The Global Sociometabolic Transition
Past and Present Metabolic Profiles and Their Future Trajectories

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Summary

We present the concept of sociometabolic regimes and use it to analyze patterns of change in global social metabolism. Sociometabolic regimes represent dynamic equilibria of society–nature interactions and are characterized by typical patterns of material and energy flows (metabolic profiles). From this perspective, industrialization appears as a process of transition from the agrarian to the industrial regime. This article presents a global data set on the socioeconomic metabolism of 175 nations for the year 2000. We group the countries into six clusters differentiated by economic development and population density, reflecting the historical path of (agrarian) development and resource endowment.

Our analysis reveals that per capita material and energy use in industrialized clusters is higher than in developing regions by a factor of 5 to 10. However, per capita use of natural resources differs significantly among industrialized clusters. A large fraction of the global population displays a metabolic profile somewhere in between the patterns typical for the agrarian and the industrial regimes. The sociometabolic transition from an agrarian to an industrial regime is thus an ongoing process with important consequences for future global material and energy demand. If we take a transition between regimes and the current characteristics of this transition as given, the global energy and materials demand is likely to grow by a factor of 2 to 3 during the coming decades. The most critical part of our findings relates to the cluster of high-density developing countries, as these countries already have a higher anthropogenic material and energy burden per unit of land area than, for example, industrial Europe, with pending further increases bound to surpass carrying capacities.
Introduction

We view the process of industrialization as a transition from an agrarian to an industrial sociometabolic regime with distinct biophysical characteristics. Although this transition allows for unprecedented economic growth and material wealth, it also fundamentally alters the patterns of social metabolism and leads to equally fundamental changes in a wide variety of ecosystems (Turner et al. 1990). We argue that an economic and a technical understanding of industrialization needs to be complemented by a sociometabolic one. The sociometabolic understanding makes us view differently not only history but also future trajectories toward (or away from) sustainability: The majority of the world’s regions and economies are still in early phases of an ongoing industrial transformation.

Whereas many authors see technological development and economic growth as a continuous, gradual process that leads from a traditional society dominated by agriculture to a modern society dominated by industry and services, we focus on the qualitative, systemic differences between the stages of this process. Following Sieferle (1997), we distinguish sociometabolic regimes, each characterized by a specific metabolic profile, that correspond to a set of impacts on the environment. These regimes are conceptualized as dynamic equilibria of complex systems of society–nature interaction; between them, transitions may occur (Sieferle et al. 2006; Fischer-Kowalski and Haberl 2007a). Industrialization is such a transition.

This article elaborates on the concepts of sociometabolic regimes and examines characteristic metabolic profiles resulting from historical analyses. It describes the biophysical characteristics and constraints of the (historical) agrarian and industrial regimes and the historic transition process from one to the other. These characteristics of the historic agrarian and the industrial sociometabolic regime (and the data describing their metabolic profiles) have been derived from a number of case studies on long-term historical changes in the social metabolism of European countries and their transformation during industrialization on different spatial scales (national, regional, local). The methods and sources for accounting for the use of energy, materials, and land in historical societies and the empirical results have been described in detail in previous publications (see, e.g., Krausmann and Haberl 2002; Schandl and Schulz 2002; Krausmann 2004; Sieferle et al. 2006; Fischer-Kowalski and Haberl 2007b). Beyond data from our own research, we draw on estimates of metabolic profiles of agrarian societies from the literature (e.g., Simmons 1989; Sieferle 2001; Malanima 2002). The description of the industrial regime is generalized from the above-mentioned historical case studies and various publications on the material and energy flows in industrial societies (e.g., Haberl et al. 2006; Schandl and Eisenmenger 2006; Weisz et al. 2006).

For contemporary metabolic patterns, we draw on a new, comprehensive global data set covering various aspects of material and energy flows as well as demographic and socioeconomic data. The data set has been compiled for the year 2000 and covers 175 individual countries, comprising more than 99% of the world’s population and territory. In this article, we present the first analysis of wider aspects of global metabolism from this data set. The most important headline indicators derived from our data, which we refer to in our characterization of sociometabolic regimes, are domestic energy consumption (DEC; energy use) and domestic material consumption (DMC; material use), which are recalculated as density (i.e., gigajoules [GJ] or tonnes per square kilometer [km²] and year) or per capita (i.e., GJ or tonnes per capita and year) values. A detailed description of the accounting principles and methods as well as data sources is provided in the Supplementary Material on the Web; all data for the 175 individual countries can be downloaded from our Web page (www.uniku.ac.at/socec/inhalt/1088.htm).

Assuming the transformation from an agrarian to an industrial regime to be a still ongoing process, we cluster the contemporary countries in this data set according to criteria derived from our theoretical reasoning and historical analysis. The findings we present confirm the assumptions made: Contemporary developing countries, despite a different world context, appear to have a metabolic profile that in many ways resembles that of the historic agrarian regime or transitory
states between the regimes. Beyond development status, population density appears to be a key variable and, irrespective of regime, has a large impact on the metabolic profile. In a final step, we discuss potential impacts of the ongoing industrial transformation on global metabolism.

Theoretical Background and Its Foundations in Historical Analysis

Our starting point is the theory of sociometabolic regimes as developed by Sieferle (1982, 2001) and elaborated by him and several other authors since (Fischer-Kowalski and Haberl 1997; Sieferle et al. 2006). The theory claims that, in world history, certain modes of human production and subsistence can be broadly distinguished that share, at whatever point in time and irrespective of biogeographical conditions, certain fundamental systemic characteristics derived from the way they utilize and thereby modify nature. Although in classical political economics the point of reference for distinguishing such modes was mainly human dynamics as manifested in the economy and social organization (see, e.g., Adam Smith’s [1776] modes of subsistence or Karl Marx’s [1867/1990] modes of production), we follow Sieferle in placing an equal focus on nature and the changes in the natural environment induced by the very functioning of particular socioeconomic systems. Such changes facilitate the functioning of socioeconomic systems but, in the long run, may also threaten their continuation—that is, create sustainability problems. Therefore, we talk about socioecological systems that consist of a structural coupling of a socioeconomic system with certain compartments or systems in the natural environment from which it draws its resources and that it modifies, either deliberately (colonization; Fischer-Kowalski and Weisz 1999) or as an unintended consequence of its metabolism. The theory claims that the energy system represents the most basic constraint for the differentiation of socioecological systems. Accordingly, socioecological systems that have in common the main source of energy and the main technologies of energy conversion will also 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 Grubler 1995), institutional characteristics, and communication patterns.

We address the classes of socioecological systems sharing a common energy system as sociometabolic regimes. Across time, sociometabolic regimes can be regarded as dynamic equilibria that are integrated across spatial scales, allow for certain change and growth processes, and feature specific environmental impacts. From a global history perspective, three major sociometabolic regimes with distinct energy systems can be discerned (cf. Sieferle 1997; de Vries and Goudsblom 2002): the regime of hunters and gatherers, the agrarian regime, and the industrial regime. The regime character of the industrial society is, however, to be contested, as neither its reliance on exhaustible resources nor its huge outflows, which exceed the sink capacity of ecosystems, allow for long-term existence (Sieferle 1997).

