Energy and Human Evolution

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Life on Earth is driven by energy. Autotrophs take it from solar radiation and heterotrophs take it from autotrophs. Energy captured slowly by photosynthesis is stored up, and as denser reservoirs of energy have come into being over the course of Earth's history, heterotrophs that could use more energy evolved to exploit them. *Homo sapiens* is such a heterotroph; indeed, the ability to use energy extrasomatically (outside the body) enables human beings to use far more energy than any other heterotroph that has ever evolved. The control of fire and the exploitation of fossil fuels have made it possible for *Homo sapiens* to release, in a short time, vast amounts of energy that accumulated long before the species appeared.

By using extrasomatic energy to modify more and more of its environment to suit human needs, the human population effectively expanded its resource base so that for long periods it has exceeded contemporary requirements. This allowed an expansion of population similar to that of species introduced into extremely propitious new habitats, such as rabbits in Australia or Japanese beetles in the United States. The world's present population of over 5.5 billion is sustained and continues to grow through the use of extrasomatic energy.

But the exhaustion of fossil fuels, which supply three quarters of this energy, is not far off, and no other energy source is abundant and cheap enough to take their place. A collapse of the earth's human population cannot be more than a few years away. If there are survivors, they will not be able to carry on the cultural traditions of civilization, which require abundant, cheap energy. It is unlikely, however, that the species itself can long persist without the energy whose exploitation is so much a part of its *modus vivendi*.

The human species may be seen as having evolved in the service of entropy, and it cannot be expected to outlast the dense accumulations of energy that have helped define its niche. Human beings like to believe they are in control of their

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destiny, but when the history of life on Earth is seen in perspective, the evolution of *Homo sapiens* is merely a transient episode that acts to redress the planet's energy balance.

Ever since Malthus, at least, it has been clear that means of subsistence do not grow as fast as population. No one has ever liked the idea that famine, plague, and war are nature's way of redressing the imbalance—Malthus himself suggested that the operation of "preventive checks," which serve to reduce the birth rate, might help prolong the interval between such events (1986, vol. 2, p. 10 [1826, vol. 1, p. 7]).[1] And in the two hundred years since Malthus sat down to pen his essay, there has been no worldwide cataclysm. But in the same two centuries world population has grown exponentially while irreplaceable resources were used up. *Some* kind of adjustment is inevitable.

Today, many people who are concerned about overpopulation and environmental degradation believe that human actions can avert catastrophe. The prevailing view holds that a stable population that does not tax the environment's "carrying capacity" would be sustainable indefinitely, and that this state of equilibrium can be achieved through a combination of birth control, conservation, and reliance on "renewable" resources. Unfortunately, worldwide implementation of a rigorous program of birth control is politically impossible. Conservation is futile as long as population continues to rise. And no resources are truly renewable.[2]

The environment, moreover, is under no obligation to carry a constant population of any species for an indefinite period of time. If all of nature were in perfect balance, every species would have a constant population, sustained indefinitely at carrying capacity. But the history of life involves competition among species, with new species evolving and old ones dying out. In this context, one would expect populations to fluctuate, and for species that have been studied, they generally do (ecology texts such as Odum, 1971 and Ricklefs, 1979 give examples).

The notion of balance in nature is an integral part of traditional western cosmology. But science has found no such balance. According to the Second Law of Thermodynamics, energy flows from areas of greater concentration to areas of lesser concentration, and local processes run down. Living organisms may accumulate energy temporarily but in the fullness of time entropy prevails. While the tissue of life that coats the planet Earth has been storing up energy for over three billion years, it cannot do so indefinitely. Sooner or later, energy that accumulates must be released. This is the bioenergetic context in which *Homo sapiens* evolved, and it accounts for both the wild growth of human population and its imminent collapse.

ENERGY IN EVOLUTION

We are caught up, as organic beings, in the natural process through which the earth accepts energy from the sun and then releases it. There has been life on Earth for at least three and a half billion years, and over this time there has been a clear and constant evolution in the way energy is used. The first living things may have obtained energy from organic molecules that had accumulated in their environment, but photosynthetic autotrophs, able to capture energy from sunlight, soon evolved, making it possible for life to escape this limited niche. The existence of autotrophs made a place for heterotrophs, which use energy that has already been captured by autotrophs.

It is not clear how photosynthesis got started, although it is a combination of two systems that can be found singly in some life forms that still exist. But blue-green algae, which are among the earliest organisms documented in the fossil record, already employed the two-stage process that was eventually handed down to green plants. This is a complex sequence of events that has a simple outcome. Carbon dioxide (of which there was an abundance in the earth's early atmosphere) reacts with water through energy from light, fixing carbon and releasing oxygen, and a portion of the energy remains captive as long as the carbon and the oxygen remain apart. Plants release this energy when and where necessary to conduct their metabolic business (Starr & Taggart, 1987).

