The Major Transitions in the History of Human Transformation of the Biosphere

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Abstract

The aim of this interdisciplinary review is to provide a new framework for the research in the history of human transformation of the biosphere. It focuses on the major transitions, which resulted in a considerable increase in our species' impact on the biosphere (in relation to the state before the transition). Six such transitions are identified, in chronological order these are: 1) the use of fire, 2) language, 3) agriculture, 4) civilization (states), 5) European conquests and 6) the technological-scientific (r)evolution and the dominance of fossil fuels as primary energy sources. Such an inquiry of our biosphere transforming activities may be of great importance in establishing ecologically sustainable societies.

Keywords: *human transformation of the biosphere, human evolution, environmental history, global change, sustainability*

Introduction

Every living organism transforms the biosphere — the part of the Earth in which life engaged in active metabolism naturally exists (Hutchinson 1970) — to a certain extent (Odling-Smee, Laland and Feldman 1996), but *Homo sapiens* is by far the most efficient species in this respect.[2] Our biosphere transforming activities have become so extended that even our own well-being — as well as the existence of many other species — is already threatened. This review outlines the history of our species' becoming so different from other species in regard to transformation of the biosphere. In other words, it describes the history of the increase in the extent (and pace) of this transformation. This increase has not been linear. Transitions can be identified, which resulted in a considerable increase in our impact on the biosphere, *not in absolute terms, but in relation to the situation before the transition*. In some cases these increases took several millennia or even more, that is the transitions were not always "revolutionary" changes. In this article the six most important transitions are examined. In chronological order these are:

- The use of fire — from at least 250,000 years ago.
- Language — from at least 40,000 years ago.
- Agriculture — from at least 10,500 years ago.
- Civilization (states) — from about 5,500 years ago.
- European conquests — from the 15th century A.D.
- The technological-scientific (r)evolution and the dominance of fossil fuels as primary energy sources — from about the second half of the 18th century A.D.

Ranking the transitions according to their importance would be a hard task and it is not the aim of this article. Nevertheless, this does not mean that each of the transitions was followed by an equal increase — either in absolute terms or in relation to the situation before the transition — in our transformation of the biosphere.[3]

The Model

In discussing the major transitions the model of Holdren and Ehrlich (1974) is used. According to this model, the extent of human transformation of the biosphere depends on three factors *directly* (and is in direct proportion to all of them): 1) population size, 2) per capita economic output, and 3) environmental impact (i.e., transformation of the biosphere) per unit economic output. (Obviously, the three factors are not independent and behind these direct causes there can be found an intricate web of indirect ones.) It is worth dividing the third factor into further elements. The environmental impact per unit economic output depends on at least three factors: 1) how "environmentally friendly" are the technologies used, 2) what is the structure of the economy (whether it is composed of economic activities causing greater or lesser environmental impact), and 3) what is the spatial pattern of the economy (to what extent the certain phases of the economic process are separated in space — in most cases environmental impact increases with greater separation).

Model and Framework: Problems and Virtues

The Holdren-Ehrlich model is highly suitable for use and provides an appropriate guideline for the discussion of this article. Nevertheless, it has some drawbacks as well. Here, one of these is worth emphasizing: the model fails to describe the dynamics of changes, in other words, it does not reflect the pace of environmental transformation. In regard to the adaptability of nature and society, however, not only the absolute extent of a certain environmental transformation, but also the length of its time interval is important (see Dietz and Rosa 1994 for more). (The chances of adaptation decrease with increasing pace of transformation.)

The above-mentioned events can be considered as transitions, because they all increased considerably at least one of the three factors in the model. However, since — at least in this model — the extent of human transformation of the biosphere cannot really be determined numerically, the identification of the major transitions is inevitably subjective. Therefore, theoretically it is possible to identify less or more transitions than those discussed in this article. In spite of this limitation, identifying the six major transitions discussed here seems to be plausible according to our current state of knowledge.

A complex approach is used to identify and discuss the major transitions. I rely on both the natural and social sciences as well as philosophy, without giving distinguished role to either of these. I believe that natural forces, social structures and ideas (or values held by people) have played almost equally important roles in shaping our biosphere transforming activities. Likewise, these activities have shaped the social structures, and ways of thinking as well. Thus, this review leans on the results of several disciplines, hopefully providing new insights not visible from narrower perspectives.

To my knowledge, the history of human transformation of the biosphere has not yet been investigated focusing on such major transitions. Although some other works are similar to this one in some respects, there are considerable differences. It is because these other papers determine the major transitions from a single aspect only (e.g., Bennett and Dahlberg 1990; Simmons 1996), concentrate on shorter time intervals (e.g., Crosby 1986; McNeill 2000; Meyer 1996; Turner et al. 1990), discuss considerably fewer major transitions (Ponting 1991), or use a different framework (e.g., Simmons 1993).

Although this article examines the history of human transformation of the biosphere from our species' origins to the present, it is inevitably fragmentary because it concentrates mostly on the periods of the major transitions, puts more emphasis on the consequences of the transitions than on their causes, and focuses mainly on the socially most important environmental changes. Furthermore, it should be considered not more than a brief account, aiming mainly at the stimulation of discourse and further research by providing a new framework.

First Transition: The Use of Fire

Our species, *Homo sapiens*, originated from *Homo erectus* about 600,000 years ago (Clark et al. 1994). The first undisputed direct evidences of human use of fire (a technological change[4]) are related to Homo sapiens. These are about 250,000 years old and derive from Europe and the Near East (Pennisi 1999). Archaeological evidence, however, indicates that humans were able to survive in northern Eurasian habitats (above about 50˚ N latitude) by about 500,000 years ago, which would have been rather difficult without fire (Stiner 2002).[5]

The domestication of fire was an important prerequisite for the use of *biomass energy* (and much later for that of fossil fuels). Biomass was our *first extrasomatic energy source* and it has remained important ever since. (The amount of extrasomatic energy available to us correlates positively with the extent of transformation of the biosphere.)

The use of fire has increased transformation of the biosphere for the following reasons (Bellomo 1994):

- Fire made possible the clearing of vegetation (even in large areas).[6] Later, it became useful in hunting large animals — by the help of fire they could have been driven toward the place of slaughtering.
- Fire could have been important in keeping off carnivores dangerous to humans. It is likely that this was our first efficient means against them. This may have resulted in the growth of human populations.
- The use of fire made easier the peopling of colder areas and made possible the inhabitation of very cold places. The expansion of the geographical area of humans is usually accompanied by the growth of the world population.
- Cooking has been an important utilization of fire. By cooking, potential foods unavailable before have become palatable and also the digestibility of some kinds of food was improved (Wrangham et al. 1999). Energy input increased in this way could have significantly contributed to the increase in the relative size of the brain (its size in relation to body size), an organ demanding a lot of energy (Aiello 1998). (This contribution certainly does not mean a simple cause-effect relation.) Relative brain size correlates positively with mental capacities and any increase in the latter results in extended transformation of the biosphere (mainly by the increase in technological complexity).

Furthermore, since cooking disinfects food, it has decreased the burden of pathogens, thus contributing to the growth of human populations.

