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A sociometabolic reading of the Anthropocene: Modes of subsistence, population size and human impact on Earth

Marina Fischer-Kowalski, Fridolin Krausmann and Irene Pallua

Abstract

We search for a valid and quantifiable description of how and when humans acquired the ability to dominate major features of the Earth System. While common approaches seek to quantify the human impact upon the carbon cycle by identifying the area of land cleared by humans, our point of departure is different human modes of subsistence, and we base our analysis on their social metabolism, in particular their energy metabolism. As a starting point, we use Ehrlich's classical IPAT formula, and give it a specific interpretation: human impact on Earth = population size × affluence (interpreted as energy available per person) × technology – for each mode of subsistence. The overall impact (or rather human pressure) then equals the composite sum of these. We qualitatively describe the functional characteristics of hunter gatherers, agrarian and industrial modes of subsistence such as population dynamics, energy regime and the technologies by which they interact with their environment. In a 'toy' model, we translate these considerations into global numbers for the past millennia: we estimate the respective population sizes and affluence (energy), and finally also technology concerning its impact on the carbon cycle. We see a major historical dividing line around AD 1500: until then, human population growth and metabolic rates carry about equal weight in increasing human pressure on the environment approximately fivefold from the year AD 1 onwards. From then on, the overall pressure of humanity upon the Earth increases by one order of magnitude; energy intensity contributes to this rise by roughly tripling the impact of population growth. Technology, because it is based upon a shift from biomass to fossil fuels (and other 'modern' energy carriers), does not moderate this impact, but enhances it by a factor of 1.5.

Keywords

CO_2 emissions, energy regime, human impact, industrial transformation, IPAT, land use, social metabolism

Institute of Social Ecology, Alpen-Adria-Universität, Austria

Corresponding author:
Marina Fischer-Kowalski, Institute of Social Ecology, Alpen-Adria-Universität, Schottenfeldgasse 29, A-1070 Wien, Austria.
Email: marina.fischer-kowalski@aau.at

Introduction

The 'Anthropocene' is defined by the observation that humanity has become a planetary force, on a par with the geological or climatic forces used to define phases of Earth history. There is ongoing debate regarding the date when the species *Homo sapiens sapiens* began to generate such severe impacts upon Earth that it appears justified to introduce a new geological epoch. Three periods of transformation have come under consideration.

1. The transition from humans as hunters and gatherers to humans as agriculturalists (the so-called Neolithic revolution) initially in the 'Fertile Crescent' some 12,000 years ago and springing up in most other parts the world during the following millennia (Kaplan et al., 2009; Ruddiman, 2003).
2. The industrial transformation, or rather the time when the industrial era gained strength on a global scale, dated by Crutzen and Stoermer (2000: 17) to the 'latter part of the 18th century'.
3. An additional discontinuity is characterized as the 'Great Acceleration' (Steffen et al., 2007), to denote the process of rapid global growth after World War II.

With regard to timing, the scientific traditions of geology differ from those in the social and historical sciences. While the first basically deal with planetary phenomena and distinguish Eras or Epochs by the global predominance of certain organisms or processes, historians (even the small group that is concerned with 'global' or 'universal' history such as Sieferle (2003a), Pomeranz (2000) or Simmons (2008)), usually operate on a much smaller grid, both temporarily and regionally. While almost all world regions experienced Neolithic revolutions, these occurred at times thousands of years apart. While, by now, all world regions have experienced an industrial transformation, these transformations started hundreds of years apart. We need a conceptual bridge between these traditions in order to identify the point when a certain mode of human operations began to dominate development at the global scale. Here, we also wish to question the notion that such a date should be determined by particular observable environmental impacts of the mode of human operation, as for example Ruddiman (2003, 2013) argues. Different environmental impacts of anthropogenic operations may occur with variable delays.[1]

In this paper we focus on the socioeconomic aspects of defining the Anthropocene and investigate the interaction of the major drivers behind the observed environmental impacts, in particular population, its resource use patterns (or social metabolism) and technology. We try to identify modes of human subsistence distinct enough to cause substantially different pressures upon the environment, and to identify the size of the populations that lived by these modes of subsistence through time. From this perspective we aim to contribute to a valid and quantifiable description of how and when humans acquire the ability to dominate major features of the Earth System.

We will take as our point of departure the classical formula of Ehrlich (1968) and Ehrlich and Ehrlich (1991):

$$I = P * A * T \tag{1}$$

where *I* is environmental impact (or rather: pressure upon the environment), *P* is human population numbers, *A* is the affluence this human population enjoys, and *T* represents the technologies by which it interacts with the environment and achieves the affluence it enjoys. In our analysis, we will give these variables a more specific interpretation.

First, we do not assume a homogenous human population, but a population differentiated into modes of subsistence, or, as we explain below, into *sociometabolic regimes*. Affluence we interpret as the metabolic rate, i.e. the average energy (and material) input into the respective socioeconomic system per individual per year. This metabolic rate must at least suffice to keep the individual alive and allow for its biological reproduction, that is it must cover the basic needs of the human organism, or else this segment of the population will die. But there can be much more affluence: average metabolic rates in certain regimes exceed the basic metabolism of humans by orders of magnitude (see Figure 3). Finally, *T* (technology) is supposed to be the coefficient by which one unit of affluence measured as material or energy use translates into a specific environmental pressure; the same amount of food, for example, may translate into widely differing areas of deforested land and greenhouse gas emissions (GHG emissions), depending on how it is produced.

We leave open what *I* (impact/pressure) may encompass – whatever we wish to measure, such as, for example, GHG emissions or biodiversity loss, are candidates for testing the validity of the results on the right-hand side of the equation.

Thus, the whole equation becomes more complex, minimally

$$I_t = P_{1t} * A_{1t} * T_{1t} + P_{2t} * A_{2t} * T_{2t} + \ldots, \quad (2)$$

where the index *t* is the point in time and the numerical index denotes the mode of subsistence (sociometabolic regime).

The full program of such an analysis, of which we can only show examples here, would allow parameterization of the environmental characteristics of sociometabolic regimes, and their coexistence and succession over time throughout human history.

In the next section we review human modes of subsistence, discuss their basic features in terms of population dynamics, affluence and the technologies they employ with reference to their environmental impact, and describe the process of transition between them. The following section then documents our efforts at quantifying these features of sociometabolic regimes in what we call a ‘toy model’ for human impact on Earth across the last two millennia. We then go on to discuss the model findings with regard to the size of human impact on Earth and the issue of dating the start of the Anthropocene, but also with regard to the future course of human history and its sustainability.

Sociometabolic regimes in human history

There is a long tradition in the social and historical sciences of distinguishing between qualitatively different modes of societal organization, modes of subsistence (in anthropology), modes of production (Marx, 2010; Smith, 1776) or stages of civilization (Spencer, 1862). The distinctions drawn, and the criteria upon which they are drawn, vary – but only rarely have they been related to society–environment relations or to the environmental consequences of human activity.

It was the special achievement of RP Sieferle (1997, 2001a) to regard the modes of societal organization not simply as socially or socio-economically distinct, but to systematize them so that they can be characterized as socioecological patterns, comprising social organization (in the widest sense of the word) and related modifications of the environment, through intended or unintended environmental impacts. Key to the distinctions Sieferle draws is the source of energy and the dominant energy conversion technology used by society. The attraction of this classification is that it increases our understanding of the differences in functional problems faced by societies when trying to establish and maintain themselves within their environment, the evolutionary advantages and drawbacks that occur and therefore, also the directionality of change.[2]

Sieferle distinguishes between the hunting and gathering mode, the agrarian mode (with some subdivisions) and the industrial mode. The energy system of hunters and gatherers is ‘passive solar energy utilization’. Hunter gatherers live on the products of recent photosynthesis (plants and animals for their food, firewood for heat). That they use fire to cook (rather grill) their food widens the spectrum of edibles – but still, only a very small fraction of their environment qualifies as food. Its collection requires mobility, both on an everyday basis and seasonally, and allows only for very low population densities. The agrarian mode, in contrast, offspring of the Neolithic revolution that occurred, at different times, on all continents but Australia, is based upon ‘active solar energy utilization’. This means that land is cleared of its natural vegetation and solar energy is as far as possible monopolized for human food plants. In effect, this leads to extensive deforestation of the Earth (and the enrichment of the atmosphere with the CO_2 that previously had been stored in trees and soils), to a sedentary way of life, and to a large human labour burden that even increases with progress in technologies designed to raise returns from the land (Boserup, 1965, 1981). The sedentary way of life (plus milk from livestock and ceramics to boil liquids) allows for a much higher fertility, and the large labour burden motivates the raising of children to share the labour. Thus higher population growth creates higher population densities and an expansion of the agrarian mode across the world. Control of territory, tools, livestock and stored reserves is essential, and frequent territorial conflicts bring forward specialised classes of people to defend and attack territories, social hierarchies to control them, and urban centres. In many parts of the world, these systems developed into major empires and civilizations that subsequently collapse (Diamond, 2005; Tainter, 1988).

