hunter-gatherers.

[36] The use of copper in agrarian societies can illustrate the low level of mineral use in agrarian societies: Copper use in agrarian China or the Roman Empire was in the range of 30 to 60 g/cap/yr (own estimates based on Hong et al 1996, Biraben 2003, Cohen, 1995). Assuming an ore grade of 3.5% (this equals average ore grades in US copper mines in 1880, see Ayres et al., 2004) an annual gross copper flow of no more than 1,7 kg/cap results.

In contrast to the mobility prevailing with hunter-gatherers, agriculturalists are characterized by a sedentary life-style. The emergence of permanent settlements was associated with the accumulation of physical stocks. Humans kept livestock, erected shelters and farm houses, urban centres and infrastructure networks emerged and tools and other durable artefacts accumulated in ancient civilisations. Buildings and livestock accounted for the largest share of material stocks, tools and other artefacts were of minor quantitative importance. It is difficult to estimate the size of physical stocks in agrarian societies. Stocks have varied between a few hundred kg/cap in simple agrarian societies with little more built infrastructure than clay huts or wooden buildings to several tons in advanced agrarian civilizations with solid farm buildings, urban centres and a network of maintained roads. We assume that in general, physical stocks in agrarian societies rarely exceeded 10 tons per capita on a large scale average. Thus, stocks were considerably larger than in hunter and gatherer societies.

3.4. Sustainability and the agrarian metabolic regime

Although the metabolism of the agrarian regime is based on the exploitation of renewable resources and on harvesting flows rather than diminishing stocks, which is an important basis for long term sustainability, it faces specific sustainability problems. The maintenance of a successful exploitation of renewable flows is based on the management of soils that have to be considered as non-renewable on human time scales. Their overuse or degradation immediately causes negative feedback at the local level: If yields decline the sufficient supply of the local population with food and feed is at risk and malnourishment pending. Ecological sustainability, therefore, is a prerequisite for survival, and mismanagement is immediately punished. However, there is no guarantee against severe fluctuations and sustainability crises or even collapse. Growth can only be achieved within certain limits and is based on efficiency increases and the optimisation of land use (see Figure 1). There tends to be positive feedback between population growth and biophysical growth and agrarian societies show an overall tendency to increase land use efficiency (output per unit of area) at the expense of labor efficiency (Boserup 1985). By and large this implies that in an agrarian regime long term per capita material wealth does not increase for the majority of the population over longer periods of time. To the contrary, in the long run the material/energy output per capita reaches a limit or even starts to decline. Thus, in general, agrarian societies face sustainability problems related to the low density of the energy supply system, which is still almost exclusively based on biomass, and related to this struggle with the long-term maintenance of soil fertility and the balance between food supply and population growth (cf. Grigg 1980; Kjaergaard 1994). Mismatches in this balance caused by population growth, soil degradation or fluctuations due to climatic conditions easily result in famine and demographic crises[37]. Often these are triggered by epidemics or wars and lead to the destabilization of the labor intensive land use systems. Pollution problems occur only locally at mining sites or in urban agglomerations (Sieferle 2003). During the historical period of the agrarian regime, global population increases slowly and amounted to some 700 mio. people at the beginning of the industrial revolution in the mid 18^{th} century (Cohen 1995).

[37] See the discussion on socio-ecological collapse and famines in Diamond 2005, Tainter 1988; Abel 1974.

		Hunters and gatherers	Agrarian*	Industrial**	Factor industrial to agrarian
Energy use (DEC) per capita	[GJ/cap/yr]	10-20	40-70	150-400	3-5
Useful work per capita	[GJ/cap/yr]	<1?	<5	30-50	5-15
Material use (DMC) per capita	[t/cap/yr]	0.5-1	3-6	15-25	3-5
Population density	[cap/km²]	<0.1	<40	< 400	3-10
Agricultural population	[%]	-	>80%	<10%	0.1
Energy use density (DEC per area)	[GJ/ha/yr]	<0.01	<30	< 600	10-30
Material use density (DMC per area)	[t/ha/yr]	<0.001	<2	< 50	10-30
Biomass (share of DEC)	[%]	>99	>95	10-30	0.1-0.3
Share of non energy use of materials	[%]	<5	<20	>50	3-10
Material stocks	[t/cap]	<0.01	<10	100-1000	10-100

Table 2: *Metabolic profile of socio-metabolic regimes. DMC…Domestic energy consumption; DEC…Domestic energy consumption. *typical values for an advanced European agrarian socio-metabolic regime (18th century). In agrarian societies based on labor intensive horticultural production with low significance of livestock, population density may be significantly higher, while per capita use of materials and energy would be lower (see text).*
***Typical values for fully industrialized economies. In countries with high population densities per capita values of DMC and DEC tend to be in the lower range, while per area values are high. The reverse is true for countries with low population densities; in this case per area values can be very low. Sources: The data compiled in Table 2 are derived from empirical studies on material and energy flows in agrarian and industrial societies (e.g. Haberl et al. 2006; Krausmann and Haberl, 2002; Schandl and Schulz 2002; Sieferle et al. 2006; Weisz et al. 2006) and literature data (e.g. Malanima 2002; Simmons 1989 and 2008).*