The transition between sociometabolic regimes is not a continuous process. Within a regime, path dependency and resilience prevail. But if a critical set of conditions of a sociometabolic system begins to transcend the range of possible dynamics of its regime, a transition process is initiated that may lead to a qualitatively different regime with distinct properties and dynamics, or, eventually, collapse may occur (cf. Tainter 1988; Costanza et al. 2007).

Biogeographical factors and resource endowment (climate, soil, access to waterways, mineral resources) contribute to the formation of subtypes of regimes with region-specific sociometabolic characteristics. They are significant for regional development paths within a regime and have been relevant for past regime transitions.

In this article, we focus on the agrarian and the industrial sociometabolic regimes and transitions between them and omit a discussion of the sociometabolic regime of hunters and gatherers.

The Agrarian Sociometabolic Regime

Although agrarian societies that have evolved around the globe over more than 10,000 years
may appear to differ considerably regarding their social structure, institutions, and cultural development, they share similarities with regard to their biophysical characteristics and the development boundaries resulting from their society–nature interactions. Agrarian societies are fueled by a solar-based energy system and rely on the energy conversion provided by plant biomass. They are tapping solar energy flows to sustain their energy needs rather than exploiting stocks of fossil energy carriers. In contrast to hunters and gatherers, agrarian societies actively manage terrestrial ecosystems to increase the output of useful biomass and energy. Therefore, the land-use-based energy system they achieve has been termed controlled solar energy system (Sieferle 2001). Biomass is the single most important source of energy for socioeconomic metabolism and amounts to more than 95% of the primary energy supply. Because of the limited ability of historical agrarian societies to convert energy technologically, the provision of certain types of energy is closely related to certain types of land use. In most cases, the provision of heat relies on firewood and woodlands, the provision of food for humans on cropland, and the supply of draft power on grassland. A certain energy mix requires a corresponding land use mix. Although water and wind power have some socioeconomic importance (as they provide for specific types of work and long-distance transport), they are quantitatively only of regional importance (such as was wind power in the Netherlands). Wind and water usually account for no more than a small percentage of the primary energy supply.

In the agrarian sociometabolic regime, the availability of land in combination with area productivity determines the amount of available primary energy. Due to the predominance of “bioconverters,” such as humans and animals, for the provision of useful energy, the overall efficiency of the conversion of primary into final and useful energy remains low, at less than 5%. 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. Clearly, there is a range of variation of energy availability, depending on the specific biogeographical conditions, the type of land use system, available technology, and the role of human and animal labor. Nevertheless, it is obvious that a sociometabolic 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).

A number of basic factors are responsible for the energetic constraints for development and growth within the agrarian regime, on the basis of a controlled solar energy system (see figure 1). At the core of this energy system is an agricultural population that invests labor to cultivate terrestrial ecosystems and to produce food, feed, fiber, and fuel. The harvest of biomass products from a given amount of land can be augmented by intensification—that is, by an increase in labor input (Boserup 1965). Under the conditions of low-input agriculture (see below), 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 specific types of biomass) has to exceed the amount of biomass-based energy that has been invested into the cultivation of the land: At a very basic level, this means that food output has to be significantly larger than the food equivalent of the invested labor; otherwise a stable population can not be maintained. The minimum energy return on investment is given by demographic requirements, but an agricultural population may even produce a significant surplus that allows it to sustain a nonagricultural population and production; its maximum fraction is ultimately limited by the attainable surplus rate and in practical terms depends on social arrangements that determine how much the agricultural population is willing or how much it can be forced to give away. Spatial differentiation and specialization are further constrained by transport limitations: Under the conditions of the agrarian regime, only waterways allow for long-distance transport of bulk materials. The energy costs of overland transport increase to a prohibitive level after only a few kilometers (Boserup 1981; Bairoch 1993). This implies limitations for the exchange and for the spatial concentration of staple food, feed, and fuel, which are produced at low energy densities (with respect to both energy content per ton and energy harvested per unit of
Figure 1 The dynamic equilibrium of the agrarian regime. An agricultural population invests labor to cultivate land and to produce different types of biomass (food, feed, fiber, fuel) sufficient to maintain a stable population. Under given climatic and soil conditions and cultivation technology, this may allow production of a surplus and provide a certain nonagricultural population and its activities with energy and raw materials. Growth of the agricultural population can be based either on territorial expansion or on increasing biomass output per unit of area. Intensification requires human or animal labor and is limited by diminishing marginal returns. The size of the nonagricultural subsystem is constrained not only by the surplus rate but also by the energy costs of transportation: Growth of the urban population can be sustained by an increase in the surplus rate—that is, by an increase in labor efficiency of the land use system in the hinterland (which is possible only within narrow limits) or access to a larger rural hinterland. Expanding the hinterland, however, increases transport distances, which ultimately constrains urban growth.

The maximum amount of primary energy that can be produced per unit of land and, hence, the number of people who can be sustained under the conditions of the agrarian regime are limited by the ecological constraints of low-input agriculture. In the absence of external energy subsidies and off-farm resources, the maintenance of soil fertility has to rely on a complex system of often 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), transfers of biomass and plant nutrients from extractively used ecosystems (e.g., woodlands, rough grazing) to intensively used plots (e.g., by litter extraction and grazing in forests), recycling of residues and wastes, and the utilization of natural regeneration and renewability rates (e.g., biological fixation and deposition of nitrogen, soil processes; Kjaergaard 1994; Mazoyer et al. 2006). In particular in temperate climates, the multifunctional use of livestock for nutrient transfers and management, power supply, and biomass conversion (residues, wastes, low-quality biomass) has been an integral part of low-input agriculture. In general, land use systems are optimized more for the long-term stabilization of overall system output than for maximizing yields per unit of area (Müller-Herold and Sieferle 1998). Although it is possible to maintain soil fertility and stabilize yields under these conditions and even to increase output within the regime’s region-specific boundaries resulting from local climatic and soil conditions, ultimately, biomass production per unit of area cannot exceed a certain maximum.

