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Analysis

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

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ABSTRACT

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 growing rapidly . If such national and local trends continue, the challenges for regional, national as well as global sustainability are immense in terms of future resource availability, social conflicts, pressure on land and ecosystems and atmospheric emissions. Using the concepts of social metabolism and material flow analysis, this paper presents an original study quantifying resource use trajectories for India from 1961 up to 2008. 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 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 taking opportunities of existing niches to make India a trendsetter.

1. 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 (Planning Commission, 2002, 2006). Obviously, this has not, and will not come without ecological consequences, both to its domestic as well as to the global environment (European Commission, 2009).

The basis for India's arguments comes from its unequal share in the consumption of the world's resources. With a population that is almost one-fifth of the global total, India in 2008 used only 7% of the global supply of material resources (in terms of mass) and 5% of global primary energy supply (Krausmann et al., 2009; Steinberger et al., 2010; The World Bank Group, 2012). 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 low, India's resource requirements are by far not negligible. For example, India is the world's fourth largest energy consumer and is third, after China and the US, when it comes to global carbon emissions (Marland et al., 2007; The World Bank Group, 2012, 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 sustainability.

This paper is an original study to explore some of the challenges faced by India and tries to interpret the meaning of its development rhetoric in a biophysical sense.[1] To be able to understand India's

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[1] This is the first detailed Material Flow Analysis (MFA) for India covering such a long time period. The data presented in this paper are available for download at: http://www.uni-klu.ac.at/socec/inhalt/1088.htm. MFA data for India are also included in a study for the Asia Pacific region (Schandl and West, 2010, see also UNEP, 2011).

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future sustainability challenges, we investigate its social or industrial metabolism, using the material and energy flow accounting framework (Ayres and Simonis, 1994; Fischer-Kowalski and Haberl, 2007; Haberl et al., 2004). Some of the derived indicators calculated 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 mean in terms of future global resource extraction and sustainability.

2. 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 to half of the country's total national income. Industry was poorly developed, dependency on imports was high that provided little impulse for economic growth. As the population grew, pressure on land for producing food increased. 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 and steel, energy, infrastructure, communication, defence) and only a small number of industrial categories were 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 on the production of goods, imports and exports, levied through heavy taxation and licence fees. 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 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; Basu, 2007; Jalan, 1992). 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.[2]

3. 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 system (Martinez-Alier, 1999). We refer to current standards of economy wide material flow accounting (Eurostat, 2009; OECD, 2008) to quantify domestic extraction (DE) of all raw materials and biomass harvested, their imports and exports 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.
- *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 sources 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 (Eurostat, 2009; Krausmann et al., 2008a). 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 Krausmann et al., 2008a; Wirsenius, 2003). 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 (United States Bureau of Mines, 1987; USGS, 2008) 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 limestone extraction for cement production and of sand and gravel used for concrete and asphalt production on

[2] In 2005, agriculture still engaged 56% of the total work force contributing 19% to the nation's GDP. Industry and services, on the other hand, employ 19% and 25% of the labour force respectively contributing 27.4% and 53.6% respectively to India's GDP (Asian Development Bank, 2007).

the basis of data on cement and bitumen consumption.[3] 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). It is generally assumed that this procedure to estimate the use on non-metallic minerals for construction produces a robust trend over time, but that the overall amount of construction minerals might be underestimated (cf. Eurostat, 2009; Gierlinger and Krausmann, 2012; Krausmann et al., 2011).

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 were 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).

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

4.1. Overall trends

In this section we report results of our calculations on material flows in India to examine the ongoing metabolic transition in India since the 1960s. Fig. 1 provides an overview of the yearly Domestic Material Consumption (DMC) between 1961 and 2008, both in absolute (Fig. 1a) and per capita (Fig. 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, when heavy emphasis for the development of infrastructure and industry was laid on attracting foreign corporations and investments.

[3] Based on Krausmann et al. (2009) and Eurostat (2009) we assumed a ratio of cement to sand and gravel in concrete to be 1:6.9 and a ratio of bitumen to sand and gravel in asphalt to be 1:20. Further, we assumed that 1.2 t of limestone is required to produce one ton of cement. To adjust for rural construction activities not related to concrete or asphalt production we further assumed a consumption of 0.3 tons per capita rural population.