4. The industrial socio-metabolic regime

4.1. The energy system of industrial societies

The energy system of the industrial regime is fundamentally different from the solar based energy systems of the other two regimes: Rather than tapping into renewable solar energy flows industrial societies rely on mineral resources to sustain their energy needs. The large scale exploitation of accumulated and, at least in human time scales, non-renewable stocks of energy carriers allowed for an increase in energy use per unit of area and per capita far above the limits of the agrarian regime.
One major reason for the decisive role fossil fuels have in the initial establishment and subsequent continuation of a new industrial metabolic regime lies in the energetic characteristics of fossil fuels, which are fundamentally different from that of biomass. First, the energy supply density of fossil energy carriers is by orders of magnitude higher than of biomass (between 1000 and 10.000 W/m^2 for fossils fuels as compared to 0.1 to 1 W/m^2 for biomass, Smil 1991). Second, fossil fuels are abundant and cheap at least on time scales of several human generations. Third, with fossils fuels large stocks are being utilized and not small annual flows.[38] Therefore annual increases in energy use are not restricted by annual reproduction rates, at least until physical depletion is approached. In short fossil fuels provide a cheap, high density, abundant and stable energy source for several hundred years.

With the use of fossil fuels the previous restrictions to develop high density energy demand systems (as for example long distance mass transport systems or mega cities, where energy demand densities can reach 1000 W/m^2) are eliminated. As Grübler (2004) has pointed out, the prevailing high energy-demand density characteristic for the industrial metabolic regime is much in line with the fossil fuel supply, conversion and distribution system. Historically, this has been one of the drivers for the pervasive adoption of fossil fuels in the transition from an agrarian to an industrial metabolic regime.

The unprecedented energy supply density of fossil fuels in combination with a huge resource endowment allowed the multiplication of available useful energy and an unprecedented concentration and upscale of social demand systems. These are the two novel characteristics that constitute the core of the industrial socio-metabolic regime. Two major processes contribute to a far reaching decoupling of the energy system from the use of productive land: First of all, biomass as key primary energy source is substituted for by area-independent sources of energy in almost all applications. But biomass remains an important raw material and the nutritional basis for humans and their livestock. In stark contrast to the declining share of biomass in the overall amount of energy and material consumption, the absolute amount of used biomass increases during industrialization (see Figure 2). Not only the use, but also the production of biomass is fundamentally affected by the new energy system and the second important land related process in the energy transition is the industrialisation of agriculture: Direct and indirect energy subsidies (e.g. mechanization and fertilization) reduce the constraints for productivity increases inherent to low input agriculture and boost both area and labour productivity of land use systems. The demand for human and animal labour in agriculture is dramatically reduced while the output of useful biomass can be multiplied (Hayami and Ruttan 1985). This reverses the role of agriculture in the socio-economic energy system: The energy inputs result in declining energy efficiency and eventually agriculture turns from a source of useful energy to an energy sink, a phenomenon first described by David Pimentel et al. (1973).

Ultimately, all of the traditional socio-metabolic constraints stemming from the controlled solar energy system are abolished: energy turns from a scarce to an abundant resource, labor productivity in agriculture and industry can be increased by orders of magnitude, the energy cost of long distance transport declines, and the number of people which can be nourished from one unit of land multiplies. This allows for an unprecedented growth of urban agglomerations and spatial differentiation of socioeconomic systems on larger scales. High population densities can be sustained by a very low portion of far less than 10% of the population engaged in agriculture.

4.2. The emergence of the industrial regime in the 19th and 20th centuries

Historically, the transition process from an agrarian towards an industrial regime was experienced for the first time in 18th century England, supported by a unique combination of a land use system with a high surplus rate, specific patterns of natural resource endowment[39], technological breakthroughs in coal extraction and metallurgy, institutional change and population growth (Sieferle 2001, Wrigley 2010). In an initial phase, coal provided not much more than a new source of fuel for limited use in urban households and to power some industrial processes. During the 19th century, the energy transition in Europe, the United States and later also Japan gained momentum through a positive feedback loop created by the emergence of the coal-steam engine-iron ore-railroad technology complex (Grübler 1998; Ayres 1990; Krausmann and Fischer-Kowalski 2010).

The implementation of the industrial regime within the industrializing countries was a gradual process and did not affect all subsystems of society equally and at the same time. Throughout the nineteenth century and early twentieth century, fossil fuel powered urban/industrial centres co-existed with a rural matrix. The agrarian periphery perpetuated the conditions of the agrarian regime over many decades (Krausmann et al. 2008c). Coal based industrialisation, while allowing for the introduction of the new industrial socio-metabolic regime, was characterized by a strong linkage between industrial production and a growing demand for human and animal labour, and population growth. The rapidly growing population had to rely on the delivery of nutrition from a largely pre-industrial low-input agriculture. In the United Kingdom as well as in most of Europe, the penetration of the fossil fuel based energy system was only completed after the 1950s, during the so called *second industrial revolution* when oil, the internal combustion engine and general electrification replaced the older coal based technologies and led to a final decoupling of industrial production and human labor, and the industrialization of agriculture (Grübler 1998). This period was characterized by rapid increases in per capita energy and material use which lasted

[39] Among these factors were the combination of low availability of fuel wood with the occurrence of easily accessible deposits of both coal and iron in close vicinity. And finally, the “river around Britain” allowed for long distance transport between locations of mining, manufacturing and consumption.

until the oil price shocks in the 1970s (see Figures 3 and 4). From then on, growth in per capita material and energy use in industrial countries slowed down markedly.

