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ABSTRACT

The goals of the Caltech Population Program are to increase understanding of the interrelationships between population growth and socioeconomic and cultural patterns throughout the world and to communicate this understanding. This series of occasional papers is one step in the process of communicating research results. The papers deal primarily with problems of population growth and the interaction of population change with such variables as resources, food supply, environment, urbanization, employment, economic development, and social and cultural values. Paper Number 2 categorizes five types of environmental problems; four of the categories are of a direct nature, while the fifth is indirect. The author feels that most attention is paid to acute problems in the direct categories, while chronic indirect problems may prove to be the most serious of all. These indirect effects on human welfare act through interference with services provided for society by natural biological systems. The paper describes man's force in the ecological system both historically and for the present and future. (LS)

Series 1 Number 2

# MAN AS A GLOBAL ECOLOGICAL FORCE

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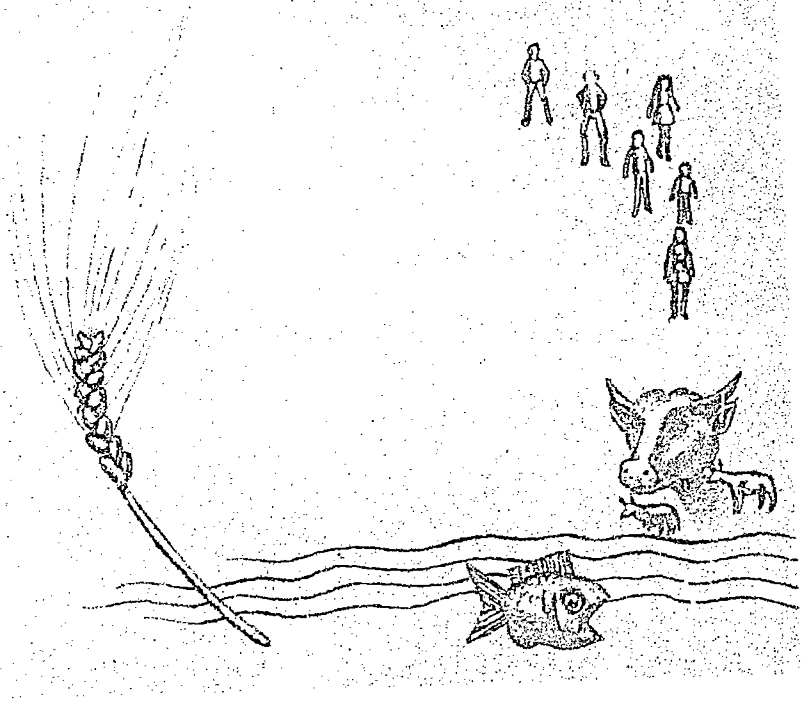

# Caltech
# Population
# Program

The Caltech Population Program was founded in 1970 to study the factors influencing population growth and movement. Its goal is to increase our understanding of the interrelationships between population growth and socioeconomic and cultural patterns throughout the world, and to communicate this understanding to scholars and policy makers.

This series of Occasional Papers, which is published at irregular intervals and distributed to interested scholars, is intended as one link in the process of communicating the research results more broadly. The Papers deal primarily with problems of population growth, including perceptions and policies influencing it, and the interaction of population change with other variables such as resources, food supply, environment, urbanization, employment, economic development, and shifting social and cultural values.

# MAN AS A GLOBAL ECOLOGICAL FORCE*

John P. Holdren

## Introduction

Environmental problems can be classified according to the nature of the damage to human beings, as follows.

(1) Direct assaults on human health (for example, lead poisoning or aggravation of lung disease by air pollution);
(2) Damage to goods and services that are provided by society for itself (for example, the corrosive effects of air pollution on buildings and crops);
(3) Social disruption (for example, displacement of people from their living areas by mining operations and hydroelectric projects);
(4) Other direct effects on what people perceive as their "quality of life" (examples of such effects are congestion and litter);
(5) Indirect effects on human welfare through interference with services provided for society by natural biological systems (for example, diminution of ocean productivity by filling estuaries and polluting coastal waters, and acceleration of erosion by logging and overgrazing).

Most of the attention devoted to environmental matters by scientists, politicians and the public alike has been focused on the four *direct* categories and, more particularly, on their acute rather than their chronic manifestations. This is only natural. It would be wrong, however, to interpret limited legislative and technical progress toward ameliorating the direct, acute symptoms of

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environmental damage as evidence that society is on its way to an orderly resolution of its environmental problems. The difficulty is not merely that implementation and enforcement of theoretical remedies is likely to be expensive and difficult; worse than this, the long-term human consequences of chronic exposure to low concentrations of environmental contaminants may be more serious—and the causes less amenable to removal—than those of acute pollution as it is perceived today. It is possible that the most serious threats of all, however, will prove to be the indirect ones generated by mankind's disruption of the functioning of the natural environment—the fifth category listed above. The purpose of this paper is to communicate the basis for the deep concern of a growing number of environmental scientists over this last set of problems.

The topic is developed in the following steps. First, the relevance of environmental disruption to human welfare is established by examining the services provided for society by nature. There follows a brief introduction to the science of ecology, which deals with the functioning of the natural systems that provide these services. Some historical examples of ecological disruption caused by human activities are given, followed by an examination of the role of contemporary civilization as an ecological force. Another section treats the role of demographic variables—population size, growth rate, and geographic distribution—in generating ecological problems. A discussion of time factors relevant to ecological problems emphasizes growth rates, sources of momentum in the factors generating the problems, the possibility of irreversible environmental damage, and the issue of imminence—is there any reason to believe that serious ecological impact on the welfare of civilization will be felt sooner rather than later?