On the basis of empirical evidence from studies on energy and material flows in advanced Central European agrarian regimes, we can estimate
the potential energy density supported by the historical agrarian regime. Assuming a mix of land use types including a certain share of low-productivity land and land not available for biomass production, we estimate that advanced agricultural land use systems under temperate climatic conditions would yield up to 30 gigajoules of primary energy per hectare (ha) and year on a large-scale average in the long run (Sieferle et al. 2006; Krausmann, Schandl, and Sieferle 2008b). We regard this value as a rough estimate of the average carrying capacity of an advanced agrarian regime over large areas (several thousand square kilometers). This figure can be much lower in regions with less favorable climates or under less advanced modes of production, or even somewhat higher when more than one harvest per year is possible. On the basis of this estimate, a typical per capita DEC of advanced European agrarian societies of 40 to 70 GJ per year translates into a maximum population density of 45 to 75 persons per square kilometre. If we assume a much lower DEC of 20 GJ per person and year because of a low demand for heat in a warm climate, a land use system primarily based on human rather than animal labor (e.g., smallholder rice farming in East and Southeast Asia), and a vegetable-based diet, then it may sustain a significantly higher population density (up to 150 people per km²; cf. Boserup 1965; de Vries et al. 2002). The inherent limitations of the biomass-based energy system—namely low energy density, lack of conversion technologies, reliance on animate power, and high energy costs of transport—shape the patterns of material use. Except for biomass, all materials are used at rather low quantities, in terms of volume per capita and per area. Our reconstruction of the historical metabolism of agrarian Austria and the United Kingdom (Schandl and Schulz 2002; Sieferle et al. 2006) shows that the yearly consumption of all materials ranged somewhere between 5 and 6 tonnes per person, of which biomass had a share of 80% to 90% (see table 1).

Although the metabolism of the agrarian regime is based on the exploitation of renewable resources and on harvesting flows rather than diminishing stocks, 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 nonrenewable on human time scales. Their overuse or degradation immediately causes negative feedback at the local level. Ecological sustainability, therefore, is a prerequisite for survival, and mismanagement is immediately punished. There is, however, 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 optimization of land use. There tends to be positive feedback between biophysical growth and population growth (see figure 1), and agrarian societies show an overall tendency to increase land use efficiency (output per unit of area) at the expense of labor efficiency. Under such circumstances, in the long run the material/energy output per capita reaches a limit or even starts to decline (Boserup 1965). Thus, in general, agrarian societies face sustainability problems related to the limited availability of natural resources, the long-term maintenance of soil fertility, and the balance between food supply and population growth (cf. Grigg 1980; Kjaergaard, 1994). Mismatches or fluctuations due to climatic conditions easily result in demographic crises (epidemics or wars), destabilizing the labor-intensive land use systems. Pollution problems occur only locally at mining sites or in urban agglomerations (Sieferle 2003).

The Industrial Sociometabolic Regime

Historical evidence suggests that industrialization is a transition process allowing populations to overcome scarcity and the sustainability problems of the agrarian sociometabolic regime. Technological and social change based on the use of a new type of energy carrier, namely fossil fuels, and new types of energy conversion gradually extends the inherent growth limits by abrogating negative feedbacks operating in the agrarian regime (Wrigley 1988; Sieferle et al. 2006). Such a transition process was experienced for the first time in England, supported by a unique combination of a land use system with a high surplus rate, specific patterns of natural resource endowment (location of coal and iron ore deposits, the “river around Britain,” scarcity of wood), technological
breakthroughs in coal extraction and metallurgy, institutional change, and population growth. In an initial phase, coal provided a new source of fuel for limited use in urban households and to power some industrial processes. The energy transition was accelerated through a positive feedback loop created by the emergence of the steam engine–iron ore–railroad technology complex (Grübler 1998; Ayres 1990).

Throughout the 19th century and until the middle of the 20th century, however, fossil fuel–powered urban/industrial centers coexisted with a rural matrix. The agrarian periphery perpetuated the conditions of the agrarian regime over many decades (Krausmann, Schandl, and Sieferle 2008b). Coal-based industrialization, although it allowed for the introduction of the new industrial sociometabolic regime, was characterized by a strong linkage between industrial production and a growing demand for human and animal labor and population growth. The rapidly growing population had to rely on the delivery of nutrition from a largely preindustrial, low-input agriculture (Krausmann, Schandl, and Sieferle 2008b). 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, when oil, electricity, and the internal combustion engine replaced the older coal-based technologies and led to a final decoupling of industrial production and human labor and to the industrialization of agriculture (Grübler, 1998). Direct (mechanical power) and indirect (artificial fertilizer) fossil fuel–based energy subsidies for agriculture removed the last limitation to increasing biomass production and allowed for a tremendous growth of area and labor productivity in agriculture, at the expense of the positive energy return on investment that agriculture had had in the agrarian regime (Leach 1976).

The fossil fuel–based energy system, which relies on the large-scale exploitation of nonrenewable stocks, is thus at the core of the industrial sociometabolic regime. The availability of an area-independent source of energy and the fossil fuel–powered transformation of agriculture from an energy-providing activity to a sink of useful energy are the two main factors that made it possible to almost completely decouple energy provision from land use and the control of territory. All of the sociometabolic 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 who can be nourished from one unit of land multiplies, allowing for an unprecedented growth of urban agglomerations.

The transition from an agrarian to an industrial sociometabolic regime not only facilitates

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**Table 1** Yearly metabolic profile of the agrarian and industrial sociometabolic regimes

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Agrarian</th>
<th>Industrial</th>
<th>Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy use (DEC) per capita</td>
<td>[GJ/cap/yr]</td>
<td>40–70</td>
<td>150–400</td>
<td>3–5</td>
</tr>
<tr>
<td>Material use (DMC) per capita</td>
<td>[t/cap/yr]</td>
<td>3–6</td>
<td>15–25</td>
<td>3–5</td>
</tr>
<tr>
<td>Population density</td>
<td>[cap/km²]</td>
<td>&lt;40</td>
<td>&lt;400</td>
<td>3–10</td>
</tr>
<tr>
<td>Agricultural population</td>
<td>[%]</td>
<td>&gt;80%</td>
<td>&lt;10%</td>
<td>0.1</td>
</tr>
<tr>
<td>Energy use (DEC) per area</td>
<td>[GJ/ha/yr]</td>
<td>&lt;30</td>
<td>&lt;600</td>
<td>10–30</td>
</tr>
<tr>
<td>Material use (DMC) per area</td>
<td>[t/ha/yr]</td>
<td>&lt;2</td>
<td>&lt;50</td>
<td>10–30</td>
</tr>
<tr>
<td>Biomass (share of DEC)</td>
<td>[%]</td>
<td>&gt;95%</td>
<td>10%–30%</td>
<td>0.1–0.3</td>
</tr>
</tbody>
</table>

Sources: The data compiled in table 1 are derived from our own empirical studies on material and energy flows in agrarian and industrial societies (e.g., Krausmann and Haberl 2002; Schandl and Schult 2002; Haberl et al. 2006; Sieferle et al. 2006; Weisz et al. 2006) and literature data (e.g., Simmons 1989; Malanima 2002).

Note: DEC = domestic energy consumption; DMC = domestic material consumption.

{a}Typical values for advanced European agrarian sociometabolic regime. In agrarian societies based on labor-intensive horticultural production with low significance of livestock, population density may be significantly higher, whereas per capita use of materials and energy is lower (see the text).