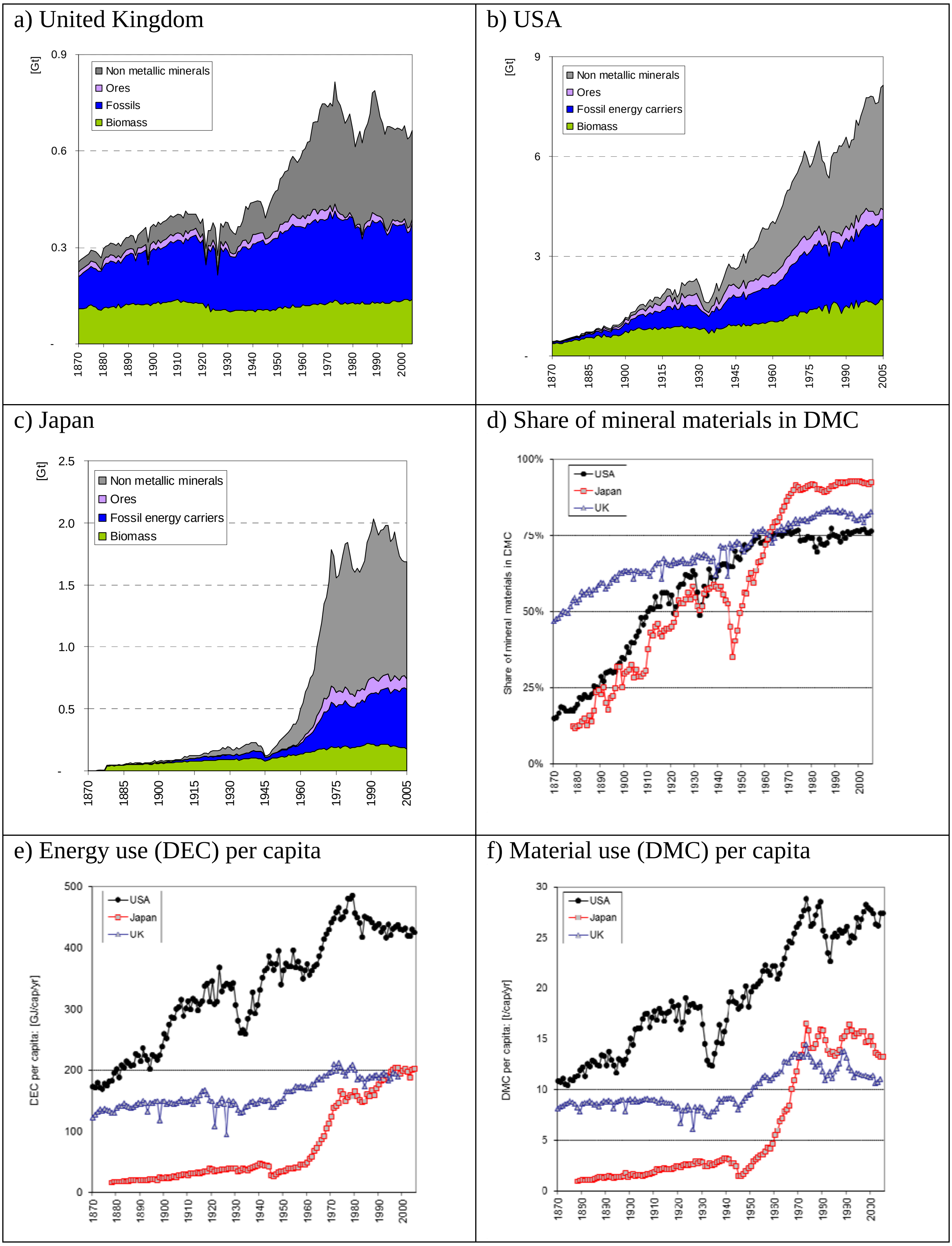

Figure 2: *Historical development of domestic material consumption (DMC) and metabolic rates (DMC and DEC per capita and year) in the United Kingdom, the USA and Japan in the period 1870 to 2005. Up to date only three comparable long term economy wide material flow accounts, covering more than a few decades, exist: UK, USA and Japan. Figure 2 shows the development of domestic material consumption in these major industrialising economies from the late 19th to the beginning of the 21st century: In 1870, the UK, the fore-runner of the industrial revolution and leading economy in the 19th century was already in an advanced stage of the metabolic transition. DMC was high and coal accounted for 30% of total DMC. At that time, the dominant material component of the social metabolism in the USA and Japan still was biomass. This changed in the 20th century, when the share of biomass rapidly declined in all economies. While the three countries differ considerably with respect to their temporal dynamics of the metabolic transition and also in their per capita material use, they do show patterns characteristic to all countries industrialising in that period: Overall material use multiplies and the share of biomass in DMC declines to less than 25%. The share of fossil energy carriers and mineral materials in DMC increases above all in the period from World War II to the oil price shocks in the 1970s, a phase of the metabolic transition during which in particular energy and material use per capita grows (Figure 2e and f). Sources: UK based on Schandl and Schulz 2002 and Eurostat 2007; Japan based on Krausmann et al., 2011; USA based on Gierlinger and Krausmann, 2011.*

4.3. Drivers of material and energy use in the industrial regime

The transition from an agrarian to an industrial socio-metabolic regime not only facilitates economic growth, structural change and a certain world-wide uniformity in social forms and institutions, but also a new pattern of mass production and consumption with distinct metabolic features of striking similarity in all industrialized economies emerges. At the core of the metabolic transition is a transition in the energy system (Sieferle 2001, Grübler 2004, Wrigley 2010), which denotes the shift from biomass to coal and later petroleum and natural gas, a process observed in all industrial countries (Gales et al. 2007, Krausmann et al. 2008c, Ayres et al. 2008). The abundance of energy carriers in combination with new energy conversion technologies and applications dramatically increase not only the amount of available primary energy but also that of useful work output. Recent accounts for changes in energy availability during industrialization show, that useful work and available power increases by one to two orders of magnitude (Warr et al. 2010). This high energy availability is a precondition for large scale mining and quarrying, for the transportation of huge amounts of bulk materials over long distances over land and for the labor efficient processing of these materials.

