SIMPLE CONCEPTS OF COMPLEX ECOLOGICAL PROBLEMS

by William E. Martin

DIVERSITY AND COMPLEXITY OF NATURE

Nobody knows for certain just how many kinds of living organisms there are because thousands of "new" species are discovered every year. Even if the species inventory were complete, evolution and extinction would keep it in a state of flux by adding and subtracting species. There might be as many as five hundred thousand species of plants, ranging in size and complexity from the microscopic bacteria that live in and on all of us, to the giant redwoods of California; and there might be as many as 1.5 million species of animals, ranging in size and complexity from the protozoa that live in the intestines of termites and enable them to digest wood, to the blue whales of polar waters that grow to one hundred feet in length and one hundred fifty tons in weight. About half the known species of animals are insects, and many biologists believe that these six-legged creatures will one day inherit the earth because: (1) all species are doomed to eventual extinction no matter how successful they may be temporarily, (2) extinction and evolution operate by chance, like a lottery, and (3) insects hold more of these "lottery tickets" than any other class of organisms.

Wherever we go in nature, we are bound to be impressed by the remarkable diversity of life. Even Star Island, as barren as it may appear to some eyes, is probably home to several hundred or one thousand different species of terrestrial and marine plants and animals. Lincoln observed that "God must have loved the common man because He made so many of them." Almost any suburbanite in the eastern United States could say the same for sparrows and starlings. Thoreau was of the opinion that "God made ferns just to show what He could do with leaves." Another anecdote in the same vein concerns a distinguished British coleopterist (beetle specialist) who, upon being asked

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by a theologian what his study of Nature had revealed to him about the nature of the Creator, replied, "Well, I'd say He seems to be inordinately fond of beetles." (There are approximately two hundred fifty thousand species of beetles.)

The diversity of nature is not limited to the large numbers and kinds of species; it extends also to the physical habitats where these species are found, to the multitudinous ways they have evolved for "making a living," and to the interrelations of organisms which, living together in the same habitats, comprise an almost endless variety of biotic communities. Each facet of a landscape or seascape appears to support a characteristic assemblage or community of organisms. Each organism in such a community interacts not only with its physical environment but also with the other organisms in the community-habitat units we call ecosystems. The complex food webs that bind the members of a biotic community together and the many kinds of organism-environment interactions that go on in ecosystems of different kinds add several ecological dimensions to the diversity and complexity of nature we have in mind when we speak of the balance of nature or the dependence of organisms on their environments and on one another.

As humans, we are unavoidably anthropocentric and inclined to think of man as a special case. Our ordinary concept of the word "environment," at least as it is used by the popular news media, is not confined to the nonliving materials (air, water, soil, etc.) and physical conditions (temperature, light intensity, pressure, etc.) which characterize our physical or abiotic surroundings; it usually includes "everything in the world but me." Even when we deliberately avoid this self-centered view of the world, we are forced to concede that man is indeed a special case. Ecologically, *Homo sapiens* is the dominant life-form on this planet, its most successful species, the sole cause of the population explosion and the ecological crisis. When we examine the many facets of man, his biological and social history, and his multitudinous cultural activities—many of which are literally changing the face of the earth—our concept of diversity and complexity in nature must again be magnified, many times over.

To many people, including some of my ecological colleagues, the diversity and complexity of nature, man, and man's nature is awesome. They are overwhelmed by it and despair of ever being able to comprehend it. Primitive man fell on his knees and worshipped the sun, the moon, and other natural objects or phenomena; he prayed to countless gods, demons, and good spirits to bring the rains, to hold back the floods, to make the crops grow, to make things turn out right. In days gone by and at present, the people we sometimes arrogantly refer to as "natives" were all pragmatic, practicing ecologists. They were closely coupled with the natural ecosystems from which they derived their "daily bread" and everything else required to stay alive; such people were, and still are, much more aware than modern man, a child of the scientific-industrial revolution, of their dependence on nature and on the balanced, well-ordered operation of natural processes.

Modern man is also somewhat inclined to be rather abject, or not quite objective, in his appraisal of nature's complexity and diversity. He is, perhaps, too much and too often inclined to assume a priori that environmental problems and the social or political problems related to them are too complex to be either understood or solved by mere men. Consequently, he may be inclined to leave all these things to the gods, the laws of chance, and the inevitable. One of my ecological friends is fond of saying that the ecosphere—meaning all of nature considered holistically—is not more complex than we think it is; it is more complex than we can think. My friend is probably right, but neither he nor I believe that mere complexity is a valid reason for giving up the effort. Just trying to understand nature is good mental exercise, and it may bring unexpected rewards. For example, the theologian and the philosopher might consider the possibility that meditation on the intricate complexity of organism-environment and organism-organism interrelations in nature and the delicate balance of ecological processes—such as those involved in the food webs of different biotic communities and in the worldwide cycling of water, oxygen, carbon dioxide, and other abiotic materials—might lead the contemplative to a higher comprehension of both Nature and Nature's Creator. In the pragmatic world, where scientists and citizens from all walks of life and cultural settings are actively trying to cope with the more mundane, two-faced problem of how to live the good life without destroying or greatly reducing the quality of the environment in which we and future generations will live, the assumption that man and nature should be capitalized because they are too complex to be understood intellectually may lead to a kind of mental paralysis that impedes or prohibits progress and amounts to nothing less than an a priori admission of defeat and helplessness.

Unifying Principles and Pragmatic Simplifications

For people who are intellectually inclined, no matter how pragmatic, phlegmatic, or spiritually inclined they may also be, the mere existence of mental confusion and/or the real or apparent inability to understand how a thing works is almost invariably frustrating and frequently intolerable. Probably, it is the desire to find meaning and order in the external universe and in the internal universe we call the soul or the id, and not mere curiosity, that drives men to learn more and more about themselves and their surroundings. The desire to understand is an almost universal human trait; and, among the approximately two million extant biological species, it appears to be almost uniquely human, in that only the human species exhibits it to a marked degree. It may be this uniquely human trait that accounts for mankind's religious transition from early animism and pantheism to intermediate polytheism and, more recently, to monotheism, which recognizes the unity and holiness of nature. It undoubtedly accounts for science's unceasing quest for simple natural laws and unifying principles to bring meaning, order, and understanding out of chaos and confusion; but science, having appeared much later than religion in man's historical and cultural development, has only reached the stage of polyscientism. Science is still searching for a set of natural laws and unifying principles to trigger the transition from polyscientism to monoscientism. Most of these searches are rather esoteric, and great segments of nature and mankind are left out of them; but the trend from polyscience to monoscience is indicated by terms such as interdisciplinary studies, cooperative investigations, team research, systems analysis, etc.

If nature is more complex than we can think and therefore too complex to be comprehended in its totality, then our desire to understand compels us either to enlarge our intellectual capacity or to simplify our concept of nature and continue the search for universal themes, unifying principles, and/or natural laws that will enable us to understand our simplified concepts, while maintaining the hope that understanding gained in this manner can be applied to the complex problems that baffled and frustrated us in the first place. Since we have not yet found a simple way to make ourselves more intelligent, we must usually be content with searching for new ways of thinking about things and hoping this will lead us to the understanding we desire to achieve. In many fields of science, this approach—the search for new and usually simpler conceptual models—has paid handsome dividends. In the field of chemistry, it led Mendeleev to the periodic table of elements which enabled others to work out the principles and laws that govern ordinary chemical reactions. In the biological field of genetics, it led Gregor Mendel to recognize some of the basic, rather simple laws of heredity; and more recently, it led Watson and Crick to the double-helix model of DNA and a preliminary understanding of the genetic code which seems to be utilized by all the two million species of living organisms now extant. In the field of physics, it led Einstein to the simple but profoundly important conclusion that $E = mc^2$, that is, that matter and energy are essentially equivalent. The question to be considered here is: Can the same approach be taken with respect to ecology, and what is the probability that this approach might lead us to find practical solutions to the ecological (i.e., environmental) problems that now confront us and show no signs of abatement in the near future? My optimistic answer to this question is: We must take this approach with respect to ecology, and the probability that it will lead us to practical solutions is reasonably good, 50 percent or better.