In the 16th century a new energy regime emerged, a fossil-fuel-based energy system that supplied society with an amount of energy never accessible before. In the UK, the use of coal instead of increasingly scarce fuel wood allowed a process of urban growth; and manufacture, textile production for export became very profitable, and sheep gradually crowded out farmers growing food. The invention of the steam engine finally kicked off what is known as industrialization. This turn of history in Europe (‘The European Special Course’; Sieferle, 2001a) could, as some argue, also have happened in the East (Pomeranz, 2000; Sieferle, 2003b), or maybe could not have happened at all. It caused large-scale ecological and social transformations and continues to spread from the industrial core countries (currently comprising about 20% of the world population) to the much larger rest of the world, at an accelerating speed (Fischer-Kowalski and Haberl, 2007; Krausmann et al., 2009). It remains an open question whether the final exhaustion of fossil fuels, a detrimental transformation of the Earth’s climate system, or politically guided change will bring this energy regime to a close. In any event, this industrial regime will have been sustained for a much shorter period than the previous regimes.

As should be apparent from the description of sociometabolic regimes, not only their defining parameters but also their dynamics are very different.

The hunting and gathering mode

For the passive solar energy utilization strategy employed by hunter gatherers, two basic technologies need to be considered.

The first is universal for humankind and of great importance: the preparation of food with the help of fire. As Wrangham (2009) shows, cooking (or rather, grilling) food by fire allows not only the digestion of some feedstuff that would otherwise not be digestible or would be poisonous, it also saves on endosomatic energy in digestion, at the expense of exosomatic energy use (fuel wood). This efficiency increase is an evolutionary advantage over other omnivorous animals, as humans can sustain themselves on a smaller food intake (and correspondingly on a smaller territory) than competitors. There are also substantial side effects of this technology highly relevant for human cultural evolution. Food is not eaten by each individual where it is found, but collected through a division of labour and brought back to a shared fireplace. This reinforces social cohesion and stimulates communication and the evolution of languages. In terms of environmental effects, this technology saves on impacts as it allows the use of low quality energy sources (firewood) for high quality food sources (thus less meat and high quality vegetable foods are required).

The second class of relevant technologies is hunting gear. Sieferle (1997: 40f) argues convincingly that technological innovations that make hunting more successful (than by, say, spears and bows and arrows) would have had a tendency to be self-defeating: they would have speeded up the depletion of the preferred prey animals and forced the community into faster migration. If we follow this argument, then food collection technologies would have been more or less equivalent in terms of most environmental pressures, with one exception: the use of fire as a pressure upon biodiversity. Firing vegetation to drive large herbivores over cliffs, for example, would have killed more animals and destroyed more biomass than could be eaten and thus represent a very wasteful technology.[3] If species extinction and biodiversity loss are the environmental impacts we wish to consider, this technology gains special weight. It is known for some regions that apparently large-scale vegetation fires have been employed by hunter gatherers; for other regions, this is not documented. If we focus on GHGs as the impact, we do not need in every case to give special weight to this technology, as vegetation regrowth would often compensate for the additional emissions.

In effect, we should not expect technology development among foragers to be very dynamic – quite the contrary. Thus we should not expect affluence – i.e. the energy and materials used per person and year – to be dynamic either. Paleoarchaeological records indicate that hunter gatherers had been relatively well nourished, on the basis of a mixed and variable diet. But their food and the firewood they needed is about all one has to consider in terms of metabolic rates. Because of their migratory lifestyles, foragers could not accumulate more personal belongings than they were able to easily carry with them and they did not build any durable infrastructures.

What about their population dynamics? Here again, we should expect only very low growth, of the order of less than 0.05% annually[4] in the long run. There are a number of arguments why this should be so. For example, the food intake of foragers provided very little fat (as wild animals typically are low on body fat, and most plant food, except for nuts, is also low in fat), and a chronic fat deficiency is known to reduce ovulation in women (Sieferle, 1990: 45). Foragers lacked containers that would allow boiling liquids over fire (such as ceramics), and thus babies fully depended on their mothers for lactation – again a factor contributing to lower fertility (and to reducing the survival chances of closely spaced siblings). On the other hand, children were important to secure the survival of the group, but there was little incentive to have the group growing; to have many children was a burden rather than an asset.

How should the transition to an agrarian or agro-pastoralist mode be envisaged? We may expect this transition to be a very slow process starting in favourable areas (such as river basins with secure water supply and rich soils, possibly well protected by mountains or deserts); in these areas, population density increased and permanent settlements were built. Foragers may have adopted elements of simple types of cultivation to support their food supply in these regions. Those that remained foragers who used to inhabit the same territory were gradually driven towards the less productive peripheries; in conflicts, they may have succeeded in raids but had little chance in the long run to win against the much more populous and maybe also increasingly fortified settlers.

Thus, in favourable environments, the agrarian mode had an inherent evolutionary advantage over foraging; social change moved slowly, but only in one direction,[5] and foraging was gradually extinguished by the advance of pastoralism and agriculture.[6] The respective population may have been partly assimilated to the new mode and partly driven into decline.[7]

The agrarian mode

As explained above, the 'active solar energy use' (Sieferle, 2003a) of the agrarian mode consists of manipulating terrestrial ecosystems so that they provide a higher return of those kinds of biomass humans wish to use in their social metabolism. Humans begin to control key parameters of ecosystems such as vegetation cover, elements of the water and nutrient cycles, and, by this, create colonized areas in which they concentrate solar energy for the photosynthesis of plants they desire.

The technologies to be considered are manifold and we refer to them here only at the most general and abstract level. First, agrarian populations share with foragers the technology of food preparation with the help of fire, but by creating fireproof containers they also become able to cook soups and broths. This widens the spectrum of plants used for human consumption, of food essential for smaller children and maybe also the elderly. Second, they convert forested land into land suitable for cultivation and thereby have a substantial impact on the carbon cycle. If the release of accumulated carbon stocks in vegetation and soil is considered as a component of I (environmental pressure/impact), this technology enhances the impact beyond the amount to be derived from metabolic rates alone.

Third, they keep domesticated animals as sources of labour and food and as a means of making extensive use of vast land areas. Keeping livestock has a massive impact on metabolic rates as the nutrition of these animals boosts socioeconomic biomass use. Further, the disease vectors of these animals, enhanced by increased density, impact on the health of humans as well as on wild species. Fourth, they deliberately intervene in the evolution of plants and animals by selectively favouring species variants more appropriate for human use, and by seeking to eradicate food competitors. This enhances the impact on biodiversity loss beyond the pressures resulting from metabolic rates and land conversion; some gain in biodiversity may also arise. Fifth, they create solid, built structures, first only houses and paths but increasingly also roads, ships, bridges, dams, urban settlements and protective walls around them and the like. All these not only require substantial amounts of materials (wood, stones, sand) and energy (thus raising metabolic rates), but they also destroy habitats and open ways for fast transportation and trade across large distances.

Sixth, they mine for minerals and metals. This constitutes a novel (if still small) compartment within the metabolic profile, and opens a huge spectrum of opportunities for human activities, among them the development of more effective weapons and of coins that function as an economic representation of value. If there is a focus on the toxicological impacts of social metabolism, metallurgy needs to be considered as an enhancer of impact. And finally, agrarian populations slowly but continuously advance their technologies to intensify their use of land, becoming able to nourish more people on ever-smaller areas, often at the expense of more human labour which substitutes for ecosystem services (Boserup, 1981). If considering the amount of land used agriculturally as an environmental impact, this technological change is beneficial, by alleviating impacts as it reduces land conversion and some of the consequences of a given metabolic rate and a growing population.

How should we regard the affluence variable within agrarian societies? Findings from historical reconstructions of biomass use (e.g. Cussó et al., 2006; Krausmann, 2004), from anthropological field studies (e.g. Coughenour et al., 1985) and from material flow studies of agrarian economies (e.g. Krausmann et al., 2008c) allow us to estimate the range of metabolic rates for the agrarian mode (see Figure 3). This range is quite wide in its extremes depending, to a large degree, on the ratio of livestock to humans. On average, metabolic rates in agrarian regimes are 3–4 times higher (both in terms of energy and in terms of materials) than those of hunter gatherers. Nevertheless, agrarian societies are energetically strongly constrained. The only major source of their affluence is land, and working the land requires population for labour. Small elites in agrarian societies may acquire additional riches by conquering and controlling larger territories (or engaging in non-agrarian trades). For the vast majority of the population, the expansion of territory may mean additional security from raids and foreign invasions, but it may also mean just the opposite, loss by continuous wars and civil strife. Elites may also increase their affluence by increasing the tax burdens on their subjects and tributaries, but also this strategy meets its limits at the subsistence boundary of those who do the agricultural work. Thus, we claim in effect that affluence (that is, average metabolic rates) in agrarian systems may rise initially when land and biomass are abundant but does not increase continuously and in the long run.

How is it possible that a technologically more dynamic mode of subsistence does not produce growing affluence for its members? The key answer to this question is population growth. As Boserup (1965, 1981) has convincingly shown, there is a trade-off of increasing area efficiency in agricultural systems: higher labour input and lower labour productivity.