A number of highly interrelated structural attributes which mutually reinforce each other are responsible for the high level of material and energy consumption in the new regime:

The new regime not only *facilitates* a high level of energy and material use of final users, its operation *requires* a surge in natural resource use per se. This strong positive feedback between energy availability and the resulting possibilities to move and process materials and the material requirements to build and run these technologies has contributed to the unprecedented rise of material consumption observed during the historic period of industrialisation, which is shown in Figure 2 for the UK, Japan and the USA. The establishment and the area wide diffusion of the new energy system and its metabolic regime require new infrastructures for extracting, distributing and processing energy carriers and material resources. Extensive infrastructures for transportation and communication, grids and pipelines for supply, distribution and disposal of materials and energy are essential features of the industrial regime and are reflected in the increasing consumption of mineral materials in the second half of 20th century, above all of materials used for construction (Figure 2). Building, maintaining and operating industrial infrastructures requires huge amounts of energy as well as ores, industrial and construction minerals. During the history of industrialization new technologies generally added new infrastructure requirements without actually replacing the old ones (e.g., rail, road and air transport infrastructures) and infrastructures and physical stocks continued to grow. Throughout industrialization, infrastructures and the services they provide were responsible for a large fraction of socio-economic energy and material use and have contributed to an unprecedented growth in material and energy use. And also in advanced industrial societies infrastructures continue to have a significant influence on the high level of material and energy throughput and constitute physical legacies, whose impact on future resource use can be considerable.

Another factor which coins the metabolic characteristics of the industrial regime is the high mobility of people, raw materials and goods. The new energy system triggered a new spatial organisation of society based on global division of labour and large scale spatial differentiation and concentration of resource extraction, industrial production, human dwellings and final consumption. As a consequence, large quantities of raw materials and consumer goods are shipped back and forth around the globe and people travel growing distances for economic and leisure reasons. The physical volume of international trade has grown from 1.2 Gt in 1960 to almost 10 Gt in 2005 and more than 40% of all extracted ores and fossil fuels are shipped across international borders (Dittrich and Bringezu 2010). The intensity of overland road transport, for example, has reached several thousand ton and passenger kilometres per capita in industrialized economies and is still growing. Throughout industrialization, transport and mobility have been responsible for a considerable share of total energy and material throughput: During early periods of industrialization rail transport consumed a large fraction of coal and iron supply and since the second half of the 20th century fuel demand for road and air transport is the most important driver of energy use in industrial countries. Additionally, building up and maintaining a still growing fleet of cars and aircraft consume large quantities of energy and metal ores and there is a strong positive feedback between mobility and infrastructure.

A third fundamental element of the metabolic pattern of modern industrial society is the emergence of a society of mass production and corresponding patterns of mass consumption. Initiating from *Fordism* in the USA in the 1930s, mass production and consumption became a general phenomenon in the industrial world in the 1950s and 1960s (Lutz 1989). The industrial production of huge amounts of consumer goods at affordable prices and the appearance of a large and increasingly wealthy middle class was a major driver for the increase in per capita resource use in the second half of the 20th century. It is still a major cause for the structure and size of the industrial metabolism and demands large amounts of energy and materials. The substitution of work derived from fossil fuels for human and animal labour facilitated the processing of much larger quantities of materials and was one of the preconditions for mass production and consumption. The increase in labour productivity not only resulted in a surge of industrial output, but it also released large quantities of human time from wage labor and household chores. With rising income and living standard, this time is used for other, often material and energy intensive activities (e.g. tourism) and consumption. Households in the industrialized countries are equipped with large stocks of energy and material intensive consumer goods, per capita use of living space linearly grows with income and the subsequent high energy demand for heating or cooling, the provision of light and to run the large number of electric devices for refrigeration, cooking, cleaning and communication contributes significantly to the high level of material and energy use in the industrial regime.

Finally and in stark contrast to the agrarian regime which was coined by diminishing marginal returns and strong negative feedbacks from physical limitations which prevented per capita economic growth for larger populations and longer periods in time, growth is a core element of industrial societies. Economic growth is a basic feature of the industrial regime and throughout industrialization economic growth has been closely linked to physical growth, both driven by population growth and increases in per capita throughput: There has been a long lasting trend of efficiency increases, that is a decline in the amount of material and energy use per unit of GDP in industrial countries. Together with a slow down in population growth in most industrialized countries, this has contributed to reduced growth rates in material and energy demand in particular during the last 30 years and in some cases as stabilisation of resource use at a high level, but there is so far no evidence that material or energy use can decline over longer periods of time while the economy continues to grow (see for example Steger and Bleischwitz (2009). It has repeatedly been argued, that energy plays a much larger role for economic growth than neoclassical theory and production functions suggest (Kümmel 1982). In a series of publications Robert Ayres has provided ample evidence that energy consumption is as much a driver as a consequence of growth (Ayres and Warr, 2009; Ayres et al., 2003). According to Ayres, growth engines are a systemic feature of the industrial society. A growth engine is a positive feedback loop, involving declining costs of energy inputs which lead to declining prices which drive increased consumption. This, in turn, triggers investments into new capital. Historically, access to cheap energy, declining relative energy prices and massive institutional support have been essential for the establishment of the new regime.