UNIVERSAL ECOLOGICAL THEMES

My own concept of ecology has grown progressively more inclusive and, in some ways, progressively simpler. To begin with, I accepted the common definition of ecology as the study of organisms in relation to environment and concentrated on the effects of various environmental factors on the vital, physiological, and other functions of different species. This simple, organism-environment approach to physiological ecology (or autecology) is intellectually satisfying, because it is usually amenable to experimental methods. On being introduced to the study of statistics, demography, and population dynamics, I realized that many organism-environment relations can be adequately described only in terms of statistical concepts and that populations (groups of organisms of the same kind) have statistical attributes (e.g., birthrates and death rates) which are unique properties of populations and are not shared with individual organisms. So I had to expand my concept and definition to include population ecology; I think of it as another aspect of autecology, because it is primarily concerned with the species level of biological organization.

As my field experience increased in relation to book and laboratory experience, I grew more and more appreciative of the importance of community-habitat relations in nature. While studying the vegetation of coastal dunes in New Jersey, I was impressed that each facet of the landscape and nearby seascape was characterized by a particular set of environmental media, conditions, and processes that determine its character as a habitat (i.e., a place in which organisms can live and complete their life cycle). Furthermore, each kind of habitat tended to be occupied by a characteristic assemblage of plant and animal populations comprising distinctly different kinds of biotic communities. Generally, similar community-habitat relations can be readily observed in any natural area, that is, any area which has not been unduly altered by man. In recognition of these habitat-community relationships, I had to enlarge my concept and definition of ecology to include the study of habitats and biotic communities, and the successional aspects of community development from pioneer to climax stages in a given kind of habitat. Much of contemporary community-habitat ecology (or synecology, as it is usually called) is devoted to the description and classification of habitats on the basis of various physical parameters and of biotic communities on the basis of species composition, successional development, and gross structure.

Later, I became more concerned with what goes on in different community-habitat units, the basic units of biogeography, and especially in the environmental and biological or ecological processes responsible for the redistribution of materials, such as radionuclides, which may be released to the environment as radioactive fallout and transported back to man in the form of contaminated air, water, and/or food. The common pathways of radionuclide transport in nature are virtually identical to the pathways of energy transfer and flow, and of mineral transfer and cycling. Studying these problems made me much more appreciative of the idea, suggested years ago by the British ecologist Tansley, that a biotic community and its habitat comprise a natural functional entity. The term introduced by Tansley to describe this community-habitat unit—a kind of super organism or ecological system—was "ecosystem." Now, we can define an ecosystem as any system composed of living organisms and nonliving environmental materials which interact in the transfer and flow of energy and the transfer and cycling of materials. Stretching the definition a little, the ecosystem concept can be made to include, at one end of the scale, a single organism and the abiotic materials in contact with it, and, at the other end of the scale, all the organisms on the earth plus the abiotic media (atmosphere, hydrosphere, and lithosphere) in which they live. This leads logically to the redefinition of ecology as the study of ecosystems.

For the past five years, I have had the good fortune to take an active part in a series of ecological studies designed to help determine the radiological-safety feasibility of using nuclear explosives to excavate a sea-level canal across the Central American Isthmus and to predict the possible effects of such a project on marine ecosystems if it were done by either nuclear or conventional means. Needless to say, this has enlarged the domain of my personal ecological interests to include cultural anthropology, sociology, public health, economics, politics, national and international law, and many other areas usually not considered as parts of ecology. As a result of growing public interest and other indications that the Age of Ecology, long gestating, and about to be born, I and my colleagues are becoming more concerned about the population explosion, environmental pollution, environmental quality, and the ecological crisis. Presently, I am inclined to define ecology as the study of the earth and its contents.

But where are the "universal ecological themes" I promised to discuss at the beginning of these memoirs? Basically, there are only two such themes—one deals with reproduction, the other concerns the universal traffic in energy and materials—but they have many ramifications and variations. Both themes can be stated, more or less axiomatically, as follows:

1. All kinds of organisms are capable of reproducing themselves. The essential biological function of each generation of each species is to produce another generation of the same species, thus preserving the continuity of life and insuring the survival of the species. It should be noted, however, that the mechanisms evolved for this purpose are imperfect and that species become extinct when their population size drops to zero or when slight differences in succeeding generations gradually lead to the evolution of a species which is quite distinct from its remote ancestors. This and the fossil record lead to the apparently paradoxical conclusions that: (*a*) all living organisms are descendants of a common ancestor, but (*b*) all extant species, including *Homo sapiens,* are inevitably doomed to eventual extinction.

2. All living organisms are transformers of energy and matter. They require inputs of energy, food, and nutrient materials which they obtain from the biotic and abiotic components of their external environment. No matter how it is acquired, the energy is eventually dissipated as heat; the materials are eventually returned to the environment, chemically and/or physically altered, in the form of excreta, dead bodies, etc.

How These Universal Themes Apply to the Study of Nature

From the preceding discussions of the diversity and complexity of nature and the universal themes of ecology, it is apparent that there is a broad spectrum of biological organization extending from the molecular level (e.g., DNA) to the *ecosphere,* a term recently introduced[1] to designate the entire earth considered as the ultimate ecosystem. The axioms or universal ecological themes concerning reproduction and the transformation of energy and matter can be applied, in one form or another, to the entire spectrum of biological organization; but the key points on the spectrum are: (1) individual organisms (unicellular or multicellular), (2) populations, (3) ecosystems, and (4) the ecosphere. Only these four levels of biological organization are considered in the following abbreviated outline of the major, nontaxonomic branches of ecology:

A. *Autecology:* ecology at the species (individual and/or population) level of biological organization
   1. Physiological ecology: the study of organism-environment relations on a physiological basis
   2. Population ecology: the study of population dynamics, including the effects of environmental factors on population dynamics and biotic interactions between populations of different species

B. *Synecology:* ecology at the ecosystem level of biological organization
   1. Biogeographical approach: emphasis on description, classification, and geographical distribution (past and present) of habitats and communities, the physical and biological processes involved in the development or modification of habitats, and the successional processes involved in the development of biotic communities, the gross structure of biotic communities, etc.
   2. Functional approach: emphasis on the interrelations of biotic and abiotic ecosystem components and, especially, on the environmental, biological, and ecological processes involved in the transfer and flow of energy and/or the transfer and cycling of biotic and/or abiotic materials

C. *Macroecology:* ecology at the regional or ecosphere level of biological organization
   1. National or regional
   2. International or worldwide
   3. Other natural or artificial units of the earth's surface including more than one kind of ecosystem.

All these branches and subbranches of ecology are related and draw upon a great variety of other fields of study for information, data, and ideas or conceptual models. Macroecology is too new to be described in very much detail—I have a feeling the term was just now invented—but it is clearly the most important, and most inclusive with respect to human society.

THE AUTECOLOGICAL APPROACH

Figure 1 illustrates the concept of viewing an individual organism as an ecosystem consisting of a biotic component plus the abiotic and