As time passed, the sheer bulk of life increased, so that more and more energy was, at any given time, stored in living matter. Additional energy was stored when carbon from once-living matter was buried, in ever-so-tiny increments, under the surface of the earth—in deposits that became coal, petroleum, and natural gas as well as in sedimentary rocks containing calcium and magnesium carbonates derived from shells. Of all the carbon that has played a part in the life process, very little was separated out and held apart in this way, but over the course of millions and millions of years, it has mounted up. More and more carbon wound up under the ground, with a greater and greater amount of oxygen in the earth's atmosphere. This separation of carbon and oxygen from a primeval atmosphere in which carbon dioxide and water were abundant represents a vast accumulation of solar energy from the past.

Life evolves to exploit every possible niche, and as autotrophs developed better ways to capture and store the sun's energy, heterotrophs developed better ways to steal it. Independent locomotion was adaptive in the search for nutrients, although it took a little more energy than being buffeted about by the elements. Cold-blooded fish and amphibians were followed by warm-blooded species, which reap the benefits of remaining active at lower temperatures, while using yet more energy in the process. The development of predation opened access to a supply of high-energy food with a further energy investment in procuring it. Throughout the history of life, as increasingly dense reservoirs of energy became available, species that made use of increasing amounts of energy evolved (see Simpson, 1949, pp. 256-57). This is the natural context of *Homo sapiens*, the most energy-using species the world has ever known.

THE HUMAN ANIMAL

The extent of human energy use is a consequence of the human capacity for extrasomatic adaptation. This capacity makes it possible for human beings to adjust to a wide variety of novel circumstances without having to wait many generations for evolution to change their bodies. A comparison of somatic and extrasomatic adaptation will show just how remarkable an ability this is: If longer, sharper teeth are adaptive for a predator, animals with teeth that are slightly longer and sharper than those of their fellows will have a slight reproductive advantage, so that genes for longer and sharper teeth will have a slightly greater likelihood of being passed on, and so, over the course of time, the teeth of average members of the population will come to be, little by little, longer and sharper. In contrast, a human hunter can imagine a longer, sharper arrowhead; he can fashion it with nimble hands; and if it is really more efficient than the short, blunt arrowheads that everybody else has been using, his peers will soon adopt the new invention. The chief difference between the two means of adaptation is speed: Humans can adapt, relatively speaking, in a flash.

Extrasomatic adaptation is possible because humans are, in the idiom of the computer age, programmable. Somatic adaptation is like building a hard-wired computer to perform a certain task better than a previous hard-wired computer. Extrasomatic adaptation is like writing a new program to perform the task better, without having to build new hardware. The use of language, with its arbitrary relationship between signs and referents, makes possible a wide variety of different software.

Programmability—the ability to learn—is not unique with human beings, but they have developed the capacity much further than any other species. Programmability probably developed as an evolutionary response to pressure for flexibility. The ability to make use of a variety of different resources runs deep in the human background, for placental mammals arose from ancestral forms in the order Insectivora that presumably ate insects, seeds, buds, eggs, and other animals. When our hominid ancestors came down from the trees to exploit the African savannas, flexibility was again advantageous. *Homo habilis* and his fellows were furtive little scavengers who picked what they could from carcasses that leopards left behind and rounded out their diet with fruits and nuts and roots (see Binford, 1981; Brain, 1981). They lived by their wits, and natural selection favored hardware that would permit quick-wittedness.

Programmability—and the consequent capacity for extrasomatic adaptation—have made it possible for human beings to advance a very old evolutionary trend at a vastly increased rate. Humans are the most recent in the series of heterotrophs that use increasing amounts of energy, but they differ from other species in this lineup in their ability to use more energy without further speciation. Over the course of humanity's short history, greater and greater amounts of energy have been used by the same biological species (see White, 1949, chapter 13).

EXTRASOMATIC ENERGY

Some human innovations have dealt with the fate of energy channeled through metabolic processes. The development of weapons, for example, made it possible to focus somatic energy so as to obtain high-energy foods with much greater efficiency. Man became a hunter. This may have been the innovation that let *Homo erectus* prosper and permitted his species to radiate out of the African cradle, pursuing game throughout the tropics of the Old World (Binford, 1981, p. 296). Similarly, the use of clothes brought about a conservation of bodily energy that helped make possible the conquest of more temperate regions.