4.4. The metabolic profiles of industrial societies

Similar to the agrarian regime also the industrial regime displays a pronounced variety in the specific metabolic patterns when measured at lower scales. This should not be surprising as an accelerated global integration of markets in combination with prevailing spatial variety in environmental and socio-economic conditions supported the formation of a global division of labour in terms of production and consumption. We therefore find the robust structure and dynamic of the industrial regimes being superimposed by different metabolic varieties, which we call metabolic profiles. In advanced industrial societies, differences in the composition of material and energy use and metabolic rates can be significant and reflect resource endowment, structure of the industrial sector, trade patterns and climate conditions (see the ranges given in Table 2). Densely populated countries with a high dependency on imports (such as Japan) typically have comparatively low rates of per capita material and energy use. On the other end of the scale are sparsely populated countries with high resource endowment per capita and high exports (such as the USA). Their level of material and energy use can be more than twice as high (Krausmann et al. 2008b).
Table 2 compares typical ranges in the metabolic profiles of hunter and gatherer, agrarian and industrial societies and summarizes major changes in social metabolism resulting from the metabolic transition (see also Figure 2). In industrial economies, material and energy use per capita exceed the level characteristic for advanced agrarian regimes by a factor of 3 to 5.

Typically more than 150 GJ of energy and 15 t of materials are used per inhabitant and year. A surge in agricultural output permits population densities up to 10 times larger than in most agrarian societies, while the share of agricultural population declines to only a few percent. Together, growth in metabolic rates and population lead to a multiplication of overall resource use. Material and energy use per unit of area can be a factor of 10 to 30 above the level typical for the agrarian regime. Not only the size of material flows, but also the composition changes fundamentally. Fossil fuels substitute for biomass as main energy carrier and the use of mineral resources increases much faster than biomass. The share of biomass in DMC and DEC is dwarfed and typically ranges between 10-30%. During early stages of industrialization coal was by far the most important mineral resource but later also other minerals, above all construction minerals, petroleum and natural gas, iron and copper and wide variety of mining products gained weight.[40] The large overlap between the energetic and the material use of resources as it prevails in the agrarian regime diminishes. In industrialized countries typically around 50% of all materials or up to 10 t/cap/yr are used for non energy purposes; mostly accumulation of buildings and built infrastructure. This also implies a shift from the dominance of throughput materials, which are used up within a short period of time (biomass or fossil fuels used as energy carriers) towards accumulating materials which can be stored in socio-economic stocks for several decades (ores, non metallic minerals). In contrast to throughput materials which loose their functionality for society once they are used, accumulating materials can also be recycled. Industrial societies build up large physical stocks of buildings, infrastructure networks and durable goods which have to be maintained. Existing estimates for Japan (Hashimoto et al. 2007; Tanikawa and Hashimoto 2009) and Switzerland (Rubli and Jungbluth 2005) suggest, that in use stocks of built infrastructure have tripled during the last 30 years and meanwhile amount to 200 to 400 t per capita in industrial societies. The enormous size which socioeconomic stocks have reached can be illustrated when compared to biomass stocks in terrestrial ecosystems: These peak at less than 200 t/ha in mature forests, compared to large scale averages of 4-500 t/ha of physical stocks in industrial societies.

Total metal stocks are significantly smaller but still huge: The USGS (2005) has calculated that iron and steel in use in the US amount to 15 t/cap, that of Aluminium to 0.5 t and of Copper to 0.4 t. It is estimated, that the stocks of iron in use accumulated in the US economy and roughly equal the size of the remaining US iron stocks in identified ores. In addition to stocks in use, large amounts of ores are accumulated in land fills (Gordon et al. 2006; Müller et al. 2006). In total, the amount of accumulated materials in the industrial regime is by several orders of magnitude above that of agrarian societies and the maintenance of these stocks is a significant factor contributing to the high level of material and energy turnover in industrial societies. The accumulated stocks in infrastructure and buildings also reduce the flexibility for a fast transition towards a structurally different metabolic regime.

Differences in the metabolic profile of industrial societies can be considerable. Material and energy flow accounts show that in mature industrial societies, per capita values of DMC and DEC can vary by a factor of two, as for example shown for the cases of the USA and Japan or the UK in Figure 2d. A host of bio-geographic and socioeconomic factors are responsible for these differences. In many cases, industrial economies with low population density appear to have high levels of material and energy use, while on the other hand densely populated countries are at the lower end of the range. Among others, this relates to the necessary size of

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[40] Accordingly, the industrial regime has also been termed “mineral economy” as opposed to the organic economy of agrarian societies (Wrigley 1988).

infrastructure networks (roads, electricity networks etc.): for the same standard of supply of a population, these networks require more energy and materials if the country is sparsely populated. Equally, the climate zone, the diet and resource endowment (the existence and accessibility of primary resources) make a difference (see Weisz et al. 2006).