## Natural Services

The most obvious services provided for humanity by the natural environment have to do with food production. The fertility of the soil is maintained by the plants, animals, and microbes that participate in the great nutrient cycles—nitrogen, phosphorous, carbon, sulfur. Soil itself is produced from plant debris and weathered rock by the joint action of bacteria, fungi, worms, soil mites, and insects. And the best protection against erosion of soil and flooding is natural vegetation.

At many stages of the natural processes comprising the nutrient cycles, organisms accomplish what humans have not yet learned to do—the complete conversion of wastes into resources, with solar energy captured by photosynthesis as the driving energy source. Human society depends on these natural processes to recycle many of its own wastes, from sewage to detergent to industrial effluents. (Reflect on the term "biodegradable.") In the course of the same cycles, the atmospheric concentrations of ammonia, carbon monoxide, and hydrogen sulfide—all poisonous—are biologically controlled.[1]

Insects pollinate most vegetables, fruits and berries. Most fish—the source of roughly 10 percent of the animal protein consumed by mankind—are produced in the natural marine environment, unregulated by man. (As is well known, animal protein is the nutrient in shortest supply in a chronically malnourished world.) Most potential crop pests—one competent estimate is 99 percent—are held in check not by man but by their natural enemies and by characteristics of the physical environment such as temperature, moisture, and availability of breeding sites.[2] Similarly, some agents of human disease are controlled principally not by medical technology but by environmental conditions, and some carriers of such agents are controlled by a combination of environmental conditions and natural enemies.[3]

Finally, the natural environment in its diversity can be viewed as a unique library of genetic information. From this library will come new food crops, new drugs and vaccines, new biological pest controls. The loss of a species, or even a loss of genetic diversity within a species, is the loss forever of a potential opportunity to improve human welfare.

These "public service" functions of the global environment cannot be replaced by technology now or in the foreseeable future. This is so in some cases because the process by which the service is provided is not understood scientifically, in other cases because no technological equivalent for the natural process has yet been devised. But in the largest number of cases, the sheer size of the tasks simply dwarfs civilization's capacity to finance, produce, and deploy new technology. The day is far away when food for billions is grown on synthetic nutrients in greenhouses free of pests and plant diseases, when the wastes of civilization are recycled entirely by technological means, and when all mankind lives in surroundings as sterile and as thoroughly managed as those of an Apollo space capsule. Until that improbable future arrives—and it may never come—the services provided by the orderly operation of natural biological processes will continue to be irreplaceable as well as indispensable.

## Some Elements of Ecology

How many of these natural services are actually threatened by human activities? Any of them? All of them? These questions call for a closer look at the operation of the biological systems that provide the services.

*Energy flow and food chains.* Energy is the currency of ecosystems. The processes by which energy and mineral nutrients are passed through biological communities are described in terms of food chains: light energy from the sun is captured and converted to chemical energy via photosynthesis in green plants, and then passed on in succession to herbivores, primary carnivores (eaters of herbivores), secondary carnivores (eaters of carnivores) and so on. Each stage in a food chain is called a *trophic level.* Organisms known as decomposers utilize the energy stored in dead plant and animal matter from all trophic levels and return mineral nutrients to the biosphere in forms usable by other organisms.

Often the term food web is used in place of food chain, since there are usually many species on each trophic level, and the food chains are interlaced—for example, each plant species is eaten by more than one species of herbivore, and each herbivore eats more than one species of plant. Moreover, some organisms feed on several trophic levels at once—man is an herbivore when he eats bread, a primary carnivore when he eats beef, and a secondary (or higher) carnivore when he eats fish.

Plant communities are at the base of all food webs and thus the basis of all life on earth. The fundamental measure of performance of a plant community is the rate at which solar energy is captured by photosynthesis to be stored in chemical bonds. In this context, *gross primary productivity* refers to the total rate of energy capture; *net primary productivity* is the total minus the rate at which captured energy is used to sustain the life processes of the plants themselves. Thus, net primary productivity measures the rate at which energy is made available to the remainder of the food web. *Net community productivity* is what remains after the other organisms in the community have used part of the net primary productivity to sustain their own life processes. The net community productivity may be exported (for example, in the form of grain from a wheat field) or it may remain in the community in the form of an enlarged standing crop of plants and animals. A community in balance may have no net community productivity at all—that is, the net primary productivity may be entirely burned up by the animals and microorganisms within the community. The productivities of various kinds of ecosystems are shown in table 1.

Table 1. Productivity of Various Ecosystems (in kilocalories of energy per square meter per year*)

| *Ecosystem* | *Net Primary productivity* | *Net community productivity* |
|---|---|---|
| Alfalfa field | 15,200 | 14,400 |
| Pine forest | 5,000 | 2,000 |
| Tropical rain forest | 13,000 | little or none |
| Long Island Sound | 2,500 | little or none |

*Source:* Eugene P. Odum, *Fundamentals of Ecology*, 3rd ed. (Philadelphia: Saunders, 1971), p. 46

*Some ecologists use grams of dry organic matter or grams of carbon in place of kilocalories. There are about 4 kilocalories of available bond energy per gram of dry organic matter, or 10 kilocalories per gram of contained carbon. The average human being metabolizes 2,500 kilocalories per day.

A final, critical point concerning energy flow in ecosystems is that each step in a food chain results in the eventual loss (as heat) of a substantial fraction of the energy transferred. A good rule of thumb for the loss is 90 percent. This means it takes 10,000 kilocalories of corn to produce 1,000 kilocalories of steer and, more generally, that available energy diminishes 10-fold at each higher trophic level. Thus, the food web is often described as an energy pyramid. One consequence of this situation is that gains in production of animal protein come at high cost in primary calories. Another is that the yield of prized food fishes such as cod and tuna is limited by their position on the fourth or fifth trophic level of the oceanic food web.