But the most remarkable human innovation is the use of extrasomatic energy, wherein energy is made to accomplish human ends outside the bodies of its users. And the most important source of extrasomatic energy, by far, is fire. Fire was used by *Homo erectus* in northern China more than 400,000 years ago, and there is sketchy evidence suggesting that it may have been used long before that (Gowlett, 1984, pp. 181-82). Through the use of fire, meat did not have to be rent by main strength; it could be cooked until tender. Fire could be used to hollow out a log or harden the point of a stick. Fire could drive game from cover and smoke out bees. Fire could hold fierce animals at bay.

The exploitation of animal power played an important role in the densification of population that was at the root of what we call civilization. Animals pulled the plow, animals carried produce to market, and animals provided a protein-rich complement to a diet of grain. Wind power was soon utilized to carry cargo by water. But fire remained the most important source of extrasomatic energy, and it made possible the development of ceramics and metallurgy.

Until quite recently, however, there was no real innovation in the fuel used to make fire. For hundreds of thousands of years, fire was made with the tissues of recently deceased organisms—principally wood. The development of charcoal improved on the energy density of untreated wood, and made a substantial contribution to metallurgy. Then, just a few millennia later, the same oxygen-deprived roasting process was applied to coal. In England, coal had been used to heat living space since the Norman Conquest, but the development of coke and its suitability for steelmaking set off the Industrial Revolution. Within an evolutionary wink, petroleum and natural gas were also being exploited, and *Homo sapiens* had begun to dissipate the rich deposits of organic energy that had been accumulating since the beginning of life. If the slow accretion of these deposits in the face of universal entropy can be likened to the buildup of water behind a dam, then with the appearance of a species capable of dissipating that energy, the dam burst.

ENERGY AND RESOURCES

According to the *American Heritage Dictionary*, resources are "An available supply that can be drawn upon when needed" and "Means that can be used to advantage." In other words, resources include all the things found in nature that people use—not just the things people use for survival, but things they use for any purpose whatever. This is a very broad concept, as required by the nature of the defining animal. The resources used by other animals consist primarily of food, plus a few other materials such as those used for nest building. But for *Homo sapiens*, almost everything "can be used to advantage."

For something to be a resource, it must be concentrated or organized in a particular way, and separate, or separable, from its matrix. Ore from an iron mine is a resource in a way that garden soil is not—even though both do contain iron. Similarly, wood from the trunk of an oak tree is a resource in a way that wood from its twigs is not.

Using a resource means dispersing it. When we quarry limestone and send it off to build public monuments, or when we mine coal and burn it to drive turbines, we are making use of a concentrated resource, and dispersing it. A large, continuous mass of limestone winds up as a number of discrete blocks spread around in different locations; and coal, after briefly giving off heat and light, becomes a small amount of ash and a large amount of gas. Resources may be temporarily accumulated in a stockpile, but their actual use always results in dispersal.

Resources may be used for their material properties or for the energy they contain. Bauxite is a material resource, while coal is an energy resource. Some resources may be used either way; wood, for example, may be used as a construction material or burned in a wood stove, and petroleum may be used to make plastics or to power cars.

The exploitation of all resources requires an investment in energy; it takes energy to knap flint or drill for oil. The exploitation of energy resources must entail a good return on investment; unless the energy they release is considerably more than the energy used to make them release it, they are not worth exploiting.

Since nothing is a resource unless it can be used, resources are defined by the technology that makes it possible to exploit them. Since exploiting a resource always requires energy, the evolution of technology has meant the application of energy to a growing array of substances so that they can be "used to advantage." In the brief time since humans began living in cities, they have used more and more energy to exploit more and more resources.

THE POPULATION EXPLOSION

The cost of energy limited the growth of technology until fossil fuels came into use, a little less than three hundred years ago. Fossil fuels contain so much energy that they provide a remarkable return on investment even when used inefficiently. When coal is burned to drive dynamos, for example, only 35% of its energy ultimately becomes electricity (Ross & Steinmeyer, 1990, p. 89). Nevertheless, an amount of electricity equal to the energy used by a person who works all day, burning up 1,000 calories worth of food, can be bought for less than ten cents (Loftness, 1984, p. 2).[3]

The abundant, cheap energy provided by fossil fuels has made it possible for humans to exploit a staggering variety of resources, effectively expanding their resource base. In particular, the development of mechanized agriculture has allowed relatively few farmers to work vast tracts of land, producing an abundance of food and making possible a wild growth of population.