Second Transition: Language

The Appearance of Language

Since language does not fossilize, the date of its origin can only be estimated by indirect (archaeological and anatomical) evidences, according to which only a relatively broad time interval can be determined. However, it is plausible to choose a broad interval, since the appearance of language was not necessarily a sudden event. It might also have been a gradual process taking tens of thousands or hundreds of thousands of years. The first widely accepted evidences of a complex, spoken language similar to ours — distinguished by the existence of syntax from the "protolanguage" of our earlier ancestors allowing only minimal communication (Calvin and Bickerton 2000)[7] — are about 40,000 years old (Holden 1998). The first undisputed signs of art date back to this time (e.g., jewels, cave paintings, musical instruments, etc.) suggesting the existence of language, since both art and language require symbols that possess the same meaning for every member of the community (e.g., Mellars 1998). However, the spectacular geographic spread of our ancestors and some older (disputed, but likely) evidences of art (e.g., Henshilwood et al. 2002; see also Balter 2002) suggest an earlier appearance of language. Moreover, some archaeological evidences (e.g., the appearance of several new technologies) indicate considerable improvements in the cognitive abilities of certain African *Homo sapiens* populations from about 280,000 years ago (McBrearty and Brooks 2000), which might refer to the existence of language, or some primitive form of it.

Nevertheless, it is also possible that language is the privilege of modern humans — the subspecies *Homo sapiens sapiens*,[8] to which every recent human belongs (Stringer 2002) — appearing first in Africa, most probably between 130,000 and 200,000 years ago (Hedges 2000). Early 130,000 year old fossils of modern humans indicate that these ancestors already possessed the brain capacity[9] and special anatomy of mouth and throat needed for (spoken) language. Therefore, they might already have had language (Holden 1998; Pinker 1994).

Consequences of the Possession of Language

More Efficient Communication, More Advanced Thinking. Obviously, language rendered communication much more efficient, making possible the appearance of more complex and better functioning human communities. Language also resulted in more advanced thinking; that is, it considerably increased our mental abilities. Thinking is the mental representation of the world and also the manipulation of this representation. Both are made more efficient by language (for example, by the recognition of conceptual relations).[10] Language made possible abstract conceptual thinking, which rendered humans capable of referring to objects remote in space or time. For instance, longer term planning built on past experiences appeared, and due to better communication, planning has increasingly become a collective action.

Through more efficient communication and increased mental abilities language caused a significant extension of human transformation of the biosphere. This was partly realized by the quite sudden and unprecedented increase in technological complexity beginning about 280,000 years ago (which suggests an early appearance of language). Not only more tools, but also qualitative changes can be observed in the findings. For example, the appearance of composite tools and single-purpose stone tools and later materials, such as bone, never or rarely used before (Mellars 1998; Ambrose 2001). New hunting tools (Bar-Yosef 2002) and skills also became widespread. For instance, better communication made collective hunting more efficient, making possible the hunting of large animal species that were probably killed only occasionally before (Diamond 1997). These achievements — together with the more efficient exchange of information because of better communication, and the increase in the distance of trade (Bar-Yosef 2002) that insured greater existential certainty in times of dearth by making distant resources available — resulted in the increased exploitation of natural resources. This in turn may have caused population growth (McBrearty and Brooks 2000), as shown by indirect evidences (Stiner, Munro and Surovell 2000).

Peopling of the Planet. Modern humans first migrated out of Africa about 100,000 years ago. In a few tens of thousands of years they have peopled most of the habitable lands on Earth (Hedges 2000), displacing or exterminating other humans formerly inhabiting those lands. According to molecular genetic data interbreeding might also have occurred in several places (Templeton 2002). It is likely that this fast spreading of modern humans was eventually a result of the possession of language, and especially the accompanying new hunting skills and tools.

The oldest East Asian finding of modern humans is 67,000 years old (Hedges 2000). However, unlike the earlier human inhabitants of this region, modern humans did not stop at the Eastern shores of Asia, but presumably built water crafts (boats or rafts) and reached Australia about 52,000–60,000 years ago. In a few thousand years after human arrival most of the continent's large animal species have become extinct. It is likely that these extinctions were caused primarily by the overhunting and habitat destruction of the first Australians (Diamond 1989, 2001).

The first archaeological evidences of sewn clothes, needles made of bone and tents made of animal skins and bones are about 40,000 years old (Stiner 2002) and originate from Europe (another destination of modern humans). These clothes and tents were indispensable for peopling colder areas uninhabited before. The first findings indicating human presence beyond the Arctic Circle are about 36,000 years old (Pavlov, Svendsen and Indrelid 2001), and a few thousand years later humans reached Siberia and Northeast Asia as well. The first human inhabitants of America arrived from these areas about 13,000–15,000 years ago. Similarly to Australia, the colonization of the continent was accompanied by the extinction of many large animal species (especially mammals). Although the contemporaneous termination of the last Ice Age may complicate the explanation, it is very likely that humans were primarily to blame for these extinctions (Diamond 1989, 1991, 2001). In each case, the peopling of new areas resulted in the growth of the world population.

Third Transition: Agriculture

Birth of Agriculture

Until the birth of agriculture all humans were hunter-gatherers. Agriculture can be defined as the production of food in most cases involving the help of domesticated species (i.e., species with special traits selected according to human goals). According to the first undisputed evidences, agriculture as defined appeared for the first time in human history in the Fertile Crescent region of the Near East about 10,500–11,500 years ago (Bar-Yosef 2002).[11] At least four causes may have been responsible for the birth of agriculture (Flannery 1969; Diamond 1997) and it is likely that a different combination of these operated in different areas of the world (Flannery 1973): 1) overhunting may have decreased the number of wild animal species available, making necessary the intentional propagation and selection of certain animals; 2) the termination of the last Ice Age may have increased the availability of cultivable wild plant species; 3) the advances in the technologies of collection, processing, and storing of wild species also made plant cultivation possible; and 4) these technologies could have triggered population growth, which in turn may have enforced the switch to food production, suitable for the provision of more people than hunting-gathering.

Consequences of the Birth of Agriculture

Population Growth. The considerable increase in population (and in population density) was not only a cause, but also a consequence of the switch to agriculture.

First, the number of people that can be supported by a given area is one or two orders of magnitude higher, if the area is dedicated to food production instead of a natural ecosystem, where people make their living by hunting and gathering. In an agricultural area most species are potential food for humans, while in a natural ecosystem there can be found a lot of organisms unpalatable for human consumption (Diamond 1997, 2002).

Second, the combination of agriculture and sedentary lifestyle (the latter usually accompanying the former[12]) led to more births. The nomadic lifestyle of most hunter-gatherers allowed childbirth in only every fourth year on average, because mothers were not able to carry more than one child at a time during foraging (at least not without impeding their own food gathering activity). Sedentary lifestyle in itself did not suffice for changing this situation. Agriculture was also required, since it has concentrated the food necessary for a human community to a smaller area making long distance foraging unnecessary, and thus allowing shorter birth intervals (Ingold 1982).[13]

Third, with the birth of agriculture the social status of women changed for the worse as they lost their vital role as food gatherers in the community. The subjugation of women can be observed in most societies in the last 10,000 years, often contributing to more childbirth than they really wanted (Gowdy 1998).