*Carrying capacity.* Any population of organisms that multiplied as rapidly as the species' own reproductive biology permitted would soon cover the earth. This is prevented from occurring by deaths caused by such factors as predators, disease, scarcity of resources (e.g., food, water, breeding sites), and many others. What factor or combination of factors determines the size limit on a population varies from species to species, from place to place, and from time to time. The maximum size of the population that can be sustained at a given time (under a given set of environmental conditions) is described as the carrying capacity of the environment for that organism. In this context, the word "sustain" implies an extended period. Animal populations often temporarily overshoot the carrying capacity of their environment—a phenomenon that is invariably followed by a population crash. Human populations are not immune to this possibility.

*Complexity and stability in ecosystems.* The intricate interlacing of most biological food webs provides a form of insurance against disruptions. If one species of plant in a complex community is eradicated by disease or drought, the herbivores in the community can survive on other kinds of plants that may be less susceptible. If a population of predators dwindles for one reason or another, an outbreak of the prey species is unlikely if there are other kinds of predators to fill the gap. Species diversity is one of a number of forms of biological complexity believed by many ecologists to impart stability to ecosystems.

Exactly what is meant by ecological stability? One definition is the ability of an ecosystem that has suffered an externally imposed disturbance to return to the conditions that preceded the disturbance. A more general meaning is that a stable ecosystem resists large, rapid changes in the sizes of its constituent populations. Such changes (called fluctuations or instabilities, depending on the circumstances) entail alteration of the orderly flow of energy and nutrients in the ecosystem. Usually this will mean disruption of the "public service" functions of the ecosystem, whether or not the instability is severe enough to cause any extinctions of species.

What kinds of complexity can influence stability, and how? Species diversity, already mentioned, presumably imparts stability by providing alternative pathways for the flow of nutrients and energy through the ecosystem. Another possible advantage of a large number of species in a community is that there will then be few empty niches. (A niche is a biological role, and an empty niche is an opportunity for invasion by a new species from outside the community, with possible disruptive effect.) Sheer number of species is not the only determining factor in this type of complexity, however; a degree of balance in population sizes among the species is also required if the capacity of the alternative pathways is to be adequate and the niches solidly occupied. (To take an oversimplified example, consider two communities each containing 1,000,000 organisms divided among 1,000 species. A situation with 1,000 populations of 1,000 individuals each should be more stable than a situation where one population contains 900,100 individuals and the other 999 populations contain 100 individuals each.) Measures of complexity exist at the population level of organization as well as that of the community. One is genetic variability, which provides the raw material for resistance against new threats. Another is physiological variability, in the form of a mixed age distribution. (Here the advantage of complexity manifests itself when threats appear that are specific to a particular stage in the organism's life cycle—say, a disease that strikes only juveniles.) There are other forms of complexity, as well, including physical complexity of habitat and variety in the geographic distribution of a given species.

The causal links between complexity and stability in ecological systems are by no means firmly established or well understood, and exceptions do exist.[4] The evidence of a general correlation between these properties is growing, however, and consists of theoretical considerations of the sort summarized above, general observations of actual ecosystems of widely varying complexity (the relatively simple ecosystem of the boreal coniferous forest—the "north woods"—is observed to be less stable than the complex tropical rain forest), and a limited number of controlled laboratory and field experiments.

*Time scales of ecological change.* Ecological stability does not mean constancy or stagnation, and ecological change can take place over much longer time spans than the month-to-month or year-to-year time scale of fluctuations and instabilities. Ecological *succession* refers to the orderly replacement of one community in an area with other communities over periods often measured in decades. *Evolution* refers to changes in the genetic characteristics of species, brought about by natural selection over time periods ranging from a few generations to hundreds of millions of years. Note that, in terms of human beings, evolution is not the solution to pollution. When significant evolutionary change does take place on the short time scale of a few generations, it is necessarily at the expense of the lives of a large fraction of the population.

## History of Human Ecological Disruption

Ecological disruption on a large scale by human beings is not a new phenomenon. Even before the advent of agriculture, man as a hunter is thought to have contributed to a reduction in the number of species of large mammals inhabiting the earth.[5] Much more significant, however, was the era of abuse of soils and habitat that was initiated by the agricultural revolution about 10,000 years ago and has continued up to the present.

One of the best known early examples is the conversion to desert of the lush Tigris and Euphrates valleys, through erosion and salt accumulation resulting from faulty irrigation practices.[6] In essence, the downfall of the great Mesopotamian civilization appears to have been the result of an "ecocatastrophe." Overgrazing and poor cultivation practices have contributed over the millennia to the expansion of the Great Sahara Desert, a process that continues today;[7] and the Rajasthan desert in India is also believed to be partly a product of human carelessness and population pressure.[8]

Much of Europe and Asia were deforested by preindustrial men, beginning in the Stone Age; heavy erosion, recurrent flooding and the nearly permanent loss of a valuable resource were the results. Overgrazing by the sheep of Navajo herdsmen has destroyed large tracts of once prime pastureland in the American Southwest.[10] Attempts to cultivate too intensively the fragile soils of tropical rainforest areas are suspected of being at least in part responsible for the collapse of the Mayan civilization in Central America and that of the Khmers in what today is Cambodia.[11] (The famous temples at Angkor Wat were built partly of laterite, the rock-like material that results when certain tropical soils are exposed to the air through cultivation.)