All species expand as much as resources allow and predators, parasites, and physical conditions permit. When a species is introduced into a new habitat with abundant resources that accumulated before its arrival, the population expands rapidly until all the resources are used up. In wine making, for example, a population of yeast cells in freshly-pressed grape juice grows exponentially until nutrients are exhausted—or waste products become toxic (Figure 1). An example featuring mammals is provided by the reindeer of St. Matthew Island, in the Bering Sea (Klein, 1968). This island had a mat of lichens more than four inches deep, but no reindeer—until 1944, when a herd of 29 was introduced. By 1957 the population had increased to 1,350; and by 1963 it was 6,000. But the lichens were gone, and the next winter the herd died off. Come spring, only 41 females and one apparently dysfunctional male were left alive (Figure 2).[4]

The use of extrasomatic energy, and especially energy from fossil fuels, has made it possible for humans to exploit a wealth of resources that

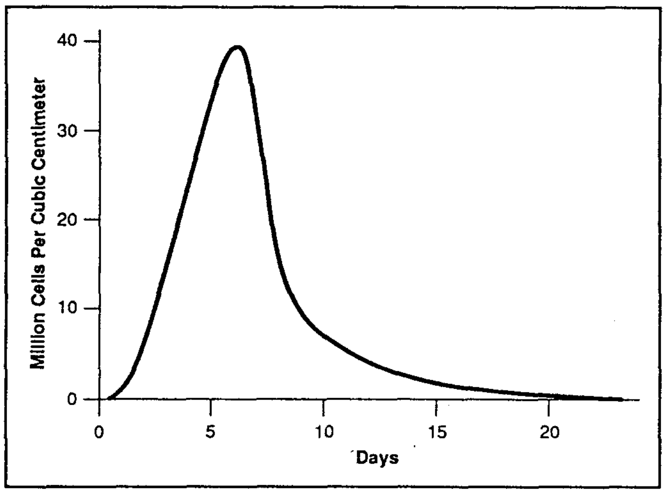

FIGURE 1. Growth of yeast in a 10% sugar solution (After Dieter, 1962:45). The fall of the curve is slowed by cytolysis, which recycles nutrients from dead cells.

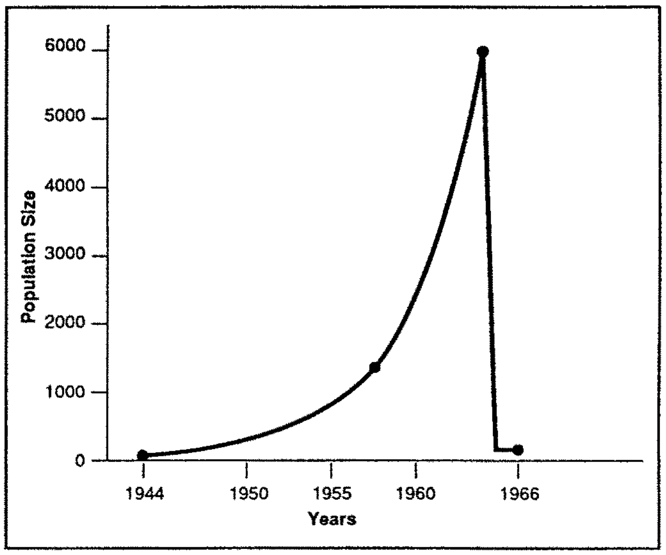

FIGURE 2. Growth of reindeer herd introduced to St. Matthew Island, Alaska (After Klein, 1968:352).

accumulated before they evolved. This has resulted in population growth typical of introduced species (Figure 3). Around 8,000 BC, world population was something like five million. By the time of Christ, it was 200 to 300 million. By 1650, it was 500 million, and by 1800 it was one billion. The population of the world reached two billion by 1930. By the beginning of the '60s it was three billion; in 1975 it was four billion; and after only eleven more years it was five billion (McEvedy & Jones, 1978; Erlich & Erlich, 1990, pp. 52-55). This cannot go on forever; collapse is inevitable. The only question is when.

THE ENERGY SUPPLY

Today, the extrasomatic energy used by people around the world is equal to the work of some 280 billion men. It is as if every man, woman, and child in the world had 50 slaves. In a technological society such as the United States, every person has more than 200 such "ghost slaves."[5]

Most of this energy comes from fossil fuels, which supply nearly 75% of the world's energy (see note 5). But fossil fuels are being depleted a

