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The Metabolism of a Human-Dominated Planet

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This Age of Humans, this Anthropocene, is ecologically like no other in the long history of the Earth's biosphere. In all natural ecosystems, energy and work flow from the 'bottom up'. Plants and phytoplankton dominate the ecological metabolism of natural ecosystems, capturing energy from the sun and converting it into chemical energy usable for the work of functioning, growing, and reproducing. Much of this captured energy is used by the plants themselves, a fraction percolates up into consumers (especially fungi, bacteria, and soil fauna), and an even smaller fraction filters up into larger creatures.

In the past 10,000 years, the blink of an eye in the 4.6 billion-year history of Earth, this upwards flow of energy in the biosphere has been fundamentally perturbed. *Homo sapiens*, a single, highly social species of large primate with an unusual ability to share complex ideas and innovations through verbal language, began to actively colonize natural ecosystems and direct their energetic production to maximize its own consumption, through the innovation of agriculture. Previously this species, a component of the biosphere like any other species, probably had less influence on Earth's life-support systems than, say, elephants or mammoths, but these innovations gradually expanded human influence on ecosystem function in many regions. Later, less than 300 years ago, this species began to exploit on a large scale a source of energy previously not significantly utilized by other denizens of the biosphere (whether plants, animals, fungi, or microbes): the fossil, energy-rich remains of ancient inhabitants of the biosphere buried hundreds of millions of years previously (ancient plants in the form of coal, and ancient plankton in the forms of oil and gas). This rapid expansion in available energy enabled humans to expand rapidly in numbers, activity, and interconnectedness, to

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colonize previously forbidding ecosystems such as tropical forests and polar latitudes, and to maximize rates of harvest of other species; to efficiently exploit previously inaccessible material resources, and to generate waste products in such quantities that they threaten to shift the entire Earth system into fundamentally different biophysical states. Uniquely in the history of Earth, this new energy supply is concentrated not at the bottom trophic level (that is, plants) but at a higher trophic level (a large primate and associated domesticates such as cattle).

Hence, when considering the question ‘is the planet full?’ from an environmental perspective, it is helpful to tackle this question in terms of resource flow, and compare the resource flow appropriated by humans to that which would have existed in the absence of humans. Here, I tackle this question in terms of arguably the most fundamental of resources: *energy*. Energy is an interesting biological metric because, in the broadest sense, it represents the capacity of an organism (whether plant, bacterium, or human) or species to do ‘work’; to exploit and modify its surroundings to advantage its survival prospects and those of its descendants. The more energy a species or organism has access to, the more able and likely it is to exploit and modify its environment. Energy is also a particularly useful metric because it enables the direct comparison of biological processes (photosynthesis, growth, metabolism) with socioeconomic processes (food production, industrial energy production) in a common energetic currency.

This chapter takes a metabolic view of the planet, and examines how the *extended metabolism* of the human species compares in magnitude to the metabolism of the entire biosphere. Describing human activity on Earth as an integral component of biosphere activity can provide a useful perspective for analysing human–biosphere relations. I demonstrate that the energetic metabolism of our species has grown in size to be comparable in magnitude to the natural metabolic cycles of the terrestrial biosphere. This feature underlies almost all environmental challenges we face in the 21st century, ranging through resource depletion; overharvesting of other species; excessive waste products entering into land, oceans and atmosphere; climate change, and habitat and biodiversity loss.

My basic thesis is that when we consider humanity and the biosphere from a metabolic perspective, it is very clear that that the Earth is ‘full’, in the sense that the natural metabolism (here defined as the metabolism of the planet as it would have been in the absence of humans, or roughly that preceding human influence) is becoming dominated by the extended metabolism of one component species, and in particular one species that [sits](#) at a high trophic level where energy flows were previously small. What this means for the long-term functioning of the biosphere, and future for ourselves and fellow denizens of the biosphere, is far from clear, but it is certain that the biosphere will

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continue to be modified in multiple ways by this abundance of human extended metabolism.

My aim is not to suggest that metabolism explains everything, in some form of universal theory of metabolic determinism. It is rather to argue that a metabolic perspective on humanity and the biosphere can give new perspectives and insights into the influence of humanity on the planet.

Definitions

Metabolism is defined as a biological process, and can be defined as the rate at which energy is exchanged between an organism and its environment; transformed within an organism; and allocated to maintenance, growth, and reproduction (Brown et al. 2004). The purely biological context can be extended to encompass human societies through the concept of ‘sociometabolism’ (Fischer-Kowalski and Haberl 1998; Krausmann et al. 2008), which is the rate at which energy is exchanged between a human society and its environment, and transformed within a society. Hence biological metabolism is fuelled almost solely by light capture by plants, and then by consumption by other organisms of the chemical free energy embodied in plant biomass. Sociometabolism, in contrast, incorporates biomass resource consumption for food or fuel, but also energy generation and consumption from other sources, including fossil fuels, and nuclear, solar, and wind power.

All biological metabolism and a significant part of sociometabolism is fuelled by the consumption of biological material (plants or animals) and is therefore strongly coupled to the flow of elements essential to biological function (in particular carbon and major nutrients such as nitrogen and phosphorus). Hence energetic metabolism is strongly linked to the mass flow of key resources such as nitrogen and phosphorus.

The Biological Metabolism of Earth

Before quantifying the relative magnitude of human energy use relative to that of the biosphere, it is informative to first estimate the metabolic energy flowing through the biosphere prior to major human influence.

Almost all of the energy that powers the biosphere ultimately originates from solar energy (a tiny fraction comes from geothermal processes). 174 PW (1 PW = 1 petawatt = 10^{15} W) of solar energy bathes the planet’s upper atmosphere, of which 30 per cent is reflected back to space. Components of the terrestrial biosphere (in particular plants and cyanobacteria) have evolved to capture a fraction of this energy in concert with capturing carbon and water,

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lock the energy into carbon-based chemical bonds through the process of photosynthesis, and then utilize this energy in a controlled manner to power metabolisms that enable growth, resource exploitation, defence, and reproduction.

Because all abundant forms of biosphere energy capture require carbon (C) atoms as the basis of the carbon-bond-based energy storage, such capture is conventionally expressed in terms of carbon units, and is termed gross primary productivity (GPP). The GPP of the biosphere is about 210 Pg C year⁻¹ (1 Pg C = 1 petagram of carbon = 1 thousand million tonnes of carbon = 10¹⁵ g C) of which 120 Pg C is on land and 90 Pg C is in the oceans (Field et al. 1998). The biosphere probably approached these levels of energy consumption in the Carboniferous period (359–299 million years ago) when plants became extensive on the land surface, and in particular during the late Cretaceous period (140–100 million years ago), when densely veined angiosperm plants with high photosynthetic capacity became the dominant form of plant life (Brodribb and Feild 2010).