The practice of agriculture—even where quality of soils, erosion, or salt accumulation do not pose problems—may encounter ecological difficulties. The most basic one is that agriculture is a simplifier of ecosystems, replacing relatively complex natural biological communities with relatively simple man-made ones based on a few strains of crops. Being less complex, agricultural communities tend to be less stable than their natural counterparts; they are vulnerable to invasions by weeds, insect pests, and plant diseases, and they are particularly sensitive to extremes of weather and variations in climate. Historically, man has attempted to defend his agricultural communities against the instabilities to which they are susceptible by means of vigilance and the application of "energy subsidies"—for example, hoeing weeds and, more recently, applying pesticides and fungicides. He has not always been successful. The Irish potato famine of the last century is perhaps the best known example of the collapse of a simple agricultural ecosystem. The heavy reliance of the Irish population on a single, highly productive crop led to 1.5 million deaths when the potato monoculture fell victim to a fungus.[12]

## Contemporary Man as an Ecological Force

*Agriculture.* Advances in agricultural technology in the last hundred years have not resolved the ecological dilemma of agriculture, they have aggravated it. The dilemma can be summarized this way: civilization tries to manage ecosystems in such a way as to maximize productivity, "nature" manages ecosystems in such a way as to maximize stability, and the two goals are incompatible. Ecological succession proceeds in the direction of increasing complexity. Ecological research has shown that the most complex (and stable) natural ecosystems tend to have the smallest *net* community productivity; less complex, transitional ecosystems have higher net community productivity; and the highest net community productivities are achieved in the artificially simplified agricultural ecosystems of man (see table 1). In short, productivity is achieved at the expense of stability.

Of course, mankind would have to practice agriculture to support even a fraction of the existing human population. A degree of proneness to instability in agricultural ecosystems must be accepted and, where possible, compensated for by technology. However, the trends in modern agriculture—associated in part with the urgent need to cope with unprecedented population growth and in part with the desire to maximize yields per acre for strictly economic reasons—are especially worrisome ecologically. There are three major liabilities.

(1) As larger and larger land areas are given over to farming, the unexploited tracts available to serve as reservoirs of species diversity and to carry out the "public service" functions of natural ecosystems become smaller and fewer. (World land use patterns are summarized in table 2.)

(2) Even in parts of the world where land area under agriculture is constant or (for economic reasons) dwindling, attempts to maximize yields per acre have led to dramatic increases in the

Table 2. World Land Use—1966 (in millions of square kilometers)

| | *Total* | *Tilled* | *Pasture* | *Forest* | *Other** |
|---|---|---|---|---|---|
| Europe | 4.9 | 1.5 | 0.9 | 1.4 | 1.1 |
| U.S.S.R. | 22.4 | 2.3 | 3.7 | 9.1 | 7.3 |
| Asia | 27.8 | 4.5 | 4.5 | 5.2 | 13.7 |
| Africa | 30.2 | 2.3 | 7.0 | 6.0 | 15.0 |
| North America | 22.4 | 2.6 | 3.7 | 8.2 | 7.9 |
| South America | 17.8 | 0.8 | 4.1 | 9.4 | 3.5 |
| Oceania | 8.5 | 0.4 | 4.6 | 0.8 | 2.7 |
| Total** | 134.2 | 14.3 | 23.6 | 40.2 | 51.2 |
| Percentage | 100% | 10.6% | 21.3% | 29.9% | 38.2% |

*Source:* Georg Borgstrom, *Too Many* (New York: Macmillan, 1969), p. 290

*deserts, wasteland, built-on land, glaciers, wetlands

**less Antarctica

use of pesticides and inorganic fertilizers, which have far-reaching ecological consequences themselves.

(3) The quest for high yields has led also to the replacement of a wide variety of traditional crop varieties all over the world with a few, specially bred, high-yield strains. Unprecedented areas are now planted to a single variety of wheat or rice. This enormous expansion of monoculture has increased the probability and the potential magnitude of epidemic crop failure from insects or disease.[13]

*Effects of pollution on ecosystems.* The expansion and intensification of agriculture has been accompanied by a continuing industrial revolution that has multiplied many times over both the magnitude and variety of the substances introduced into the biological environment by man. It is useful to classify these substances as *qualitative pollutants* (synthetic substances produced and released only by man) and *quantitative pollutants* (substances naturally present in the environment but released in significant additional amounts by man).

Well known qualitative pollutants are the chlorinated hydrocarbon pesticides, such as DDT, the related class of industrial chemicals called PCBs (polychlorinated biphenyls), and some herbicides. These substances are biologically active in the sense of stimulating physiological changes, but since organisms have had no experience with them over evolutionary time the substances are not usually biodegradable. Thus, they may persist in the environment for years and decades after being introduced, and be transported around the globe by wind and water. Their long-term effects will be discovered only by experience.

Within the category of quantitative pollutants, there are three criteria by which a contribution made by mankind may be judged significant.

(1) Man can perturb a natural cycle with a large amount of a substance ordinarily considered innocuous, either by overloading part of the cycle (as we do to the denitrifying part of the nitrogen cycle when we overfertilize, leading to the accumulation of nitrates and nitrites in ground water); by destabilizing a finely tuned balance (as we may do to the global atmospheric heat engine, which governs global climate, by adding $CO_2$ to the atmosphere via combustion of fossil fuels); or by swamping a natural cycle completely (as could happen to the climatic balance in the very long term from man's input of waste heat).

(2) An amount of material negligible compared to natural global flows of the same substance can cause great damage if released in a sensitive spot, over a small area, or suddenly (for example, the destruction of coral reefs in Hawaii by silt washed from construction sites).

(3) *Any* addition of a substance that can be harmful even at its naturally occurring concentrations must be considered significant. Radioactive substances fall in this category, as does mercury.