Increase in Social Inequality — Centralization. Since in the hunter-gatherer societies everyone shared the same main task (acquiring food) and the nomadic lifestyle made the accumulation of wealth or food surplus meaningless, or even impossible,[14] these societies were more or less egalitarian regarding power, wealth, and social status (Woodburn 1982; Gowdy 1999).[15] In contrast, agriculture and sedentary lifestyle led to greater inequalities within the society. The appearance of *storable food surplus*[16] has allowed societies to provide for specialists dedicating less time to food production (e.g., chiefs) and sedentary lifestyle has made possible the possession of non-moveable properties. As a consequence, people began to differ in their power, wealth, and status in many agricultural societies.

By the increase of social inequality, competition among people (and groups of people) — often involving violence, even armed violence — for more power, wealth, and higher social status has become more frequent (Knauft 1991). This competition among individuals or groups has been a major cause of the transformation of the biosphere, increasing all the three factors of the Holdren-Ehrlich model. Population growth has been promoted by competition among groups of people, since a group consisting of more people has had a greater chance to win the competition. This can be true even if many people have lost their lives in the violent conflicts. Competition may be seen as an important reason for the above-mentioned pressing of women to give birth to more children. The value of the other two factors has been increased by competition among both individuals and groups. The means increasing success in competitions have been acquired by increasing economic output. The latter in turn has been realized by the spread of technologies that cause increasing transformation of the biosphere (especially the increasing exploitation of natural resources).

Because of social inequalities, population growth, and an increasing competition among groups of people many (but not all) agricultural societies have become centralized. This means that power elites have acquired power-exerting, economic, informational, and jurisdictional monopolies. Thus, they have been able to put other people in the service of their own competitions, exploiting, for instance, the muscle power or the mental abilities of others. This has increased transformation of the biosphere, since in a sense they have often created "megamachines" consisting of people (Mumford 1967), though these have become frequent and really mega-sized only with the appearance of civilization. Power elites have been interested in promoting population growth, since more people mean a bigger army and more taxes, both increasing the power of these elites (Bodley 1994).

Detachment From Nature — The Transformation of Natural Ecosystems. By the appearance of agriculture and a sedentary lifestyle, natural ecosystems have increasingly become mere resources instead of places of living. People — and in particular power elites making decisions and usually in command of the means of production — have become increasingly detached from nature, thus feeling less and less the environmental effects of their actions and their dependence on natural processes.

Agricultural ecosystems have been substituted for natural ones, resulting mainly in deforestation, since most crops are not woody and many domestic animals need pastures. Likewise, the increased need for timber (e.g., as a building material required for sedentary lifestyle) has also sped up the rate of deforestation, which usually led to increased soil erosion. In order to gain new arable lands, people also began to break up grasslands and drain wetlands. Fodder growing for certain domestic animals has been another reason for bringing more land into cultivation.

Increase of Technological Complexity. Agriculture and a sedentary lifestyle triggered the increase of technological complexity for three reasons: 1) the appearance of specialists (until the birth of civilization only part-time specialists) dealing with technology became possible, 2) the appearance of non-moveable properties accelerated the increase in the complexity of some already existing technologies, such as pottery or weaving (Diamond 1997, 2002), and 3) the increasing competition among individuals and groups was also important in this respect.

The Janus-Faced Triumph of Agriculture

Why did almost every human society switch from hunting and gathering to agriculture? Beside the four causes mentioned earlier, a fifth one can also be outlined relying on the previously mentioned facts: food producers gained ascendancy over hunter-gatherers. In the fight between food producers and hunter-gatherers the former had the advantage of a bigger population, a more complex technology, and later, professional soldiers as well. Also, food producers had more pathogens helping the conquest of hunter-gatherers (Diamond 1997).[17] Eventually, food producers gradually displaced the groups of hunter-gatherers. Though the latter still exist in small numbers (cf., Lee and Daly 1999), they have managed to survive only on lands virtually unsuitable for agriculture.

Food-producing societies —even ones without civilization — have often undermined the ecological basis of their living, causing their own collapse (though many of these societies have been very stable, lasting for thousands of years), while there is much less evidence of such a "suicidal" feature among hunter-gatherer societies (Diamond 1991, 1994; McDaniel and Gowdy 1999). Without agriculture, however, civilization would have never emerged.

Fourth Transition: Civilization (states)

Civilization is a notoriously vague term that for the purposes of this paper can be defined as the "complex of cultural phenomena which tends to occur with the particular form of socio-political organization known as the state" (Flannery 1972 — see also for a definition of state).[18] Important features distinguishing the state from other forms of socio-political organization include — among others — cities and social stratification. The former also means that sedentary lifestyle — not always necessary for agriculture — was essential for civilization (Higgs and Vita-Finzi 1972). Writing, the use of metals, mechanical devices amplifying the power of muscles, agricultural practices intensifying food production (particularly irrigation and the plow) and the use of new energy sources (particularly the muscle power of domesticated animals) are frequent (but not essential) further ingredients of states (civilizations) playing a significant role in the transformation of the biosphere.

Early Urbanization. The appearance of the first cities in Mesopotamia — symptoms of population growth — meant the birth of the first civilization about 5,500 years ago. The beginning of the use of animal traction helped urbanization significantly (see also below). The detachment from agriculture by moving to cities has resulted in further separation from nature: when living in cities the environmental effects of our various actions and our dependence on natural processes are experienced to a lesser degree.

Social Stratification/Increased Centralization. Full-time, non-food-producing specialists (e.g., kings, soldiers, scribes, etc.) were virtually absent from human societies until the rise of civilization (Childe 1950). Then, however, their appearance became possible due mainly to enough storable food surplus. Societies began to stratify, for instance, occupational castes or classes of craft specialists appeared (Flannery 1972, 1995). Full-time specialists dealing with technology (e.g., craftspeople) triggered the increase of technological complexity. With increasing stratification, which also means greater social inequalities, both competition among individuals or groups and centralization have usually become more pronounced, which has led to the accentuation of their previously-discussed consequences.

Writing. Although the most ancient civilizations of the world evolved before the appearance of writing (first in Eurasia about 5,000 years ago), it can be found in most civilizations. Writing has made easier the passing of information within a generation. Furthermore, it has made possible a more efficient long-term, intergenerational preservation of information and the preservation of more information as well. Accordingly, writing has significantly helped centralization.[19] Because of the above-mentioned reasons — though only indirectly, for example through the better organization of economic activities — writing has contributed to the extension of the human transformation of the biosphere.

Metals. The use of metals started with copper about 6,000-8,000 years ago, before the rise of civilization. However, "classic" metallurgy involving smelting and casting began contemporaneously with civilization, about 5,500 years ago in the Near East, also with copper (Smil 1994). Pronounced social stratification was likely to be an important condition for the appearance of more complex metallurgy, since metalworkers have nearly always been full-time specialists (Childe 1950).