For our purposes (and in a common currency of metabolic energy), it is useful to express the rates of global photosynthesis in units of energy conversion. The standard free energy for the reduction of one mole of carbon dioxide (CO₂) to the level of glucose is + 478 kJ mol⁻¹, or 39.83 kJ g C⁻¹. Using this conversion factor, the total global (terrestrial and marine) photosynthetic metabolism of the biosphere is 265 TW (1 TW = 1 terawatt = 10¹² W), of which 150 TW (60 per cent) is through the land biosphere, and 115 TW (40 per cent) through the marine biosphere. This total biosphere metabolism represents 0.2 per cent of total surface solar energy.

This is the total photosynthetic flux. About 50–70 per cent of this captured energy is used by the plants and phytoplankton themselves to power their own metabolisms (termed autotrophic respiration) and about 30–50 per cent is used to produce plant/phytoplankton biomass (termed net primary production, or NPP), which is eventually consumed and metabolized by herbivores, detritivores, bacteria, and fungi (in what is termed heterotrophic respiration) (Malhi, Baldocchi and Jarvis 1999). Expressing NPP in energy units and using the values of terrestrial NPP and conversion factors outlined above, the total biomass energy made available by plants to other organisms is therefore about 75 TW on land, and 57 TW in the oceans.

The Metabolism of the Human Organism

The average active adult human metabolizes sugars to produce energy at a rate of 120 W (Burnside et al. 2012; equivalent to two typical old-fashioned tungsten light bulbs, or the amount of sunlight falling on an A3 sheet of paper

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when the sun is overhead in the tropics). A basal resting human metabolism is 60–80 W (Brown et al. 2004). This roughly corresponds to what would be expected for a mammal of our size, though our energy use is disproportionately allocated to maintenance of our unusually large and resource-demanding brains (which consume 20–25 per cent of our basal metabolic energy, around 15–20 W). As a result, less energy is allocated to other aspects such as growth, and humans have an unusually slow growth rate for a mammal our size. Despite our high mammal metabolism, we grow at the rate of an equivalent mass reptile (for example, a boa constrictor), an order of magnitude times slower than would be expected for a mammal our size (Burnside et al. 2012: 196).

The History of Human Sociometabolism

Next I explore how human energy use (human sociometabolism) compares to the natural energy use of the biosphere. This term includes the direct consumption of resources for our biological metabolism, but also indirect consumption through appropriation of ecosystems (agriculture) and animal domestication, and the use of biomass, fossil fuel, or other energy supplied for societal activity.

First we examine the human use of energy and materials during three stages of human societal development: preagricultural, agricultural, and industrial. This section draws on the concept of sociometabolic regimes and transitions introduced by Haberl (2006). Quantifying the sociometabolism of humanity requires accounting for both energy flows (which are relatively easily garnered for modern societies from energy statistics) and material flows (the flow of biomass used for human or livestock nutrition). The material flows are an important component of the metabolism of pre-industrial societies, and can still be a significant component of modern societies.

The hunter-gatherer sociometabolism

Prior to the Neolithic revolution in agriculture, the estimated global human population was low. Modern *Homo sapiens* had expanded out of Africa 50,000–100,000 years ago, and managed to displace pre-existing *Homo* populations such as Neanderthals in Europe, *Homo erectus* in Asia, and most likely other recently discovered but poorly described human species such as Denisovans and the enigmatic Red Deer Cave People (Krause et al. 2010; Curnoe et al. 2012). Quite what gave *Homo sapiens* such a competitive advantage is the subject of intense debate, but a very plausible hypothesis is the development of complex language that enabled transmission of complex knowledge, rapid

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cultural evolution, and the emergence of increasingly social and interconnected human societies. By 40,000 years ago *Homo sapiens* had reached hominid-free Australia; by 10,000 years ago it had crossed the Bering Straits and rapidly colonized the hominid-free Americas.¹

Despite this global spread, human societies remained hunter-gatherer, as they had been during the millions of years of preceding evolution, albeit becoming increasingly effective hunters through the development of improved technologies such as spears, arrows, and fish hooks. Hunter-gatherer lifestyles did not have an entirely benign effect on ecosystems. The use and spread of fire altered many ecosystems, for example in Australia (Rule et al. 2012). There is abundant evidence of extensive extinction of large animals in many continents coinciding with the arrival of human hunters (Barnosky et al. 2004). The impact of preagricultural humans on ecosystems is often underappreciated. Prior to human arrival, much of North and South America and Australia would have appeared as African game parks appear today, abundant in large herbivores and carnivores, some familiar (lions, cheetahs, elephants) and some exotic (giant marsupial lions and wombats, sabretooth tigers, giant ground sloths, armadillo-like glyptodonts). Around the time of human arrival, 33 species of large animal (typically only animals of body mass equivalent or larger than human mass) became extinct in North America, 50 species in South America, and 21 species in Australia (Barnosky 2008). The only regions with low extinction rates were Africa, and to a lesser extent South Asia, where the megafauna had co-evolved with *Homo sapiens*, and perhaps had learned to be wary of this puny, strange-sounding, ground-dwelling primate. The extinction of the large fauna had knock-on consequences for ecosystem structure and nutrient cycling, with the encroachment of forests into previously browsed grasslands in ecosystems ranging from Siberia to the tropics, and reduction of movement of nutrients through animal dung (Doughty, Wolf, and Malhi 2013). The expansion of dark boreal forests into mammoth-maintained grasslands at high latitudes in the wake of mammoth extinction may indeed have induced an early, moderate global warming (Doughty, Wolf, and Field 2010). In high latitudes the light absorption effect of trees (especially in snow cover conditions) outweighs any carbon dioxide-associated cooling effect from carbon storage (Bala et al. 2007).

Examination of modern-day hunter-gatherer societies can give some indication of energy use by preagricultural societies. Table 8.1 summarizes an estimate of sociometabolism of hunter-gather societies, derived from Krausmann et al. (2008). The energy use per capita of a hunter-gatherer is about

¹ See Goldin, Cameron, and Balarajan (2011, ch. 1) for a brief account of human migration from prehistory to Columbus.

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Table 8.1. Aspects of the sociometabolism of hunter-gatherer, pre-industrial agricultural, and industrial societies

Metric	Units	Socio-metabolic mode		
		Hunter-gatherer	Agricultural	Industrial
Population density	Humans km ⁻²	0.02–0.10	40	400
Agricultural population	%	0	>80	<10
Extended metabolism	W per capita	300	2000	8000
Total energy use per unit area	W km ⁻²	6–30	82 × 10 ³	3.3 × 10 ⁶
Proportion of biome metabolism	%	<2 × 10 ⁻⁴	3–6	210
Biomass share of energy use	%	> 99	> 95	10–30
NPP appropriation	Mg C km ⁻² year ⁻¹	0.005–0.024	62	515
Proportion of local NPP	%	6–30 × 10 ⁻⁴	8	69

Source: derived from Krausmann et al. (2008 table 1).