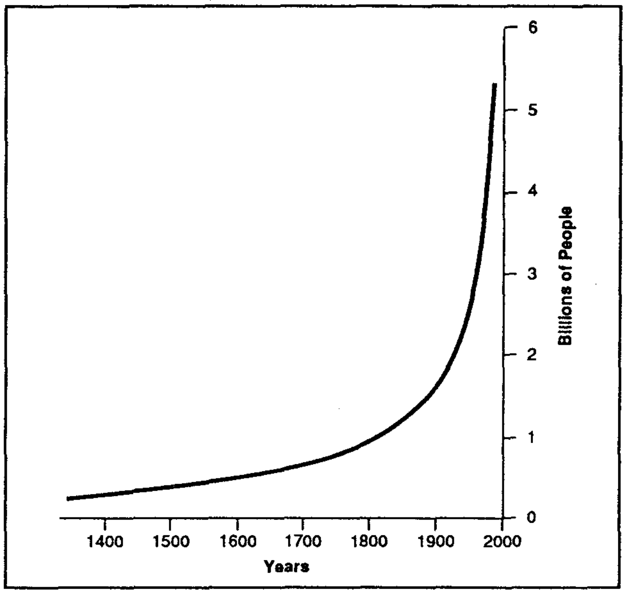

FIGURE 3. Growth of worldwide human population (Adapted from Corson, 1990:25).

hundred thousand times faster than they are being formed (Davis, 1990, p. 56). At current rates of consumption, known reserves of petroleum will be gone in about thirty-five years; natural gas in fifty-two years; and coal in some two hundred years (WRI/IIED, 1990, p. 145).[6]

It should not be supposed that additional reserves, yet to be discovered, will significantly alter these figures. Recent advances in the geological sciences have taken much of the guesswork out of locating fossil hydrocarbons and the surface of the earth has been mapped in great detail with the aid of orbiting satellites. Moreover, these figures are optimistic because the demand for energy will not remain at current rates; it can be expected to grow at an ever-quickening pace. The more concentrated a resource, the less energy it takes to make use of it; and the less concentrated a resource, the more energy it takes. Consequently, the richest deposits of any resource are used first, and then lower-grade deposits are exploited, at an ever-increasing cost. As high-grade mineral ores are worked out, more and more energy is needed to mine and refine lower-grade ores. As old-growth timber vanishes, more and more energy is necessary to make lumber and paper out of smaller trees. As the world's fisheries are worked out,

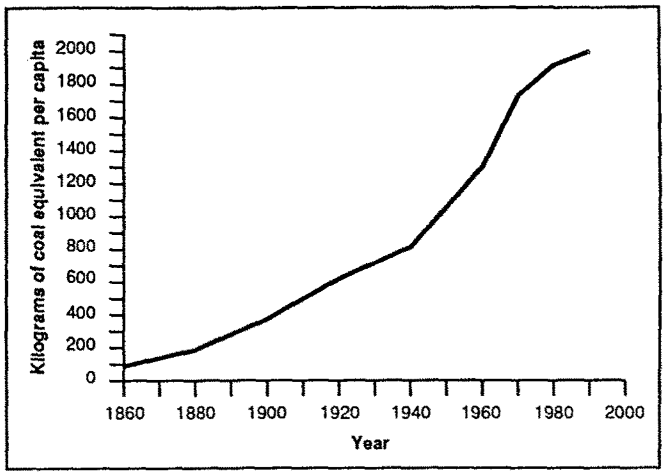

FIGURE 4. Worldwide energy consumption. Estimates of the world's annual consumption of energy, at twenty-year intervals beginning in 1860, appear in Dorf, 1981:194. World population for these years is calculated from a graph in Corson, 1990:25. Per-capita energy use for more recent years is given in the *Energy Statistics Yearbook*, which is published yearly by the United Nations. Figures differ somewhat from volume to volume; I have chosen to use more recent ones, which are presumably based on more accurate information.

it takes more and more energy to find and catch the remaining fish. And as the world's topsoil is lost—at a rate of 75 billion tons a year (Myers, 1993, p. 37)—more and more energy must be used to compensate for the diminished fertility of remaining agricultural land.

The system that sustains world population is already under stress. The growth in per-capita energy use, which had been increasing continually since the advent of fossil fuels, began to slow down some twenty years ago—and the accelerating pace at which it has been slowing down suggests that there will be no growth at all by the year 2000 (Figure 4). Agriculture is in trouble; it takes more and more fertilizer to compensate for lost topsoil (Erlich & Erlich, 1990, p. 92), and nearly one-fifth of the world's population is malnourished (Corson, 1990, p. 68). In fact, the growth rate of the earth's human population has already begun to fall (Figure 5).