Metals have been very significant concerning human transformation of the biosphere. The mining of ores — especially open mining — has often caused serious environmental damages. Metallurgy has consumed a considerable amount of energy, initially gained mainly from the burning of charcoal, which resulted in the acceleration of deforestation (Perlin 1989). In addition, several polluters have found their ways to the environment during this process (Nriagu 1996). Furthermore, metal tools have made environmental transformation easier. Certain metals — in particular heavy metals, such as cadmium, lead, and mercury — polluting the air, soil, and water are toxic for almost every living organism.

However, transformation of the biosphere due to the use of metals increased only gradually over millennia in three steps (the second and the third are related to the next two transitions). First, the extent of transformation of the biosphere increased due to the widespread use of iron from the 1st millennium B.C. For instance, iron tools have made deforestation easier and iron horseshoes and plowshares have increased agricultural yields, thereby triggering population growth (Smil 1994, 1999a). Second, metals reached new continents due to the European conquests (they were known by some societies in America, but were not used for practical purposes, and were completely unknown in Australia). Third, due to the changes in metallurgic technologies, beginning already in the 16th century, and the enormous amount of energy becoming available by the spread of fossil fuels, a greater amount of metals have become worked and spread widely (Nriagu 1996). Moreover, the mass production of more kinds of metals and alloys has become possible.

New Mechanical Devices. New mechanical devices amplifying the power of muscles also appeared. The three simplest of these — levers, pulleys, and inclined plains — have been used in virtually every civilization and their variations and combinations (e.g., wedges, screws, and gearwheels) have also become widespread (Smil 1994).

New Agricultural Technologies. Population growth and the interests of power elites led to the intensification of food production involving new agricultural technologies. The use of some of these has resulted in detrimental ecological effects, afflicting human societies again and again ever since. *Irrigation* — first applied in Egypt about 5,000 years ago — has often resulted in the salinization of soils, a virtually irreversible change on human time scale, since it takes a very long time for these soils to be suitable for cultivation again (Meyer 1996; see Jacobsen and Adams 1958 for ancient examples on salinization). The use of the *plow* — first appearing in Mesopotamia also about 5,000 years ago — has increased erosion by pulverizing the soil and weakening its cover of plants. Despite these drawbacks, the new agricultural technologies increased yields, making possible the further growth of population, and therefore leading to further specialization within the society. This in turn created new possibilities for the increase of technological complexity.

New Energy Sources: Animal Muscles, Water, and Wind. A new extrasomatic energy source, the muscle power of domesticated animals has been used since about 5,000-6,000 years ago, first in the Near East (Sherratt 1981).[20] Horses and bovines played an especially important role in extending human transformation of the biosphere. They increased mobility and made transportation easier, whereby distant resources became more easily accessible, resulting in the growth of both the economic output and the population.[21] Domestic animals also rendered agricultural work easier and thus helped agricultural intensification. Although there are a few examples of the existence of civilizations without the use of animal traction (particularly in the New World before the European conquests), the muscle power of animals greatly eased the birth and maintenance of civilizations. It was mainly because animals made much easier the transport of goods from adjacent areas necessary for supporting dense urban populations (Sherratt 1981).

Further extrasomatic energy sources appeared a few millennia after the rise of the first civilizations. Due to the increase in technological complexity, the energies of water (from about the 1st century B.C.) and wind (from about the 10th century A.D.[22]) have become available to people. However, in most societies these two energy sources have never become dominant (Smil 1999a).

Fifth Transition: European Conquests

Proximate Causes of the Conquests

By the 15th century A.D. Europeans were able to reach other continents, to subjugate the natives, and to settle down. Following are the proximate causes of the conquests, factors not possessed (or possessed only to a lesser degree) by the subjected peoples (Crosby 1986, 1994; Diamond 1997). Ocean-going ships made long travels possible. Centralized state administration, together with writing and printing greatly helped the organization of the conquests. In the subjugation of the natives, Europeans relied on weapons not possessed by the subjugated (e.g., guns or swords of steel). They also had their horses and most significantly the "domesticated" pathogens. The domestic plant and animal species carried with them were essential for settling down on the new continents. However, since almost all of these species were suitable for temperate climates only, Europeans managed to displace native people from large areas in America and in Australia, but were able to settle down only in the southern region of Africa. Other parts of this continent were "merely" colonized by them.[23]

Consequences of the Conquests

As a consequence of the conquests, the inhabited continents of the planet (Eurasia[24], Africa, America, and Australia), which were more or less separated before, have become linked together in biological, social, and economic sense.[25] The exchange of people, other living organisms, raw materials, goods, and information began among the continents. Particularly important was the spread of certain ingredients of the European (Eurasian) civilization that were almost unknown in the New World until then (e.g., the plow, metals, animal traction and wheeled vehicles used in transport). All the above changes had important consequences regarding human transformation of the biosphere.

Introduction of Wild Species. By the establishment of connections among the continents, humans — in most cases unintentionally — initiated the migration of many species mainly from Eurasia to new continents (Crosby 1986). The introduction of non-native species has been a problem ever since, in fact, an ever more serious one with the expansion of world trade and tourism. The invasion of introduced species is among the major causes of the current mass extinction of species (Diamond 1989) and alters ecosystem processes as well (Vitousek 1990).[26]

Exchange of Domestic Species and the Beginning of the Population Explosion. As a result of the conquests, the exchange of domestic species also began. Not only those of European origin (e.g., wheat and barley) spread around the world (together with European agricultural technologies), but also many American domestic species (especially plants) found their ways to other continents. For instance, manioc and sweet potato originating from South America have proved well cultivable on many lands of Africa and Asia that were considered unproductive before, and both of them are among the most important tropical crops today. Crops coming from America also reached temperate climates. In Europe, corn and potato have become the most important American newcomers. These two plants had several advantages compared with native Eurasian crops. For example, they were more productive per unit of land, and were cultivable on lands unsuitable for the native crops (Crosby 1994).

Increased agricultural yields due to the exchange of domestic species contributed to considerable population growth on every continent (Crosby 1994), which was further increased by other factors later. Consequently, a rapid growth of the world population began from about the mid-17th century. In the time of Christ about 250 million people lived on the planet and this number doubled only by about the mid-17th century. However, the next duplication took only 150 years: the world population reached 1 billion during the first decade of the 19th century (Cohen 1995).

The Birth of World Economy. Trade began to flourish as a consequence of the conquests. From the conquered areas mainly raw materials arrived in Europe, while primarily manufactured goods and less significantly technologies flowed in the opposite direction. Europeans introduced the production of luxury crops in several colonies and these were imported to the home-countries. World economy was born in the 17th century with Europe as its center and main beneficiary. Later, other areas inhabited mostly by people of European origin (e.g., North America and Australia) have also become dominant in the world economy.

The global separation of the different phases of the economic process has become more and more common due to the birth of world economy (Chisholm 1990). Consequently, people — including economic decision-makers — have been less and less confronted with the environmental damages taking place during the economic cycle of a certain product (Princen 2002).