In the agrarian sociometabolic regime, there is both an opportunity and a motive for high fertility. The opportunity derives from the sedentary mode of living that allows mothers to take care of a large number of children simultaneously and to feed small children also from sources other than breast milk, thus allowing for short child spacing. The motivation derives from an insatiable need for labour in agriculture, for both simple tasks that even small children easily can do (such as weeding, or looking after goats), and for heavy, physically demanding tasks that older people cannot do any more, and that require more mature children to take over.[8] In the cultural and religious systems of practically all agrarian societies, many children within marriage are usually considered a blessing, and methods for controlling their number (contraception techniques and abortion) are usually banned. At the same time, there are strong controls to prevent sexual relations and child birth outside of marriage. Another entry point for the cultural regulation of fertility is through prescriptive conventions concerning prerequisites for marriage. These may constitute economic limitations, (dowry requirements, requirements for the man to be able to support a family[9]) leading to the creation of substantial celibate population segments, and/or strictures linked to age (Grigg, 1980). So religious authorities and agrarian communities worldwide are clearly not interested in allowing for unsupported and landless children, but they do support high fertility within the confines of marriage and land tenure. An additional motivation for fertility may be security: a rural community, comprising an ethnic or religious subgroup, is stronger against outside attacks if it is larger, and has many young men to defend itself.

Thus the expansion of agricultural land and the intensified use of land both generate what ecological economics calls a ‘rebound effect’, feeding population growth and annihilating gains in affluence for the individual.

With regard to the components of our IPAT formula we therefore assume for the agrarian sociometabolic regime that there is, after an initial increase in metabolic rates from hunter gatherer levels (with the spread of livestock keeping), no substantial further growth and eventually even a slow decline of affluence over time. While metabolic rates remain largely constant, substantial population growth strains the boundary conditions of the agricultural mode (Malthusian hypothesis). With technologies, we assume there to be slow learning processes subject, on the one hand, to a rebound effect on population and, on the other hand, to the need to be differentiated according to the type of impact variable chosen.

How should the transition from the agrarian to the fossil-fuel-based sociometabolic regime be envisaged? In contrast to the Neolithic revolution that originates in many locations across millennia, the transition to fossil fuels originates in one region, Western Europe, in particular the UK (and also to some degree, the Netherlands) and spreads from there by processes of trade, technology transfer, imitation and economic domination across the world within centuries. The introduction of fossil fuels during the 16th century, peat in the Netherlands and then coal in the UK, first provided a highly valuable opportunity for urban growth. Urban growth, and with it the growth of manufacture, trade and other non-agricultural occupations, had been severely constrained, particularly in those two countries, by a lack of fuel wood. The removal of this constraint set in motion, or allowed for, scores of novel economic processes.[10] For the agrarian population in these countries, this offered mainly an opportunity to deliver their produce to larger urban markets and to migrate to the cities and seek employment.

The fossil-fuel-based industrial mode

If we date the beginnings of the industrial mode back to the beginnings of fossil fuel use for everyday subsistence, then we are back in the early 16th century – at least for the Netherlands and the UK.[11] By AD 1500, these two countries accounted for less than 2% of world population. This is where and when the fossil fuel energy subsidy to humanity started that would gradually enhance the human range of activity beyond anything ever possible before. Initially, peat and coal were used solely as a fuel for hearths in the households of manufacturing workers in growing urban centres, whose increasing requirements could no longer be supplied by fuel wood. The use of coal in the UK gained momentum with the redesign of houses so that coal could be used without suffocating the inhabitants (brick chimneys, iron stoves, see Allen, 2012); coal could be transported at low cost via waterways. Before even the invention of the steam engine by Newcomen in 1715, coal supplied already 20% of the UK's primary energy.[12] The use of steam engines finally enabled the conversion of heat into mechanical power; this not only introduced a positive feedback in coal mining (with the steam engine coal supplied mechanical power to pump out the water from coal mines and thus harvest ever more coal in ever deeper pits), it also revolutionized the transport system by railways (Grübler, 1998). The mechanical performance of coal-powered machines created conditions for large numbers of jobs in final manufacturing, and accelerated urban growth (see also Figure 1).

At the very core of the industrial mode there is an increase in affluence in the sociometabolic sense in which we use this term: affluence in energy. Before the technologies are developed that allow use of the additional energy source efficiently and for all kinds of purposes, there is a 250 year period of learning. By 1800, the primary energy available to the UK had increased fivefold, even by 50% per capita, despite substantial population growth. This signifies a doubling of metabolic rate over the previous agrarian level. In the earlier phase, there is mainly a build-up of production capacity and infrastructure with high environmental impact. Subsequently, owing to the intermediate phase of accelerated population growth, there follows a phase of only limited growth in average affluence per capita. This is followed by a later phase dominated by oil rather than coal (globally after World War II) leading to a strong growth in affluence. Across the whole sociometabolic regime up to a certain saturation in mature industrial countries, there is around a quadrupling of affluence over previous agrarian levels (Krausmann and Fischer-Kowalski, 2013; Krausmann et al., 2008a). This long-term change has been demonstrated by Wiedenhofer et al. (2013) for a number of now mature industrial countries, showing also that indeed there seems to have been a kind of saturation in metabolic rates in those economies from the 1970s onward (see also Gales

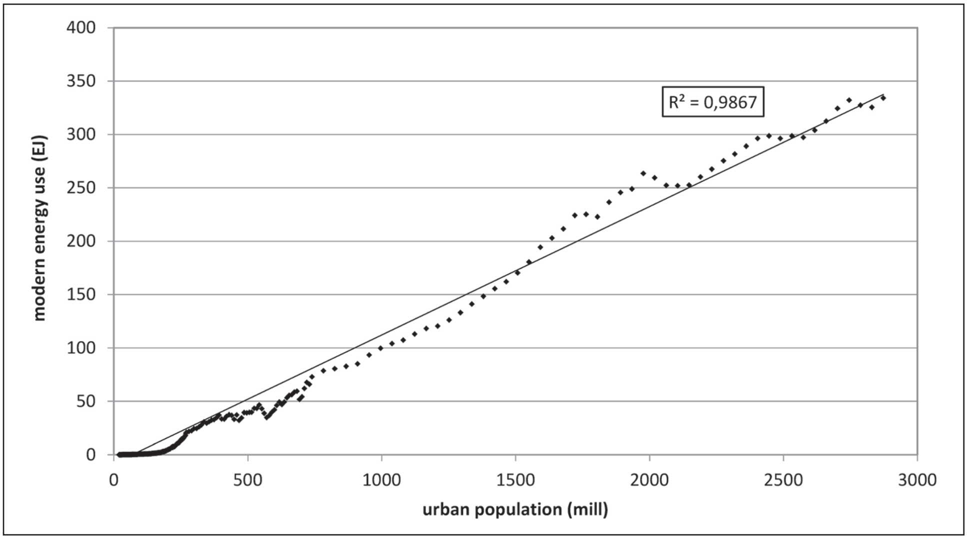

Figure 1. Global urban population numbers and global modern energy use (AD 1500–2000).
Sources: own calculation; urban population from Klein Goldewijk et al. (2010) (settlements with 2500 inhabitants or more); modern (primary) energy use includes fossil energy carriers such as peat, coal, petroleum and natural gas, hydropower and nuclear. Time series based on data compiled in Krausmann et al. (2009), Pallua (2013), Podobnik (2006). See also Figure S3, available online.

et al., 2007; Warr et al., 2010). While (slow) technological innovation in the agrarian regime feeds into population growth, in the industrial regime (fast) technological innovation feeds into affluence.

As far as population dynamics is concerned, a most dramatic transformation takes place that is commonly, but we think insufficiently, described by the term '(contemporary) demographic transition'. If we consider the full process of transformation up to the situation that dominates contemporary mature industrial countries, we see a demographic system of very low mortality rates, but even lower fertility, and a substantial prolongation of generation spacing (Lutz et al., 2004). In terms of biological reproduction, this is a system of negative population growth.

Functionally speaking, fertility decline comes about for good reasons. Under industrial conditions, from the perspective of parents the use-value of children is low: while they cost time and money and complicate the organization of daily life, of which the largest part is spent at a workplace away from home, they may provide comfort and emotional satisfaction – but these benefits can easily be reaped by one or two children. At the same time, parents can expect to be able to manage their (prolonged but healthier) old age on their own, and neither wish to nor can confidently rely on support from their children. This intergenerational setting is supported by the welfare state; if the welfare state should happen to break down, this would possibly again strengthen family ties, but it would simultaneously make children even more expensive for parents and shorten the life expectancy of the elderly: few families would be able to shoulder the high health expenditures that incur in late stages of a prolonged life. From the perspective of young people, there is no longer any barrier to enjoying a full sexual life without either marriage or pregnancy: both a technical and a moral decoupling of sex and childbearing has taken place. The educational career of young people, increasingly also of women,[13] takes up many years of reproductive age, and the start of a satisfactory job career, particularly for educated women, takes time, as does the search for an appropriate partner. In effect, many women begin their active reproduction towards the very end of their biological capacity, if at all.