People who believe that a stable population can live in balance with the productive capacity of the environment may see a slowdown in the

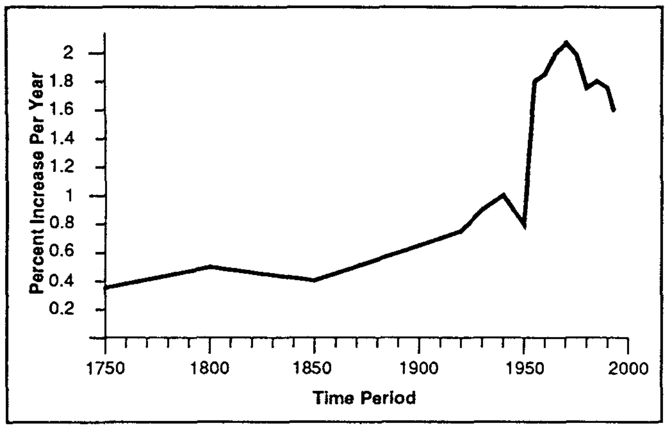

FIGURE 5. Growth rate of world population. Based on an average of estimates by Willcox (1940) and Carr-Saunders (1936) as adjusted and presented in United Nations, 1953:12; United Nations, 1993:6-7; and CIA, 1993:422.

growth of population and energy consumption as evidence of approaching equilibrium. But when one understands the process that has been responsible for population growth, it becomes clear that an end to growth is the beginning of collapse. Human population has grown exponentially by exhausting limited resources, like yeast in a vat or reindeer on St. Matthew Island, and is destined for a similar fate.

FALSE HOPES

To take over for fossil fuels as they run out, an alternative energy source would have to be cheap and abundant, and the technology to exploit it would have to be mature and capable of being operationalized all over the world in what may turn out to be a rather short time. No known energy source meets these requirements.

Today's second-most-important source of energy, after fossil fuels, is biomass conversion. But all the world's wood fires, all the grain alcohol added to gasoline, and all the agricultural wastes burned as fuel only provide 15% of the world's energy (WRI/IIED, 1988, p. 111). And biomass conversion has little growth potential, since it competes for fertile land with food crops and timber.

Hydropower furnishes about 5.5% of the energy currently consumed (see note 5). Its potential may be as much as five times greater (Weinberg & Williams, 1990, p. 147), but this is not sufficient to take over from fossil fuels, and huge dams would submerge rich agricultural soils.

The production of electricity from nuclear fission has been increasing, but nuclear sources still supply only about 5.2% of the world's total energy needs (see note 5). Fission reactors could produce a great deal more, especially if fast-breeder reactors were used.[7] But anyone with a fast-breeder reactor can make nuclear weapons, so there is considerable political pressure to prevent their proliferation. Public confidence in all types of reactors is low, and the cost of their construction is high. These social constraints make it unlikely that fission's contribution to the world's energy needs will grow fifteen-fold in the next few years.

Controlled thermonuclear fusion is an alluring solution to the world's energy problems because the "fuel" it would use is deuterium, which can be extracted from plain water. The energy from one percent of the deuterium in the world's oceans would be about five hundred thousand times as great as all the energy available from fossil fuels. But controlled fusion is still experimental, the technology for its commercialization has not yet been developed, and the first operational facility could not come on line much before 2040 (Browne, 1993, p. C12).

Visionaries support the potential of wind, waves, tides, ocean thermal energy conversion, and geothermal sources. All of these might be able to furnish a portion of the energy in certain localities, but none can supply 75% of the world's energy needs. Solar thermal collection devices are only feasible where it is hot and sunny, and photovoltaics are too inefficient to supplant the cheap energy available from fossil fuels.

While no single energy source is ready to take the place of fossil fuels, their diminishing availability may be offset by a regimen of conservation and a combination of alternative energy sources. This will not solve the problem, however. As long as population continues to grow, conservation is futile; at the present rate of growth (1.6% per year), even a 25% reduction in resource use would be obliterated in just over eighteen years. And the use of any combination of resources that permits continued population growth can only postpone the day of reckoning.

THE MECHANISMS OF COLLAPSE

Operative mechanisms in the collapse of the human population will be starvation, social strife, and disease. These major disasters were recognized long before Malthus and have been represented in western culture as horsemen of the apocalypse.[8] They are all consequences of scarce resources and dense population.

Starvation will be a direct outcome of the depletion of energy resources. Today's dense population is dependent for its food supply on mechanized agriculture and efficient transportation. Energy is used to manufacture and operate farm equipment, and energy is used to take food to market. As less efficient energy resources come to be used, food will grow more expensive and the circle of privileged consumers to whom an adequate supply is available will continue to shrink.