Sustainability of the industrial regime

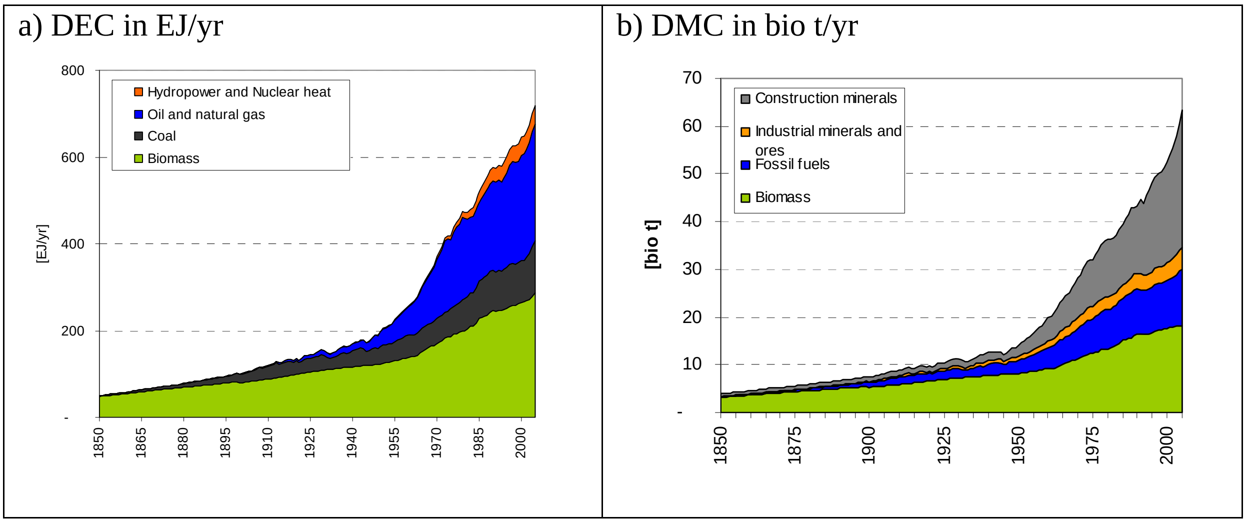
While in the agrarian regime scarcity and poverty, and an overexploitation of natural resources are always pending, the dominant impression within mature industrial regimes is that of abundance (however unevenly distributed). Due to its enormous material and energy use, the industrial regime currently faces output-related sustainability problems resulting from pressure upon the regional and global absorptive capacity of natural ecosystems for wastes and emissions. Some of these problems have been solved technologically (e.g. acid rain), but other local and global environmental problems of the industrial socio-metabolic regime continue to emerge or get worse. The list of severe sustainability problems experienced by the industrial socio-metabolic regime includes a change in atmospheric composition threatening world climate, and unprecedented biodiversity loss. And also the abundance experienced relative to the previous agrarian regime may come to limits as well: the current industrial socio-metabolic regime is based on the use of exhaustible key resources. Unless we assume unlimited substitutability of resources due to technological change – against which Bob Ayres (2007) has recently argued very convincingly – the industrial socio-metabolic regime, by definition, lacks the potential for sustainability. Sieferle (1997), therefore, considers it to be a transitory stage rather than a stable new regime. A transition to a sustainable industrial regime would imply that we need to find ways to drastically reduce the throughput of materials and energy in the industrial regime and to maintain the high energy density on the basis of new and renewable energy resources.

5. Long term global trends in material and energy use

In the last section of this article we take a look at the long term development of global material and energy use. This allows us to get an aggregate view on the historical transitions processes discussed in this chapter. It reveals the full dimension of the metabolic transition and its impact on the extraction and use of materials and energy at the global scale.

During human history, human induced flows of materials and energy have greatly increased. We estimate that during the period of hunter-gatherers DMC has increased towards some 7 Mt of biomass at the advent of the Neolithic revolution. During the approximately 10.000 years from the emergence of agriculture to the advent of the industrial revolution in the 18th century, the size of global metabolism increased to roughly 2 Gt tons and by 1850, when most European countries had joined the British path, material use had doubled to about 4 Gt. Figure 3.3 shows the development of global energy use (DEC) and of global material use (DMC) since then. The period 1850 to present covers a large part of the history of Western industrialization and the subsequent spread of the industrial metabolic pattern across the globe. The most striking feature is the overall growth of socio-economic material and energy use during this 150 years period. Energy use grew by a factor 13 and material use by a factor 15. In 2005 roughly 680 EJ of primary energy and 60 billion tons of materials have been extracted. Today, human induced flows of materials and energy are in the same order of magnitude as natural flows in terms of size: Global annual net primary production, for example, is estimated to amount to 120 bio t of biomass compared to 60 bio tons of human material extraction. Growth was accompanied by a change in the composition of material and energy use. By 1850, the global economy was still largely based on biomass reflecting the dominance of the controlled solar energy system and the agrarian regime. At that time, biomass accounted for 80% of all material and more than 95% of all energy inputs. During the 19th century, the significance of biomass was gradually reduced to 75% and at an accelerated pace in the 50 years since WWII to roughly 30% in 2005. Similarly, the non energy use of materials increased. At the beginning of the industrial revolution the largest part of all materials was used for energy provision in the form of food, wood fuel. Coal, ores and other minerals accounted only for a few percent of global extraction. During the 150 years, the consumption of metals and minerals increased at a much faster pace compared to that of the sum of energy carriers. The rapid increase in accumulating minerals indicates that large physical stocks were built up at a global level. No global estimates of the amount of physical stocks are available so far, but the expansive networks of roads, rail lines and pipelines and dams, the number of buildings and the stock of cars and machinery indicates large numbers.

The per capita use of all mineral materials has been growing at a rapid pace throughout the last 150 years except for biomass: Per capita DMC of biomass has slightly declined and amounted to 2.9 t/yr in 2005. This may be attributed to direct and indirect substitution effects such as the loss of significance of wood fuel and draft animals which accompanied economic development in many regions of the world. At least of equal importance are efficiency increases, though: The ratio of primary biomass extraction to consumable biomass products has improved due to technological improvements such as increases in harvest index or improvements in livestock conversion (Smil 2000). These efficiency gains even outgrew the effect of the surge in the demand for biomass intensive animal products. Only in some regions, above all in Sub-Saharan Africa, an observed decline in overall biomass consumption per capita actually indicates increasing scarcity of food and other final biomass products.