Why, then, can it be that under conditions of a world dominated by fossil fuels and industrial development, we have had in the past decades, and still have on the global level, substantial population growth? The answer we give, derived from our theory of sociometabolic regimes, is the following: population numbers in the industrial sociometabolic regime do not increase by biological reproduction but by economic ‘development’, that is, a shift from the agrarian to the industrial regime that encompasses a larger and larger part of the global population – in urban industrial centres in developing countries, in large urban populations in emerging economies, and through immigration to fully industrialized countries. The cultural and demographic changes that go with the industrial regime may occur with some delay, while its benefits, such as medical assistance and long-distance food transport, reduce mortality also in the (co-existing) agrarian populations. Thus, in the past six decades, globally there has been both rapid population growth (culturally driven by the agrarian regime plus industrial technical assistance) and growth in affluence (driven by the fossil fuel regime). Both processes together make for a ‘great acceleration’ of impacts.

A toy model for populations and their affluence by mode of subsistence

As explained above, our point of departure is the IPAT model. Whatever environmental impact (I) we consider, we suppose it to be a function of population numbers (P), affluence (A) and a technology parameter (T) that tells us how this affluence is acquired. The main explanatory power lies in population numbers and affluence. For each sociometabolic regime, we can derive ‘affluence’ as a typical sociometabolic rate, technically speaking, as material or energy use per capita and year, from material and energy flow accounts and estimates provided in the literature (see Haberl et al., 2011; see Figure 3).[14] We believe that this parameter is a reasonably good indicator for a range of impacts. If there is a specific intervening variable between metabolic rate and a certain impact, this has to be captured by the T parameter in the equation. Of course, there is a range of variation and of uncertainty in metabolic rates within regimes. In those cases in which we see affluence within a metabolic regime as dynamic, we have to specify this dynamic. This we try to do in the following paragraphs; but the first task we have to resolve is providing estimates for the size of the changing human population through time, for each mode of subsistence.

Estimating population numbers by modes of subsistence

While there are increasingly reliable estimates for world population through time (Klein Goldewijk et al., 2010; Kremer, 1993; Livi-Bacci, 2006; McEvedy and Jones, 1978; Maddison, 2001, 2008; Thomlinson, 1975), estimating the share of each mode of subsistence remains to be resolved. Our effort at a solution was inspired by Heinz von Förster’s ‘doomsday equation’ (Cohen, 1995: 90). This equation models world population as the sum of two exponential functions: an originally large population with very low growth rates, plus a new, initially minute population with very high growth rates.[15] For a long period of history, this portrays well the simultaneous existence of a hunter gatherer and an agrarian population. On top of this, we need to represent the population of the industrial regime, which since the 16th century is growing despite an endogenous negative growth rate. Its rise in population numbers, we claim, is mainly fed by ‘conversions’ from the agrarian regime, be it by migration (to cities or industrial states) or by the development of national economies from agrarian to industrial.

How can we generate an estimate of hunter gatherer populations? We have little choice but to build on the population growth dynamics known from literature. In Table S1 (available online), we assemble a few such estimates. Apparently, growth rates are very low, but these populations existed over very long time periods.

- Based upon the information in Table S1, we assume an average 'endogenous' annual growth rate from 10,000 BC onward of 0.036%[16] annually. We assume that this growth rate turns negative when hunter gatherers are confronted with an agrarian majority, which happens in the last centuries BC.
- Finally, we assume that by AD 1500 the populations in North America and Oceania are still hunter gatherers, while there are only a few hundred thousand left in the rest of the world.[17]
- In the 16th to 19th centuries, we assume hunter gatherer populations to become largely extinct.

In a next step, we need to generate an estimate for the agrarian population. There are two pathways to arrive at such an estimate. One is to calculate the difference between our estimate of the hunter gatherer population and the total global population (demographic estimate) up to the onset of industrialization. This can be cross-checked by a second, independent estimate which rests on sociometabolic assumptions (metabolic estimate). This estimate rests of the following arguments: in agrarian populations, urban centres emerge (in contrast to hunter gatherers, where no urban agglomerations develop). From a sociometabolic perspective, urban populations are distinct from rural populations by not producing food,[18] and therefore they metabolically depend on a rural-agrarian population to provide them with staples. According to what we know about pre-industrial agriculture, urban centres typically need a large hinterland and a substantial number of peasants working the land from which to extract the surplus food and fodder to sustain a city (Fischer-Kowalski et al., 2013). Thus we can use the existing estimates of the development of the global urban population and assumptions on how large a rural population is required to feed one city dweller to generate an estimate of the total agrarian population.[19] Table S2 (available online) summarizes our assumptions and estimates.

As we can gather from Table S2, there is not a bad fit between the two estimates of agrarian population: the sociometabolic estimates stay nicely within the range of population we need to combine with the hunter gatherer population to generate a full world population. In effect, we may assume that the agrarian population overtook the hunter gatherers in numbers in the late centuries BC and dominated them from thereon at the global level, but some world regions (such as North America and Oceania) were still only occupied by hunter gatherers (see Figure 2).

In the succeeding period to AD 1500, we see quite substantial population dynamics on the part of the agrarian population. Assuming a gradual absolute decline of hunter gatherers from the first century AD onwards, growth rates of the agrarian population must have been rising in order to achieve the observed overall world population growth.[20] During this period, there is also a slightly disproportional increase in urban populations. If we refer this urban population to the agrarian population, we find the share of urban population increasing slightly, from about 2% to 3.5% of the agrarian population (see Table S2). This is quite plausible in the face of gradual technological improvement in agriculture.

The year AD 1500 is a dividing line, as at that point fossil fuels enter the stage. Recent research (Gales et al., 2007; Gerding, 1995) provides quantitative data on the use of peat in the Netherlands; the use of peat as energy source started slowly in the late Middle Ages, but by 1550 peat already amounted to 10% of primary energy supply and helped the Netherlands in its 'Golden Age' to an

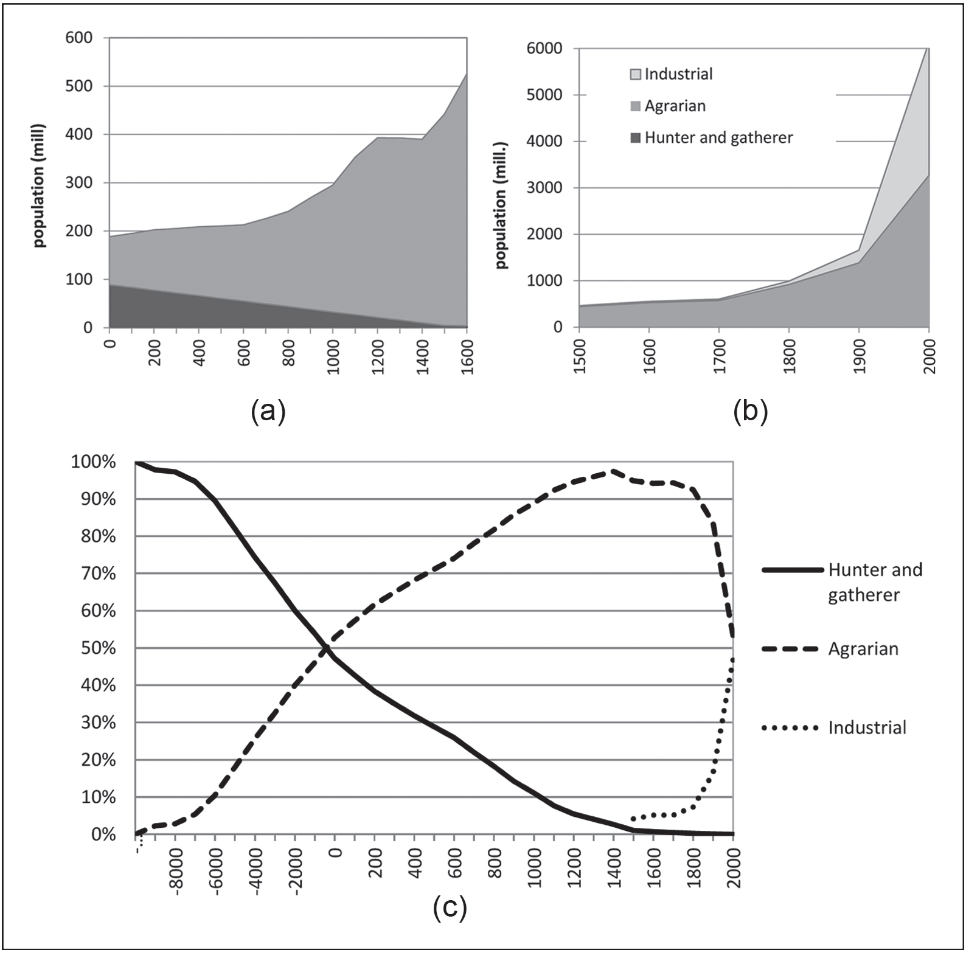

Figure 2. Global population dynamics 10,000 BC–AD 2000 by modes of subsistence. (a) Hunter gatherers and agrarian population (AD 0–1500). (b) Rise of the industrial population (AD 1500–2000). (c) Global shares and transitions, 10,000 BC–AD 2000.
Note: Time axis is not to scale for different periods: 10,000 BC to AD 0: 1000 year intervals; AD 0–1900: 100 year intervals; AD 1950–2010: 10 year intervals. See Table S3 (available online) for data and sources.

energy level per inhabitant above any other European country – and also to the highest urbanization level in Europe (Centre for Global Economic History, 2013; De Zeeuw, 1978; Livi-Bacci, 2003). Next in line is the case of coal in the UK. According to recent estimates, by 1550 coal amounted to 3% of its primary energy supply. While the Netherlands gradually ran out of peat in the next century, the UK could steadily increase its use of coal, export coal to other European countries and move along a learning track towards industrial technologies while substantially increasing its urban population.