Until the 1980s the population grew at a slightly faster pace than DMC. Throughout the 1960s and 1970s, material use remained at a low and slowly declining level of less than 3 t/cap/yr (Fig. 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/year, 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% (Fig. 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 $ (Fig. 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 more or less constant material intensity of these materials of slightly less than 4 kg per $.

4.2. India's biomass system

Biomass is the most essential of the four material groups, providing food, feed, fuel and raw materials. Domestic consumption of biomass doubled from around 1 Gigaton (or 1 billion $=10^9$ tonnes) per year in 1961 to 2 Gt/year in 2008 (Fig. 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.

Aggregate imports and exports range in the level of only 1% of domestic consumption of biomass throughout the time period. A strong change in trend in India's foreign trade in biomass can be observed (Fig. 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/year (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.

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 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).[4] Average cereal yields rose by a factor of almost 2.8 between 1961 and 2008,

[4] 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.

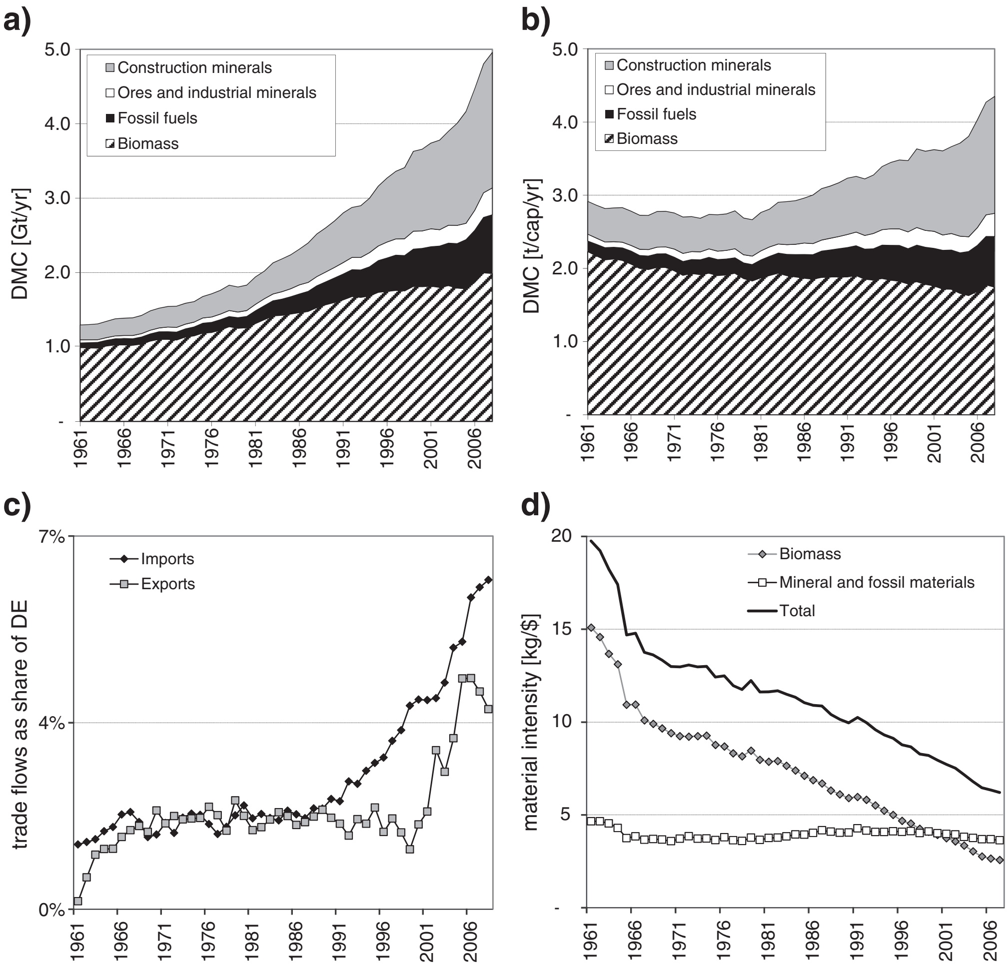

Fig. 1. Trends in material use and material intensity: a) domestic material consumption (DMC) by main material groups; b) domestic material consumption per capita; c) imports and exports as share of domestic extraction (DE); d) material intensity (DMC per unit of GDP in intl. 1990 $) of the Indian economy. Sources: own calculations, see text.