Disappearance and Weakening of Pre-Conquest Cultures. The pre-conquest cultures weakened or even disappeared completely in many of the conquered areas. As a consequence, in many places the traditions of the sustainable management of natural resources also disappeared, and were often substituted by unsustainable practices (e.g., Johannes 1978). The establishment of generally monocultural plantations (e.g., coffee and rubber tree) together with logging has resulted in massive deforestation (e.g., Perlin 1989). Certain export crops (e.g., cotton and tobacco) have quickly exhausted soils, enforcing the expansion of cultivation to further and further virgin areas. The substitution of agricultural lands for tropical rainforests has had a similar consequence. In most cases, thin soils under these forests are suitable for cultivation only for a few years, after which further deforestation is needed. Also, the mining of raw materials has often caused serious environmental damages on the conquered continents. These processes have resulted in the transformation of natural ecosystems, the extinction of many species, the acceleration of soil erosion, the alteration of biogeochemical cycles, and in several cases climatic changes as well. The disappearance of pre-conquest cultures contributed to the population explosion by resulting in the abandonment of traditional mechanisms of population control in several cases (e.g., Kirch 1997).

Sixth Transition: The Technological-Scientific (R)evolution[27] and the Dominance of Fossil Fuels as Primary Energy Sources

The sixth transition can be traced back to the conjugated effects of three factors: 1) the development of European science, 2) the cumulative increase in the complexity of European technology (which was significantly accelerated by the conquests due to the raw materials arriving from other continents), and 3) the spread of fossil fuels. The intimate intertwining of these factors started in the second half of the 18th century, when coal became the main fuel for the new machines. It became significant around the mid-19th century, from which time the results of basic scientific research have been widely used for creating the technological basis of an economy that has been based on coal, and later on other types of fossil fuels as well.[28] In addition to an increase in the use of natural resources due to this transition, an increase in pollution, which means the alteration of the biogeochemical cycles (Vitousek et al. 1997), has also occurred. Pollution has become a significantly more serious problem than ever before.[29]

Fossil Fuels and Electricity

Coal has been used in Europe since the 12th century (and in China it was burned 2,000 years ago). It first became a dominant energy source only in the 17th century in England, followed by some other European countries in the 18th century. By this time, due to the clearance of forests, the availability of fuelwood decreased in Europe, forcing many countries to import timber, sometimes even from other continents. Technological changes (e.g., the appearance of the blast furnace making the processing of coal easier) also contributed to the switch to coal. As a consequence, extraction of coal became cheaper than that of fuelwood.

The massive use of coal provided humanity with energy in a concentration never witnessed before. This huge amount of energy significantly contributed to the outset of the Industrial Revolution beginning in England in the second half of the 18th century. Industry became more and more based on machines instead of handicraft, and it gained an ever greater role in the economy at the expense of agriculture. Nevertheless, it is likely that in the beginning technological changes — especially the spectacular increase in the reliability of the new prime movers, steam engines in the second half of the 18th century — played a more important role in industrialization than coal itself. This view is supported by the fact that at first industrialization in the United States — which was richer in forests than Europe — was based mainly on wood (and water power) and it was only at the end of the 19th century that coal became the dominant energy source. In the later stages of industrialization, however, the energy demand of the economy increased to such an extent that — counting on the technologies of those times — satisfying it without fossil fuels would have been impossible.

In the mid-19th century a second type of fossil fuel, *crude oil* — having an even greater energy density (measured in J/kg) than coal — appeared. Crude oils have become the propellants of internal combustion engines. These prime movers were developed from the mid-19th century, and were lighter and more efficient than steam engines. In the 20th century crude oil became the dominant energy source of the world, and this situation has not changed, despite the two oil crises in the 1970s decreasing its significance (Flavin and Dunn 1999). The third type of fossil fuel, *natural gas*, became widespread only in the second half of the 20th century.

The basis for the widespread use of *electricity* was laid down when, in 1831, Michael Faraday demonstrated electromagnetic induction. He showed that mechanical energy can be converted into electricity and vice versa. By the end of the 19th century the invention of the first cheap and reliable transformers made possible the long-distance transmission of electricity. This invention, together with electric motors, prime movers powered by electricity and also invented at about the same time, caused a steep rise in energy use. From the end of the 19th century part of the fossil fuels [30% in 2000 (Smil 2000)] have been converted to electricity in power plants, making easier the delivery of fossil fuels' energy to locations remote from their reserves. (Beside fossil fuels, electricity can be generated from other primary energy sources as well, such as from water or wind power.) Although the first power plants were operated by steam engines, in a short time they were replaced by the more efficient, lighter and smaller new prime movers, steam turbines. This change was an indispensable condition for the large-scale generation of electricity. Today about 80% of the global electricity supply is generated by steam turbines (Smil 1994, 1999a).

There was an increase of approximately 40-fold in the total energy use of the world between 1800 and 2000 (McNeill 2000), due primarily to the use of fossil fuels and electricity. Today, world economy is based on fossil fuels. Coal, crude oil, and natural gas together supply about 75% of the global energy demand (Flavin and Dunn 1999). The machines driven by these energy sources and the products of these machines have made possible a significantly greater extent of transformation of the biosphere than ever before. The burning of fossil fuels has been contributing to several serious environmental problems (e.g., global climate change, urban smog and acid deposition).

The Birth of Market Economy

Market economy is an economy governed, in an ideal case, exclusively by market prices. This means that the production and distribution of goods are entrusted to a self-regulating mechanism. Though the institution of market has been known for millennia, it did not play a dominant role in the economies of human societies until the 19th century. In other words, profit made on exchange was virtually never an important element of the economy. The number and significance of markets began to increase in the 16th century. However, in the beginning societies were not yet transformed by them and the idea of self-regulating markets was unknown as well. Market economy was born in England following the Industrial Revolution in the first half of the 19th century. As soon as production became accomplished with the aid of complex machinery in a commercial society, the idea of self-regulating market economy appeared. This happened because complex machines were expensive and therefore their use was rewarding only if large quantities of goods were produced by them. (This, in turn, became feasible due to fossil fuels increasing the amount of available energy.) Thus, the profitable operation of these machines was possible only if both the sale of manufactured goods and the availability of primary goods (e.g., natural resources) feeding the machines were guaranteed. For the successful operation of this system it became necessary to treat nature as a fictitious commodity, which means that it had to become subordinated to market mechanisms. At the same time, society had to be reorganized as well. While in earlier times the economy was controlled by the society, now this control weakened and the situation turned around. Society has become more and more subordinated to market economy (cf., the term "market society"), and profit making has become one of the most important motives of people's actions (Polanyi 1944).

Colonization and World Trade: The Expansion of Industrialism and Market Economy

Industrialization and fossil fuels gave an impetus to colonization and world trade. While in 1800 the value of world trade was only 3% of the world economic output, it rose to 33% by 1913. Then, following the decline caused by the two world wars and the global economic recession in the 1930s, it recovered to the level of 1913 by the 1980s and has been further increasing ever since (Chisholm 1990).