{b}In economies with high population densities, per capita values of DMC and DEC tend to be in the lower range, whereas per area values are high. In countries with low population densities, per area values can be very low (see the text).
economic growth, structural change, and a certain worldwide uniformity in social forms and institutions, but it is inherently linked first to population growth and later to a surge in material and energy use per capita. The availability of and cheap access to fossil fuels of high-energy density and new and efficient technologies (e.g., internal combustion engine, electric engine) to convert primary energy into useful work allows for the emergence of novel patterns of mass production and consumption, which, in turn, stabilize a high level of energy and material use (McNeill 2000). Among the key factors responsible for the structure and size of typical metabolic patterns of the industrial regime are material- and energy-intensive industrial production systems (including agriculture); the installation, operation, and maintenance of large infrastructures (e.g., buildings, roads) and physical stocks (e.g., cars); the high level of mobility of goods and people in a spatially highly differentiated economy; and a high material standard of living (e.g., central heating/air conditioning, electrical household appliances, dietary patterns or tourism activities).

Table 1 gives an overview of the metabolic profile of current industrial economies: Material and energy use per capita exceeds the values characteristic for advanced agrarian regimes by a factor of 3 to 5. In addition, a surge in agricultural output permits population densities up to 10 times larger than in agrarian societies. Thus, the material and energy use per unit of area will have multiplied by a factor of 10 to 30. The share of biomass in DEC and DMC drops to 10% to 30%; however, this relative decrease does not imply a decline in the absolute amount of used biomass. On the contrary, the absolute amount of biomass used in the industrial regime is higher than ever before. Due to the tremendous increases in agricultural labor productivity, industrial regimes may be sustained by a very low portion of the population engaged in agriculture (less than 10%).

As with the agrarian regime, we find characteristic phases and development pathways within the industrial regime. During its initial stages, there is a strong need for human (nonagricultural) labor and a move of people and labor out of agriculture into urban–industrial centers. In later phases, much of the human labor in production processes is replaced by mechanized (and, finally, computerized) work. Population growth recedes, and a process of suburbanization sets in. The next phase is marked by the final incorporation of agriculture into the industrial regime and a shift of employment to service sector activities. At a later stage, the outsourcing of labor-, resource-, and emission-intensive activities to the global periphery occurs, accompanied by a certain stagnation in the energy and material use that had been increasing so rapidly in the earlier phases of the transition process (cf. Haberl et al. 2006). Even if “mature” industrial economies have lost the strong momentum of biophysical growth, a high level of energy and material use is maintained. What can be observed in the mature industrial core countries is interlinked with processes in all other regions of the world, regions that dwell at another stage of this transition process or may eventually take a different pathway in a globalized world and with new technological options.

Whereas in the agrarian regime scarcity, 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 on 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 sociometabolic regime continue to emerge or get worse. The list of severe sustainability problems experienced by the industrial sociometabolic regime includes a change in atmospheric composition threatening world climate and unprecedented biodiversity loss. The abundance experienced relative to the previous agrarian regime may thus come to limits as well: The industrial sociometabolic regime is based on the use of exhaustible key resources. Unless we assume unlimited substitutability of resources due to technological change—against which Ayres (2007) has recently argued very convincingly—the industrial sociometabolic regime, by definition, lacks the potential for sustainability. Sieferle
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(1997), therefore, considers it to be a transitory stage rather than a stable new regime.

The Contemporary World From the Perspective of Sociometabolic Regimes

As outlined at the beginning of this article, we view the contemporary world as still involved in a fundamental and ongoing process of transition from the agrarian to the industrial sociometabolic regime. We claim the very process of industrialization or “development” to be exactly this. We seek to back up this claim with an exploratory analysis of our global data set (covering 175 countries, or 99% of the world population) by combining some more common demographic and economic indicators with biophysical indicators that describe the countries’ metabolic profiles. Although the data do not allow us to follow the development path of individual countries, they present a snapshot for the year 2000 of countries at various stages in this transition process, bearing also the marks of their previous history.

Clustering Countries

For the analysis, we have clustered the countries according to considerations discussed in the previous section. We distinguish, on the basis of United Nations (UN) classifications, between industrialized and developing countries. This distinction, as claimed above, we believe to coincide with different stages in a process of transition from an agrarian to an industrial regime and therefore with very different metabolic profiles. Next to development status, we use population density as a variable that reflects the preindustrial history of a country. According to our theoretical considerations, and in close correspondence with Boserup’s (1965, 1981) approach to agricultural development, population density is a crucial variable reflecting various aspects related to sociometabolic regimes and their transition: A high population density across a larger territory presupposes a long history of intensive agricultural colonization. It takes many centuries of an agrarian regime to bring about a high population density, and there is no densely populated country without such a long agrarian history.

The reverse is not equally true. If population density is low, this may have either historical reasons (i.e., no long, uninterrupted history of agrarian colonization), or biogeographical reasons (i.e., natural conditions not suitable for intensive agriculture, e.g., aridity, cold climate, or adverse terrain). Thus, low population density may, in some cases, simply indicate that there has been a shorter history of human settlement altogether, because the region has been difficult to access from the African origin of our species, such as the so-called New World (cf. Cohen 1977; Crosby 1986), or there might have been a long period of human settlement but naturally adverse conditions for agriculture (e.g., in the arid regions of the Near East). Population density not only reflects biogeographical conditions and agricultural history, it also systematically differentiates between areas of high and low per capita availability of natural resources. This is certainly true for an area-dependent resource such as biomass, where the availability of land per capita is immediately related to biomass availability per capita. Equally, for statistical reasons in sparsely populated countries (which, in most cases, cover large territories), in general the per capita endowment of mineral resources is higher than in regions with high population density. This is further enhanced by the historical argument outlined above. Countries with a high population density usually have a longer history of resource exploitation and hence have often exhausted their domestic resource base (as is the case for many mineral resources in most European countries). Again, very close to Boserup’s (1965, 1981) argument, a high density of people and a high density of natural resources will prevail in different areas. For this reason, and because sparsely populated countries require a higher input of energy and materials for the same level of supply of services per person compared to densely populated countries, population density can be expected to have a significant impact on metabolic profiles (Haberl et al. 2006; Weisz et al. 2006).

We have clustered the 175 countries from our data set according to development status (developing and industrialized countries) and population density (high density and low density). According to the considerations discussed above, we further separate the two
low-population-density clusters according to their agrarian history, into Old World and New World countries. Applying this classification, we arrive at six clusters that should, according to our theoretical considerations, constitute contemporary “subtypes” of the historically observed sociometabolic regimes and, correspondingly, show qualitatively and quantitatively distinct metabolic profiles (see table 2).