from 0.8 t/ha/year in 1961 to 2.2 t/ha/year 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 only by 2% between 1961 and 2008). 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 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 (Birner et al., 2009; Gupta, 2008). 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 in 2005.[5] 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. This 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 Fig. 2c. Per-capita availability of biomass declined from 2.2 t/cap/year in 1961 to 1.7 t/cap/year in 2008. While primary crop production even outpaced population growth, all other biomass categories including wood grew at a similar pace as population, and the only material group which actually did decline in relation to population growth was grazed biomass. 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,[6] began to decline (Fig. 2d). The overall per capita consumption of biomass declined but it was not at the cost of per capita availability of food crops that actually increased from 1,917 to 2154 kcal/cap/day (FAO). 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, although the overall feed conversion ratio (output of animal products per unit of feed input) was low with 1.8%

[5] 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).

[6] The share of cattle and buffalo in total feed demand declined from 90% in 1961 to 85% in 2008.

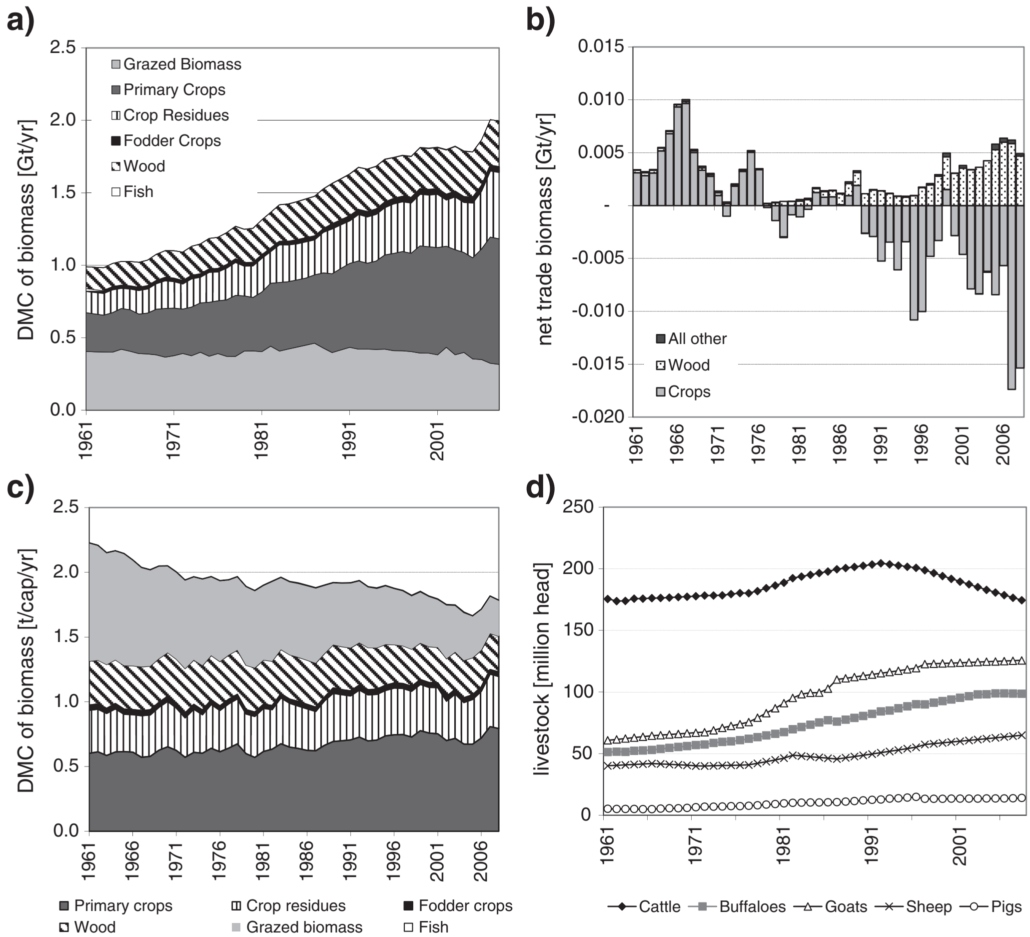

Fig. 2. Development of biomass flows and livestock: a) domestic material consumption (DMC) of biomass by main material groups; please note that the material group fish is very small (between 0.1 and 0.3% of DE and DMC) and therefore not visible in the graph. As net trade with biomass is very small compared to DE, the values for DE and DMC of biomass are very similar. b) physical net trade (imports minus exports) with biomass; c) domestic consumption (DMC) of biomass; d) change in livestock by major livestock species. Sources: own calculations, see text.

compared to an average of 6.1% in Eastern Asia in the year 2000 (Krausmann et al., 2008a).[7]

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/year to 153 kg/cap/year; the importance of non-grain food such as sugar crops or fruit increased even more strongly. Milk consumption almost doubled to 69 kg/cap/year. 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 than other Asian countries.[8] 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 although the number of cattle will possibly decline. 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/year in 2008, only about half of the value of China (6.6 t/ha/year) or Japan (6.4 t/ha/year) (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/year still far below many countries in the region, such as China (276 kg/ha/year), Bangladesh (155 kg/ha/year) or Pakistan (135 kg/ha/year) (FAO, 2009; Planning Commission, 2006). More fertilizer implies more energy use, however. The irrigation system could be further improved