The volume and the speed of transport increased significantly due to three factors: 1) fossil fuels, 2) the considerable improvements in road quality beginning in the mid-18th century, and 3) the appearance of the new prime movers light and small enough to be built in vehicles. Due to the easier availability of distant resources, increasing mobility and easier transportation resulted in the growth of economic output and population[30]. The use of steamships and locomotives from the 1830s made possible the appearance of the first reliable transcontinental and global transport networks. New industrial processes and inventions increased the demand on several raw materials coming from the colonies (e.g., the introduction of vulcanization increased the demand on rubber.) The improvements in communication technology have also contributed to global economic integration.

Most societies in the Third World were obliged to switch from autarky to production for the world market. Moreover, in most cases their production has been reduced to just a few (or even only one) export products (e.g., crops or metal ores), and the money received in turn has been applied to import other goods. Thus, the Third World has become dependent upon world market prices, without being able to exert any significant influence on them. As a consequence, the richer countries have been able to exploit the natural resources of the Third World at a reduced price, and therefore rather easily (Ropke 1994). In many cases the demands of distant markets have meant a suction force much too powerful to attain sustainable resource management (e.g., McDaniel and Gowdy 1999). Colonization, however, has resulted not only in the takeaway of resources from the Third World, but also the spread of commodities and technologies coming from the richer countries. While the diffusion of commodities has been rather unhindered, this has not always been true for technology transfer (Headrick 1990).

Market economy has gradually expanded worldwide and this process was only temporarily hindered by the world wars and the global economic recession in the 1930s, and is therefore still flourishing. The main flywheel of this system is profit making. Since it can only be attained by increasing the possibilities for investments, economy is virtually destined to perpetual growth. More importantly, because of several real or alleged reasons, economic growth has been promoted by virtually all states in the world — and not only states with market economy — competing with each other economically (Daly 1999). Moreover, economic growth has generally been considered as one of the most desirable social goals.

The growth of the world economy gathered momentum from about 1820, and from the beginning of the 1870s its rate of increase reached unprecedented heights. Apart from the period between 1914 and 1945 (when there was only moderate growth) this rate of increase has been more or less continuous ever since. Between 1820 and 1992 there was growth of about 40-fold in the world economy, indicating a per capita growth of about 9-fold. In contrast, in the previous centuries per capita economic output stagnated (McNeill 2000). Most of the energy required for this growth was supplied by fossil fuels (and the growth in the 20th century was based mainly on crude oils). Beside this huge amount of energy, technological and scientific changes were the most important foundations for economic growth (Ayres 1996). The growing scale of the world economy has resulted in an ever increasing use of natural resources and an ever increasing production of wastes and pollution.

The Boom in Chemical Industry

The increase in the amount of available energy, together with the application of new scientific results, played an important role in the very quick unfolding of the chemical industry in the 19th century. The synthetic compounds produced by this industry — about 150,000 of them have seen commercial use (McNeill 2000) — have caused several environmental problems. For example, halogenated hydrocarbons have damaged the stratospheric ozone layer, and several types of plastics (many of them are derivatives of crude oils) widely used since 1945, have caused problems mainly as wastes (see also below).

The Industrialization of Agriculture and Fishing

Agriculture underwent a huge transformation due to industrialization. Machines and machine made tools appeared in the fields. As a consequence, agricultural yields have increased due to both the more intensive cultivation and the increase in the area of cultivated lands. The latter has led to the further decrease in the areas occupied by natural ecosystems. From the 20th century chemical industry has provided agriculture with huge amounts of synthetic pesticides and fertilizers, causing serious environmental problems (e.g., Matson et al. 1997). The pumping of groundwater has made possible irrigation — and therefore agricultural production — on lands considered much too arid before, and it has contributed to the intensification of irrigation elsewhere. Today, pumped water is used on about half of the world's irrigated lands (Smil 1994).

From the 19th century, the increase in yields caused by the industrialization of agriculture has been one of the important causes (and also consequences) of the rapid population growth. In this respect, *nitrogen fertilizers* have played a particularly important role. Nitrogen is a limiting resource in many ecosystems and for a long time this was true for the majority of agricultural ecosystems as well. However, the invention of (industrial) ammonia synthesis, a highly energy-intensive process (in most cases natural gases are used for supplying the energy), made possible a significant increase in agricultural yields. The mass application of nitrogen fertilizers started at the beginning of the 1950s and it has been increasing very rapidly ever since, contributing significantly to the post-war increase in the growth rate of human population. In 1950, world population was about 2.5 billion (Cohen 1995), while it reached 6 billion by the end of the 20th century. For at least one third, but perhaps even two fifths of the current world population, the nitrogen content of proteins in food is supplied by synthetic nitrogen fertilizers. This means that human ammonia synthesis is essential for the existence of a significant proportion of people living today. At the same time, the application of nitrogen fertilizers has contributed to several environmental problems, such as the global climate change and the destruction of the stratospheric ozone layer, by increasing the atmospheric concentration of nitrous oxide (Smil 1991, 1999a, 1999b).

The fishing process also became industrialized in the early 19th century, as indicated by the use of, for example, steam trawlers, power winches, and from the 20th century, diesel engines, freezer trawlers, etc. This has resulted in unsustainable fishing practices and the depletion of many of the world fisheries indicated by the decline of global catches since the late 1980s (Pauly et al. 2002).

Mass Urbanization

Before the fossil fuel era, the size of cities and the number of big cities were limited by the fact that their energy demand (e.g., fuels and food) had to be supplied from biomass energy with low power density (measured in W/m^2) coming from the areas surrounding them. In the absence of powerful prime movers, the possibility of transport from distant areas was also limited. Fossil fuels with high power density changed this situation. It was not by accident that in the beginning many big cities were born near coalfields. Later, due to the widespread use of electricity and vehicles driven by the new prime movers, the proximity of fossil fuels ceased to be an important condition for the rise of big cities (Smil 1994).

At the beginning of the 19th century only about 2.5% of the world population lived in cities. This proportion reached about 10% by the dawn of the 20th century (Ponting 1991), and — to a large extent due to Third World urbanization starting in the 20th century — about 50% by the beginning of the 21st century (McNeill 2000). Both the number of cities and the number of their inhabitants have been increasing.

The new factories of cities absorbed a large part of the working force freed by the industrialization of agriculture. This has resulted in a further separation from nature for masses of people. Cities and industrial areas have expanded to the detriment of natural ecosystems and agricultural lands. This process has been boosted by increased mobility. Urbanization has brought about the genesis, the worsening, and the increase in the frequency of several local urban environmental problems (e.g., air pollution, noise, etc.).

Scientific (R)evolution and the Change in the Dominant Worldview and Set of Values

It is not very likely that the sudden increase in the extent and pace of human transformation of the biosphere characterizing this sixth transition would have been so spectacular without the significant changes in people's ideas about the surrounding world.[31] Presumably, these changes were both the causes and consequences of the increase in transformation of the biosphere. Worldview changes can be traced back to a large extent to the Scientific (R)evolution unfolding in the 17th century — but rooting in the Middle Ages (White 1967) — and particularly to the works of René Descartes (1596-1650) and Isaac Newton (1642-1727). Later, the European worldview and set of values have become almost universal.