Social strife is another consequence of the rising cost of commercial energy. Everything people want takes energy to produce, and as energy becomes more expensive, fewer people have access to goods they desire. When goods are plentiful, and particularly when per-capita access to goods is increasing, social tensions are muted: Ethnically diverse populations often find it expedient to live harmoniously, governments may be ineffective and slow to respond, and little force is needed to maintain domestic tranquillity. But when goods become scarce, and especially when per-capita access to goods is decreasing, ethnic tensions surface, governments become authoritarian, and goods are acquired, increasingly, by criminal means.

A shortage of resources also cripples public health systems, while a dense population encourages the spread of contagious diseases. Throughout human history, the development of large, dense populations has led to the appearance of contagious diseases that evolved to exploit them. Smallpox and measles were apparently unknown until the second and third centuries AD, when they devastated the population of the Mediterranean basin (McNeill, 1976, p. 105). In the fourteenth century, a yet larger and denser population in both Europe and China provided a hospitable niche for the Black Death. Today, with extremely dense population and all parts of the world linked by air travel, new diseases such as AIDS spread rapidly—and a virus as deadly as AIDS but more easily transmissible could appear at any time.

Starvation, social strife, and disease interact in complex ways. If famine were the sole mechanism of collapse, the species might become extinct quite suddenly. A population that grows in response to abundant but finite resources, like the reindeer of St. Matthew Island, tends to exhaust these resources completely. By the time individuals discover that remaining resources will not be adequate for the next generation, the next generation has already been born. And in its struggle to survive, the last generation uses up every scrap, so that nothing remains that would sustain even a small population. But famine seldom acts alone. It is exacerbated by social strife, which interferes with the production and delivery of food. And it weakens the natural defenses by which organisms fight off disease.

Paradoxically, disease can act to spare resources. If, for example, a new epidemic should reduce the human population to a small number of people who happen to be resistant to it before all the world's resources are severely depleted, the species might be able to survive a while longer.

AFTER THE FALL

But even if a few people manage to survive worldwide population collapse, civilization will not. The complex association of cultural traits of which modern humans are so proud is a consequence of abundant resources, and cannot long outlive their depletion.

Civilization refers, in its derivation, to the habit of living in dense nucleated settlements, which appeared as population grew in response to plentiful resources. Many things seem to follow as a matter of course when people live in cities, and wherever civilization occurred, it has involved political consolidation, economic specialization, social stratification, some sort of monumental architecture, and a flowering of artistic and intellectual endeavor (Childe, 1951).

Localized episodes of such cultural elaboration have always been associated with rapid population growth. Reasons for the abundance of resources that promoted this growth vary from one case to another. In some instances, a population moved into a new region with previously untapped resources; in other instances the development or adoption of new crops, new technologies, or new social strategies enhanced production. But the Sumerians, the Greeks, the Romans, the Mayas, and even the Easter Islanders all experienced a surge of creative activity as their populations grew rapidly.

And in all cases, this creative phase, nourished by the same abundance that promoted population growth, came to an end when growth ended. One need not seek esoteric reasons for the decline of Greece or the fall of Rome; in both cases, the growth of population exhausted the resources that had promoted it. After the Golden Age, the population of Greece declined continually for more than a thousand years, from 3 million to about 800,000. The population of the Roman Empire fell from 45 or 46 million, at its height, to about 39 million by 600 AD, and the European part of the empire was reduced by 25% (McEvedy & Jones, 1978).

Even if world population could be held constant, in balance with "renewable" resources, the creative impulse that has been responsible for human achievements during the period of growth would come to an end. And the spiraling collapse that is far more likely will leave, at best, a handfull of survivors. These people might get by, for a while, by picking through the wreckage of civilization, but soon they would have to lead simpler lives, like the hunters and subsistence farmers of the past. They would not have the resources to build great public works or carry forward scientific inquiry. They could not let individuals remain unproductive as they wrote novels or composed symphonies. After a few generations, they might come to believe that the rubble amid which they live is the remains of cities built by gods.

Or it may prove impossible for even a few survivors to subsist on the meager resources left in civilization's wake. The children of the highly technological society into which more and more of the world's peoples are being drawn will not know how to support themselves by hunting and gathering or by simple agriculture. In addition, the wealth of wild animals that once sustained hunting societies will be gone, and topsoil that has been spoiled by tractors will yield poorly to the hoe. A species that has come to depend on complex technologies to mediate its relationship with the environment may not long survive their loss.

INTO THE DARK

For Malthus, the imbalance between the growth of population and means of subsistence might be corrected, from time to time, through natural disasters, but the human species could, in principle, survive indefinitely. Malthus did not know that the universe is governed by the Second Law of Thermodynamics; he did not understand the population dynamics of introduced species; and he did not appreciate that humans, having evolved long after the resource base on which they now rely, are effectively an introduced species on their own planet.