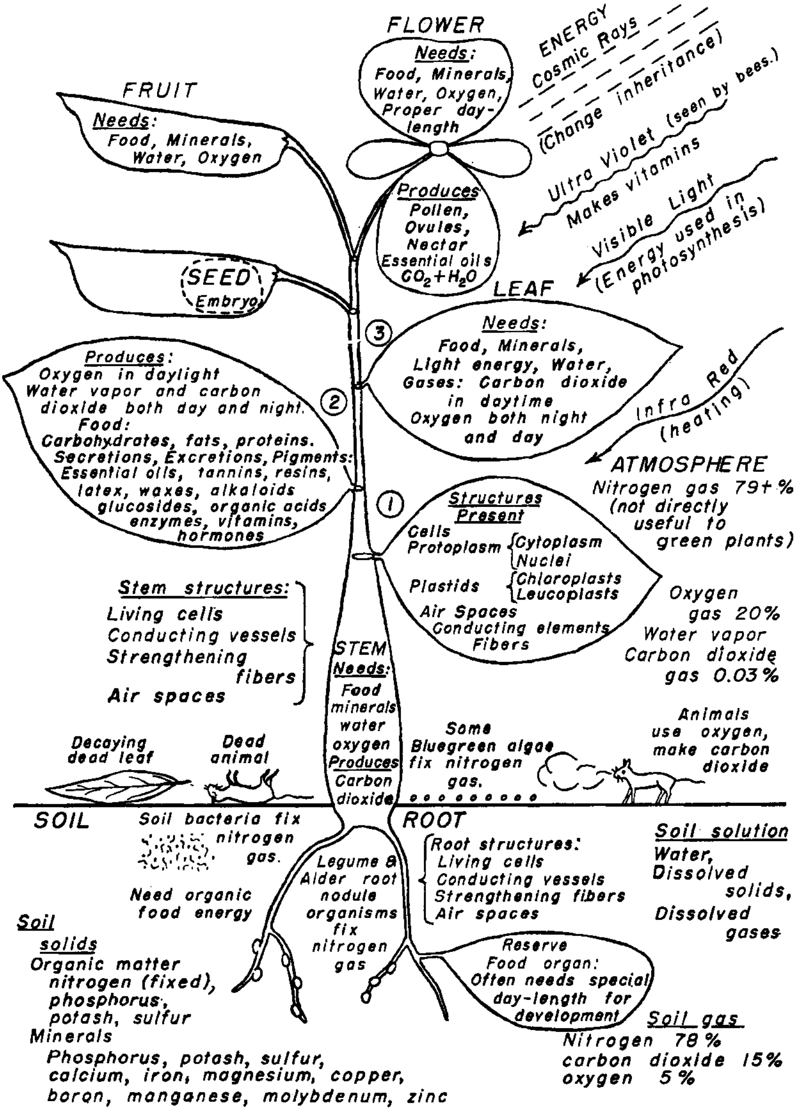


FIG. 1.—An individual plant treated as an ecosystem (D. B. Lawrence and W. Monserud, unpublished).

biotic components of its environment with which it is directly in contact. In this particular case, the organism is a plant. Its energy requirement is derived through photosynthesis from sunlight. During photosynthesis, the plant takes carbon dioxide from the atmosphere and returns oxygen. At night, when respiration is greater than photosynthesis, the process is reversed. Water and minerals are absorbed from the soil. Most of the water is released to the atmosphere; the minerals taken in and the organic materials elaborated by the plant's metabolic processes are returned to the soil and atmosphere by decay processes which take place after the plant dies. Parts of the plant may be eaten before or after the plant dies, thus transferring some of the excess energy produced by photosynthesis, as well as the minerals and other kinds of materials contained in the plant tissue to the animal members of the community of which the plant is a part. The connection of the plant with past generations and its contribution to the continuity of life in the next generation is a seed or some other kind of propagule.

Figure 2 illustrates the multiplicity of environmental factors that may have some influence on the vital functions, physiological and reproductive, of an individual plant or other kind of organism, and

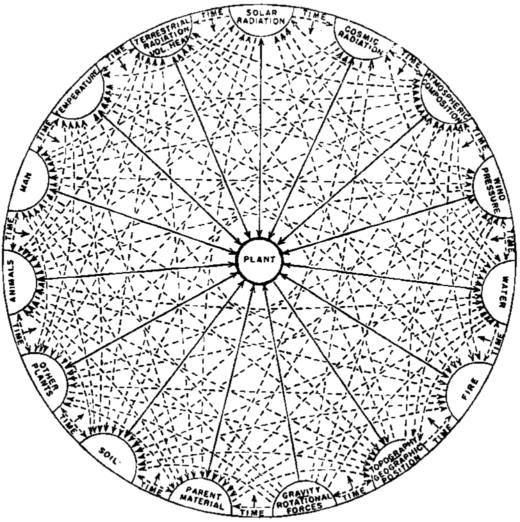


FIG. 2.—A holocoenotic environmental complex. Solid lines show plant-factor relations. Dashed lines show relations between factors. Arrows show the general direction of effect. If the effect is reciprocal, arrows are placed at both ends of the line. (After Billings 1952, unpublished)

thus influence or determine its distribution in nature, survival as a species, or functional role in the biotic community. Note the many interactions among the different environmental factors, as well as the direct actions or interactions between organism and environment.

This is a fairly simple concept, but the multidimensional matrix of organism-environment relations implied by it is overwhelming in its apparent complexity. Generally speaking, each species exhibits a range of tolerances to different environmental factors—for example, a maximum temperature tolerance which is just below the lethal temperature, an optimum temperature range for different physiological functions, and a minimum temperature which is just above the lethal lower temperature. Different stages in the life cycle of a given species may have different tolerance ranges to a given factor, and tolerances to one factor may be altered by the action of others. In addition to the intensity of a given factor, its variations in time and space and in relation to other factors may be critical in determining the tolerance range of a given stage in the life cycle of a given species. If we consider the large number of species in the world (each of which may have several distinctly different stages of development), the tremendous number of environmental factors involved in even a simple environment, and the virtually infinite variety of factor combinations and variations in time and space, we can easily understand why ecologists are constantly searching for the limiting factor—that is, the factor or combination of factors present in excessive or deficient intensities or amounts, and thus most important with respect to organism-environment interactions.

Figure 3 shows the results of a simple experiment in which a test tube filled with sugar solution was inoculated with a small number of yeast cells. Then, small samples were removed at regular intervals and analyzed to determine the number of yeast cells per unit volume of environmental medium in the test tube. These numbers were plotted on the vertical scale and time on the horizontal scale, yielding a characteristic sigmoid or logistic curve. It is apparent from the curve that the population growth rate was slow at first, perhaps because the yeast cells in the initial inoculum required a little time to become acclimated to their new environment. This was followed by a period of rapid growth at an exponential rate. An exponential growth rate is typical of populations flourishing in a nonlimiting environment. The period of exponential growth was followed by a decreasing growth rate and leveling off of the population size near an upper limit or asymptote. This was probably due to exhaustion of the sugar which the yeast cells use as food, and the increasing concentration of alcohol,