300 W, and this is almost entirely in the process of acquiring food for consumption, and to a much lesser extent other materials and the use of fire. This sociometabolism is greater than the 80–120 W required for human physiological metabolism, because of the inefficiencies in both acquiring foodstuffs, and in human conversion of food into metabolic energy, and also in the use of biomass energy sources for fuel.

The hunter-gatherer lifestyle can only appropriate a small fraction of the energy in the ecosystem landscape (fruit, tubers, other foodstuffs, animals, wood fuel), and can therefore only support low human population densities (typically 0.02–0.10 humans km⁻²; Table 8.1). The overall impact is low (albeit heavy on the animals hunted), with low appropriation of ecosystem productivity typically of a magnitude of 5–24 kg C km⁻² year⁻¹, equivalent to 6–30 W km⁻². This compares to a baseline ecosystem metabolism of 3.2 MW km⁻² (GPP 2500 Mg C km⁻² year⁻¹; NPP 1250 Mg C m⁻² year⁻¹) for a tropical savannah environment (Roy and Saugier 2001). Hence human sociometabolism was six orders of magnitude smaller than the biological metabolism of the surrounding African savannah landscape in which we first appeared.

Homo sapiens and its antecedent *Homo* species have existed in a hunter-gatherer lifestyle for over a million years, with slow improvement in resource gathering efficiency as brains expanded and technologies improved, and notable waves of global expansion out of Africa. From a metabolic perspective however, total human metabolic activity was low and had modest impact on the planet; probably less impact than elephants and mammoths. This pattern was punctuated by a major transition that began about ten thousand years ago: the Neolithic revolution and the advent of farming.

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The Agricultural Sociometabolism

Farming originated almost simultaneously (on human prehistory timescales) at several locations in the early Holocene (5,000–10,000 years ago), including in Mesopotamia and Anatolia, the Yangtze valley, New Guinea, West Africa, Meso-America, and the Andes (Diamond 2002). This suggests that this transition was somewhat inevitable given the stage of human language ability and cultural connectedness, and once the climate had moistened and stabilized sufficiently after the latest ice age. Following the development of farming, Neolithic cultures carried agricultural and pastoralist knowledge and approaches across the terrestrial surface, to the extent that hunter-gatherer cultures now form a tiny minority of humankind. The Neolithic transition did not necessarily lead to an improvement in individual human well-being, as health and life expectancy declined in congested, disease-ridden communities, and nutrition declined with monotonous agricultural diets (Larsen 1995). Through their efficient colonization and exploitation of ecosystem metabolism, however, the agricultural societies were able to support much greater populations of humans, and hence outcompete hunter-gatherer societies. The languages of the expanding Neolithic or Iron Age farmers and pastoralists dominate the global language maps of modern humanity, whether Indo-European across Eurasia (Bouckaert et al. 2012), Chinese in East Asia, or Bantu in sub-Saharan Africa. The transition from hunter-gatherer to farmer/pastoralist is largely complete for most of the human population. A very small fraction of humanity still retains a hunter-gatherer lifestyle.

Colonization of ecosystems

From a metabolic viewpoint, the key advance of the Neolithic revolution was the ‘colonization’ of the ecosystem landscape, with many ecosystem processes ending up being regulated or controlled by humans. Instead of harvesting or slightly modifying whatever foodstuffs the natural ecosystem was able to provide, the vegetation landscape was effectively ‘colonized’ (Fischer-Kowalski and Haber 1998) and altered to produce a higher density and abundance of foodstuffs well suited for human consumption, especially cereals such as wheat (Middle East), rice (Asia) and maize (Americas). The domestication of key animals also greatly increased our colonization of natural ecosystems, with increased grazing by cattle, pigs, and goats (among others) converting large areas of human-inedible foodstuffs into small amounts of nutrient-rich meat. Biomass (either directly for fuel or as food for animals) is still the dominant energy source of agricultural societies, despite occasional use of wind or hydropower.

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Pre-industrial agricultural societies often reduced the natural NPP of the regions they inhabited, as the natural ecosystem was replaced by a less optimized agricultural system (Haberl et al. 2007). A notable exception was semi-arid river valleys such as the Indus and Nile, where irrigation and controlled water flow greatly increased the previous productivity of the landscape. On a regional level, a large fraction of NPP can be appropriated and utilized by agricultural societies.

The intensity and efficiency of agricultural production increased over time. Table 8.1 presents data on sociometabolism from an advanced pre-industrial agricultural society (in this example an Austrian agrarian society in the mid-18th century, just prior to the industrial revolution). Compared to the hunter-gatherer sociometabolic regime, by the 18th century human sociometabolism per capita had increased by one to two orders of magnitude. Such a society supports a population density of up to 40 people km⁻², with a sociometabolism of around 2,000 W per capita. This is equivalent to a per unit area energy consumption of 82 kW km⁻² (or 65 Mg C km⁻² year⁻¹), three to four orders of magnitude greater than that of a hunter-gatherer society. This is still only 3–6 per cent² of the natural metabolism of the ecosystem that has been colonized (the temperate ecosystems most extensively colonized have about half the metabolism of tropical savannahs). Unlike the case of the hunter-gatherer, the ecosystem has been substantially altered to provide for this sociometabolism, and such alteration now represents a significant modification of local biological metabolism.

Locally, non-industrial agricultural societies can appropriate up to 80 per cent of NPP (Haberl et al. 2007), especially in densely populated, highly productive agricultural regions such as the Ganges plain, East China, and Java. By the time of the onset of the industrial revolution, humans had appropriated approximately 4 per cent of global terrestrial NPP. In suitable regions with high natural fertility the degree of agricultural appropriation of ecosystem metabolism was high, but there remained vast regions of the biosphere, most notably much of the tropical and boreal forest realm, where humanity did not have the metabolic resources to effectively colonize the biosphere.

A key feature of agricultural sociometabolism is its strong dependency on land area. The sociometabolism of a pre-industrial agricultural society was largely a function of the amount of ecosystem land area it was able to colonize. Agriculture made permanent settlement both possible (there was no need to roam a large area as per area energy density increased) and also necessary (it was necessary to nurture, manage, and protect crops). Hence the size of

² The figures have been calculated from the information in table 8.1.