Based upon these forerunners, it makes sense to date the onset of the human use of fossil fuels rather precisely at the beginning of the modern era; from a sociometabolic perspective we would argue that the control of a new energy source with an hitherto unknown power (Smil, 2003) that allows expanding social energy use much beyond previous levels is highly relevant

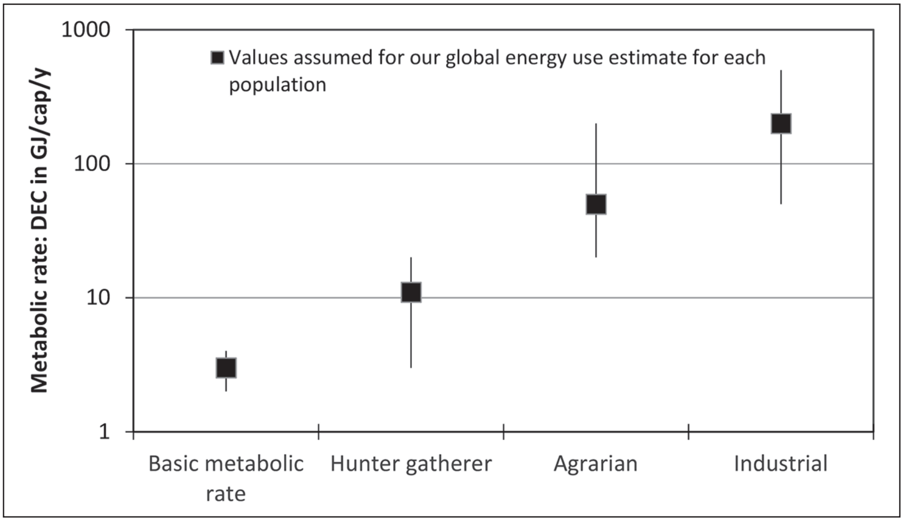

Figure 3. Metabolic rates (primary energy use) of different modes of subsistence. See text for underlying assumptions.

– even if the technologies to make efficient and diverse use of this energy evolve and spread only gradually. The functional inter-linkage with urban growth is apparent from the beginning: without a source providing heat for a rapidly increasing number of urban households and trades no proto-industrialization would have taken place. But even more so: on the global level, there is a near-perfect fit between urban population numbers and the amounts of fossil fuels used globally, across the next 500 years (see Figure 1).

It is interesting to see that across the urbanization literature, a link between urbanization and energy is not seen or is sometimes even categorically denied (e.g. Dyson, 2011); Bairoch (1990), Davis (1955) and Livi-Bacci (2003) provide notable exceptions. It is well beyond the scope of this paper to join that debate, but for the purpose of our toy model, we find it legitimate to use the global urban population as an approximation for the size of the population living by the standards of the industrial sociometabolic regime. They rarely hunt and gather anymore; and they do not sustain themselves by working the land; they sustain themselves by earning money for non-food-producing activities and satisfy their needs via markets. In very simple terms, this describes the industrial mode. Of course there has, for a long time, been urban populations living on agricultural surplus as their energy base; but the share of these populations remained, as we have shown above, very small. By including these into the 'industrial population' estimate we overestimate this population by a few percent. The other possibility would have been to define the size of the industrial population by some, for example, UN-based classification of countries. Apart from the fact that such classifications would not reach far enough back in history, we then would ignore the gradual nature of countries' transition to the industrial mode. So we decided to base our estimate of population living by the industrial mode on the population living in settlements with more than 2500 inhabitants ('urban settlements'). The size of this population extends much beyond the inhabitants of current OECD countries,[21] but we think with good reason this is linked to fossil fuel use: these urban populations outside the OECD could not live as they do unless an energy-rich system driven by fossil fuels provided them with the commodities they require. Even if people sustain themselves at a very low level (e.g. as a beggar in one of the megacities of the developing world), they share more characteristics with the other inhabitants of the city than with a traditional rural farmer or day labourer under an agrarian regime.

But how could this population rise as fast as it did, and what role did fossil fuels play in this? In a first, admittedly superficial, answer, we can say the following: fossil-fuel based-technologies have been instrumental in:

- reducing mortality through hygienic and medical interventions (fighting infectious diseases, antibiotics …);
- providing reliable and fast long-distance transport (for example of food);
- raising agricultural output per area (about fivefold);
- providing fast global information exchange (and thus accelerating learning).

Still, as demographers rightly say, people only come from people. Can our hypothesis hold that all or at least most of the population increase in both the agrarian world population, and in the industrial population, has been fed by agrarian population growth? Mathematically, an average annual population growth rate of 0.46% on the part of the agrarian population since 1400 would have sufficed to populate both regimes. Such a growth rate looks adequate (see Grigg, 1980).

This cross-check is our last step towards reconstructing global population numbers by sociometabolic regimes from AD 1 to the year 2000. Figure 2 presents our results in three different time frames in order to keep smaller changes visible.

According to our population estimates, the world had been populated once by a maximum of about 90 million hunter gatherers around 500 BC, then the numbers began to decline; in the last century BC, hunter gatherers had been overtaken by agrarian populations that rose to about 450 million by AD 1500 and kept rising until today (AD 2000) to 3 billion people. The rise of the industrial population started around AD 1500 and continued to a population of also 3 billion by AD 2000, just matching the agrarian world population (see Table S3).

Estimating affluence by modes of subsistence

In a next step, we have to attribute to these populations a certain affluence, following our introductory arguments. As we are heading for environmental pressures/impacts, and nature is insensitive to money, we operationalize affluence in biophysical terms: we use indicators derived from material and energy flow accounting (MEFA) to quantify the socioeconomic use of energy and to estimate metabolic rates in energy terms.[22] Energy use in MEFA is defined in a more comprehensive way than in conventional energy statistics (Haberl, 2001). The indicator DEC (domestic energy consumption) not only includes 'technical' primary energy such as fuel wood, coal, oil, gas or hydro and nuclear power (as is included in the more common indicator TPES, total primary energy supply), but also all types of biomass used as food and feed for domesticated animals or as raw material. It is thus a more appropriate measure to also characterize energy use in foraging and agrarian societies (see section 'Sociometabolic regimes in human history'). The sum total of the DEC of all population groups corresponds to global energy extraction. DEC per capita and year is defined as average energetic 'metabolic rate' (of a certain society or regime).

Reliable data on metabolic rates only exist for the last two or three centuries (Haberl et al., 2011; Krausmann and Fischer-Kowalski, 2013) and global energy use is usually not differentiated by modes of subsistence. Some authors have provided rough estimates of metabolic rates for material and energy by metabolic regimes (see Haberl et al., 2011; Krausmann, 2011; Krausmann et al., 2008b). While the estimates for per capita DEC in hunter gatherer and agrarian societies do carry considerable

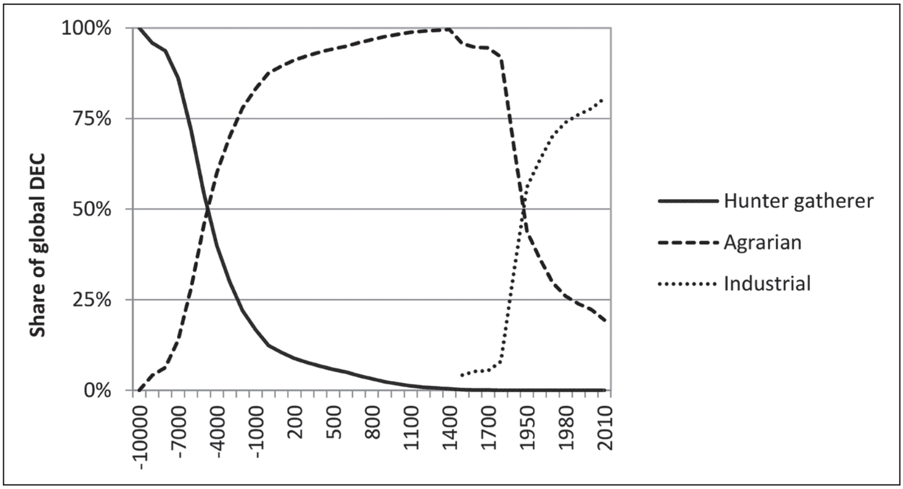

Figure 4. The share of different modes of subsistence in global affluence (indicated as DEC).
Notes: Global DEC comprises biomass (including all food for humans, feed for livestock and all biomass used as fuel or raw material) and modern energy carriers (primary energy) such as fossil fuels, nuclear heat and hydropower (see Table S3 for data and sources). Time axis is not to scale for different periods: 10,000 BC to AD 0: 1000 year intervals; AD 0–1900: 100 year intervals; AD 1950–2010: 10 year intervals.

uncertainty (see Figure 3), we assume that the general differences in metabolic rates between modes of subsistence are robust enough to be used in our toy model to estimate the global use of biomass, their exclusive energy source, across a time span of 10,000 years (see Figures 4 and 5). For the industrial regime and modern energy carriers (fossil fuels, hydro- and nuclear power) we can base our estimate on data available from long-term global energy flow accounts (Cleveland, 2011; Krausmann et al., 2009; Podobnik, 2006).