[7] Our data show that the output of animal products per unit of feed input (both in tons dry matter) increased from 0.01 to 0.03 t/t; total output per unit of grazed biomass even surged from 0.01 to 0.06 t/t. 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 providing labour, manure and milk in subsistence agriculture towards the production of meat and milk.

[8] 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/year, respectively, as compared to 3.3 in India).

(Birner et al., 2010; Planning Commission, 2006) 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[9]; this difference is even larger on cropland where it is 69% (Haberl et al., 2007a).

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 by anthropologists since the 1960s (Harris, 1966). Considerable efficiency increases in livestock production thus seem possible.

4.3. 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 total 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 were used at a rate of only 0.7 t/cap/year. By 2008 their per capita consumption almost quadrupled to 2.6 t/cap/yr and the share in total 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.

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 Fig. 3a). Since, DMC of construction minerals tripled and reached 1.6 t/cap/year 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 railroad infrastructure and the 3.3 million km road network. This contributes to a growing demand of construction minerals. Although the amount of motor vehicles in use has been growing at an annual rate of almost 10%, still 14 vehicles per 1000 inhabitants is extremely low (Mitchell, 2003).

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 (Fig. 3b). India is a major producer and exporter of iron ore. 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/year in 2008 (Fig. 3a), a very low value in international comparison.

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 (Fig. 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/year) 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.[10] Lagging somewhat behind consumption, also imports of fossil energy carriers, mostly petroleum, have soared (Fig. 3d). Import dependency (i.e. the share of net imports in DMC) 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% (Fig. 3b and d).

At the beginning of the 21st century, India's DMC of fossil energy carriers is still dominated by coal (Fig. 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% 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 are 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.[11] 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. In general, there is an observed gradual shift away (in percentage terms) from

[9] 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).

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

[11] 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).