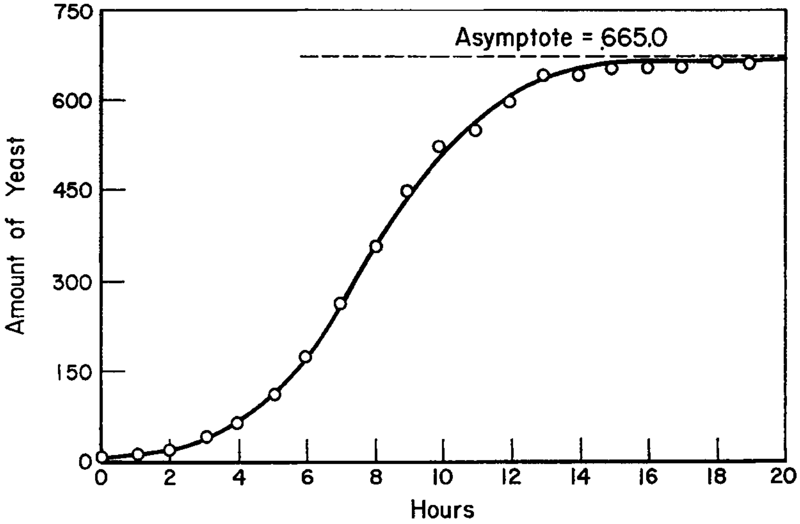


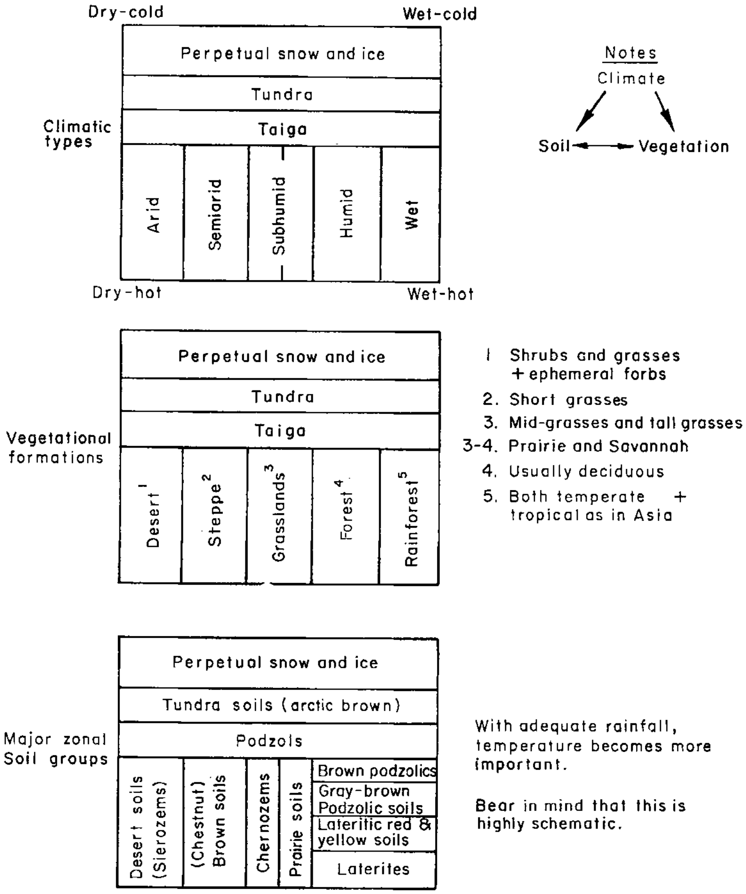
FIG. 3.—Growth of yeast population in test tube culture. "Amount of yeast" refers to the number of yeast cells per standard unit volume at the time indicated (adapted from Allee et al., *Principles of Animal Ecology* [Philadelphia: W. B. Saunders Co., 1949], from *The Biology of Population Growth*, by Raymond Pearl. © 1925 by Alfred A. Knopf, Inc.; renewed 1953 by Maude Pearl. Reprinted by permission of Alfred A. Knopf, Inc.).

a by-product of yeast metabolism which is apparently toxic to yeast in high concentrations. Had the experiment been continued longer, the yeast population would have declined until yeast became extinct in the test tube. In this case, extinction could be attributed directly to the effects of the yeast population on its environment—that is, exhaustion of the food supply (sugar) and production of toxic waste materials (alcohol and others). However, by carefully manipulating the quality of the environment in the test tube—that is, by controlling the rate of sugar input and the rate of alcohol and other waste-product output, and maintaining both of these at optimum or near-optimum concentrations—it should be possible to maintain a self-regenerating population of yeast cells at or near the asymptote or carrying capacity.

THE SYNECOLOGICAL APPROACH

Figure 4 is a map of the major vegetation types of North and Central America. Since the distribution of animals tends to correlate very well with the distribution of vegetation types, this map can be interpreted as representative of the major categories of biotic communities, habitats, and ecosystems of the area. Much more detailed maps are avail-

Fig. 4.—Principal vegetation types of North and Central America (after a privately printed map by Transeau).



1 Shrubs and grasses + ephemeral forbs
2. Short grasses
3. Mid-grasses and tall grasses
3-4. Prairie and Savannah
4. Usually deciduous
5. Both temperate + tropical as in Asia

With adequate rainfall, temperature becomes more important.

Bear in mind that this is highly schematic.

FIG. 5.—Interrelated distribution of climatic types, vegetational formations, and major zonal soil groups (after D. S. Blumenstock and C. W. Thornthwaite, "Climate and the World Pattern," in *USDA Yearbook: Climate and Man* [Washington, D.C.: Government Printing Office, 1941], pp. 99–127).

able for smaller areas, but this one serves the purpose of suggesting the geographical diversity of terrestrial ecosystems. Figure 5 is a simplified block diagram which provides a simple conceptual key to the principal habitat-community relations of North America.

Figure 6 is part of a more detailed vegetation map of a part of Island Beach, an offshore sandbar in New Jersey. At first glance the pattern appears to be a random mosaic, but actually it is well ordered. Each facet of the landscape represents a particular kind of habitat. The

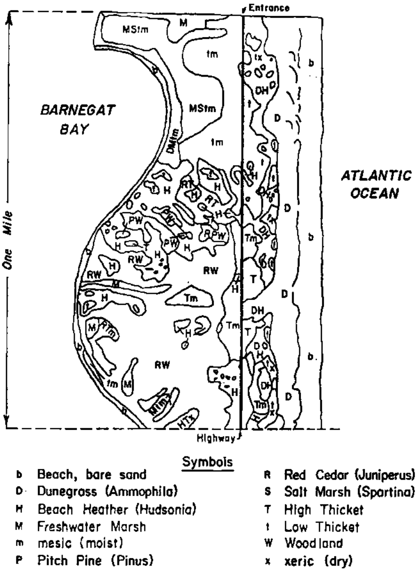


FIG. 6.—Detailed vegetation map of first one-mile segment of Island Beach State Park, New Jersey. Note the zoned mosaic pattern and compare with figure 7 (after W. E. Martin, "The Vegetation of Island Beach State Park, New Jersey," *Ecological Monographs* 29 [1959]: 1–46).

different plant communities in similar habitats are successionally related to one another. More important, and even more apparent, is the marked zonation of both habitats and plant communities. The orderly distribution and zonation of landforms, habitats, and plant communities are summarized and illustrated by figure 7.

Now let us consider some of the simple, functional aspects of ecosystems. These have to do primarily with the traffic in energy and materials. First, we note that each organism is an open system with regard to the exchange of energy and materials between it and its external environment. This idea is illustrated in figure 8. The organism is represented by a box or compartment, and the inputs and outputs of energy and materials are represented by arrows. If the organism is stable (i.e., neither growing nor changing its composition), the volume or mass of the compartment is constant, and the concentration of energy or of a particular material in the compartment is also constant. In this case, the rate of input equals the rate of output. If the organism is unstable (i.e., growing, shrinking, or changing its composition), the concentration of energy or material in the compartment may remain

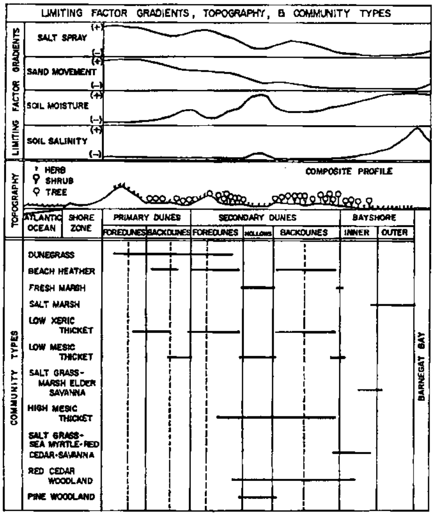


FIG. 7.—The interrelation of topography, limiting factor gradients, and plant communities. (+) indicates increasing and (—) indicates decreasing amounts or intensities of the limiting factors. The bars opposite the names of community types indicate their principal habitat ranges (from Martin 1959 [see fig. 6, above]).

constant, but the quantity is changing, and the rates of input and output are not equal.

The source of energy for the metabolism of all organisms is food, and the general term for the food and nutritional relations of organisms (i.e., food chain relationships, feeding rates, etc.) is "trophic dynamics." All organisms can be assigned to one or another of three trophic kingdoms, depending on how they obtain food. These are: (1) producers or autotrophs—green plants or other organisms, for example, which manufacture their own food by means of photosynthesis or some similar process; (2) consumers or heterotrophs, which are organisms (mostly animals) that feed on living plants or animals; and (3) decomposers

FIG. 8.—Organisms are open systems. They require inputs of energy and materials which then become outputs and are returned to the environment. Energy input (food) is dissipated (output) as heat. Materials are returned to the environment (output) as excreta or dead bodies. If the chemical composition and energy content of the organism remain constant, the corresponding inputs and outputs are equal.

or saprotrophs, which are organisms (either plants or animals) that feed on or otherwise manage to digest dead organic matter, primarily the dead bodies and excreta of other organisms.