In the following paragraphs, we briefly explain the rationale and the assumptions on which we base our estimates for the metabolic rates by mode of subsistence.

Hunter gatherers. The literature suggests that the metabolism of hunter gatherers is larger by a factor of 2 to 4 than the basic (endosomatic) metabolic rate of human beings (Figure 3) (Boyden, 1992; Sieferle, 2001b; Simmons, 2008). Energy use of hunter gatherers is, by and large, restricted to two components: the amount of food they extract from their environment, and fuel wood. The amount of food (including waste and losses) may range between 200 and 300 kg/capita per yr, with an energy content of 3–4 GJ/capita per yr. The use of fuel wood can probably vary largely depending on climate and availability of wood. As a rough proxy, we assume wood consumption to be around 500 kg/capita per yr, or 7 GJ/capita per yr. This adds up to a total metabolic rate of 11 GJ.

Agrarian societies. Next to more sophisticated processing of food, the use of crop residues, rising demand for wood for constructing shelter and tools, and above all animal husbandry drive biomass use in agricultural societies:[23] agriculturalists keep animals to provide them with labour, fertilizer, food and raw materials, thus increasing their socioeconomic level of biomass use considerably (Krausmann, 2004). This is even more so in pastoralist societies, which keep animals to make use of often vast land areas with comparatively little input of labour. Pastoralists keep several large

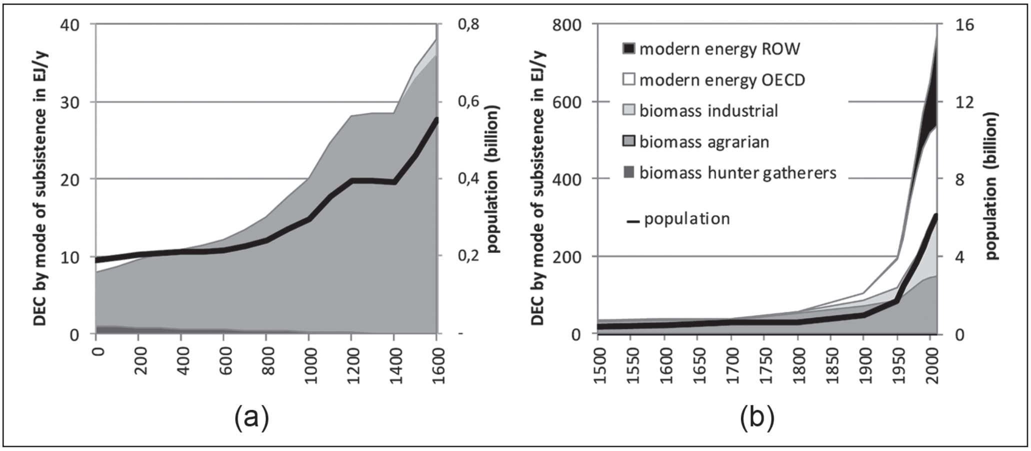

Figure 5. Global human pressure on Earth expressed as population × affluence during the last two millennia. (a) Global human environmental pressure (DEC) for AD 1–1600. (b) Global human environmental pressure (DEC) for AD 1500–2010.
Note: For modern energy use of the global industrial population, we distinguish between modern energy use in OECD countries and in developing emerging countries (rest of the world, ROW).

animals per capita and these animals graze substantial amounts of biomass (e.g. Coughenour et al., 1985). Their biomass consumption may easily be an order of magnitude more than the biomass demanded by the corresponding human population. Overall, the range of biomass use in agrarian societies probably ranges from a level which is not much different to that of hunter gatherers for simple shifting cultivation, to several 100 GJ/capita per yr in pastoralist communities (Krausmann, 2011). Mixed farming systems range most likely somewhere between 20 and 80 GJ/capita per yr – as global accounts of biomass harvest in the last century indicate (Krausmann et al., 2013). For our toy model, we have tried two assumptions:

(1) Lacking any reliable information on long-term trends in metabolic rates of biomass use, we may assume constant average metabolic rates for agricultural societies of 45 GJ/capita per yr according to general information of energy use across metabolic regimes (Haberl et al., 2011; Krausmann et al., 2008b, and see Figure 3).
(2) In a more sophisticated version, we assume that early agrarian societies used 50% more biomass than the hunter gatherer average. We further assume that as long as land and biomass were abundant, this rate increased slowly to 75 GJ/capita per yr, in particular as livestock numbers grew at a faster pace than population and civilizations became more complex. With rising population pressure the relative significance of livestock began to decline (population was growing faster than livestock numbers) – a process which has been observed in Europe in the Middle Ages (Abel, 1978; Montanari, 1994) and has been described as horticulturalization for China (Helbling, 2003). In the absence of any reasonable global information on these trends, we use the European trends and assume that metabolic rates of agrarian societies stabilized around AD 1000 and began a slow decline after AD 1500 to the global average of 45–50 GJ/capita per yr that we observe for the last century (Krausmann et al., 2013). While approach (2) results in a steeper increase in global biomass use between AD 0 and AD 1000 and a level of 17 EJ/yr compared with 12

EJ/yr in approach (1), this difference is not significant for the long-term trends of energy use that we are interested in. Therefore, we only refer to results from method (2) in Figures 4 and 5 and the text; a comparison of the results of both approaches is provided in Figure S5 (available online).

Industrial societies. Energy use in the industrial mode of subsistence (AD 1500–2010) comprises biomass (food, feed, fuel wood and raw material) and what we call 'modern' energy carriers (peat, coal and other fossil fuels, hydro- and nuclear power). We assume that average metabolic rates of biomass use in the industrial population segment are the same as in agrarian societies (45–50 GJ/capita per yr). This lies well within the observed range of patterns and long-term trends of biomass use in industrial countries (Krausmann et al., 2008b). For modern energy carriers we can use data from estimates of global energy and material use (Krausmann et al., 2009; Podobnik, 2006; Schaffartzik et al., unpublished data, 2013). Based on population estimates and regional data, we arrive at average metabolic rates for modern energy carriers which increased in the industrial core countries from 0.3 GJ/capita per yr in AD 1500 to 85 GJ/capita per yr in AD 1900 and further to 280 GJ/capita per yr in 1980; since then they slightly declined. The rates of modern energy carriers for the industrial population in developing economies rose from 4 GJ/capita per yr in 1900 to 99 GJ/capita per yr in 2010.

As visualized in Figure 3, human affluence as expressed as the use of primary energy per person has been increasing by roughly one order of magnitude from one sociometabolic regime to the next. The average differences in affluence between regimes obscure the differences within: we see a more or less log-linear increase.

The long-term change in the shares of modes of subsistence and their different levels of affluence now allow us to locate temporally the transitions in global dominance between regimes in terms of their shares in human energy use, or global affluence (see Figure 4). We see the hunter gatherer mode dominating global energy use until about 5000 BC, followed by the agrarian mode dominating until about the end of World War I, and then the industrial mode achieving a share of three-quarters of global human energy use, and still on the rise.

As each consecutive mode of subsistence is by one factor more energy intensive than the previous one, the global dominance between them in terms of share in global affluence shifts at an earlier point in time than their share in population (compare Figures 2(c) and 4).

Discussion: The human impact on Earth through time

Based on our estimates of population and affluence we can, in a first step, explore the overall size of human impact – or rather pressure – on Earth as far as it is derived from these two factors; the third factor, technology, is implicitly set as 1, which is a rather conservative assumption as impact per unit of socioeconomic energy use has increased from the hunter gatherer to agrarian and to industrial regimes, as we shall show below. For the time period AD 1 to 1600 (Figure 5a) the increase in pressure/impact results from the agrarian population dynamics plus higher metabolic rates compared with hunter gatherers. In effect, we see an almost five fold (4.8) increase of human impact between AD 1 and 1500 if we consider both population growth and differential affluence (energy use). In contrast, population growth alone would only account for a 2.4 fold increase in impact. Thus, increasing affluence doubles the pressure/impact of population during this time period.