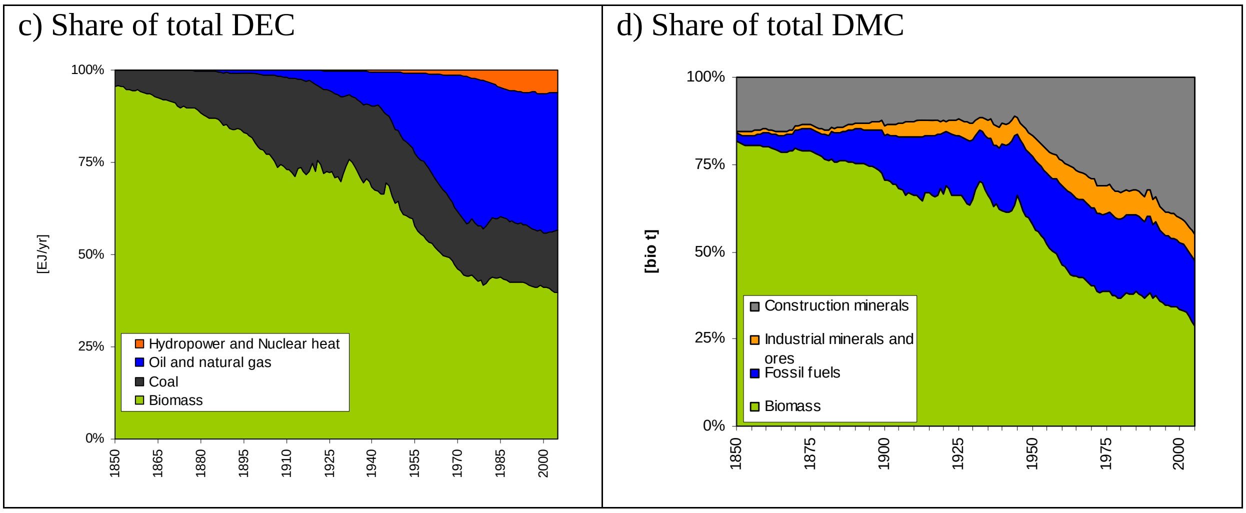


Figure 3: *Global use of energy (DEC) and materials (DMC) in the period 1850 to 2005*
Source: Krausmann et al. 2009

Plotting the development of global GDP against material and energy use reveals that the economy has experienced a continuously declining material and energy intensity (Figure 4b). In 1850 more than 4.5 kg of materials were used per $ of economic output (GDP). This ratio declined to less than 1.5 kg/$ in 2005. In spite of these remarkable gains, longer periods of absolute decoupling economic growth and resource use at the global never occurred. The only periods of a decline in material energy use occurred during major economic depressions and lasted only a few years. Moreover, if we remove the biomass fraction from global DMC the trend changes: Figure 4 shows, that overall, no significant gains in material productivity for the mineral materials has been achieved in the observed period. Material intensity even increased in the 19th century and only began to decline at a slow pace in the 1960s. This is a further indication, that global economic growth is still tightly linked to the use of non renewable resources.

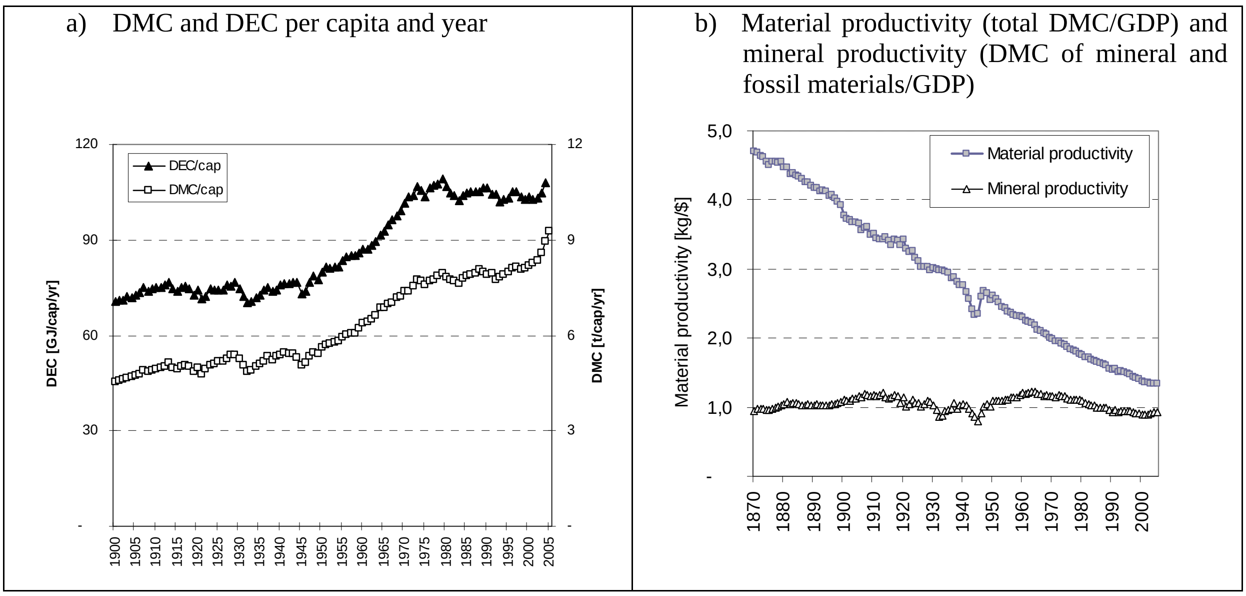


Figure 4: *Metabolic rates (DMC and DEC per capita) and material productivity (DMC per GDP and mineral DMC per GDP). Source: Krausmann et al. 2009; GDP in international Geary-Khamis $ of 1990 and Population from Maddison 2008.*