Before we further discuss the metabolic profiles of these clusters, there is a need for a short review of their methodological basis. The clusters have been aggregated from countries classified according to certain theoretical considerations, as explained above (see table 2). Countries are a very awkward unit of analysis: Formed as political entities that share a certain—and in some cases only a short—history, they spread across four orders of magnitude in terms of territory, population, and gross domestic product (GDP; e.g., India or Canada vs. Malta) and may be very heterogeneous internally. Nevertheless, they are an indispensable unit of analysis, as most socioeconomic data are available in international databases only at the national level. To check whether the countries grouped together in a cluster are reasonably similar, we ran a first test for homogeneity by checking coefficients of variation ($\sum |x - \eta|/\eta$) for each cluster against the worldwide coefficient of variation (see Supplementary table S4 on the Web). There are four groups of variables in table 3 (and Supplementary table S3 on the Web): The first group (population density and GDP/capita) represents information used to define the clusters. On the basis of these variables, of course, the clustering produces differentiated entities with an internal variation below the overall variability. The second and third groups of variables describe the respective metabolic profiles: energy (DEC) and material (DMC) use per capita, and some more specific technological and metabolic indicators, again per capita. For these indicators, the difference between industrialized and developing countries is—with few exceptions—substantial and follows the patterns we predicted. It is also apparent, though, that there are some sources of variation not captured by the theory

<table>
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<th>Industrialization</th>
<th>Industrialized countries</th>
<th>Developing countries</th>
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<tbody>
<tr>
<td>High pop. density</td>
<td>High-density industrial (HDI): European countries, Japan, South Korea (N = 30)</td>
<td>High-density developing (HDD): Most of southern/eastern Asia, including India and China, Central America, some African countries (N = 63)</td>
</tr>
<tr>
<td>Low pop. density</td>
<td>Low-density industrial—New World (LDI-NW): North America, Australia, New Zealand (N = 4)</td>
<td>Low-density developing—New World (LDD-NW): South America (N = 22)</td>
</tr>
<tr>
<td>History of agrarian colonization</td>
<td>Low-density industrial—Old World (LDI-OW): Countries of the former Soviet Union, Scandinavian countries (N = 15)</td>
<td>Low-density developing—Old World (LDD-OW): Northern Africa and Western Asia, parts of Africa, some Asian countries (N = 41)</td>
</tr>
</tbody>
</table>

Note: Industrialized countries include all developed countries and transition markets; developing countries include developing and least developed countries (based on the classification of UNSD 2006). All countries with a population density higher than 50 persons per km² are considered high density; all others are considered low density (based on data from FAO 2005). See table S2 in the Supplementary Material on the Web for a complete list of countries. N = number of countries in the cluster; pop. = population.
of sociometabolic regimes. One of them is the particular history of decline of the former Soviet Union, which puts the low-density industrialized Old World countries (LDI-OW) cluster, in some respects, in between industrial and developing countries. Another source is related to unique patterns of natural resource endowment: For instance, the oil-exporting countries of the Near East have extraordinarily high levels of consumption of fossil fuels and a low share of agricultural population, irrespective of their overall low development status. In a similar way, the occurrence of other mineral deposits can contribute to exceptionally high levels of apparent consumption (cf. Giljum 2004).

Our classification is also not sensitive for the momentum of growth: Countries with steep economic growth tend to have a higher consumption of strategic materials, such as cement, than others, due to growing infrastructure. A fourth group of variables expresses energy and material use per unit area. Here we expect, as outlined above, population density to explain most of the difference: Densely populated countries, on each level of development, are bound to have higher energy and materials use per hectare and thus—other things being equal—exert a higher pressure on their natural environment through their socioeconomic metabolism (see table 3). Even now, at an economic level 10 times lower than for the low-density industrialized New World countries (LDI-NW), the high-density developing countries (HDD) exert roughly twice the pressure on their territory than those of the industrial New World.

These four groups of variables are complemented by data on global trade. In table 4, the physical trade balances of biomass, ores, and minerals turn out as expected: The country clusters with high population density, irrespective of their development status, have higher raw material imports than exports, whereas the clusters with low population density export more materials than they import. The same pattern does not fully hold true for fossil fuels: The highly industrialized high-density industrial (HDI) and LDI-NW clusters, which are gradually exhausting their domestic stocks, both heavily depend on fossil fuel imports, whereas all other clusters, even the HDD region, are net exporters of fossil fuels.

The Metabolic Profiles of Contemporary Clusters of Nation States

As table 3 shows, the key overall patterns of the metabolic profiles across the country clusters correspond very well to the above theory of sociometabolic regimes: Developing countries gain half or more of the energy they use from biomass, whereas for industrial countries this proportion is less than a quarter, with three quarters from fossil fuels (and other industrial-type energy sources), quite homogeneously across subtypes. Half of the population of developing countries is engaged in agriculture, as compared to less than one tenth in the industrial clusters. Average per capita material and energy use in the industrialized countries is larger than in the developing world by a factor of three to four. These differences are very pronounced and correspond mainly to development status, as predicted. Other differences regarding the sociometabolic profile of the six clusters also relate to development status, but in a more complex way, mediated by the other variables considered. The differences between the six country clusters and their metabolic peculiarities are discussed in detail in the following sections.

HDI

This cluster consists of the densely populated industrialized countries of Europe, including the formerly planned economies of Eastern Europe and the industrialized economies of Asia. These countries have a long history of agricultural development and industrialization and face relative scarcity of natural resources or wilderness reserves as a result of high population density. Dependence on raw material imports is very high. Despite a highly industrialized land use system, 7% of the demand for biomass, half of the demand for fossil fuels, and two thirds of total mineral requirements have to be imported from other regions (see tables 3 and 4).

The countries of this cluster occupy only 4% of the global land area but contain 12% of the world population (see figure 2). They produce 46% of the world GDP. The cluster is composed of very advanced or rapidly modernizing economies with a high level of income. The level of use of iron, cement, animal-based food, and electricity per capita is among the highest in the world. Despite
Table 3  Metabolic profiles of six country clusters for the year 2000