Figure 9 illustrates the general trophic structure of a typical terrestrial ecosystem and shows the principal pathways of transfer and exchange of energy and a few essential nutrient materials. Note that the system is open with respect to energy because the ultimate source of energy, sunlight, is extraterrestrial. A small fraction of incoming solar radiation is converted by photosynthesis into chemical or food energy. The food energy that flows from producers to consumers and then to decomposers or to some environmental sink is either dissipated as heat or temporarily removed from the system. With respect to materials, it is a partially closed system. There are some inputs from outside the system and some outputs that leave the system, but most of the materials comprising the system are conserved and recycled again and again.

APPLICATION OF ECOSYSTEM CONCEPTS TO PRACTICAL PROBLEMS

As I mentioned earlier, I have spent the past five years on a program of ecological studies designed to help determine the feasibility of using nuclear explosives to excavate a sea-level canal across the Central American Isthmus. The primary objective of this program was to estimate the potential external and internal radiation doses to which

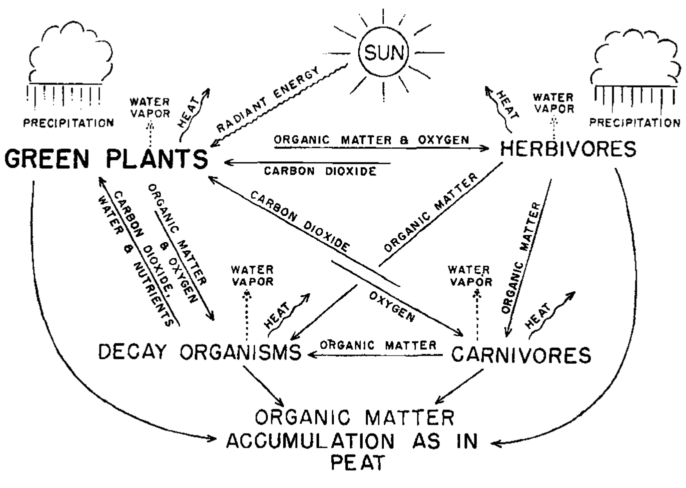


FIG. 9.—Major pathways of energy flow and materials cycling in a typical terrestrial ecosystem (D. B. Lawrence and W. Monserud, unpublished).

indigenous populations might be exposed as a consequence of nuclear excavation. These estimates were then compared with established radiation-protection criteria to provide a basis for recommending procedures which might be required before, during, and after the nuclear-excavation phase of canal construction, in order to insure that neither project personnel nor indigenous populations would be exposed to unacceptable radiation doses.

The basic elements of the dose-estimation problem are fairly simple, but actually solving the problem is rather difficult. Advances in the design of nuclear explosives and the technology of nuclear excavation have greatly reduced the total quantities of radionuclides produced and released to the environment, but the total elimination of radionuclide production by nuclear explosives is impossible. Experiments have shown that about half the total radioactivity produced by a nuclear-excavation explosion remains in or falls back into the crater. Between 25 and 45 percent is deposited on the ground very close to the crater. The small fraction remaining is more widely distributed as fallout. People would not be allowed in the area close to the detonation site; for even if there were no radioactivity, ground shock, air blast, and flying rocks would make this area hazardous. If people were to live in the fallout-contaminated area, they would be exposed externally to radioactive materials deposited in their environment and internally to radionuclides that enter food chains or related environmental pathways and are ingested with food and water. Inhalation of contaminated air and submersion in contaminated air or water are other possible modes of exposure, but these are less important than external exposure to radioactive materials deposited in the environment and internal exposure to radionuclides contained in foods and water.

Nuclear excavation would be accomplished by dividing the canal route into some twenty segments. Each segment would be excavated by simultaneous detonation of from three to fifty nuclear devices buried in a row along the canal alignment. At least two (and perhaps several) years would be required to complete the whole series of detonations, and none of these would be allowed to proceed until meteorological conditions were such that fallout would be confined to the exclusion area (i.e., the area to which fallout is confined and from which people are excluded during the nuclear excavation phase of canal construction).

Data required to calculate potential exposures to external radiation include predictions of: (1) kinds and quantities of radionuclides produced by each detonation, (2) initial geographical patterns of radioactive ejecta and fallout deposition, (3) gamma decay rates for the mixture of radionuclides produced by each detonation, and (4) period of exposure (i.e., time in and time out of contaminated area). Estimates of potential external radiation exposure within the exclusion area have indicated that, due to the rapid decay rates and relatively small quantities of most radionuclides, the hazard associated with external radiation exposure could be simply avoided by not allowing native poulations to resettle the exclusion area for a period of several months to a few years after the last detonation.

The problem of estimating potential internal radiation doses is more complex. Some of the radionuclides involved have relatively long half-lives (i.e., their radioactivity disappears very slowly), and radionuclides deposited in different kinds of ecosystems are redistributed by a variety of environmental and ecological processes which may cause either dilution or concentration. Some radionuclides may be transported to man via many diverse and complicated pathways. Data required to calculate potential internal radiation doses include the data required to calculate external radiation doses and much more. One must study the dietary habits of the different human populations involved, in order to determine the kinds and quantities of food, water, and other materials included in their diets and to determine the environmental sources of these materials. Having determined the individual items that make up the total diet and the environmental source of each item, it is then necessary to go to the ecosystem from which these items are derived and trace the pathways of radionuclide transport leading from the point of radionuclide introduction into the system to man.

Figure 10 shows the approximate distribution of the major ethnic or cultural groups of eastern Panama. Dietary habits and diet composition vary with respect to ethnic group, age group, geographical location, time of year, and other factors. For all ethnic groups, the principal subsistence activity is slash-burn agriculture, a fairly primitive technique that involves no plowing, but requires long fallow periods which permit renewal of soil fertility. The principal crops are banana, plantain (similar to banana), upland rice, corn, coconut, and various root crops. Plant products provide most of the calories. Fish and other freshwater or marine organisms, upland game, cattle, and swine provide protein. Vitamins and other micronutrients are provided by a variety of wild and cultivated fruits. As illustrated by figure 10, the population shows a decided riverine-coastal distribution pattern. Water