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metabolism per capita was broadly limited by the area per capita appropriated, notwithstanding gradual improvements in agricultural efficiency over the millennia. Eventually, many agrarian societies faced a Malthusian trap where population density increased in response to greater sociometabolic energy (and was needed as labour to exploit that sociometabolic energy), but the total amount of energy available was constrained by land area. Such an agricultural landscape is 'full' in the sense that the population exists at near the metabolic carrying capacity of the landscape, and is vulnerable to shocks; droughts and political instability can tip the sociometabolism into decline and lead to famine and depopulation.

The Industrial Sociometabolism

Pre-industrial agricultural humanity derived almost all of its energy, whether food or fuel, from natural ecosystems, and thus its sociometabolism ultimately was constrained by land area. Agricultural efficiency could be improved, but there were basic challenges to how much energy could be extracted from a specific land area of ecosystem, and therefore how dense a human population could be supported.

The next major sociometabolic transition was the industrial revolution, which, while having technological precedents, began to fundamentally shift societies in the mid-18th century in north-west Europe. The key characteristic of the industrial revolution was large-scale access to new dense sources of fossil energy not directly dependent on contemporary ecosystems, and hence not directly area dependent as hunter-gatherer or agricultural sociometabolism was. Hence humanity introduced a deep time dimension to its energy supply; rather than only being able to exploit embodied solar energy captured by the biosphere in the preceding few years, it started exploiting fossil energy—embodied solar energy that was captured by the biosphere many millions of years ago and slowly accumulated and concentrated in the lithosphere.

From its initiation in north-west Europe, the industrial transition intensified and spread across Europe and North America in the 19th century, and in the second half of the 20th century underwent further rapid expansion in much of Asia and parts of Africa and South America. The transition is still underway, and a substantial fraction of humanity still lives a predominantly agricultural lifestyle. This fraction is decreasing rapidly in the 21st century, most notably in and around the expanding cities and megacities of Asia, Latin America, and Africa.

It might be expected that abundant fossil energy might ease and displace pressure on the biosphere, by reducing pressure on fuelwood extraction, for example. In fact, the extra energy availability through industrialization also

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enables higher NPP extraction and material flows from the biosphere. For example, there is more metabolic energy available to do the work of extracting nitrogen from the air or phosphorus from rocks to make and transport fertilizer, to chop down forests to make new available land, or to build transportation networks linking remote regions of biosphere—such as the American West in the late 19th century or the Amazon frontier in the late 20th century—to centres of industrial metabolism. The availability of abundant fossil energy has generally led to increased exploitation of the biosphere (Ellis et al. 2010). There are interesting local exceptions; in mature industrial societies woodlands are no longer viewed as fuel or food reserves and have been much less intensively exploited or managed for fuel, and on marginal agricultural areas (such as the Eastern United States), agricultural lands have been abandoned to encroaching forests.

Two key features of industrial sociometabolism are (1) that biomass energy (whether for food or fuel) is only a small contributor to total sociometabolism compared to fossil fuels and other high-density energy sources, and (2) that there is sufficient surplus energy to build and maintain efficient transportation networks, meaning that population centres do not need to be co-located with food and energy production centres. Hence human sociometabolism and population density are decoupled from land area, enabling populations to both grow rapidly and be concentrated in towns, cities, and megacities, where human cultural and information exchange and partition of labour is much more efficient. As part of this transition humanity is moving from being an overwhelmingly rural creature to a predominantly urban one.

Table 8.1 shows the sociometabolism of a typical modern industrial society; England (not the whole United Kingdom) around 2010. Per capita energy consumption is here calculated as the sum of human biological metabolism (daily calorific intake) plus the energy obtained from all other sources (including fossil fuels and renewable energy sources). England has a sociometabolism of about 8,000 W per capita and a population density of 407 people km⁻². Hence its mean sociometabolism is 3.3 MW km⁻², approximately double that of the temperate forest ecosystem it has colonized and displaced (shown in Table 8.2). Biomass consumption makes up 10–30 per cent of this metabolism, or about 300–900 kW km⁻² (Table 8.1).

Table 8.2 compares England with another advanced industrial society, the conterminous United States, which has higher per capita sociometabolism (about 12,000 W) but much lower population density (38 people km⁻²). For this society its area-mean sociometabolism is 0.5 MW km⁻², about 15 per cent of the ecosystem metabolism (Table 8.2). However, this includes the thinly populated central regions; in areas such as California or the East Coast the sociometabolism exceeds the natural biological metabolism, as it does in England.

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Table 8.2. The modern sociometabolism of high-density and low-density industrial societies (England and the conterminous USA) compared to natural biome metabolism

Region	Per capita sociometabolism ^a	Population density ^b	Per area metabolism	Total sociometabolism	Biometabolism ^c
England	8000 W	407 km ⁻²	3.3 MW km ⁻²	0.4 TW	0.2 TW
Conterminous USA	12000 W	38 km ⁻²	0.5 MW km ⁻²	4 TW	9 TW

Notes

^a derived from Krausmann et al. (2008, table 1).

^b ONS (2013: 2) and derived from USCB (2013).

^c extracted from the dataset for specific countries in Field et al. (1998)

Source: author's calculation unless otherwise stated.

Globally, the mean per capita metabolism of humanity today is 2,200 W, reflecting the fact that much of humanity still lives a low-income, agricultural lifestyle.

A World of Resource-Consuming Giant Apes

Other animals have very limited sociometabolism beyond their basic biological metabolism; their total energy appropriation is very close to their metabolic need, and they tend to forage from ecosystems rather than colonize and modify ecosystems through agriculture. How does our extraordinarily enhanced sociometabolism compare to the *biological metabolism* of other animals?

To answer this question we can draw on insights from the metabolic scaling theory of ecology (Brown et al. 2004), and in particular Kleiber's Law, the observation that animal metabolism, B , scaled with body mass, M , approximates as a three-quarter power law:

$$B = k.M^{3/4} \text{ or } B/M = k.M^{-1/4}$$

This implies that larger animals have slower metabolisms per unit of mass. An elephant uses much less energy per unit of mass than a mouse. The metabolic theory of ecology proposes that this decline in metabolic rate is associated with the constraints of the transport network (blood circulation, artery and vein architecture) in larger organisms, which limits maximum metabolic rates. The exact mechanism and value of the power coefficient (here three-quarters) is the subject of some debate (Price et al. 2012), but the broad observation remains valid, that metabolism scales with body mass as a power law that approximates to $M^{3/4}$.