Descartes considered the whole material universe (and also living organisms) similar to a machine operating according to the laws of mechanics and governed by exact mathematical principles. This became the dominant paradigm of science until the 20th century, and though it was already fundamentally reinterpreted — mostly by some physicists of the previous century — our way of thinking is still under its influence. Furthermore, Descartes categorically separated mind from matter, creating the philosophical basis for the later desacralization of nature. Obviously, the exploitation and manipulation of a nature viewed in the Cartesian way is easier than, for example, that of a Mother Earth considered as a living organism (Capra 1982).[32] Furthermore, Descartes — foreshadowing the subsequent marriage of science and technology — emphasized that by means of science humanity would become the master and possessor of nature.

Newton put the ideas of Descartes into practice. Building mainly on the results of Copernicus, Kepler, Galileo, and Descartes, he elaborated the mathematical principles of the mechanistic view of nature. Newtonian physics served as a model for most of the new scientific disciplines born in the 18th and 19th centuries (Capra 1982). This is also true for modern economics emerging in the second half of the 18th century. Neoclassical economics, the currently dominant school in economic science, which generally neglects the natural constraints imposed on economic activities, is the successor of classical economics, and therefore of the Newtonian mechanistic worldview as well (Norgaard 1985).

The works of Descartes and Newton played an important role in the unfolding of *The Enlightenment* propagating the liberation of humankind from natural constraints by the help of reason and science from the 18th century. Secularization was a characteristic feature of the Enlightenment. Consequently, the behavior of most people ceased to be regulated by coherent religious worldviews. Due to secularization and the birth of market society, human behavior has become more and more characterized by instrumental rationality (that is, action aimed at the realization of arbitrarily determined goals by the help of the most suitable instruments), which hardly existed before and based on abstract conceptual thinking. Thus, the consideration of the justness of goals has been more and more eclipsed by the importance of the efficiency of instruments. This has also proved to be true for science. Modern, Cartesian-Newtonian science acting in the spirit of instrumental rationality (i.e., a narrowly interpreted rationality) has aimed at the construction of a special kind of knowledge that is predictive, technologically constructive, and suitable for the manipulation of nature (Prigogine and Stengers 1986).

Belief in progress, which virtually did not exist in earlier societies (at least in a mundane sense) was also a product of the Enlightenment. Due mainly to the fast and spectacular changes of science and technology, several thinkers started to believe that human history is a chronicle of perpetual progress. Moreover, a reverse effect has risen as well: the necessity of progress (or that of the quasi-synonymous "development") has become one of the central ideas of societies, stimulating economic growth and increase in technological complexity.

While it is hard to determine to what degree the ideas of philosophers or scientists and those of other people overlap (though this overlap is probably significant), by the promotion of increase in technological complexity, Cartesian-Newtonian science has undeniably contributed to the extended transformation of the biosphere. In this respect, the above-mentioned boom in the chemical industry and the use of nuclear energy from the 20th century should be emphasized. The latter has caused an increase in the concentrations of certain radioactive isotopes in several parts of the biosphere, often damaging living organisms, including human beings.

Medical Science and Chemical Industry Against Pathogens

Through decreasing mortality — mainly owing to the rather successful combat against pathogens — medical science played an important role in the unfolding of the population explosion. The most important milestone in this respect was perhaps the establishment of *germ theory* by Louis Pasteur and Robert Koch in the 1860s and 1870s. This theory is the recognition that infectious diseases are caused by microbes. It was a prerequisite for the development of vaccines against infections — discovered already several decades before, but applied only against smallpox until then. It also gave impetus to the improvement of sanitation beginning already in the first half of the 19th century.[33]

The marriage of medical science and chemical industry has resulted in the appearance of many types of new medicines. *Antibiotics* have been particularly important among these. Their systematic development began after the discovery of penicillin by Alexander Fleming in 1929. The use of antibiotics has become widespread after World War II, greatly helping the fight against infectious diseases, and thus contributing to the acceleration of world population growth after 1945. *Synthetic pesticides used against insect vectors of diseases* had the same effect (Cohen 1995).[34]

A Different Future?

Nowadays, the worsening of the ecological crisis urges the need for a transition resulting in a considerable decrease of our impact on the biosphere. However, the experiences of the past (e.g., the switch from hunting and gathering to agriculture or the European conquests) are not really encouraging. These show us that in general human societies have been selected for short-term economic and military success rather than long-term ecological sustainability. *On a global scale* there is no evidence of any past transitions resulting in a significant decrease in the extent of transformation of the biosphere. *On a local scale*, however, at least one case is known — that of the Micronesian island Tikopia (Kirch 1997) — when a society *intentionally* decreased the extent of its environment transforming activities for the sake of its survival.

Although there are still no signs of decrease regarding our impact on the biosphere, processes operating in this direction have been observed in the last few decades. This is true in the case of all the three factors directly determining the extent of our transformation of the biosphere: 1) the growth rate of the world population — after reaching a historical maximum with 2.1% per year in the second half of the 1960s — has been decreasing or stagnating for more than thirty years (Smil 1999c; Engelman, Halweil and Nierenberg 2002), 2) there has been made an ever increasing number of attempts at realizing ecologically sustainable economies (e.g., Dauncey 1996; Mirvis 1994), and 3) "environmentally friendly" technologies have become ever more widespread (e.g., von Weizsäcker, Lovins and Lovins 1998; but see Kemp, Schot and Hoogma 1998). More and more people have been trying to create paths leading to ecologically sustainable societies, to find and realize the institutional, ethical, and technological changes necessary for attaining these societies.

In this respect, understanding the history of human transformation of the biosphere may also be of great importance. Putting an end to the ecologically unsustainable practices of today's societies will be easier if their origins become better understood.

Endnotes

1. Email: takacssp@hu.inter.net
2. In some cases human transformation of the natural environment goes beyond the boundaries of the biosphere (e.g., the depletion of the

stratospheric ozone layer). For the sake of simplicity, these processes are also considered as transformations of the biosphere in this article. The use of the term "biosphere" is preferred here instead of "environment" or "nature," because it is more well-defined than the others. Throughout the article, all the environmental transformations taking place in the biosphere are put in the category of "transformation of the biosphere" independently of their spatial scales.