In the period from AD 1500 onwards, the rate of increase in pressure/impact is much steeper. From AD 1500 to 1800 it more than doubles, which is substantially faster than the 23% growth across the three centuries before. From then on a veritable take-off can be observed. From 1700 onwards, human impact doubles every century, from 1900 on it doubles in 50 years, and from 1950 on it triples in 50 years, with no sign of saturation yet. But Figure 5(b) also shows that in recent decades the contribution of the old industrial core (OECD countries) to the overall growth in modern energy use has become less significant and that the dynamic is increasingly driven by growing industrial population and by rising metabolic rates in emerging and developing countries (ROW countries). All components – population, and affluence in terms of biomass energy and modern energy carriers – play together to generate the rocketing rise of global energy use shown in Figure 5(b).

So far we have kept the technology coefficient constant over time. But the question arises as to whether technology rather enhances or mitigates the effect of growth in population and affluence on pressures/impacts. As we have explained above, while population numbers and affluence may be considered as being responsible for a wide range of possible pressures/impacts, technology needs to be examined with reference to specific pressures/impacts. In a second step, following the tradition of the Holocene/Anthropocene discussion (e.g. Boyle et al., 2011; Ruddiman and Ellis, 2009), we focus on carbon emissions as one major global environmental pressure. We can only develop a very crude scenario for the development of the technology coefficient and overall carbon emissions during the last two millennia. In order to do this we need to make assumptions on the technology coefficient for the different modes of subsistence and energy types, respectively. In the absence of any data we assume that hunter gatherers do not cause net emissions of carbon; we assume that all C emitted through their biomass use and the vegetation fires they induce is assimilated again by vegetation regrowth. Hence, their technology coefficient for carbon emissions in our equation is set at zero. In contrast, agriculturalists cause large-scale lasting deforestation, and substantial amounts of carbon are emitted from reductions in carbon stocks in vegetation and soils (Boyle et al., 2011; Houghton 2008; Kaplan et al., 2011). With growing population, land use intensifies and the output per unit of land that has already been cleared is increased. This improves the intensity of carbon release through biomass utilization: the amount of net carbon emissions per unit of biomass harvested will slowly decline. Finally, in the industrial metabolic regime a new source for carbon emissions is added: carbon from burning fossil fuels. Fossil fuel combustion releases more carbon per unit energy than biomass (see Figure 6). That is, with the transition to the industrial regime, the aggregate technology factor increases. In later stages, this is counteracted to some degree by two factors: the adoption of less carbon-intensive energy carriers and forms (oil, gas, hydro, nuclear) and the (fossil fuel driven) industrialization of agriculture which boosts biomass harvest while aggregate deforestation slows down.[24]

For the time period from 1800 to 2010 we can draw on estimates of both carbon emissions from land use change and from fossil fuel combustion and we can use these data to derive values for the technology coefficient. Figure 6 shows that the average amount of carbon emitted per unit of energy used (biomass and modern energy) increased from 1800 to 1950 by roughly 65%, and then the intensity of carbon use begins to improve (by 16% until 2000, see Figure 6).[25]

Based on the assumptions outlined above and the empirical evidence we have for the last two centuries we can provide a rough estimate for carbon emissions during the last centuries. In this scenario the aggregate technology factor for C emissions per unit of energy use shows a slow increase during most of the last two millennia. From 1800 onwards, growth in the intensity of carbon use began to accelerate until 1960, when it began a slow decline which lasted until 2000. In spite of all uncertainties involved in this calculation, it is evident that technological change in the long run did not moderate, but further enhanced, the effect of population growth and increasing

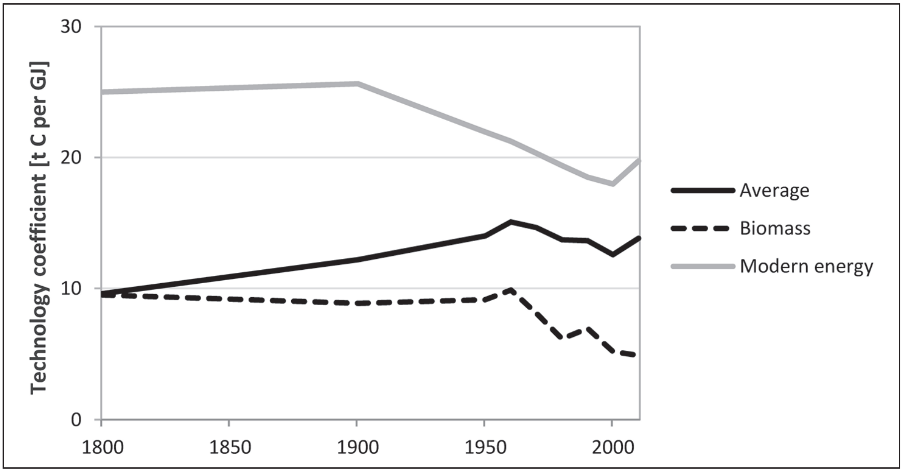

Figure 6. Development of technology coefficients for carbon emissions in t carbon per unit energy use (DEC).
Note: This empirical reconstruction of technology coefficients is based on information on energy use (DEC) and carbon emissions from land change and fossil energy combustion. The technology coefficient for biomass is here defined as C emissions from land use and land cover change per unit of biomass extraction; that of modern energy is defined as C emissions from fossil fuel combustion per unit of modern energy use (this also includes fossil fuels used to intensify land use). The black line shows the aggregate technology coefficient (total C emissions per total energy use).
Sources: own calculations based on DEC data and emissions data from Houghton (2008) and Boden et al. (2013).

affluence by a factor of 1.5 (see Figure 7); only in the last decades has it had a slight counteracting effect.[26] Overall, our calculations result in a rise of global human carbon emissions by two orders of magnitude during the past two millennia, accelerated by technological change in the generation of human affluence through a shift towards using fossil fuels. This is certainly unprecedented in human history.

Conclusions

Constructing the toy model and playing with it has yielded a number of interesting insights. We show that it is reasonably possible to estimate the size of pre-industrial agrarian populations from the size of urban populations. We find that there seems to be a log-linear function of increasing average energetic metabolic rate from human basic metabolism across hunter gatherers and the agrarian mode to the industrial regime; and that from AD 1500 onwards, there is a very close relation between the urban population and fossil fuel use. We see a major historical dividing line around AD 1500: up to then, human population growth and metabolic rates carry about equal weight in increasing human pressure on the environment approximately fivefold over the year AD 1. From then on, fossil fuel use gradually raises the socially disposable energy to unprecedented levels and the overall pressure of humanity upon Earth increases by one order of magnitude; rising metabolic rates contribute to this increase by roughly tripling the impact of population growth. Technology, because it is based upon a shift from biomass to fossil fuels (and other 'modern' energy carriers), does not moderate this impact, but enhances it by a factor of 1.5.

The analysis based on sociometabolic theoretical assumptions, in contrast to much other research, includes the observation that metabolic rates in the fossil fuel/industrial mode have run

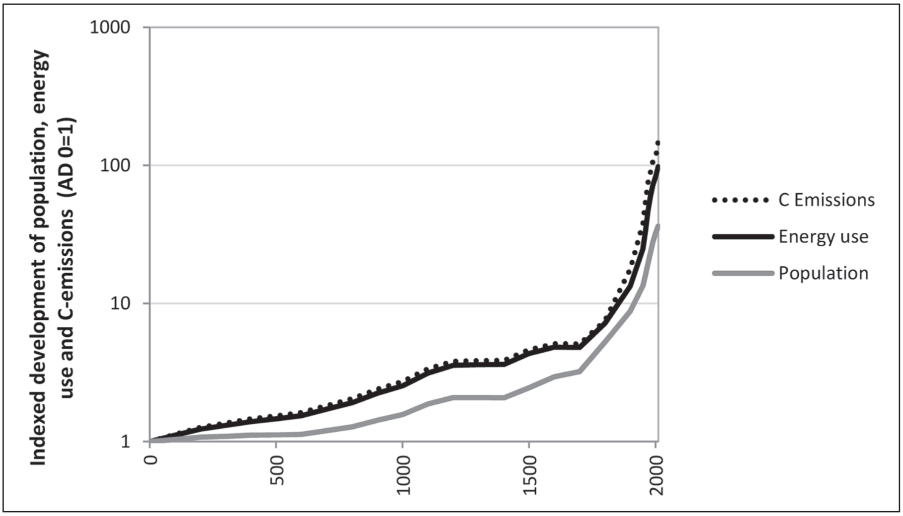

Figure 7. Change in human pressure/impact in terms of global carbon emissions during the past two millennia, resulting from population numbers, affluence (energy use) and technological emission intensity.

into saturation and the industrial population, at least by endogenous biological growth, is running into decline. While environmental impacts therefore might be expected to decline eventually (even without assuming any external constraints), this reversal in trend may occur too late to prevent climate change seriously damaging human civilization.

Overall, our findings clearly point to a dividing line in the scale and dynamics of human impact upon Earth with the onset of fossil fuel use, which coincides with what the cultural historians regard as modernity. The virtue of this solution would lie in the temporal coincidence between using a new geological resource (fossil fuels) with a discontinuity observed in cultural history. While there was a period of latency in which only rising urbanism and so-called proto-industry in some countries benefited from the increasing energy availability, the breakthrough of major technologies was being gradually established that would then reshape the world.