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>World</th>
<th>Industrialized</th>
<th>Developing</th>
<th>HDI</th>
<th>LDI-NW</th>
<th>LDI-OW</th>
<th>HDD</th>
<th>LDD-NW</th>
<th>LDD-OW</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. countries</td>
<td></td>
<td>175</td>
<td>49</td>
<td>126</td>
<td>30</td>
<td>4</td>
<td>15</td>
<td>63</td>
<td>22</td>
<td>41</td>
</tr>
<tr>
<td>Indicators defining clusters</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GDP/capita [$/cap]</td>
<td></td>
<td>6,665</td>
<td>18,829</td>
<td>3,124</td>
<td>18,364</td>
<td>30,540</td>
<td>6,333</td>
<td>2,866</td>
<td>6,312</td>
<td>2,802</td>
</tr>
<tr>
<td>Population density [cap/km²]</td>
<td></td>
<td>45</td>
<td>24</td>
<td>60</td>
<td>149</td>
<td>12</td>
<td>12</td>
<td>140</td>
<td>19</td>
<td>17</td>
</tr>
<tr>
<td>Regime-related metabolic profile</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Share of agricultural population [%]</td>
<td></td>
<td>42</td>
<td>8</td>
<td>52</td>
<td>9</td>
<td>2</td>
<td>14</td>
<td>56</td>
<td>19</td>
<td>52</td>
</tr>
<tr>
<td>Share of biomass of DEC [%]</td>
<td></td>
<td>36</td>
<td>21</td>
<td>55</td>
<td>20</td>
<td>22</td>
<td>20</td>
<td>53</td>
<td>68</td>
<td>49</td>
</tr>
<tr>
<td>Energy use (DEC)/capita [GJ/cap/yr]</td>
<td></td>
<td>102</td>
<td>253</td>
<td>59</td>
<td>190</td>
<td>443</td>
<td>192</td>
<td>49</td>
<td>131</td>
<td>76</td>
</tr>
<tr>
<td>Material use (DMC)/capita [t/cap/yr]</td>
<td></td>
<td>10</td>
<td>19</td>
<td>7</td>
<td>15</td>
<td>29</td>
<td>14</td>
<td>6</td>
<td>15</td>
<td>6</td>
</tr>
<tr>
<td>Additional sociometabolic parameters</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cement consumption/capita [kg/cap/yr]</td>
<td></td>
<td>266</td>
<td>421</td>
<td>221</td>
<td>529</td>
<td>400</td>
<td>169</td>
<td>234</td>
<td>211</td>
<td>141</td>
</tr>
<tr>
<td>Iron consumption/capita [kg/cap/yr]</td>
<td></td>
<td>137</td>
<td>396</td>
<td>62</td>
<td>440</td>
<td>468</td>
<td>197</td>
<td>61</td>
<td>109</td>
<td>42</td>
</tr>
<tr>
<td>Animal-based food/capita [GJ/cap/yr]</td>
<td></td>
<td>0.70</td>
<td>1.29</td>
<td>0.53</td>
<td>1.28</td>
<td>1.58</td>
<td>0.99</td>
<td>0.52</td>
<td>0.87</td>
<td>0.31</td>
</tr>
<tr>
<td>Electricity/capita [GJ/cap/yr]</td>
<td></td>
<td>9</td>
<td>29</td>
<td>3</td>
<td>22</td>
<td>52</td>
<td>20</td>
<td>3</td>
<td>7</td>
<td>4</td>
</tr>
<tr>
<td>Metabolic pressures on the environment</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Energy use (DEC)/area [GJ/ha/yr]</td>
<td></td>
<td>46</td>
<td>62</td>
<td>35</td>
<td>284</td>
<td>54</td>
<td>24</td>
<td>69</td>
<td>25</td>
<td>13</td>
</tr>
<tr>
<td>Material use (DMC)/area [t/ha/yr]</td>
<td></td>
<td>4.4</td>
<td>4.6</td>
<td>4.3</td>
<td>23.1</td>
<td>3.6</td>
<td>1.7</td>
<td>9.0</td>
<td>2.9</td>
<td>1.1</td>
</tr>
</tbody>
</table>

Note: Data are from our own calculations; see Supplementary Material on the Web (www.blackwellpublishing.com/JIE) for a complete list of countries, details on data sources, and accounting principles. Extensive variables are presented in supplementary table S3 on the Web. All described indicators are available on a country-by-country basis for 175 countries and can be downloaded from our Web site (www.uni-klu.ac.at/socec/inhalt/1088.htm). HDI = high-density industrialized; LDI-NW = low-density industrialized—New World; LDI-OW = low-density industrialized—Old World; HDD = high-density developing; LDD-NW = low-density developing—New World; LDD-OW = low-density developing—Old World; GDP = gross domestic product; DEC = domestic energy consumption; DMC = domestic material consumption.
Table 4 Net trade with biomass, minerals, and fossil fuels of country clusters. Net imports: positive values; net exports: negative values

<table>
<thead>
<tr>
<th>Country Cluster</th>
<th>Biomass [million t]</th>
<th>Fossils [million t]</th>
<th>Ores and minerals [million t]</th>
</tr>
</thead>
<tbody>
<tr>
<td>HDI-NW</td>
<td>215</td>
<td>1,561</td>
<td>411</td>
</tr>
<tr>
<td>LDI-NW</td>
<td>-220</td>
<td>268</td>
<td>-89</td>
</tr>
<tr>
<td>LDI-OW</td>
<td>-53</td>
<td>-491</td>
<td>-165</td>
</tr>
<tr>
<td>HDD</td>
<td>87</td>
<td>-367</td>
<td>107</td>
</tr>
<tr>
<td>LDD-NW</td>
<td>-80</td>
<td>-184</td>
<td>-211</td>
</tr>
<tr>
<td>LDD-OW</td>
<td>43</td>
<td>-955</td>
<td>-40</td>
</tr>
</tbody>
</table>

Sources: FAO (2005), IEA (2004), and UN (2006).

Note: The absolute value of all net imports and net exports on the global level should be equal (global net trade is zero). Occurring differences are due to flaws in bilateral trade matrices. HDI = high-density industrialized; LDI-NW = low-density industrialized—New World; LDI-OW = low-density industrialized—Old World; HDD = high-density developing; LDD-NW = low-density developing—New World; LDD-OW = low-density developing—Old World.

a material standard of living similar to that of the LDI-NW, per capita material and energy use of this cluster is significantly lower. In addition, DEC and DMC per unit of area are by far the highest on the globe: 284 GJ of primary energy and 23 t of materials are used per hectare and year in this cluster (see table 3). From this perspective, it is not surprising that the countries in this cluster undertake considerable efforts to increase the efficiency of their material and energy use and recycling as well as their use of renewable resources. The metabolic profile of this group of countries is that of an advanced industrial economy with high population density. The HDI countries consume a quarter of the world’s annual energy and a fifth of its material supply (see figure 2).

LDI-OW

This cluster is dominated by countries of the former Soviet Union but also includes the advanced Scandinavian economies. The successor states of the USSR are a special case and combine characteristics of both high-density (European Russia) and low-density (Asian territories) industrial core countries as well as developing countries. In terms of their history of agricultural colonization, there are some similarities with the New World countries: Agriculture gradually extended into the vast hinterlands of European Russia only in the 20th century, with the expansion of railroads and irrigation. The region experienced a process of rapid industrialization during the 20th century under the political and economic conditions of communism and a planned economy. In the 1980s, however, the region experienced severe crises and economic decline, which resulted in the political collapse of the system. By the year 2000, this once-advanced region was still suffering from an economic breakdown while also experiencing a thrust of economic growth. This is reflected in a mix of characteristics of both industrial and developing countries. The natural resources, experienced rapid industrialization in the late 19th and early 20th centuries and are among the most advanced economies, with a high material standard of living. The average per capita income is by far the highest on the globe. Covering one fifth of the global land area, this cluster comprises just 6% of the global population but produces one third of the global GDP (see figure 2). The per capita levels of DMC and DEC are by far the highest of the six country clusters, and all other material and energy use variables are also in the high range. Due to the low population density (only 12 persons/km²), however, DMC and DEC per unit of area are low. The New World countries are further characterized by high availability of natural resources and extensive wilderness areas (35% of land area) and provide the global economy with large amounts of biomass and minerals/ores (respectively, 61% and 18% of total net exports; see table 4). Despite a domestic use of biomass in the high range (7.3 t/cap/yr), the share of biomass in DEC amounts to only 22%.