The most general effect of pollution of all kinds or ecosystems is the loss of structure or complexity.[14] Specifically, food chains are shortened by pollution via the selective loss of the predators at the top. This is so because predators are more sensitive to environmental stresses of all kinds—pesticides, industrial effluents, thermal stress, oxygen deficiency—than are herbivores. This increased sensitivity results from several mechanisms: the predator populations are usually smaller than those of the prey species, so the predator populations tend to have a smaller reservoir of genetic variability and, hence, less probability of harboring a resistant strain; top predators are often exposed to higher concentrations of toxic substances than organisms at lower trophic levels, owing to the phenomenon of biological concentration of pollutants as they move up the food chain; and, finally, the direct effects of pollution on predators are compounded by the fact that pollutants "compete" with predators for the food population. Loss of structure may also occur at lower trophic levels when, for a variety of reasons, one species of herbivore or lower carnivore proves especially sensitive to a particular form of environmental stress. One does not have to eradicate the food pyramid from top to bottom to have significant differential effects.

The adverse effects of loss of structure on the "public service" functions performed by ecosystems are varied and serious. The vulnerable top predators in marine ecosystems are generally the food fishes most highly prized by man. The loss of predators on land releases checks on herbivorous pests that compete with man for his supply of staple crops. Damaging population outbreaks of these pests—the classic "instability"—are the result. The loss of structure of ecosystems also increases the load on the aquatic food webs of decay, which are already heavily stressed by the burden of mankind's domestic and agricultural wastes. The resulting overload precipitates a vicious progression: oxygen depletion, a shift from aerobic to less efficient anaerobic bacterial metabolism, the accumulation of organic matter, and the release of methane and hydrogen sulfide gas.

*Vulnerability of the sea.* The ocean, presently indispensable as a source of animal protein, may be the most vulnerable ecosystem of all. Its vast bulk is deceiving. The great proportion of the ocean's productivity—over 99 percent—takes place beneath 10 percent of its surface area, and half of the productivity is concentrated in coastal upwellings amounting to only 0.1 percent of the surface area.[15] The reason is that productivity requires nutrients, which are most abundant near the bottom, and sunlight, available only near the top. Only in the coastal shelf areas and in upwellings are nutrients and sunlight both available in the same place.

The coastal regions, of course, also receive most of the impact of man's activities—oil spills, fallout from atmospheric pollutants generated on the adjacent land, and river outflow bearing pesticide and fertilizer residues, heavy metals, and industrial chemicals. Almost perversely, the most fertile and critical components of all in the ocean ecosystem are the estuaries into which the rivers empty; estuaries serve as residence, passage zone, or nursery for about 90 percent of commercially important fish.[16] To compound the problem of pollution, the salt marshes that are an integral part of estuarine biological communities are being destroyed routinely by landfill operations

Overfishing is almost certainly also taking a heavy toll in the ocean, although it is difficult to separate its effect from that of pollution and destruction of the estuarine breeding grounds and nurseries. The combined result of these factors is clear, however, even if the blame cannot be accurately apportioned. Since World War II, the catches of the East Asian sardine, the California sardine, the Northwest Pacific salmon, the Scandinavian herring and the Barents Sea cod (among others) have entered declines from which there has been no sign of recovery.[17]

*Flows of material and energy.* Many people still imagine that mankind is a puny force in the global scale of things. They are persuaded, perhaps by the vast empty spaces visible from any jet airliner in many parts of the world, that talk of global ecological disruption is a preposterous exaggeration. The question of the absolute scale of man's impact, however, is amenable to quantitative investigation. Natural global flows of energy and materials can be reasonably calculated or estimated, and these provide an absolute yardstick against which to measure the impact of human activities.

The results are not reassuring. As a global geological and biological force, mankind is today becoming comparable to and even exceeding many natural processes. Oil added to the oceans in 1969 from tanker spills, offshore production, routine shipping operations, and refinery wastes exceeded the global input from natural seepage by an estimated 20-fold.[18] The minimum estimate for 1980, assuming all foreseeable precautions, is 30 times natural seepage. Civilization is now contributing half as much as nature to the global atmospheric sulfur burden and will be contributing as much as nature by the year 2000.[19] In industrial areas, civilization's input of sulfur (as sulfur dioxide) so overwhelms natural removal processes that increased atmospheric concentrations and acidic surface water are found hundreds to thousands of kilometers downwind. Combustion of fossil fuels has increased the global atmospheric concentration of carbon dioxide by 10 percent since the turn of the century.[20] Civilization's contribution to the global atmospheric burden of particulate matter is uncertain: estimates range from 5 to 45 percent of total annual input.[21] Roughly five percent of all the energy captured by photosynthesis on earth flows through the agricultural ecosystems

Table 3. Mankind's Mobilization of Materials (in thousands of metric tons per year)

| *Element* | *Geological rate (river flow)* | *Man's rate (mining and consumption)* |
|---|---|---|
| Iron | 25,000 | 319,000 |
| Nitrogen | 3,500 | 19,800 |
| Copper | 375 | 4,460 |
| Zinc | 370 | 3,930 |
| Nickel | 300 | 358 |
| Lead | 180 | 2,330 |
| Phosphorus | 180 | 6,500 |
| Mercury | 3 | 7 |
| Tin | 1.5 | 166 |

*Source:* Report of the Study of Critical Environmental Problems (SCEP), *Man's Impact on the Global Environment* (Cambridge: M.I.T. Press, 1970)

supporting the metabolic consumption of human beings and their domestic animals—a few out of some millions of species.[22] The rates at which mankind is mobilizing critical nutrients and many metals (including the most toxic ones) considerably exceeds the basic geological mobilization rates as estimated from river flows (see table 3). Such figures as these do not prove that disaster is upon us, but, combined with the ecological perspective summarized above, they are cause for uneasiness. In terms of the scale of its disruptions, mankind is for the first time operating on a level at which global balances could hinge on our mistakes.