3. The space dedicated to the certain transitions in this article does not necessarily reflect their relative importance, but rather the amount of information available, which is obviously greater in the cases of the more recent transitions. Moreover, with increasing remoteness in time, not only the quantity but also the certainty of information decreases. Therefore, in many questions discussed here several competing hypotheses exist. Because of the limited space these cannot be surveyed in this article, in most cases only the most plausible scenario is outlined (but some of the references cited give a deeper insight).
4. Technology is a system of means helping us to increase economic output (and therefore also transformation of the biosphere) by extending our biological abilities. On a rough scale the increase in technological complexity corresponds to the increase of transformation of the biosphere, but on a finer scale this is not always true, as indicated for example by the sophisticated "green" technologies of our times (e.g. photovoltaic cells).
5. Debatable evidences (the earliest being 1.8 million years old) might indicate the use of fire even by *Homo erectus* (Wrangham et al. 1999; Wuethrich 1998).
6. Systematic vegetation clearing by the help of fire occurred, for example, among Australian Aborigines in the last few millennia (e.g., Flannery 1994).
7. The definition of language is equivocal (e.g., Milo and Quiatt 1993), which also increases the uncertainty about its time of origin.
8. Many researchers use the name *Homo sapiens* only for modern humans and classify earlier forms as one or more other species.
9. Their relative brain size was much larger than that of earlier humans (Kappelman 1996; see Aiello 1998 for the significance of large brains to language).
10. Therefore, thinking is virtually mute speech. Although we often think in pictures, purely grammatical elements (e.g., conjunctions) are always required (Maynard Smith and Szathmáry 1995).
11. In a sense it is not worth determining a date for the birth of agriculture, since there is no sharp division between hunter-gatherer and food producer societies (e.g., Higgs and Jarman 1972). It is appropriate to think about them as the endpoints of a continuum, since some food production occurs among certain hunter-gatherers, but often without the domestication of species (e.g., May 1984), and even our modern food producing societies gain some food from species living in the wild (especially marine fishes).
12. In a given area sedentary lifestyle could have preceded agriculture in some cases (Balter 1998), but the opposite may have also been true sometimes (Pringle 1998). Certain food producers (e.g., some pastoralists) follow a nomadic lifestyle and certain hunter-gatherers are sedentary (Testart 1982). There are also transitionary forms between nomadic and sedentary lifestyle (Higgs and Vita-Finzi 1972).
13. Moreover, sedentary lifestyle has not always been a necessary condition for the increase of fertility, since, for example, nomadic food producers have been able to carry toddlers by the help of their animals.
14. This is not necessarily true for nomadic food producers, since they have been able to move the accumulated wealth or food surplus by the help of their animals and/or their means of transport.
15. The term "more or less" is used here because in many hunter-gatherer societies conspicuous social inequalities can be observed. These are sometimes even greater than the inequalities in certain simpler food producing societies (Testart 1982; Woodburn 1982). However, it is hardly disputable that in the aggregate hunter-gatherer societies are considerably more egalitarian than food producers.
16. Agriculture was not always necessary for the appearance of storable food surplus; storage (implying food surplus in many but not all cases) has been observed in several hunter-gatherer societies. Therefore non-storing and storing hunter-gatherers can be distinguished (though a certain degree of storage has been observed in every hunter-gatherer society). The latter group contains mostly sedentary or semi-sedentary societies (Testart 1982). However, since in the time of the appearance of agriculture the technologies of collection, processing and storing of food were less advanced than today, it is likely that non-storing hunter-gatherer societies outnumbered storing ones. Moreover, because of the less advanced technologies and less potentially acquirable food, even the total amount of food surplus may generally have been smaller in hunter-gatherer societies than in food producer ones.
17. The fact that food producers acquired more pathogens than hunter-gatherers had at least three causes. First, increase in population density made the emergence of epidemics more likely. Second, sedentary lifestyle worsened hygiene, since people became obliged to live in their own dirt. Third, the closeness of domestic animals also increased the danger of infection. Almost every insidious human pathogen evolved from diseases of domestic animals. Though pathogens were disadvantageous in the short run, human populations have gradually become accustomed to them (i.e., the survival of resistant individuals was more likely than that of susceptible ones). Societies possessing a lot of pathogens while being quite resistant to them gained ascendancy over societies not possessing these and, therefore, being susceptible to them. Microbes often were the most dangerous "weapons" of the former against the latter (Diamond 1997).
18. Forms of socio-political organization characteristic to agrarian societies without civilization are the tribe and the chiefdom (Flannery 1972).
19. These features of writing have been further accentuated by the use of printing from the 15th century A.D.
20. In this respect, not only the muscle power, but also the manure of domestic animals has been important. Besides increasing the productivity of soils it has also been used for gaining energy (a kind of biomass energy).
21. Beside domestic animals, the wheel — first used in Eurasia about 5,500 years ago — made possible the appearance of vehicles used in transport, so it was also important in this respect.
22. This date refers to the first windmills. To a lesser degree, wind energy has been used for driving sailboats for millennia.
23. The settling down of Europeans in the tropics was also hindered by pathogens formerly unknown to them.
24. Here, Eurasia also includes the part of Africa north of the Sahara,

since the Mediterranean Sea was a more permeable barrier for people than the Sahara.

25. Linkages between Eurasia and Africa were relatively frequent even before, since the "breakthrough" of the Southern Ocean and the Sahara occurred before the 15th century. However, in the cases of the further five possible pairings of the continents connections were very rare.
26. The introduction of species is an example of those human-caused environmental changes for which the Holdren-Ehrlich model is not completely adequate. This is because the lifting of biogeographical barriers, due to the establishment of connections among continents, does not necessarily imply changes in any of the three factors of the model.
27. It is virtually a matter of taste whether we talk about evolution or revolution in this context. On the one hand, both technological and scientific changes were results of cumulative processes beginning already in the Middle Ages. On the other hand, it is indisputable that technology and science have caused revolutionary changes in the societies from the 18th century onwards. The same is true for the term "Industrial Revolution" to be used later in the text.
28. There are only sporadic examples for the intertwining of science and technology from earlier times (White 1967).
29. Of course, some examples for pollution are known even from ancient times, for instance the pollution due to metal smelting (Hong et al. 1994, 1996; Nriagu 1996).
30. The increase in mobility stimulated population growth for another reason as well. Fewer and fewer societies remained isolated from the rest of the world for longer periods of time, and as a result people became less susceptible to pathogens (Cohen 1995). However, the later increase in the speed of transport and the volume of tourism led to the appearance of a reverse effect. Nowadays, pathogens can travel around the world in only a few hours and these shortened traveling times decrease the chance of the operation of a "quarantine effect" inhibiting their spread.
31. It is possible that changing worldviews also played a role in some of the previous transitions. However, due to the lack of written records these cannot be reconstructed in the cases of the first four transitions, and there is no convincing evidence for them in the case of the fifth one, the European conquests. Here, it is worth mentioning the famous thesis of White (1967) tracing back our ecological crisis to a large extent to the Judeo-Christian worldview. Although many scholars consider this idea plausible, it is rather disputable (see Livingstone 1994 for references and a review of arguments and counter-arguments), and therefore it is not discussed here in detail.
32. Nevertheless, considering nature as a living organism was not always enough in itself for ecological sustainability. For instance, in the Mediterranean region the cult of the goddess Gaia (dubbed differently in different cultures) flourished in ancient times, yet serious environmental damages (e.g., soil erosion due to massive deforestation) were caused by people living in that area in those times.
33. In this respect, particularly important achievements were the introduction of antiseptic methods, the improvements in urban and personal hygiene, and the protection of food and water supplies.
34. By the 1960s and 1970s humanity seemed to have won the war against pathogens, but the tables have turned since then. Because of, for instance, the appearance of AIDS, or the increasing resistance to antibiotics among bacteria, the number of deaths caused by infectious diseases has been increasing even in rich countries in the last decades (Cohen 2000; Lederberg 2000).

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