Figure 8.1 plots physiological metabolism against body size for a number of representative animals, including humans. Elephants have larger biological

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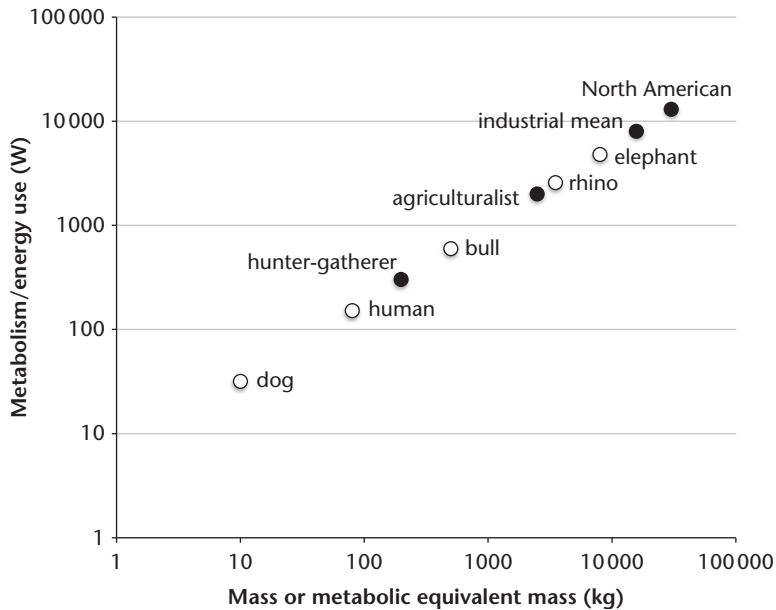


Figure 8.1. Kleiber’s law re-examined

Note: Open circles plot biological metabolism against mass for a variety of animals. The solid circles plotting sociometabolism for humans represent various stages of history: hunter-gatherer, pre-industrial agrarian, and modern industrial (with a separate plot for North American).

Method: The values of animal biological metabolism are calculated by the application of Kleiber’s Law to the average mass of adult animals (sourced from Wikipedia). The equivalent for human sociometabolism calculated from the values in Table 8.1 and the inverse application of Kleiber’s Law.

Source: author

metabolisms than humans, but per unit mass their metabolism is slower, and associated correlates of metabolic rate (such as heart rate) are smaller and timescales (gestation time, gut residence time, natural lifetime) are longer.

Next let us explore sociometabolism for various stages of human lifestyle, plotted on the same diagram (based on Table 8.1). In this case the position on the horizontal axis represents the metabolic equivalent mass: how large the human would have to be to have a biological metabolism of the same size as their sociometabolism. The average hunter-gatherer has a sociometabolism of 300 W, roughly three times their physiological metabolism. This includes direct extraction of food, and also use of materials for fuel. The pre-industrial agrarian human (18th-century agrarian Austria) has a sociometabolism of 2000 W, almost all derived from the colonization of the biosphere through agriculture. This is equivalent to the physiological metabolism of a 2.5-tonne rhino. A modern industrial human has a sociometabolism of 8000 W (or 12,000 W if a North American). This is equivalent to the physiological metabolism of a 10-tonne mammal (or a 15-tonne mammal in North America),

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about 1.4 to 2 times the mass of a large African elephant, the largest extant land mammal. A 10–15-tonne primate, such as King Kong, has existed only in literature (Moses 2005). For an alternative perspective on human impacts on the natural environment, imagine the United Kingdom as a landscape with 63 million 10-tonne apes roaming the landscape, or the United States as a landscape with 310 million 15-tonne King Kongs!

Our access to (primarily) fossil energy has enabled us to sustain exceptional levels of resource consumption and exceptional population densities. We are something new in the metabolic history of this planet; a hypersocial mega-faunal mammal, half-ape and half-ant. It is inevitable that such an organism has major impacts on the functions and metabolism of the wider planet.

A Timeline of Global Sociometabolism

We can multiple the per capita consumption rates of different types of human society by global population estimates to estimate the global sociometabolism of humanity (Haberl 2006; Haberl et al. 2011). Prior to the Neolithic revolution, the total metabolism of humanity was about 300–3000 MW (0.0003–0.003 TW). This compares with global terrestrial GPP of 150 TW, or NPP of 75 TW, and was thus five to six orders of magnitude smaller than terrestrial ecosystem metabolism (Table 8.3).

Following the Neolithic revolution and the colonization of ecosystems, human sociometabolism gradually grew from about 0.3 TW ~~at~~ in the early Neolithic (10,000 years ago), to about 3 TW just prior to the industrial revolution; an increase of between three and four orders of magnitude over pre-agricultural metabolism, but still only 2 per cent of global terrestrial GPP (Table 8.3). (Regionally, this fraction could be much larger.)

The industrial transition, which is far from complete for two-thirds of humanity, has thus far increased human sociometabolism to about 25 TW (Haberl 2006), about 17 per cent of potential terrestrial GPP or 34 per cent of NPP³ (Table 8.3). Of this total metabolism, around 50 per cent is still powered by the biosphere by material flows of biomass food and energy. The remaining 50 per cent is powered by other sources, and overwhelming by fossil fuels (Haberl 2006). Hence currently it is the ability of humanity to exploit the energy that was locked up in the deep past by the biosphere (a fourth, temporal dimension of energy exploitation) that has powered the current

³ Brown et al. (2011) estimated a smaller number for global total human sociometabolism of 17 TW. However, for material flows they only considered human biological metabolism, not including other material flows such as the metabolism of domesticated animals or biomass appropriation for fuel. Hence a higher number such as 25 TW is more plausible. These higher estimates modified from Brown et al. are the basis of the calculations on the next two pages.

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Table 8.3. Global human sociometabolism in comparison to the metabolism of the land biosphere, in various sociometabolic stages and under alternative scenarios for 2050

Period	Global metabolism	Percent of land biosphere metabolism	Human population	Biomass-derived metabolism
Pre-agricultural	0.0003–0.003 TW	2–20 × 10–4%		0.0003–0.003 TW
Pre-industrial	3 TW	2%		3 TW
Modern	25 TW	17%	7 billion	13 TW
2050 (WEC/UNDP)	48 TW	32%	9.3 billion	20 TW
2050 'Global US'	180 TW	120%	9.3 billion	
2050 'Global China'	60 TW	40%	9.3 billion	

Note: The derivation of the final three rows is explained in the main text.

Source: first three rows derived from Haberl (2006) and Haberl et al. (2011).

rapid expansion of human sociometabolism. The 13 TW of metabolism that come directly from biomass are equal to 22 per cent of terrestrial biomass production. The remainder of the sociometabolism is overwhelming powered by fossil fuels.

The total sociometabolism of the conterminous United States is about 4 TW (about 19 per cent of which is biomass material flow). The total natural metabolism (GPP) of the same area is about 9 TW (Table 8.2). For England, the total sociometabolism is around 0.4 TW, and the total natural metabolism is around 0.2 TW—hence in England sociometabolism already dominates over natural metabolism.