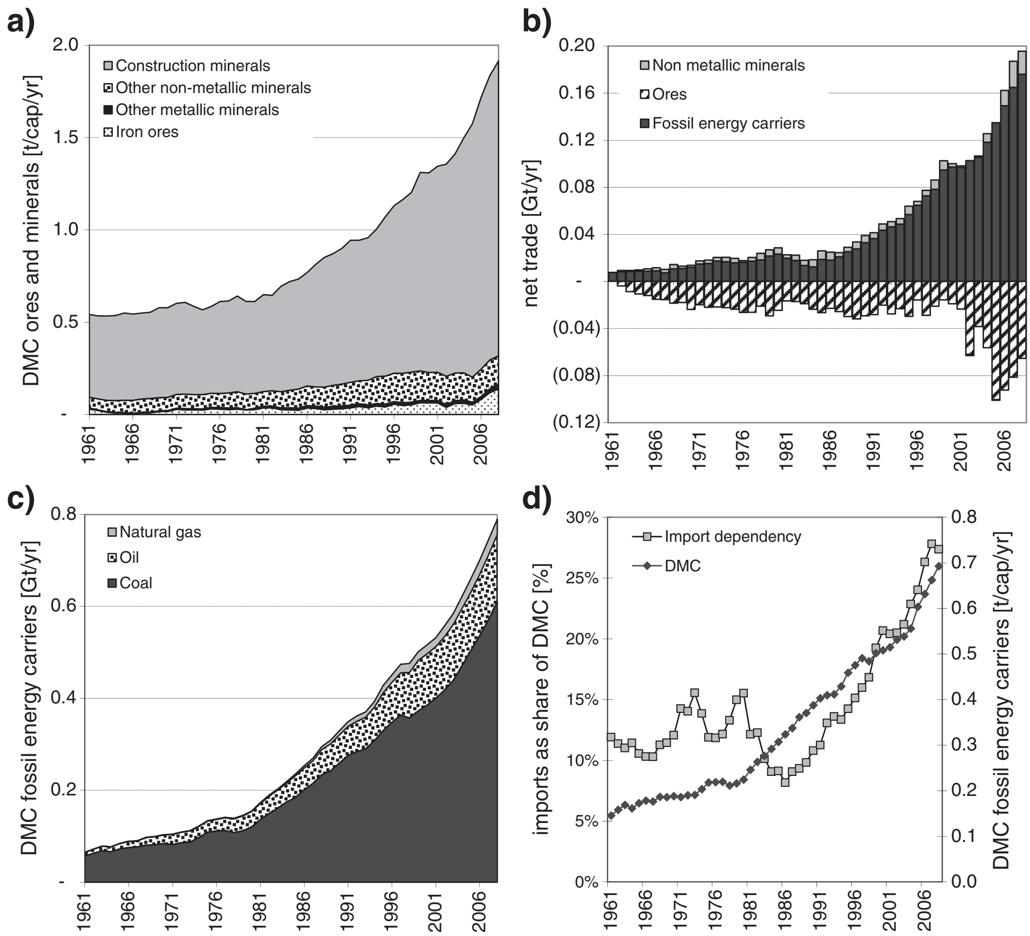

Fig. 3. Development of flows of fossil and mineral materials: a) per capita domestic consumption (DMC) of ores and non-metallic minerals by main material types; b) physical net trade (imports minus exports) with fossil and mineral materials; c) DMC of fossil energy carriers, d) per capita DMC and import dependency (net imports as share of DE) of fossil energy carriers.

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 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 (Fig. 1d).

Table 1
DMC [t/cap/year] of the three main groups of mineral and fossil materials and their average annual growth rates (%) in comparison to population and GDP.

	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%

Sources: Material and energy flows: own calculations; GDP and Population: The World Bank Group, 2010.

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 dematerialisation. India is only beginning to build up large networks of built infrastructure, material intensive patterns of settlements, and mobility and with rising income material intensive consumption patterns typically 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

Table 2
Comparing metabolic profiles and sustainability indicators, 2000.

	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%

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).

is to achieve an increase in energy efficiency by 25% through a variety of measures[12] 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 with 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). New biomass energy sources (like Jatropha) will be negligible, and will compete for scarce water resources (Ariza-Montobbio and Lele, 2010; Ariza-Montobbio et al., 2010).

5. 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; Haberl et al., 2011; Krausmann et al., 2008b), but is still far behind industrialised nations where the per capita 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). 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/year, and far below Europe's 14.1 t/cap/year. 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.