The short tenure of the human species marks a turning point in the history of life on Earth. Before the appearance of *Homo sapiens*, energy was being sequestered more rapidly than it was being dissipated. Then human beings evolved, with the capacity to dissipate much of the energy that had been sequestered, partially redressing the planet's energy balance. The evolution of a species like *Homo sapiens* may be an integral part of the life process, anywhere in the universe it happens to occur. As life develops, autotrophs expand and make a place for heterotrophs. If organic energy is sequestered in substantial reserves, as geological processes are bound to do, then the appearance of a species that can release it is all but assured. Such a species, evolved in the service of entropy, quickly returns its planet to a lower energy level. In an evolutionary instant, it explodes and is gone.

If the passage of *Homo sapiens* across evolution's stage significantly alters Earth's atmosphere, virtually all living things may become extinct quite rapidly. But even if this does not happen, the rise and fall of *Homo sapiens* will eliminate many species. It has been estimated that they are going extinct at a rate of 17,500 per year (Wilson, 1988, p. 13), and in the next twenty-five years as many as one-quarter of the world's species may be lost (Raven, 1988, p. 121).

This is a radical reduction in biological diversity, although life has survived other die-offs, such as the great collapse at the end of the Permian. It is unlikely, however, that anything quite like human beings will come this way again. The resources that have made humans what they are will be gone, and there may not be time before the sun burns out for new deposits of fossil fuel to form and intelligent new scavengers to evolve. The universe seems to have had a unique beginning, some ten or twenty billion years ago (Hawking, 1988, p. 108). Since that time, a star had to live and die to provide the materials for the solar system—which, itself, is several billion years old. Perhaps life could not have happened any sooner than it did. Perhaps *Homo sapiens* could not have evolved any sooner. Or later. Perhaps everything has its season, a window of opportunity that opens for a while, then shuts.

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NOTES

1. In the 1798 version of his essay, Malthus said that population grows geometrically while subsistence grows arithmetically. In later editions, he said that arithmetical growth was the most optimistic possible hypothesis; he was well aware that the availability of fertile soils must actually be diminishing.
2. The distinction between "nonrenewable" and "renewable" is arbitrary. Petroleum is considered nonrenewable, because when it's used, it's gone; while sunlight is considered renewable, because its energy can be used today and the sun will shine again tomorrow.

But given enough time, today's forests could become tomorrow's petroleum, and given an astronomical sweep of time, the sun itself will burn out. Only in terms of human time is an energy resource renewable or nonrenewable; and it is not even clear how human time should be measured. Wood is often considered a renewable resource, because if one tree is chopped down, another will grow in its place. But if a tree is taken off the mountainside rather than allowed to rot where it falls, nutrients that would nourish its successor are removed. If wood is continually removed, the fertility of the forest diminishes, and within a few human generations the forest will be gone.

3. Loftness actually says six cents. I have changed the figure to ten cents as a rough correction for inflation.
4. When the resources exploited by an introduced species are living organisms, they can reproduce—and they may eventually evolve defense mechanisms that promote an equilibrium between predator and prey (see Pimentel, 1988). The topsoil, minerals, and fossil fuels exploited by human beings do not have this capacity, however. They are more like the finite amount of sugar in a vat or the plentiful but slow-growing lichens on St. Matthew Island.
5. Worldwide production of energy from fossil fuels in 1992 was 302.81×10^{15} Btu, while energy from nuclear reactors was 21.23×10^{15} Btu and from hydroelectric sources was 22.29×10^{15} Btu (Energy Information Administration, 1993:269). Biomass is thought to account for about 15% of the world's extrasomatic energy (WRI/IIED, 1988:111). Other sources of energy make only a minor contribution (Corson, 1990:197). Thus, the total extrasomatic energy used in the world must be on the order of 407.45×10^{15} Btu per year. World population is taken as 5.555 billion (CIA, 1993:422). The energy expended by an individual in doing a hard day's work is taken to be 4,000 Btu (Loftness 1984:2, 756). Energy consumption in the United States is on the order of 82.36×10^{15} Btu (Energy Information Administration, 1993:5). U.S. population is taken as 258 million (CIA, 1993:404).
6. These are reserves known in 1988, depleted at 1988 rates. I have subtracted six years from the figures cited to account for time that has already elapsed.
7. Loftness (1984:48) says the same amount of uranium, used in a fast-breeder reactor, will provide 60 times as much energy as in a light-water reactor. Häfele (1990:142) says one hundred times as much.
8. According to a traditional interpretation, the four horses stand for war, famine, pestilence, and the returned Christ. The original text (Revelations 6:2-8) is not so clear.

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