The Metabolism of the 21st Century

Now let us examine the 21st-century world. How does contemporary socio-metabolism compare with the current metabolism of the terrestrial biosphere? I focus on the land biosphere, as human appropriation of energy from the biosphere is still overwhelmingly from land, despite intensive harvesting of ocean fisheries. As we have seen, the total photosynthetic energy use of the land biosphere (GPP) is about 150 TW, and the total rate of energy fixation in plant biomass (NPP) is about 75 TW. Hence current human sociometabolism is equivalent to 11 per cent of terrestrial photosynthesis, or 22 per cent of NPP. For comparison, the Amazon rainforest, which amounts to about half of the world's rainforests, accounts for approximately 17 per cent of global photosynthesis (Malhi 2012), or 25 TW of metabolic energy. Human socio-metabolism is approaching that of the entire Amazon rainforest biome, the most biologically productive region of the land biosphere.

The figure of human metabolism accounting for 11 per cent of global terrestrial metabolism may appear reassuringly small, but in fact it is

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astonishing that a single vertebrate species has a total metabolism that approaches that of global vegetation. In natural ecosystems (with the exception of heavily grazed grasslands) all vertebrates have typically accounted for much less than 1 per cent of metabolic activity. As calculated above, in densely populated and industrialized regions such as Western Europe or Eastern China, human sociometabolism already greatly exceeds pre-existing or remnant natural metabolism.

Moreover, there is every indication that, if possible, human sociometabolic activity will increase rapidly this century if energy and resource supply limitations can be met. Using a medium World Energy Council energy use scenario, and a medium United Nations Population Division scenario of 9.3 billion people, human sociometabolism is on course to reach 48 TW by 2050 (Haberl 2006: 94), 32 per cent of terrestrial GPP and 64 per cent of NPP (Table 8.3). The biomass-derived component of metabolism is expected to rise to around 20 TW, or 28 per cent of terrestrial NPP (Table 8.3). The human superorganism would be consuming one third of the biological production of the land surface.

There are strong correlates between energy use and standard of living, and it is hard to conceive of increasing the standards of living of the world's population without a commensurate increase in energy use. To raise the global population of 6.6 billion⁴ to the standard of living of the United States would require an increase of global energy consumption from 25 to 113 TW (as in Brown et al. 2011, but modified to the higher estimate of contemporary sociometabolism calculated here), equal to 1.5 times all of terrestrial NPP or 75 per cent of terrestrial photosynthesis. For a projected global population of 9.5 billion in 2050, maintaining a lifestyle equivalent to current United States lifestyle would require 180 TW, seven times current global energy use, and 1.2 times the total metabolism of the terrestrial biosphere. Even a global population at current mean Chinese standards of living would require 60 TW, 2.5 times current global energy consumption and 40 per cent of total terrestrial metabolism.

Urban metabolism

It is insightful to explore the current human socio-economic metabolism in the context of urban areas. Just as the Neolithic revolution heralded the transformation of our species from a nomadic species to a predominantly small settlement (village) species, the industrial revolution heralded the

⁴ The projection cited here is based on 2006 data. World population reached 6.7 billion in mid 2007, and continues to expand well beyond the 7 billion mark.

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transformation to a predominantly large settlement (urban) species. The facts that our energy supply is no longer tied to immediately accessible land area, and that our abundance of energy has enabled development of efficient transportation and distribution networks have made it possible for *Homo sapiens* to live in high density urban areas.

In the early 21st century we are in the full fury of this transition: over 50 per cent of the human population is now urban and this proportion is expected to approach 70 per cent by 2050 (UN-DESA 2012). For most continents, urban dwellers already exceed 70 per cent of the total population, and in the two less urban continents (Asia and Africa) the urban proportions are around 39 to 45 per cent and are increasing at 2 to 4 per cent per decade (UN-DESA 2012). This trend is not just in the high-profile megacities, but in numerous smaller towns and cities. We are increasingly a hypersocial species living in colonies of hundreds of thousands to millions of individuals, akin to ~~the~~ social insects (Wilson 2012). How does the metabolism of our cities compare to that of the social insects, say in a termite colony?

First, let us consider social insect colonies. Rather surprisingly, social insect colonies seem to follow Kleiber's Law, in an extrapolation of the metabolism of individual insects (Hou et al. 2010). In terms of metabolic physiology, a termite colony behaves much like a single gigantic termite of equivalent size. This means that the metabolism per unit mass of termite (or per individual termite) is slower in a large colony than in a small one. Quite why this happens remains a puzzle, but may be associated with the decreased amount of foraging required per individual in a large termite colony.

Now let us turn to social *Homo sapiens* colonies, in the form of cities. Do towns or cities also 'slow down' (per individual human) as they get larger? As anyone from the hinterland who spends a day in London, New York, São Paulo, Lagos, Mumbai, or Tokyo can testify, they most certainly do not. Bettencourt et al. (2007) compiled data of various measures of activity in cities worldwide. They found that many metrics scaled superlinearly with city size ($\beta > 1$). This included (most amusingly) the rate at which people walk, but also other metrics such as wages, income, gross domestic product, bank deposits, and rates of invention. All of these are approximate metrics of sociometabolism.

A number of metrics associated directly with population scaled isometrically with city size ($\beta \sim 1$), including the number of jobs, number of houses, and consumption of water. These are metrics that broadly track individual human needs, and hence track human population. Other metrics associated with infrastructure networks (for example, number of fuel stations, length of electrical cables, total road surface) scale sublinearly ($\beta < 1$). These metrics show economies of scale in energy transport, similar to individual organisms and termite colonies.

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So, unlike social insects, social humans become more active the bigger their colony gets, because of the intensified opportunities of knowledge exchange, innovation, and efficient partition of labour. Rather than functioning like termite colonies, human cities are more akin to stars, which burn more fiercely the larger they get (Bettencourt 2013). Cities are immense social reactors for humanity, burning more fiercely with activity and innovation the larger their human mix.

Growth driven by linear scaling is exponential (Bettencourt et al. 2007). Hence insect megacolonyes show sub-exponential growth in metabolism over time; human megacolonyes show superexponential growth. Superexponential growth has its challenges, though—under fixed background conditions it is impossible to sustain because ultimately the resources needed to sustain the city's sociometabolism become limited (that is, the city reaches environmental carrying capacity—its environment becomes 'full'), leading to possible metabolic collapse.

How have cities circumvented this? Bettencourt et al. (2007) suggest that innovation is the key. Innovation in the generation, extraction, transportation, and use of socio-metabolic energy and other resources avoids resource collapse. Cities are founts of local innovation, and also now increasingly connected to exchange innovation at a global scale. Each innovation staves off resource collapse, but also points to the next resource limitation. Bettencourt et al. (2007) illustrate this by examining time series data of New York City's rate of population growth, and show periods of increased and decreased growth that match this model. The innovation can be technical, but can also come in the form of governance, such as well-organized public transport systems.