The global development of material and energy use shown in Figure 3 and 4 reflects many of the characteristics of the transition from the agrarian towards the industrial metabolic regime as outlined in the previous sections. During the last 150 years, humans have managed to continuously expand the carrying capacity of the planet by investing labor and fossil fuel based energy. Population grew by a factor 6 from 8 to 48 Persons/km²; the declining significance of biomass indicates the extent of the decoupling of energy provision of land use and the growth rates of per capita use of mineral and non energy use materials underline that the metabolic transition is an ongoing process.

		Least developed	Developing	Newly Industrializing**	Industrialized	World
Share of global population		11	37	36	15	
Income (GDP per cap) in PPP	[USD of 2000]	998	2,742	5,400	27,288	7,288
Energy use (DEC) per capita	[GJ/cap/yr]	37	49	95	296	102
Biomass (share of DEC)	[% of DEC]	93%	57%	37%	21%	36%
Electricity consumption per capita	[GJ/cap/yr]	0	2	7	35	9
Material use (DMC) per capita	[t/cap/yr]	3	5	9	17	8
Share of mineral materials in DMC	[% of DMC]	24%	54%	67%	72%	64%
Steel consumption per capita	[kg/cap/yr]	2	34	145	466	137
Population density	[cap/km²]	32	77	43	29	45
Agricultural population	[% of pop.]	69%	46%	47%	4%	42%
Energy density (DEC per area)	[GJ/ha/yr]	12	38	41	85	46
Material density (DMC per area)	[t/ha/yr]	1	4	4	5	4

Table 2.3*: Metabolic profile of country groups in the year 2000 (global averages*)*
**global averages are weighted averages is calculated as the global total of variable A devided by the global total of variable B (in contrast to multinational averages).*
***this group includes the so called newly industrializing countries, the successor states of the former USSR and the oil exporting countries of Northern Africa and Western Asia.*
Source: Krausmann et al. 2008b and Steinberger et al. 2010 (Global MFA dataset version 2.0).

Currently less than one billion people or just about 15% of the world population live in countries with a metabolic profile typical for the industrial metabolic regime. On average one inhabitant of the industrialized world uses 17 t of materials and 296 GJ of primary energy per capita and year. Industrialized countries consume one third of all globally extracted raw materials and 44% of global primary energy supply and an even higher share of key natural resources such as copper (67%), aluminum (72%) or electricity (60%). In the past, the development in these few countries has coined the changes in the global metabolic rates.

Their dominating role in global in the global metabolic transition is even more obvious from a cumulative perspective on global resource use: According to data from Marland et al. (2007), two fifths of all CO_2 emissions since 1700 (and roughly an equal share of all fossil fuels which have ever been combusted on this planet) have been emitted in the currently industrialized countries including the planned economies of Eastern Europe and the USSR. The overwhelming share of the globally extracted ores, industrial minerals and fossil energy carriers has been consumed or accumulated during the comparatively short history of industrialization by the currently industrialized economies.

Even though the industrial metabolic regime is not limited to the fully industrialized world but is prevailing also in an increasing web of urban-industrial centers in less developed economies the great majority of the global population live in regions and countries which are characterized by a metabolic profile somewhere between the agrarian and the industrial regime. 11% of the global population live in countries with an average metabolic rate of 37 GJ of energy and 3 t of materials per cap and year, a share of biomass in DEC of 93% and mineral materials accounting for only one quarter of DMC – patterns much closer to the agrarian than the industrial regime. The overwhelming part of the global population lives in countries somewhere between these extremes, some of which are rapidly industrializing, like China or Brazil. These countries currently adopt key metabolic characteristics of the prevailing industrial regime and increasingly coin the global development of material and energy use (e.g. Schandl and West 2010; Russi et al. 2008).

5.1. The metabolism of the "post-industrial" society

During the last decades growth of material and energy use in the industrial world has slowed down markedly and in some rare cases even began to decline (e.g. Japan and UK in Figure 2). Even if "mature" industrial economies have lost the strong momentum of biophysical growth, a high level of energy and material use is maintained (Haberl et al. 2006; Weisz et al. 2006). The shift towards a post-industrial or service economy which has been observed since the 1970s has not resulted in abolishing the energy and material intensive structural characteristics of the industrial regime or in a significant decline in natural resource use in industrial economies. Despite the fact, that the fast growing service sector contributes, to some extent, to further economic growth at a lower material and energy intensity than the industrial sector, the post-industrial economy rather builds on the industrial regime than replacing it and it rather not substitutes but adds to its material and energy intensive metabolic profile. Infrastructures, mobility and mass production and consumption are not vanishing but their significance continues even in the so called post-industrial economy. And also some core sectors of the service economy, such as tourism or health care are associated with quite significant material and energy requirements (Bullard and Herendeen 1975, 1977; Suh 2006). Therefore, the repeatedly expressed hope that the transition from the industrial to the post-industrial or service economy will automatically lead to an absolute decoupling and alleviate the sustainability problems associated with industrial metabolism is unlikely to realize.

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