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 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, and some parts are becoming raw material providers, a large section of the population still live on subsistence and semi-subsistence agriculture (selling their surplus) and lack access to modern infrastructure such as electricity,[13] 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 low per-capita numbers become problematic while discussing overall sustainability of the Indian biophysical economy. India consumes 7% of the global DMC and is the third largest emitter of carbon dioxide to the atmosphere from fossil fuel combustion, despite the below-per-capita-average of 1.4 tCO_2-equivalents/cap/year, which is rank 142 in the global national comparison (the global average is at 4.6 tCO_2-equivalents/cap/year; Marland et al., 2007).

Even with such modest per capita consumption of materials and energy, in an absolute sense the Indian economy causes 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/year, 70% above the Chinese level and almost at par with the European Union.

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 low per capita consumption, 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/year, 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), and negative pressures on biodiversity. 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 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 land use induced productivity changes 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 (Global Footprint Network and Confederation of Indian Industry, 2008; WWF, 2010) 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" (Moran et al., 2009; Wackernagel and Giljum, 2001), do not play a prominent role for this "overshoot". The difference between HANPP on India's territory

[12] For example, increasing coal use efficiency in power generation, promote energy efficient vehicles in public and freight transport, promote energy efficient appliances and minimum life cycle cost purchase, establish benchmarks of energy consumption, and introduce energy audits for energy intensive industries (Planning Commission, 2005).

[13] 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 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. However, substantial trade flows occur at the sub-national level (Erb et al., 2009).

Our analysis has shown that India's per capita levels of material use are still far below the global average, while pressures on the regional, national and global environments 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 1.69 billion in 2050 (UN Population Division, 2010) would have 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 58% to the current levels of global extraction of fossil energy carriers, and 35% in case of minerals. India's total DMC would increase from currently 4 Gigatons per year to roughly 22 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 34%.

Thus, 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. The 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).

6. 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. 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 1.7 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 would need a new resource revolution. But unlike the green revolution, which boosted the output of plant based raw materials through increasing inputs of energy and fertilizers, the next revolution must reduce both the use of fossil fuels and mineral materials. Extraction and processing of mineral materials not only exacerbates the need for more fossil energy, but is often reported to cause social conflicts, dispossession and violence (Padel and Das, 2010; Temper and Martinez-Alier, 2007). While 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 solar energy system, solar refrigeration in dairy, and the use of wind power) should be widely considered, together with a high rate of use of the internet for communications and work.

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. 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 (van den Bergh and Bruinsma, 2008; Wiskerke and Van der Ploeg, 2004). India is not to expect a top-down transition driven by national policies and programmes alone, but to focus on multi-level transitions based on socio-technological innovations compatible with culture, markets, organisation, regulation and infrastructures (Geels, 2010; Smith et al., 2010). Markets, entrepreneurship, and innovation should play an important role. The challenge, however, is that capacities in terms of securing an educated population, creating green jobs, science and technology institutions, markets and governance system needs considerable improvement.[14] These seem to be the prime obstacles in achieving sustainability and could be overcome by improved coordination between various governance sectors and institutions across scales, as well as sound policies for an inclusive growth that takes into account people and the environment. Systematic research on the links between the increased social metabolism and ecological distribution conflicts (and resistance movements that propose alternative solutions) would be useful. 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, the world's largest democracy, also a trendsetter in seeking a new definition of quality of life and human well-being in line with a viable and healthy environment.

Table 3
A projection of India's DMC in 2050 under the assumption of the current Japanese metabolic profile.

		India 2000	India 2050	Increase in global DE
Population	[billion]	1.01	1.69	
Biomass	[Gt/year]	2.0	2.4	3%
Fossil fuels	[Gt/year]	0.5	6.2	58%
Industrial minerals and ores	[Gt/year]	0.1	1.9	35%
Construction minerals	[Gt/year]	1.4	11.4	50%
Total DMC	[Gt/year]	4.0	22.0	34%

Source: Using population projections of the UN and per capita DMC of Japan from Krausmann et al. 2008b.

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[14] According to the Democracy Ranking 2011 based on a range of political, economic and social indicators, India is placed 70, having moved up from 73 in 2006. This is a very modest gain as compared to its neighbour Bangladesh that moved 11 ranks higher in the same period (Campbell et al., 2011).

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