LDI-NW

This cluster consists of industrialized economies of North America, Australia, and New Zealand. In America, after their arrival in the 15th century, European settlers decimated the aboriginal population, pushed it back to marginal regions, and introduced new modes of production and land use systems. The New World economies, endowed with abundant
LDI-OW countries feature a large heavy industry sector and highly industrialized agriculture. The per capita level of material and energy use is considerable and only slightly lower than that of the HDI cluster, and the share of biomass in DEC is extremely low. Income, however, is in the lower range (which of course does not hold true for the Scandinavian countries), and the proportion of the population engaged in agriculture is comparatively high. The region is sparsely populated and, similar to the LDI-NW cluster, controls large deposits of natural resources. One fifth of its land area is considered to be wilderness. The LDI-OW cluster provides important raw materials for the world economy and accounts for 15% of the net exports of biomass, 23% of fossil fuels, and 33% of minerals (see table 4). The LDI-OW cluster is the only one for which the UN population estimate assumes a significant decline (17%) in population by 2050.

HDD
This is the largest group of countries and covers most of South and East Asia (including the large economies of India and China) but also Central America and some African countries. Most of these countries share a long history of continuous agrarian colonization, but the cluster still comprises a very heterogeneous group of countries, including many of the least developed as well as rapidly industrializing economies.

On 20% of the global land area, this cluster is home to almost two thirds of the world population but produces only 11% of the global GDP (see figure 2). It contains the world’s most densely populated and poorest countries. Average per capita GDP amounts to less than US$3,000; however, economic growth rates are high in some rapidly industrializing countries, such as China. The per capita levels of DMC and DEC are the lowest in the world, the share of biomass in DEC amounts to 53%, and 56% of the population is engaged in agriculture (see table 3). Despite this low level of per capita material and energy use, high population density is responsible for comparatively high levels of DMC and DEC per unit of area. Some of the most densely populated regions in this cluster appear to be close to the limits of the productive and absorptive capacity of their ecosystems. This cluster depends on considerable
net imports of biomass but provides almost one fifth of total net exports of fossil fuels (this is due to a few important fossil fuel–exporting countries, e.g., Iraq, Kuwait, Nigeria, Mexico, and Indonesia). Overall, the metabolic pattern of this country cluster is much closer to the agrarian regime than to the industrial regime. Due to its large population, however, it consumes 30% of the global energy supply and 42% of the global material supply, despite low per capita flows (see figure 2). The population of the HDD cluster is expected to grow by 50% by 2050.

**Low-Density Developing New World Countries (LDD-NW)**
This cluster includes Latin America (except for Central America) and some Oceanic countries. Similar to the LDI-NW cluster, European settlers largely replaced traditional societies and their modes of subsistence in the centuries after their arrival. These countries are sparsely populated, with a high level of natural resource extraction. The LDD-NW cluster, like the LDI-OW region, appears as a net exporter of all three material groups. It contributes 22% of total global net exports of biomass, 42% of minerals, and 8% of fossil fuels (see table 4). The cluster contains some rapidly industrializing economies (Brazil, Argentina), and the average income is considerable, although still significantly below the level of the fully industrialized clusters. This is also reflected in the metabolic profile, which appears to be somewhere between that of an agrarian and an industrial sociometabolic regime. The levels of DMC and DEC per capita are comparatively high, and the share of agricultural population is low (see table 3). Nonetheless, the consumption of electricity, iron, and cement is substantially lower than in the industrial core regions, and the share of biomass in DEC is high. Here we assume raw material and energy-intensive processes externalized from industrial countries to occur. Due to the low population density, material and energy use per unit of area are rather low.

**Low-Density Developing Old World Countries (LDD-OW)**
This is a very heterogeneous group of countries, including many of the oil- and gas-exporting North African and Middle Eastern countries but also sparsely populated and poor countries in Central and Southern Africa as well as a few Asian countries. In terms of area, it is the largest cluster, occupying 24% of the world’s land area; however, almost a third consists of uninhabitable desert. Population density is low (17 persons/km$^2$) but expected to grow by 130% by 2050 (UN 2006). This is one of the three clusters depending on net imports of biomass (see table 4). Together with the HDD cluster, this group shows the lowest level of income, although it provides more than half of the world’s total net exports of fossil fuels. The metabolic profile of this cluster is characterized by a very low level of material and energy consumption, a high share of agricultural population, and a high proportion of biomass in DEC. Per capita consumptions of cement, iron, electricity, and animal products are among the very lowest on the globe. The low levels of per capita consumption and low population density result in extremely low material and energy flows per unit of land area (see table 3).

**The Global Sociometabolic Transition, and Where It May Lead**
Quite similar to the spatial patterns of the Old World industrialization process in the 19th century, a patchwork of coexisting features of the agrarian and the industrial sociometabolic regimes can currently be observed. The global economy is in a transition in which industrial core regions and industrial centers in the developing countries are interlinked by fossil fuel–powered infrastructure, transport, and communication networks, with large populations in non-industrialized regions still embedded in the traditional agrarian matrix.

Of course, in a globalized economy, information and technology diffusion penetrate even the most remote socioeconomic systems, with some features typical for the industrial regime, such as modern transport networks, agricultural technology, electricity supply, or energy- and material-intensive consumer goods—or their images, at least. Therefore, it is very surprising how large a part of the world displays a more or less agrarian metabolic pattern. In particular, the LDD-OW and HDD clusters are characterized by very low
levels of material and energy consumption. Their energy system is still largely based on biomass, a majority of the population is engaged in agriculture, and the per capita use of key physical industrial resources, such as electricity and iron, is extremely low.

If the metabolic transition hypothesis holds true, then these regions are on their way to a per capita material input three to five times higher than now, up to the level typical for the industrial regime. Population growth will further contribute to physical growth in these regions. The current UN population scenarios expect a 60% population growth by 2050 in the three nonindustrialized clusters. A simple extrapolation exercise demonstrates the potential impact of this process on global material and energy flows (see Supplementary table S4 on the Web). Let us assume that both LDI-NW and HDI manage to reduce their per capita throughput by 30% due to efficiency improvements. Let us further assume that industrialization in the other clusters will raise their per capita DMC and DEC to this level (i.e., the densely populated HDD countries will increase their resource use to the new level of the Old World industrial core, and all others will increase to the new level of the sparsely populated New World industrial core). In combination with the expected population growth (8.5 billion by 2050), this would boost global energy use by 360% and material use by 310%. In this fully industrialized world, the share of the three former developing clusters would be twice what it is now and amount to roughly 80% of world energy and materials use. In densely populated countries, such as India, material use per unit of area would grow to 50 t/ha, implying an increase in environmental pressure unprecedented worldwide.