But is incorporating the complexities of modes of subsistence and sociometabolic rates in the calculation of human pressure on Earth actually warranted? Don't they just more or less replicate what is known from the dynamics of human population numbers? Here we arrive at the limitations of Ehrlich's IPAT model. It cannot be assumed that the three components – population, affluence and technology – are independent from one another. On the contrary: they are functionally deeply interlinked, but in ways that differ between sociometabolic regimes. In the hunter gatherer regime, population numbers basically are constrained by available food energy, and the availability of food from ecosystems can hardly be controlled by humans. In the agrarian regime, the relation between food and population becomes more complex: While food energy still constrains population numbers, population growth allows investing more labour and drives technological progress increasing the overall amount of food energy available from agro-ecosystems. Thus we have not only a 'Malthusian' (Malthus, 1803), but also a 'Boserupian' (Boserup, 1965, 1981) relation; this generates a rebound effect on fertility. In the industrial regime, the link between land and energy availability is largely disrupted, as well as the link between available energy and population dynamics. But still, the industrial regime, while reducing its own fertility below reproduction rates, subsidizes population growth in the remaining agrarian population segments by reducing mortality. Furthermore, the new energy source also allows drastically increased food availability independent of labour. Thus we do not only have an interdependence between the factors driving human impact within each regime, but also an interdependence between regimes.

We argue that it is exactly these qualitative changes in functional interrelations among socioeconomic characteristics, interlinked with functional changes in humanity's relation to the Earth System, that make it impossible to use homogenous indicators for human impact across all of human history. This is particularly apparent when we think of future prospects. Earth's carrying capacity will not allow for the projected human population to sustain itself by the energy standards of the current industrial regime, not least because fossil fuels are a finite resource. Thus a transition to another regime is inevitable, and it may re-link human population and land use in novel ways.

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Notes

1. Just to illustrate our point: we would not be tempted to name an age in which severe climate change and sea level rise eradicated all major human civilizations as 'Anthropocene' – irrespective of the fact that these changes in the natural environment had been triggered by human activities a few centuries before.
2. It is also interesting to see how older and often Eurocentric distinctions based upon property rights, the division and organization of labour or forms of stratification neatly fall in place when applying Sieferle's distinctions.
3. Concerning the extinction of megafauna see, for example, for North America, Gill et al. (2009); for Australia and the role of fire regimes (where human arrival rather than climate impacts seems to have caused extinction of animal and plant species) see Rule et al. (2012).
4. In a recent study of genetic data Gignoux et al. (2011) calculated annual growth rates of Pre-Neolithic foraging populations in Europe, Western Africa and Southeast Asia: In Europe, where the period from 23,000–1000 BC was analysed, the annual growth rate was 0.021%, in Western Africa 0.007% (48,000–10,000 BC) and in Southeast Asia 0.011% (48,000–10,000 BC). The low growth rate depends heavily on the long birth intervals in foraging societies (for an explanation, see for example Ellison (2008)). Birth intervals in forager populations were twice as long as in (pre-industrial) agrarian populations (Ammermann and Cavalli-Sforza, 1984).
5. Flannery (1998) explains the lack of a Neolithic revolution in Australia by ENSO and the periodic occurrence of very long droughts that would have made any effort at agricultural cultivation futile and forced people back into the hunting and gathering mode of subsistence. This could be an example where the evolutionary advantage of the agrarian mode could not play out.
6. Sieferle (1990: 55) sees a functional explanation of the Neolithic revolution viewing it as a process of self-organizing dynamics in which one emergent pattern is evolutionarily superior and creates a pathway of no return.
7. A narrative of this for sub-Saharan Africa across the millennia, based upon synthesized knowledge from various sources, may be found in JA Michener (1980).
8. See the case studies put together in Clark and Haswell (1967); see also a new volume containing a number of case studies replicating Ester Boserup's work (Fischer-Kowalski et al., 2014).
9. Oesterdiekhoff (2001) seeks to explain the relatively moderate fertility among the agrarian populations in western and northern Europe as compared to Asia, as a result of the 'collateral' (in contrast to

patrilineal) family type that originated from (urban) Rome and requires the young man to have an independent economic existence before marriage, while the typical agrarian patrilineal pattern allows him to bring his wife into his father's family. Thus marriage in Europe occurred at a later age and is responsive to economic downturn situations. In effect, population growth was slower and less volatile than for example in most of Asia.

10. Only European countries that had thrived on overseas trade (such as Portugal, Italy, Spain, Greece and the Netherlands) in that period already have a substantial proportion of urban population, that is 15–20%, as defined for example in the Clio-Infra DB 2013 (settlements with more than 3000 inhabitants) (Centre for Global Economic History, 2013). See also Grigg (1980). For the rest of Europe, urban proportions lay between 2% and 10%.
11. Ayres (1956) and Pomeranz (2000) give anecdotal evidence for earlier use of coal in China. Quantitatively, this seems not to have been very widespread and according to Pomeranz possibly have been terminated by the Mongol invasion in the 14th century (Pomeranz, 2000: 63).
12. For the Netherlands, we find a decline of peat use from 1650 onwards, related to government reactions to peat mining threatening agricultural land; but also in the Netherlands, peat supplied 18% of primary energy in 1650 (Gerding, 1995).
13. Lutz and Samir (2011) argue female education to be the most powerful key to reducing fertility, even in the Global South. We would argue that a rise in female education does not happen unless there is a transition towards the industrial regime ongoing. So these processes are intertwined.
14. For a more detailed description of the conceptual foundations of material and energy flow accounting and the underlying accounting principles and system boundaries see Fischer-Kowalski et al. (2011); Haberl (2001).
15. This function is termed 'doomsday', because it leads to an infinite population within a finite time. The parameters used for the year AD 1 are 250 million people for the slow-growth, and 1 person for the high-growth compartment. Respective annual growth rates are 0.01% and 1.125% (Cohen, 1995: 90). This leads to 5.2 billion people in the year 2000.
16. We keep the annual growth rate of 0.036% constant for the period 10,000–0 BC. The size of this population was calculated applying a basic exponential model $P_t = P_0 (1 + r)^t$. P_0 is the population size at time 0, t is the duration of the process (years) and r is the annual growth rate. This is a very rough-and-dirty estimate as such a growth rate may vary very strongly between favourable and unfavourable environmental conditions (for example between North America and Oceania, see Table S1).
17. The only source we could find estimates a share of 1% hunter gatherers among the global population in 1500 (Rakelmann, 2004), which would be 4.61 million people, out of which about 2.6 million would have lived in North America and Oceania (Klein Goldewijk et al., 2010).
18. This distinction may not always be as sharp: people in urban centres keep chicken and rabbits, an occasional goat and horse, grow vegetables and fruits … But the staple food cannot, for lack of area, be grown within urban centres. In some regions (of Italy, for example) though, there exist traditional settlement patterns where the peasants do not live among their fields, but in compact villages that may grow to small towns of the size we define as 'urban'.
19. We have deliberately chosen a very low cutting point for what we treat as 'urban': settlements of 2500 inhabitants or more (if we go by the data from Klein Goldewijk et al., 2010) or 3000 and more according to the Clio-Infra data base.
20. Of course our toy model cannot adequately represent negative population growth impacts such as the Bubonic Plague and the Mongolian raids in the 14th century, nor the stagnation caused by the collapses of the Roman Empire in the West and the Han Dynasty in the East (see McEvedy and Jones, 1978).
21. This assumption neglects the fact that in the second half of the 20th century agriculture also became industrialized in the industrial core and the shrinking rural population of fully industrialized economies rapidly adopted industrial metabolic rates. From a systemic perspective, the non-urban populations in OECD countries (roughly 0.4 billion since 1950) should therefore also count as 'industrial population'.

22. It would also be reasonably justified to express 'affluence' in material terms, as quantity of materials used in a society. We decided in favour of energy use for reasons of better data availability, on the one hand, and because energy and material use are very highly correlated, anyway.
23. We neglect wind and water power in our estimate of energy use in agrarian societies. While these energy technologies can be significant at a regional and local scale, their quantitative contribution to global primary energy use before industrialization has been very small (e.g. Gales et al., 2007; Smil, 2008).
24. As shown in Figure 6, net carbon emissions from land cover change (deforestation) per unit of harvested biomass decline in the second half of the 20th century. This improvement in the intensity of carbon use is partly offset by high fossil fuel inputs of industrial agriculture. Overall, the increase in biomass harvest was considerably larger than direct and indirect fossil fuel use in agriculture (see Krausmann et al., 2013). While carbon intensity of biomass as shown in Figure 6 only includes net C emissions from land cover change, direct and indirect fossil fuel use in agriculture is included in the average carbon intensity of energy use (black line in Figure 6).
25. The turn upward after the year 2000 is due to the renewed globally increasing use of coal.
26. This has been shown empirically for Asia and the Pacific for the last two decades (see Schandl and West, 2012; United Nations Environment Program (UNEP), 2011) by a decomposition analysis according to the Ehrlich formula for the period 1980–2005.

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