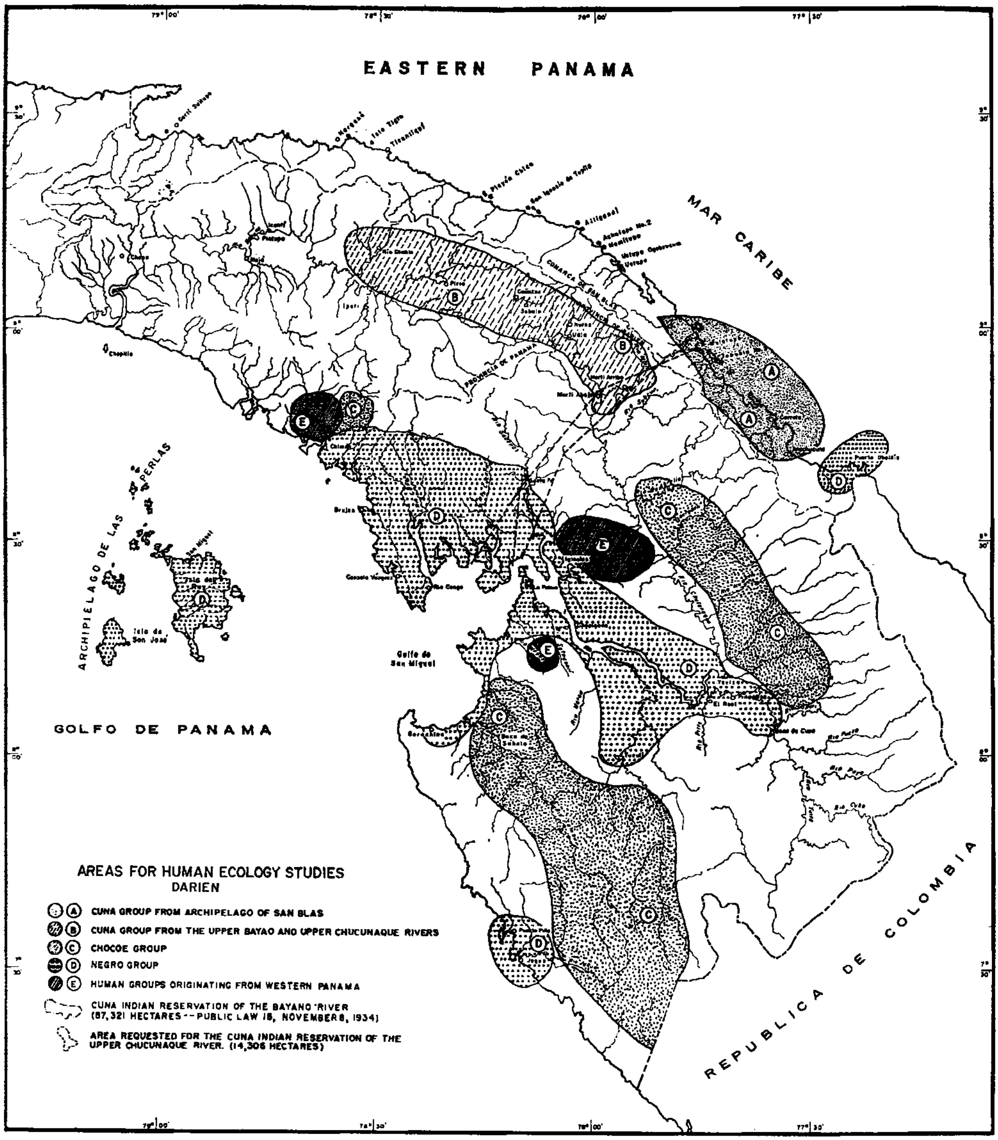


FIG. 10.—Approximate distribution of major ethnic groups of eastern Panama. The subsistence culture of each group is determined partly by cultural heritage and partly by the ecology of the area in which it lives (from Reina Torres de Araúz, "Demographic and Dietary Data for Human Groups Inhabiting the Eastern Region of the Republic of Panama," *BioScience* 19 [1969]: 331–36).

for domestic use is taken from rivers or smaller streams which also serve as highways and sanitary sewers. Not counting medicinals and other miscellaneous consumables, over two hundred species of wild and domesticated plants and animals are included in the diets of these populations. All but an insignificant fraction of the total diet is derived from the agricultural, forest, freshwater, estuarine, and marine ecosystems that comprise the immediate environment of each population.

Figure 11 shows a somewhat simplified diagram of radionuclide transport pathways, while figure 12 shows an extremely simplified but still valid diagram of the major pathways. Our estimates of potential dietary intakes by people living in radionuclide-contaminated areas were based on this ten-compartment food-web diagram and a mathematical model consisting of a system of ordinary and partial differential equations—one for each compartment—which simulates the intercompartmental transfers of various radionuclides.

A comparison of figures 11 and 12 provides an idea of the extent to which we found it necessary to simplify our concept of the problem. What was involved in this conceptual simplification of a complex problem, and why was it necessary? Consider the principal dimensions of the matrix of parameters that had to be considered. There are four ethnic groups and five critical age groups in each; further subdivision of each of these according to sex gives $4 \times 5 \times 2 = 40$ subpopulations. Except for infants (0–1 year), the total diet of each group, considered over a twelve-month period, may include approximately two hundred

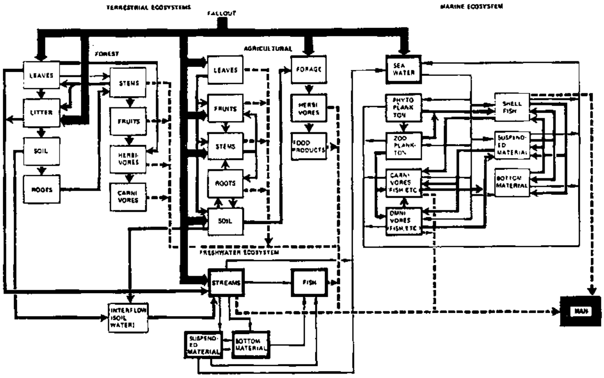


FIG. 11.—Major pathways of radionuclide redistribution and transport to man in tropical ecosystems, such as occur in eastern Panama and northwestern Colombia.

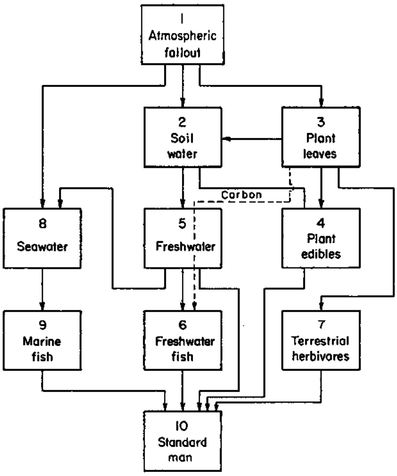


FIG. 12.—Ten-compartment radionuclide transport diagram corresponding to mathematical model used to estimate potential rates of radionuclide intake by people living in fallout-contaminated, tropical ecosystems.

different items, and each of these dietary items represents the second, third, fourth, or fifth link in a chain or pathway. A detailed flow diagram considering only these parameters would have between four hundred and one thousand compartments. Multiply this by twenty detonations, three hundred radionuclides, and ten to fifteen critical organs plus transfer coefficients and other parameters which may vary with respect to location, time of year, etc., and the result is a computational nightmare. Even if a computer program could be developed to handle all these details, some ten to thirty years of field and laboratory studies might be needed to estimate the parameters required to make the computation. A few men with picks and shovels might dig a canal before all this could be completed.

Faced with this kind of task, we developed a hierarchical system of models and screening procedures designed first to identify the potentially critical radionuclides, pathways, and population groups. Many of the over three hundred radionuclides are produced in such small quantities or have such short half-lives that their potential contributions to internal radiation doses are negligible. Many of the over two hundred transport pathways are also insignificant, because they do not lead to man, or represent only small quantities of foods which are consumed infrequently, and/or by only a small fraction of one or a few subpopulations. To compensate for uncertainties and possible errors, initial assumptions and parameter-value selections were all conservative (i.e., deliberately designed to result in overestimation of potential doses). Very simple, superconservative models were used to screen the initial inventory of radionuclides. As the list of radionuclides became progressively shorter, the models used for dose estimation became progressively more sophisticated and less conservative, until the most sophisticated, most realistic, and least conservative model was applied to only the ten to thirty radionuclides that account for over 95 percent of the potential internal radiation dose to the critical organ of the critical population group (i.e., the group which because of its age and dietary habits would receive the highest internal radiation dose).

Those who are fond of being awestricken by the diversity and complexity of nature, and those who are fond of turning over every stone on the beach, may be impressed only by the hundreds of variables and millions of calculations eliminated by this procedure. In my opinion, the hierarchical method of modeling and screening a massive matrix of variables, in order to identify and focus attention on those which are most important, is a scientifically valid procedure for reducing impossibly intricate problems to manageable proportions and conceptual comprehensibility.

What Does All This Have to Do with Man?

Before trying to give a direct answer to the question, What does all this have to do with man? I would like first to consider a related question, What makes man a special case? Man or mankind, whether we dignify him with capital letters or not, is a member of earth's biotic community, and whether he thinks so or not, his survival depends on what goes on in the ecosphere. We can send a few men to the moon, but we cannot migrate to another world. The earth is our spaceship, and whether we keep it shipshape or let it run down is up to us. It is also our test tube, and the success or failure of the human experiment is in our hands. That man is dependent on natural ecosystems is quite clear to the people of eastern Panama, because their daily lives and their entire subsistence economy are closely coupled with the natural ecosystems in their immediate environment. Their way of life is simple, and they live in close ecological harmony with their environment. They cut down bits of forest but they do not destroy watersheds. They dump their personal waste products into the sea or the rivers that run past their front doors, but generally these organic wastes have been converted into fish before the tide comes in again or before the stream reaches the next human settlement. Their impact on local ecology and environmental quality is, all things considered, rather negligible.

There are other parts of the world (most of India and Southeast Asia, parts of Africa, and other parts of Central and South America, for example) where the subsistence cultures of human populations are almost as simple as those of eastern Panama, but the populations are too big. There are more people than the land can support, food has to be imported to prevent famine, and intensive farming gradually reduces the productivity of the land, further intensifying the problem.