Some of the forms of disruption just described are, of course, amenable in principle to elimination or drastic reduction through changes in technology. Civilization's discharges of oil, sulfur dioxide, and carbon dioxide, for example, could be greatly reduced by switching to energy sources other than fossil fuels. In the case of these pollutants, then, the questions involve not whether the disruptions *can* be managed but whether they *will* be, whether the measures will come in time, and what social, economic, and new environmental penalties will accompany those measures. At least one environmental problem is intractable in a more absolute sense, however, and this is the discharge of waste heat accompanying all of civilization's use of energy. I refer here not simply to the well-publicized thermal pollution at the sites of

Table 4. Energy Flows (in billion thermal kilowatts)

| | |
|---|---|
| Civilization's 1970 rate of energy use[a] | 7 |
| Global photosynthesis[b] | 80 |
| 15 billion people at 10 thermal kilowatts/person | 150 |
| Winds and ocean currents[c] | 370 |
| Poleward heat flux at 40° north latitude[d] | 5,300 |
| Solar energy incident at earth's surface[c] | 116,000 |

*Sources:* a: *Statistical Yearbook, 1971* (New York: United Nations, 1972)
b: George M. Woodwell, "The Energy Cycle of the Biosphere," *Scientific American* (September 1970)
c: M. King Hubbert, in *Environment*, ed. William Murdoch (Stamford, Conn.: Sinauer Associates, 1971)
d: William D. Sellers, *Physical Climatology* (Chicago: University of Chicago Press, 1965), p. 67

electric generating plants, but to the fact that all the energy we *use*—as well as that we waste in generating electricity—ultimately arrives in the environment as waste heat. This phenomenon may be understood qualitatively by considering the heat from a light bulb, the heat from a running automobile engine and the heat in the exhaust, the heat from friction of tires against pavement and metal against air, or the heat from the oxidation of iron to rust—to name a few examples. Quantitatively, the ultimate conversion of all the energy we use to heat (most of this occuring near the point of use and almost immediately) is required by the laws of thermodynamics; the phenomenon cannot be averted by technological tricks.

The usual concern with local thermal pollution at power plants is that the waste heat, which is usually discharged to water, will adversely affect aquatic life. Most of the waste heat from civilization's energy use as a whole, by contrast, is discharged directly to the atmosphere, and the concern is disruption of climate. Again, it is instructive to compare the scale of human activities with that of the corresponding natural processes, in this case the natural energy flows that govern climate. One finds that the heat production resulting from (and numerically equal to) civilization's use of energy is not yet a significant fraction of the solar energy incident at the earth's surface on a global average basis (see table 4); even if the present 5 percent per annum rate of increase of global energy use persists, it will take another century before civilization is discharging heat equivalent to 1 percent of incident solar energy at the surface worldwide.[23]

Considerably sooner, however, as indicated in table 4, mankind's heat production could become a significant fraction of smaller natural energy transfers that play a major role in the determination of regional and continental climate (e.g., the kinetic energy of winds and ocean currents, and the poleward heat fluxes). It is especially important in this connection that civilization's heat production is and will continue to be very unevenly distributed geographically. Human heat production already exceeds 5 percent of incident solar radiation at the surface over local areas of tens of thousands of square kilometers, and will exceed this level over areas of millions of square kilometers by the year 2000 if present trends persist.[24] Such figures could imply substantial climatic disruptions. In addition to the effects of its discharge of heat, civilization has the potential to disrupt climate through its additions of carbon dioxide and particulate matter to the atmosphere, through large-scale alteration of the heat-transfer and moisture-transfer properties of the surface (e.g., agriculture, oil films on the ocean, urbanization), through cloud formation arising from aircraft contrails, and, of course, through the combined action of several or all of these disruptions.

Much uncertainty exists concerning the character and imminence of inadvertent climate modification through these various possibilities. It is known that a global warming of a few degrees centigrade would melt the icecaps and raise sea level by 50 meters, submerging coastal plains and cities. A few degrees in the opposite direction would initiate a new ice age. Although such global warming or cooling is certainly possible in principle, a more complicated alteration of climatic *patterns* seems a more probable and perhaps more imminent consequence of the very unevenly distributed impacts of civilization's use of energy. It is particularly important to note that the consequences of climatic alteration reside not in any direct sensitivity of humans to moderate changes in temperature or moisture, but rather in the great sensitivity of food production to such changes[25] and, perhaps, in the possible climate-related spread of diseases into populations with no resistance to them.[3]

## The Role of Population

*Multiplicative effect.* The most elementary relation between population and environmental disruption is that population size acts as a multiplier of the activities, consumption, and attendant environmental damages associated with each individual in the population. The contributing factors in at least some kinds of environmental problems can be usefully studied by expressing the population/environment relation as an equation:

environmental disruption = population x consumption per person x damage per unit of consumption.

Since consumption of goods or services per person is a measure of affluence, and since environmental damage per unit of goods or services consumed depends in part on the character of the technology used, the above equation has sometimes been abbreviated as "pollution equals population times affluence times technology." Needless to say, the numerical quantities that appear in such an equation will vary greatly depending on the problem under scrutiny. Different forms of consumption and technology are relevant to each of the many forms of environmental disruption. The population factor may refer to the population of a city, a region, a country or the world, depending on the problem being considered. (This point, of course, raises the issue of population *distribution.*) The equation, therefore, represents not one calculation but many.