Summary and Conclusions: An Anthropocene Perspective

In this chapter I have argued that a socio-metabolic perspective can provide valuable insights into the question 'is our planet full?'. In the sense that our species' metabolism is coming to dominate and overwhelm the natural background metabolism of the planet, the answer to that question is an undeniable 'yes'. This does not mean that it cannot or will not be filled even more, but that such fullness is having inevitable consequences on all aspects of planetary and biosphere function.

Most of the current range of environmental challenges can be traced back to the size of our sociometabolism relative to that of the local ecosystem or the planet as a whole, from resource overconsumption (overfishing, habitat loss, biodiversity loss, depletion in phosphorus) to excessive metabolic waste productions (atmospheric pollution and climate change, excess nitrogen,

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waste-disposal capacity). Hence many of the current challenges of sustainability can be viewed through the lens of energetic metabolism. How do we reduce carbon dioxide waste by-products while maintaining the work done by our global metabolism? How do we maintain the biomass supply our metabolism requires without other species losing habitat and living space? Even with a potential future cheap and non-polluting energy supply (cheap solar, or nuclear fusion) can we continue to increase our sociometabolism indefinitely, or will limits to other material sources (food biomass, or phosphorus) constrain it? And what are the consequences for the other denizens of the biosphere?

Humanity, this hyperactive, hypersocial, megafaunal ape, has a heavy impact on the planet, fundamentally powered by a fossil fuel sociometabolism that provides us with abundant energy to transform the planet. Even if our sociometabolism shifts from fossil fuels to some form of energy with less problematic waste products, the other consequences of our active ability to consume and transform the planet remain.

The preceding examination of urban areas is a good analogy for our human predicament as a whole (not least because humanity has become more and more urban, and will become overwhelmingly urban over the course of the 21st century). Modern human history is a constant race between resource overconsumption and innovation. As humans aggregate in the social reactors that are cities and communicate with ever-greater intensity through planet-spanning telecommunications, and as greater numbers of human minds become embedded in this planet-spanning communications network, the pace of innovation has managed to keep pace with the pace of resource consumption, leading to ever-increasing global sociometabolism that in many regions greatly exceeds the metabolism of the natural biosphere. As global sociometabolism approaches the total biological metabolism of the land surface biosphere, will innovation be able to keep winning the race against resource overconsumption? And can this state of continuous dynamic instability be sustained indefinitely, or will a new stable state of resource use be attained? If the latter is even possible, what would it look like?

The innovations that our urbanized and interconnected species can bring to bear on these challenges are not only technological; they can also be innovations in governance and administration, as we continually seek new ways to self organize our local, regional, and global polity to effectively utilize our shared and limited resources, to limit our impacts on fellow species, and to meet the challenge of collectively managing our global resources. A great challenge of our time is that the size and global reach of our sociometabolism has led to resource-limitation and waste-production challenges at a global scale—a scale at which our existing governance structures struggle to act effectively. One obvious example is the slow pace of progress to a global

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agreement for action on climate change, despite the rapid rise of greenhouse gases in the atmosphere that is apparent to (almost) all.

Is there a limit to the size of global human sociometabolism? Can we determine some sort of planetary boundary for sociometabolism that to some extent integrates several existing proposed planetary boundaries? The answer is not clear. One aspect that is likely to be limited is the fraction of metabolism (currently 50 per cent of our total sociometabolism) linked to material resource flow, as it is difficult to change the ability of the biosphere to increase its supply of such resources while at the same time providing some resources and space for its other inhabitants and maintaining overall function and stability. The portion of sociometabolism not directly linked to biosphere material resource flow (most of industrial energy) is not so strongly constrained by the ability of the biosphere to supply, and any planetary boundary in sociometabolism needs to be considered in terms of its impacts on the biosphere, atmosphere, and hydrosphere, whether through waste products (especially in the case of fossil fuels) or simply through the effects of the sheer number and activity of high-energy industrial humans in altering the planet's surface and biospheric function.

As a major 'force of Nature' humanity has come to define the Anthropocene. The human expansion and domination of the Earth system over the past 10,000 years, albeit fleetingly recent in the 4.6 billion year context of Earth history, represents a major transition in the nature of life on Earth, comparable energetically to the colonization of land by plants. A major challenge of our time is to innovate and develop the global governance structures to minimize the overexploitation and degradation of the global commons, and to avoid critical and dangerous thresholds in the biosphere and atmosphere, while at the same time maintaining the creativity and ability of humanity to innovate in both the social and technological spheres. The innovations can be technological, but they can also be innovations in governance, as we continually seek new ways to self organize our global polity to effectively govern our shared and limited resources, to limit our impacts on fellow species, and to meet the challenge of collectively managing the Anthropocene.

References

- Bala, G., Caldeira, K., Wickett, M., Phillips, T. J., Lobell, D. B., Delire, C., and Mirin, A. (2007). 'Combined Climate and Carbon-Cycle Effects of Large-Scale Deforestation', *Proceedings of the National Academy of Sciences*, 104(16): 6550–5.
- Barnosky, A. D. (2008). 'Megafauna Biomass Tradeoff as a Driver of Quaternary and Future Extinctions', *Proceedings of the National Academy of Sciences*, 105: 11543–8.

Is the Planet Full?