In the so-called developed or industrialized nations of the world almost everyone has plenty to eat, but most of the population and industrial facilities are crowded into a few metropolitan areas. These countries have high standards of living, and most of their citizens enjoy good health and long lives. But, they are faced by the twin problems of burgeoning population growth and increasing environmental deterioration, aggravated by urbanization and industrialization. Part of the world suffers from poverty and hunger, the remainder from affluence and pollution.

Man, like all other organisms, is a transformer of energy and materials. As an animal and a consumer, he has several special attributes. Compared to his closest relatives, the apes, *Homo sapiens* has unusually well-developed buttocks which have enabled him to assume an upright position and a bipedal mode of locomotion, thus freeing his forelimbs for other functions. He has an opposable thumb and agile fingers which enable him to manipulate objects and to use tools. He has a remarkable digestive system which enables him to thrive on almost any kind of diet. He has a well-developed nervous system, including a much enlarged brain which enables him to solve fairly simple problems of his own conception. (It is frequently reported that *Homo sapiens* is intelligent, but this is debatable because the thin line between cleverness and intelligence is rather difficult to detect.) Even at his so-called highest level of cultural development, man is characterized by a number of curious behavioral traits which seem to bear no relationship to his alleged intelligence or immediate circumstances, but can be traced uncertainly to the earlier, more biological, stages of his evolution as a clever ape.

The most outstanding feature of man's short history as one of some two million extant species has been the shift from biological to cultural evolution. His ability to solve problems, remember the solutions, and transmit this information directly or indirectly to subsequent generations is not unique in the animal world, but it has developed in man to such a marked degree that it has given rise to an innovative kind of heredity which we can call cultural heredity, to distinguish it from genetic or biological heredity. The existence of cultural heredity has led to the process of cultural evolution, which is much faster than biological evolution, and has apparently permitted man to circumvent or delay many of the ecological limitations that keep other species in check. The "invention," about one million years ago, of intelligence and cultural heredity set the stage for what is undoubtedly the most spectacular natural experiment that has occurred during some two billion years of biological evolution. The results so far have made man the dominant species of the planet, but the experiment is still in progress. The final outcome is uncertain.

Cultural evolution, aided and abetted by the agricultural revolution (some eight thousand years ago) and the scientific-industrial revolution (still in progress), has enabled man to live in almost every kind of habitat found on this world and, at least for a short time, in a few habitats (space capsules and lunar excursion modules, for example) that are out of this world. He has appropriated about one-fourth of the earth's land surface for his own private food production and is casting hungry eyes on much more. He gobbles about 1 percent of all the food energy available in the ecosphere, more than ten thousand times his share; and, theoretically, he might learn to increase his utilization efficiency to about 10 percent. He has invaded the air and the sea and burrowed into the earth in search of raw materials for his industrial activities. His kind has become so numerous, that they could qualify as a planetary plague. To support this prolific increase, he has invented thousands of synthetic organisms, such as automobiles, nuclear reactors, all kinds of factories, and machines, that may not be able to reproduce themselves but do a whale of a job of transforming energy and matter.

SYSTEMS IN CONFLICT

The synthetic organisms invented by man, like living organisms, are open systems. They require an input, an output, and a source of energy. They "ingest" all manner of natural resources or raw materials. Then, using various sources of energy, they transform these materials into a great variety of products and by-products, some of which are consumed by man and some of which are not. These synthetic organisms—all products of cultural evolution—have given rise to an economic system which is frequently in conflict with the natural ecosystem (or ecosphere), a product of biological and environmental evolution.

Figure 13 illustrates my simple-minded concept of how an industrialized economic system based on synthetic organisms appears to operate. The process of extracting raw materials from natural resources and the process of producing altered materials (consumer products, fuels, machines, etc.) for consumption are performed primarily by synthetic organisms. These "products" are consumed by other synthetic organisms (automobiles, television sets, home furnaces, etc.) or by man himself. These three primary economic processes (extraction, production, and consumption) yield by-products in the form of environmental pollutants, trash, junk, and garbage. In figure 13, I use "garbage" as the family name for all outputs we try to get rid of by returning them to the environment (air, water, soil) or by depositing them on the garbage and forgetting them. The lines connecting the boxes or process compartments represent the functions of transportation and communication networks.

"Conspicuous consumption" is a term invented by Thorstein Veblen,[2] an economist, to call attention to the fact that actual consumption is greater than necessary consumption. Man is a social, competitive, political, and territorial animal. He is also a hierarchical animal. In social insects, such as bees or termites, the hierarchical organization of the community or colony is genetically determined. Chickens, rats, and many other animals establish peck orders or social hierarchies by a round robin of fights and scuffles. Some species engage in elaborate display rituals, mock battles, and other peculiar behavior patterns, apparently for the same reason. In our society, there are many methods of establishing hierarchies, and there are many yardsticks for measuring one's status or position in different hierarchies. Wealth, power, prestige, and intellectual productivity are but a few of these. Perhaps the most common is wealth, but the mere possession of wealth is not sufficient. It must also be displayed, and conspicuous consumption is

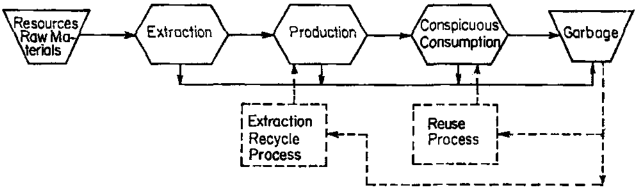


FIG. 13.—Simple-minded concept of an economic system designed to convert natural resources into garbage.

a rather silly but very common method of displaying wealth. Compared with other methods of establishing first- and/or second-order social hierarchies (e.g., physical or verbal fighting, civil disobedience, strikes, riots, wars, etc.), conspicuous consumption is commendably nonviolent, but it too has some disadvantages.

In a very real sense, conspicuous consumption is the keystone of our economic system; it is the force that drives the production and extraction processes. During the century or so since the scientific-industrial revolution began to gain significant momentum, almost every member of industrialized society has become wealthier. The level of consumption required to be conspicuous has increased accordingly. What Veblen called conspicuous consumption a few decades ago should now be called galloping consumerism. Production, aided by technology, has responded to increased per capita consumption and population growth, and this has accelerated both the extraction of raw materials from natural resources and the introduction of garbage into the environment. In the United States and elsewhere, we call this "progress" or "economic growth." In fact, it is a kind of pernicious, ecological myopia.

The fly in the ointment is that the kind of economic system illustrated by figure 13 is open-ended. Resources flow in at one end, and garbage is produced at every step. Its apparent purpose is to convert all natural resources into garbage and to deposit all the garbage in the environment. Population growth and economic growth are accelerating this conversion. As soon as one essential resource has been exhausted or made useless by pollution, perhaps before this happens, some vital link in the ecosystem may be permanently unplugged. When this happens, the ecosystem and the economic system will turn themselves off. Sic transit *Homo sapiens!*

An obvious way to keep the economic system going would be to close the cycle, as indicated by the dotted lines, by inserting processes that reuse or recycle garbage. Since this may not be technologically feasible for all the wastes and by-products here classified as garbage, it would be prudent to identify those which are nonreusable, nonrecyclable, or toxic, and stop producing them. An ideal but probably impractical solution would be to persuade society to give up the conspicuous-consumption habit, control population size, and manage the economic system to achieve balance with the ecosystem. I suggest that this is an impractical course of action, at least at present, because it seems to me that much of the political, industrial, and social reluctance to inaugurate technologically feasible measures designed to protect the ecosystem (i.e., to restore, improve, or maintain environmental quality) may stem from an even stronger desire to protect and further stimulate the growth of the economic system. Apparently, the majority of us are inordinately fond of affluence, whether we have it or not. no matter what effluents may happen to accompany it.

WHAT ABOUT THE POPULATION EXPLOSION?

Both population growth (increase in number of individuals) and economic growth (increase in per capita consumption rates) contribute to increasing rates of resource depletion and environmental degradation. In the United States and other industrialized countries, economic growth (4–10 percent per year) contributes more than does population growth (1–5 percent) to the ecological crisis. In the United States and in other industrialized nations, the currently conspicuous symptoms of the ecological crisis are environmental pollution and general degradation of environmental quality, especially in urban areas. In the undeveloped or nonindustrialized countries, economic growth and food production are unable to catch up with population growth. In these countries, the conspicuous symptoms of the ecological crisis are poverty, poor health, and hunger.