How far does the historical parallel carry, and where does it end? Unfortunately, it carries us further than we would like it to. A significant number of developing countries seem to be on a path resembling the industrial transformation process that today’s industrial core ran through. China, like several Southeast Asian and Latin American economies, is a good example for this. The pathway of rapid industrialization is largely coal powered and characterized by energy-, material-, and labor-intensive heavy industries. Large infrastructure and physical stocks are being built up, and mobility is growing, initially supported by public transport networks and increasingly by automobiles. Rising income triggers the consumption of energy- and material-intensive goods and services. From a world history perspective, it is, of course, fair that these countries should have the opportunity to catch up and provide their populations with a material standard of living others have enjoyed for decades.

Nonetheless, the preconditions are different than what they used to be in the first and second waves of industrialization. There is no wilderness frontier, no new worlds to be conquered anymore; fossil fuel energy supplies are running low and becoming more expensive. This characterizes the system environment for all developing countries today, even though the options and development paths within the three developing clusters vary considerably.

For the largest cluster, the HDD, there is one more condition that will compel countries to seek an alternative pathway: Their population density is already, after a long history of agrarian civilization, higher than that of the Old World industrial core after a hundred years or more of industrial development. A replication of the historical material- and energy-intensive dirty pathway could quickly lead to local and regional disaster. Politically, countries such as China have realized some of this and promote a “circular economy” approach to resource use. But to understand the full breadth of the problem, a sociometabolic perspective is required. The only adequate response to the dimension of the problem is a worldwide effort to invent, to design, and to experiment with infrastructures, renewable resources, and new technologies for a novel industrial transformation, a transformation that does not build human communication, creativity, and happiness upon gigatonnes and megajoules.

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Wiesinger for statistical support. We also would like to acknowledge the critical comments of three anonymous reviewers, which have greatly helped to improve the article.

Notes

1. One gigajoule (GJ) = 10^9 joules (J, SI) ≈ 2.39 × 10^3 kilocalories (kcal) ≈ 9.48 × 10^3 British Thermal Units (BTUs). One tonne (t) = 10^3 kilograms (kg, SI) ≈ 1.102 short ton. Unless otherwise noted, metric tons are used throughout this article. One square kilometer (km^2, SI) = 100 hectares (ha) ≈ 0.386 square miles ≈ 247 acres.

2. The indicator DMC measures the apparent consumption (i.e., the sum of domestic extraction and imports minus exports) of all types of biomass, industrial minerals and ores, construction materials, and fossil energy carriers (Weisz et al. 2006). The indicator DEC measures the apparent consumption of primary energy and is conceptually equivalent to the indicator total primary energy supply (TPES) used in energy statistics. DEC includes not only technical energy carriers such as coal, mineral oil, natural gas, wood fuel, nuclear heat, and hydropower but also all types of biomass harvested by humans or their livestock (Haberl, 2001). DEC also includes biomass of fossil fuels for nonenergy use. The terms material use and energy use are used synonymously for DMC and DEC. For more details, see the Supplementary Material on the Web.

3. In previous publications (e.g., Krausmann et al. 2008b; Fischer-Kowalski and Haberl 2007b) we have used the term socioecological regimes. In accordance with Sieferle and colleagues (2006) we have switched in this article to the more precise notion of sociometabolic regimes to avoid confusion with the concept of socioecological systems/regions as it is used by others (e.g., the resilience alliance; see the work by Gunderson and Holling [2002], who draw a much finer distinctions between regimes).

4. Biogeographic factors do not influence the basic character of a regime and its metabolic profile, but they are relevant for the metabolic characteristics of subtypes of regimes and their specific development paths. For the regime of hunters and gatherers and the agrarian regime, climatic conditions and soil quality are the most significant biogeographical factors. They constrain available energy density, the appropriate modes of production (land use systems), and, ultimately, the sustainable population density. In the extreme, adverse climate or soil conditions may prevent agriculture altogether. On a local level, other biogeographical factors can come into play that may codetermine the metabolic profile of agrarian societies; these include access to water, endowment with mineral resources, and the possibility of water transport (e.g., rivers, coastline). Biogeographical factors, in particular the local endowment with accessible coal and ore deposits and water transport, were important prerequisites for the kick-off of the agrarian–industrial regime transition in 18th-century England (cf. Wrigley 1988; Pomeranz 2000; Sieferle et al. 2006). Under the present conditions of a globalized economy, biogeographic factors are of less significance for the overall metabolic characteristics of industrial economies. But even in industrial societies, patterns of natural resource endowment can be related to exceptionally high levels of apparent per capita consumption of certain materials, whereas extreme climatic conditions contribute to, for example, high per capita energy consumption for heating and cooling (cf. Haberl et al. 2006; Weisz et al. 2006; Krausmann et al. 2008b).

5. See also the exergy-growth hypothesis (Ayres and Warr 2005).

6. One hectare (ha) = 0.01 square kilometers (km^2, SI) ≈ 0.00386 square miles ≈ 2.47 acres.

7. The per capita level of biomass use (and therefore of DEC) in agrarian regimes is largely determined by the significance of livestock: Keeping livestock for the provision of draft power, nutrient management, or milk production requires large amounts of feed and litter. In European land use systems, where livestock is of key importance, more than 80% of all agricultural biomass is used in the livestock subsystem. The more livestock there are per capita, the higher is the level of biomass use per capita and, consequently, DEC. The highest level of DEC per capita, therefore, occurs where area-intensive herding is linked to very low population density and low primary energy consumption per area. Contrary, DEC 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 (Hayami and Ruttan 1985; Krausmann, Erb, et al. 2008a).

8. One should not assume, though, that there is only a single development path within the agrarian regime. Depending on climatic and topographic conditions, we can recognize, on the one hand, a development toward multicropping and abolishment of animals in the tropics; in temperate, rainfed regions, animals maintain their
relevance for farm labor and fertilizer management in mixed farming systems, and multicropping is not an option. In arid or alpine regions, finally, communities use land optimally by keeping livestock only and leading a nomadic existence. Thus, “maturing” within the agrarian regime may follow different pathways leading to fairly different metabolic profiles (cf. Hayami and Ruttan 1985; Netting 1993; Mazoyer et al. 2006).

9. As with the agrarian regime, there is not simply one development pathway within the industrial regime. On the one hand, industrial economies with low population density have high levels of material and energy use, whereas, on the other hand, densely populated countries are at the lower range. Among other factors, this probably relates to the necessary size of 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 the existence and availability of primary resources (e.g., mining, agriculture) make a difference (see Weisz et al. 2006).

10. The world average population density of 45 persons/km² is rather atypical for individual countries: The density distribution is fairly polarized, with a large cluster (3.5 billion people in 39 countries) on the high-density side (more than 120 persons/km²) and a large number of countries (51 with 1.2 billion inhabitants) with very low population densities (fewer than 30 persons/km²).

11. Data on the share of wilderness of total area were derived from a publication by Erb and colleagues 2007 (based on Sanderson et al. 2002).

References


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Supplementary Material

The following supplementary material is available for this article:

Appendix: The global dataset: Sources, accounting principles and derived indicators.

This material is available as part of the online article from http://www.blackwellpublishing.com/doi/abs/10.1111/j.1530-9290.2008.00065.x (this link will take you to the article abstract).

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