The quantitative use of the population/environment equation is best illustrated by example. Suppose we take as an index of environmental impact the automotive emissions of lead in the United States since World War II. The appropriate measure of "consumption" is vehicle-miles per person, which increased twofold between 1946 and 1967. The impact per unit of consumption in this case is emissions of lead per vehicle-mile, which increased 83 percent or 1.83-fold in this period.[26] Since the U.S. population increased 41 percent or 1.41-fold between 1946 and 1967, we have

relative increase in lead emissions = 1.41 x 2.00 x 1.83 = 5.16 or 416 percent

Note that the dramatic increase in the total impact arose from rather moderate but simultaneous increases in the multiplicative contributing factors. None of the factors was unimportant—if population had *not* grown in this period, the total increase would have been 3.66-fold rather than 5.16-fold. (Contrast this result with the erroneous conclusion, arising from the assumption that the contributing factors are additive rather than multiplicative, that a 41 percent increase in population "explains" only one tenth of 416 percent increase in emissions.)

Calculations such as the foregoing can be made for a wide variety of pollutants, although with frequent difficulty in uncovering the requisite data. Where data are available, the results show that the historical importance of population growth as a multiplicative contributor to widely recognized environmental problems has been substantial, but not dominant. Neither, however, has either of the other contributing factors been consistently dominant.[27]

*Nonlinear effects.* While it is useful to understand what proportion of the historical increase in specific environmental problems has been directly attributable to the multiplier effect of population growth, there is a more difficult and perhaps more important question than this historical/arithmetical one. Specifically, to what extent may nonlinear effects cause a small increase in population to generate a disproportionately large increase in environmental disruption? These effects fall into two classes. First, population change may *cause* changes in consumption per person or in impact upon the environment per unit of consumption. Second, a small increase in impact upon the environment—generated in part by population change and in part by unrelated changes in the other multiplicative factors—may stimulate a disproportionately large environmental change.

An obvious example in the first category is the growth of suburbs in the United States at the expense of central cities, which has had the effect of increasing the use of the automobile. Another is the heavy environmental costs incurred in the form of large water projects when demand (population times demand per person) exceeds easily exploited local supplies. Still another example is that of diminishing returns phenomena in agriculture, in which increases in yield needed to feed new mouths can be achieved only by disproportionate increases in inputs such as fertilizer and pesticides. (The evidence that this has, in fact, been taking place worldwide is summarized in table 5.) In each case, the point is that the contributing factors in the population/environment relation can no longer be considered to be

Table 5. Diminishing Returns with Respect to Industrial Inputs for Food Production (world increase during period 1955-65)

| | |
|---|---|
| Food | 34% |
| Tractors | 63% |
| Phosphate fertilizer | 75% |
| Nitrate fertilizer | 146% |
| Pesticides | 300% |

*Source:* Report of the Study of Critical Environmental Problems (SCEP), *Man's Impact on the Global Environment* (Cambridge: M.I.T. Press, 1970)

independent. In mathematical terms, the equation is *nonlinear.*

Many phenomena that have the effect of generating disproportionate, or nonlinear, consequences from a given change in demographic variables cannot easily be expressed in the framework of a single equation. One such class of problems involves technological change—the substitution of new materials or processes for old ones that provided the same types of material consumption. Obvious examples are the substitution of nylon and rayon for cotton and wool, of plastics for glass and wood and metals, of aluminum for steel and copper. Such substitutions may be necessitated by increasing total demand, or they may be motivated by other factors such as durability and convenience. Substitutions or other technological changes that are motivated by the pressure of increased total demand, and that lead to increases in environmental impact per unit of consumption, should be considered as part of the environmental impact of population growth.

Environmental disruption is not, however, measured strictly by man's inputs *to* the environment—what *we* do to *it.* Equally important is how the environment responds to what we do to it. This response itself is often nonlinear; a small change in inputs may precipitate a dramatic response. One example is the existence of thresholds in the response of individual organisms to poisons and other forms of "stress." Fish may be able to tolerate a 10-degree rise in water temperature without ill effect, whereas a 12-degree rise would be fatal. Carbon monoxide is fatal to human beings at high concentrations but, as far as we know, causes only reversible effects at low concentrations. Algal blooms in overfertilized lakes and streams are examples of exceeding a threshold for the orderly cycling of nutrients in these biological systems.

Another nonlinear phenomenon on the response side of environmental problems involves the simultaneous action of two or more inputs. A disturbing example is the combined effect of DDT and oil spills in coastal waters. DDT is not very soluble in sea water, so the concentrations to which marine organisms are ordinarily exposed are small. However, DDT is very soluble in oil. Oil spills therefore have the effect of concentrating DDT in the surface layer of the ocean where much of the oil remains, and where many marine organisms spend part of their time.[18] These organisms are thus exposed to far higher concentrations of DDT than would otherwise be possible. As a result of this mechanism, the combined effects of oil and DDT probably far exceed the individual effects. Many other synergisms in environmental systems are known or suspected: the interaction of sulfur dioxide and particulate matter in causing or aggravating lung disease; the interaction of radiation exposure and smoking in causing lung cancer; enhanced toxicity of chlorinated hydrocarbon pesticides when plasticizers are present.

The exact role of population change varies considerably among the various forms of nonlinear behavior just described. A nonlinearity in the environment's response to growing total input—such as a threshold effect—increases the importance of all the multiplicative contributors to the input equally, whether or not population and the other contributors are causally related. Some other forms of nonlinearity, such as diminishing returns and certain substitutions, would occur eventually whether population or consumption per capita grew or not. For example, even a constant demand for copper that persisted for a long time would lead eventually to increasing expenditures of energy per pound of metal and to substitution of aluminum for copper in some applications. In such instances, the role of population growth—and that of rising consumption per capita—is simply to accelerate the onset of diminishing returns and the need for technological change, leaving less time to deal with the problems created and increasing the chances of mistakes. With respect to other phenomena, such as the effects of population concentration on certain forms of consumption and environmental impact, population change is clearly the sole and direct cause of the nonlinearity.