- Barnosky, A. D., Koch, P. L., Feranec, R. S., Wing, S. L., and Shabel, A. B. (2004). 'Assessing the Causes of Late Pleistocene Extinctions on the Continents', *Science*, 306: 70–5.
- Bettencourt, L. M. A. (2013). 'The Origin of Scaling in Cities', *Science*, 240, 1438–41.
- Bettencourt, L. M. A., Lobo, J., Helbing, D., Kuhnert, C., and West, G. B. (2007). 'Growth, Innovation, Scaling, and the Pace of Life in Cities', *Proceedings of the National Academy of Sciences*, 104: 7301–6.
- Bouckaert, R., Lemey, P., Dunn, M., Greenhill, S. J., Alekseyenko, A. V., Drummond, A. J., Gray, R. D., Suchard, M. A., and Atkinson, Q. D. (2012). 'Mapping the Origins and Expansion of the Indo-European Language Family', *Science*, 337: 957–60.
- Brodribb, T. J. and Feild, T. S. (2010). 'Leaf Hydraulic Evolution Led a Surge in Leaf Photosynthetic Capacity During Early Angiosperm Diversification', *Ecology Letters*, 13: 175–83.
- Brown, J. H., Burnside, W. R., Davidson, A. D., DeLong, J. P., Dunn, W. C., Hamilton, M., Mercado-Silva, N., Nekola, J. C., Okie, J. G., Woodruff, W. H., and Zuo, W. Y. (2011). 'Energetic Limits to Economic Growth', *Bioscience*, 61: 19–26.
- Brown, J. H., Gillooly, J. F., Allen, A. P., Savage, V. M., and West, G. B. (2004). 'Toward a Metabolic Theory of Ecology', *Ecology*, 85: 1771–89.
- Burnside, W. R., Brown, J. H., Burger, O., Hamilton, M. J., Moses, M., and Bettencourt, L. M. A. (2012). 'Human Macroecology: Linking Pattern and Process in Big-Picture Human Ecology', *Biological Reviews*, 87: 194–208.
- Curnoe, D., Xueping, J., Herries, A. I. R., Kanning, B., Taçon, P. S. C., Zhende, B., Fink, D., Yunsheng, Z., Hellstrom, J., Yun, L., Cassis, G., Bing, S., Wroe, S., Shi, H., Parr, W. C. H., Shengmin, H., and Rogers, N. (2012). 'Human Remains from the Pleistocene-Holocene Transition of Southwest China Suggest a Complex Evolutionary History for East Asians', *PLoS ONE*, 7(3): e31918.
- Diamond, J. (2002). 'Evolution, Consequences and Future of Plant and Animal Domestication', *Nature*, 418: 700–7.
- Doughty, C. E., Wolf, A., and Field, C. B. (2010). 'Biophysical Feedbacks Between the Pleistocene Megafauna Extinction and Climate: The first Human-Induced Global Warming?' *Geophysical Research Letters*, 37(15): L15703.
- Doughty, C. E., Wolf, A., and Malhi, Y. (2013). 'The Legacy of Pleistocene Megafaunal Extinctions on Nutrient Distribution in Amazonia', *Nature Geoscience*, Advanced Online Publication, DOI: 10.1038/NGEO1895.
- Ellis, E. C., Goldewijk, K. K., Siebert, S., Lightman, D., and Ramankutty, N. (2010). 'Anthropogenic Transformation of the Biomes, 1700 to 2000', *Global Ecology and Biogeography*, 19: 589–606.
- Field, C. B., Behrenfeld, M. J., Randerson, J. T., and Falkowski, P. (1998). 'Primary Production of the Biosphere: Integrating Terrestrial and Oceanic Components', *Science*, 281: 237–40.
- Fischer-Kowalski, M. and Haberl, H. (1998). 'Sustainable Development: Socio-Economic Metabolism and Colonization of Nature', *International Social Science Journal*, 50(158): 573–87.
- Goldin, I., Cameron, G., and Balarajan, M. (2011). *Exceptional People: How Migration Shaped Our World and will Define our Future*. Princeton, NJ: Princeton University Press.

The Metabolism of a Human-Dominated Planet

- Haberl, H. (2006). 'The Global Socioeconomic Energetic Metabolism as a Sustainability Problem', *Energy*, 31: 87–99.
- Haberl, H., Erb, K. H., Krausmann, F., Gaube, V., Bondeau, A., Plutzer, C., Gingrich, S., Lucht, W., and Fischer-Kowalski, M. (2007). 'Quantifying and Mapping the Human Appropriation of Net Primary Production in Earth's Terrestrial Ecosystems', *Proceedings of the National Academy of Sciences*, 104, 12942–5.
- Haberl, H., Fischer-Kowalski, M., Krausmann, F., Martinez-Alier, J., and Winiwarter, V. (2011). 'A Socio-Metabolic Transition Towards Sustainability? Challenges for Another Great Transformation', *Sustainable Development*, 19: 1–14.
- Hou, C., Kaspari, M., Zanden, H. B. V., and Gillooly, J. F. (2010). 'Energetic Basis of Colonial Living in Social Insects', *Proceedings of the National Academy of Sciences*, 107: 3634–8.
- Krause, J., Fu, Q., Good, J. M., Viola, B., Shunkov, M. V., Derevianko, A. P., and Pääbo, S. (2010). 'The Complete Mitochondrial DNA Genome of an Unknown Hominin from Southern Siberia', *Nature*, 464(7290): 894–7.
- Krausmann, F., Fischer-Kowalski, M., Schandl, H., and Eisenmenger, N. (2008). 'The Global Sociometabolic Transition', *Journal of Industrial Ecology*, 12(5–6): 637–56.
- Larsen, C.S. (1995). 'Biological Changes in Human Populations with Agriculture', *Annual Review of Anthropology*, 24: 185–213.
- Malhi, Y. (2012). 'The Productivity, Metabolism and Carbon Cycle of Tropical Forest Vegetation', *Journal of Ecology*, 100(1): 65–75.
- Malhi, Y., Baldocchi, D. D., and Jarvis, P. G. (1999). 'The Carbon Balance of Tropical, Temperate and Boreal Forests', *Plant Cell and Environment*, 22: 715–40.
- Moses, M. E. (2005). *Metabolic Scaling from Individuals to Societies*. Ph.D. Thesis, University of New Mexico.
- ONS (2013). 'Population and Household Estimates for the United Kingdom, March 2011', *Statistical Bulletin*, 21 March. Newport: Office for National Statistics. Last accessed 31 August 2013. <http://www.ons.gov.uk/ons/dcp171778_304116.pdf>.
- Price, C. A., Weitz, J. S., Savage, V. M., Stegen, J., Clarke, A., Coomes, D. A., Dodds, P. S., Etienne, R. S., Kerkhoff, A. J., McCulloh, K., Niklas, K. J., Olf, H., and Swenson, N. G. (2012). 'Testing the Metabolic Theory of Ecology', *Ecology Letters*, 15, 1465–74.
- Roy, J. and Saugier, B. (2001). 'Terrestrial Primary Productivity: Definitions and Milestones', in J. Roy, M. A. Mooney, and B. Saugier (Eds), *Terrestrial Global Productivity*. San Diego, USA: Academic Press, pp. 1–6.
- Rule, S., Brook, B. W., Haberle, S. G., Turney, C. S. M., Kershaw, A. P., and Johnson, C. N. (2012). 'The Aftermath of Megafaunal Extinction: Ecosystem Transformation in Pleistocene Australia', *Science*, 335: 1483–6.
- UN-DESA (2012). *World Population Prospects: The 2011 Revision*. New York: United Nations, Department of Economic and Social Affairs, Population Division.
- USCB (2013). *United States Census, 2010*. Washington, DC: United States Census Bureau. Last accessed 29 August 2013. <<http://www.census.gov/>>.
- Wilson, E. O. (2012). *The Social Conquest of Earth*. New York: Liveright Publishing Corporation.