## Time Factors

*The pattern of growth.* All rational observers agree that no physical quantity can grow exponentially forever. This is true, for example, of population, the production of energy and other raw materials, and the generation of wastes. But is there anything about the 1970s—as opposed, say, to the 1920s or 1870s—that should make this the decade in which limits to growth become apparent? It should not be surprising that, when limits do appear, they will appear suddenly. Such behavior is typical of exponential growth. If twenty doublings are possible before a limit is reached in an exponentially growing process (characterized by a fixed doubling time if the growth rate is constant), then the system will be less than half "loaded" for the first nineteen doublings—or for 95 percent of the elapsed time between initiation of growth and exceeding the limit. Clearly, a long history of growth does not imply a long future.

But where does mankind stand in its allotment of doublings? Are we notably closer to a limit now than we were 50 years ago? We are certainly moving faster. The number of people added to the world population each year in the 1970s has been about twice what it was in the 1920s. And according to one of the better indices of aggregate environmental disruption, total energy consumption, the annual increase in man's impact on the environment (in absolute magnitude, not percentage) is ten times larger now than then.[28] We have seen, moreover, that man is already a global ecological force, as measured against the yardstick of natural processes. While the human population grows at a rate that would double our numbers in 35 years, ecological impact is growing much faster. The 1970 M.I.T.-sponsored Study of Critical Environmental Problems estimated that civilization's demands upon the biological environment are increasing at about 5 percent per year, corresponding to a doubling time of 14 years. This implies a fourfold increase by the year 2000. It is difficult to view this prospect with complacency.

*Momentum, time lags, and irreversibility.* The nature of exponential growth is such that limits can be approached with surprising suddenness. The likelihood of overshooting such a limit is made even larger by the momentum of human population growth, by the time-delays between cause and effect in many environmental systems, and by the fact that some kinds of damage are irreversible by the time they are visible.

Momentum can be thought of as the tendency of a system to continue in the direction it is already moving. The momentum of human population growth has its origins in deep-seated attitudes toward reproduction and in the age composition of the world's population—37 percent is under 15 years of age. This means there are far more young people who will soon be reproducing—adding to the population—than there are old people who will soon be dying—subtracting from it. Thus, even if the momentum in attitudes could miraculously be overcome overnight, so that every pair of parents in the world henceforth had only the number of children needed to replace themselves, the imbalance between young and old would cause population to grow for 50 to 70 years more before leveling off. (The *exponential* phase of growth would stop when replacement fertility became a universal reality, but population would still climb 30 percent or more during the transition to stability.) Under extraordinarily optimistic assumptions about when replacement fertility might *really* become the worldwide norm, one concludes that world population will not stabilize below 8 billion people.[29]

The momentum of population growth manifests itself as a delay between the time when the need to stabilize population is perceived and the time when stabilization is actually accomplished. Forces that are perhaps even more firmly entrenched than those affecting population lend momentum to growth in per capita consumption of materials. These forces create time lags similar to that of population growth in the inevitable transition to stabilized levels of consumption and technological reform. Time delays between the initiation of environmental insults and the appearance of the symptoms compound the predicament because they postpone recognition of the need for any corrective action at all.

Such environmental time delays come about in a variety of ways. Some substances persist in dangerous form long after they have been introduced into the environment (mercury, lead, DDT and its relatives, and certain radioactive materials are obvious examples). These may be entering food webs from soil, water, and marine sediments for years after being deposited there. The process of concentration from level to level in the food web takes more time. Increases in exposure to radiation may lead to increases in certain kinds of cancer only after decades and to genetic defects that first appear in later generations. The consequences of having simplified an environmental system by advertently wiping out predators or by planting large areas to a single high-yield grain may not show up until just the right pest or plant disease comes along a few seasons later.

Unfortunately, time lags of these sorts usually mean that, when the symptoms finally appear, corrective action is ineffective or impossible. Species that have been eradicated cannot be restored. The radioactive debris of atmospheric bomb tests cannot be reconcentrated and isolated from the environment, nor can radiation exposure be undone. Soil that has been washed or blown away can be replaced by natural processes only on a time scale of centuries. If all use of persistent pesticides were stopped tomorrow, the concentrations of these substances in fish and fish-eating birds might continue to increase for some years to come.

## Conclusions

The momentum of growth, the time delays between causes and effects, and the irreversibility of many kinds of damage all increase the chances that mankind may temporarily exceed the carrying capacity of the biological environment. Scientific knowledge is not yet adequate to the task of defining that carrying capacity unambiguously, nor can anyone say with assurance how the consequences of overshooting the carrying capacity will manifest themselves. Agricultural failures on a large scale, dramatic loss of fisheries productivity, and epidemic disease initiated by altered environmental conditions are among the possibilities. The evidence presented here concerning the present scale of man's ecological disruption and its rate of increase suggests that such possibilities exist within a time frame measured in decades, rather than in centuries.

One should not conclude from these arguments, however, that the situation is hopeless, or that civilization's influence on the environment is invariably detrimental. Examples of sound and apparently stable intervention in natural systems exist—the rice-paddy agriculture of Southeast Asia, for instance, has flourished without noticeable diminution of productivity for thousands of years. It is clear also that technological, economic, and social tools are available, in principle at least, to ameliorate many of the disruptive impacts of civilization that have been discussed in the foregoing pages. The purpose of emphasizing here the destructive side of civilization's historical and contemporary vironmental interventions—and of attempting to clarify the

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