The basic population growth rate equation is quite simple—that is, $r = b - d$ where, r is the population growth rate, b is the birth rate ($b \neq 0$), and d is the death rate ($d \neq 0$).

For man, of course, and for most other animals that live more than a few days, population growth is never quite as simple as the basic equation implies, because both b and d are age-dependent and the population is made up of groups of different ages. However, the basic equation still holds true. If b is greater than d, r is positive and the population grows. If d is greater than b, r is negative and the population shrinks. If b and d are equal, r is zero and population size does not change.

If r is positive, it can be made to approach zero by decreasing b or by increasing d. Herein lies the real significance of the population explosion. Limited resources will not support an unlimited number of people. Sooner or later, a balance must be achieved between the number of people in the world and the earth's carrying capacity for people. For this balance or steady state to be maintained over a period of time, the value of r for the same period must average out to zero. This can be achieved by means of birth control (i.e., deliberately reducing the birth rate) or by death control (i.e., allowing or causing the death rate to increase). We can exercise our alleged intelligence to control our population dynamics and our economic system or we can wait for Mother Nature to call up the Four Horsemen of the Apocalypse—

there may be a whole regiment of such horsemen for all I know—to set things right. What could be simpler? Or more difficult to accept?

Thomas Malthus described the basic facts of population growth versus food production some 182 years ago. In his now famous and still controversial essay, he wrote:

> Population, when unchecked, increases in a geometrical ratio. Subsistence increases only in an arithmetical ratio. A slight acquaintance with numbers will shew the immensity of the first power in comparison of the second.
>
> By that law of our nature which makes food necessary to the life of man, the effects of these two unequal powers must be kept equal.
>
> This implies a strong and constantly operating check on population from the difficulty of subsistence. This difficulty must fall some where and must necessarily be severely felt by a large portion of mankind.[3]

Of course, Malthus did not reckon with the scientific-industrial revolution which has enabled man to increase his efficiency in utilizing natural resources, especially with respect to food production, and to put off the day of reckoning with ecological checks on population growth, but his basic premise is still correct. Population size *can* increase more rapidly than the means of subsistence, food production and population growth "*must* be kept equal," and the consequences of not doing so *are* "severely felt by a large portion of mankind."

Man's food energy, like that of virtually all other living organisms, comes ultimately from the sun (fig. 9). Until we invent an autotrophic man, solar energy must be transformed by photosynthesis into food energy and then transferred to man via ordinary food chains involving producers, consumers, decomposers, and the physical environment (air, water, and soil). Materials essential to the maintenance of life in the ecosphere must be conserved and recycled. Too many people result in excessive consumption of both renewable and nonrenewable resources, environmental pollution, interference with normal biogeochemical cycles, and other physical or biological changes which tend to upset the normal operation of the ecosphere and degrade the general quality of man's environment. We can see such processes taking place right now in our own country; but, more to the Malthusian point, millions of people in the undeveloped countries of the world are starving or suffering from serious malnutrition, in spite of the so-called Green Revolution, simply because there are more people in those countries than the ecosphere can provide with food.

Although the symptoms of overpopulation are easy to recognize, we cannot yet calculate precisely the ecosphere's ultimate carrying capacity for people. There is a good deal of evidence to indicate that the world population is already somewhat larger than the earth's long-term carrying capacity. If the economic system of the United States, where the annual per capita consumption of resources is at least fifty times higher than that of India, were extended to all people now living, the effective population size would surely exceed the long-term carrying capacity. One serious difficulty in attempting to estimate the earth's carrying capacity for people is that we do not know for certain which factor may be limiting—that is, which factor is most likely to unplug the ecosphere. Phosphorous appears to be the nutrient element in shortest supply; but, before we run out of phosphorous, atmospheric pollution might trigger worldwide climatic changes or pollution of the oceans might permanently upset the carbon dioxide cycle.

We can, however, estimate an upper limit to the earth's carrying capacity by assuming, as did Malthus, that food production establishes a limit to population size. In 1958, when the earth's human population was approximately 2.7 billion persons, Cole estimated that "if man were to feed exclusively on plants he would require almost exactly 1 percent of the total productivity of the earth."[4] Many ecological studies[5] indicate that the maximum ecological efficiency for consumers is about 10 percent. These two estimates taken together suggest a maximum carrying capacity of about 27 billion persons. If we also make the uncertain assumption that the present population (about 3.6 billion) is below the carrying capacity, we can say (with some trepidation) that the earth's carrying capacity for people is probably between 3.6 and 27 billion persons. If the average population growth rate is 2 percent per year, population size will double in approximately thirty-five years. To prevent widespread famine, food production must double in the same period of time, but the probability that this rate of increase in food production can be accomplished or sustained appears to be rather low. In the absence of effective birth control measures, inadvertent death control appears to be inevitable within a few years or decades.

I have made another rough estimate of the earth's carrying capacity for people based on the following set of optimistic assumptions concerning future technological developments with respect to food production:

1. Double the present harvest of sea food. (It is unlikely—perhaps impossible—that this could be done using present or improved fishing methods, but new maricultural techniques might make it possible.)

2. Bring one-half of all land surface, excluding Antarctica, under cultivation. (Only 25 to 30 percent of the land surface is now considered arable, but irrigation and other reclamation techniques might possibly bring the effective total to 50 percent, for at least a short period of time.)

3. Increase the worldwide average agricultural productivity to five thousand calories per square meter per year. (This is approximately twice the present world average but about equal to the best yields for wheat and rice.)
4. Consume one-half of all agricultural production directly, feed the other half to animals, and eat all the animals. (This would allow for efficient use of the inedible parts—stems, leaves, roots—of crop plants, but it would not allow for severe losses due to plant diseases, insects, unfavorable weather conditions, etc.)

If all these technological advances could be achieved, the ecosphere might produce enough food to provide approximately 12 billion persons with an average intake of two thousand calories per person per day. Most moderately active adults would lose weight on such a diet, and they would probably suffer a variety of vitamin deficiencies. Infant and child mortality rates would probably be sufficiently high, as a result of malnutrition, to balance fairly high birth rates and reduce the population growth rate to zero or to a negative value.

At an average growth rate of 2 percent per year, world population will reach 12 billion persons in about sixty years. That does not give us much time to achieve the technological advances assumed above, and the results would not be very attractive. There would be enough food for 12 billion persons to survive, but only a privileged few would be able to lead a vigorous, healthy life. Even this state of affairs could be maintained only if the population growth rate were then reduced to zero, and this brings us back to the major premise. Sooner or later, we will have to choose between birth control and death control because the equation will be balanced one way or another.

WHAT MUST BE DONE?

There is nothing new about the processes that have led to conflicts between social or economic systems and ecosystems, between mankind and the ecosphere. Like most other rich veins of human thought, many of the ideas, concepts, and causes for alarm briefly sketched in this paper can be traced back to the dawn of recorded history; and clear evidence of the adverse environmental effects of overpopulation and exploitation or mismanagement of environmental resources is available for a much longer period of human history recorded only in the landscape. For hundreds, perhaps thousands, of years there have been prophets of doom, who could see where we were going and cried out in the wilderness. Now there is a chorus of doomsday prophets, but there are also many reasons for optimism.

What is new is the widespread recognition that we have indeed reached a time of ecological crisis, a time for things to begin to change for better or for worse, and a general realization that the options available to the next generation and the one after that will depend on the action or inaction of this generation. What is new is the suddenly increased magnitude of attention being given to ecological problems, population growth, air and water pollution, land-use policies, degradation of urban and rural environments, and a variety of related problems by the news media, federal, state, and local governments, a plethora of civic action groups made up of people calling themselves "environmentalists" and/or "conservationists," educators, scientists and engineers, and the general public. What is new is an apparently sincere desire at almost all levels of society to make changes for the better, take direct action to restore, protect, or preserve environmental quality, and establish management policies and practices for multiple uses of land, air, and water on a long-term productive basis.

A preview of things to come and a brief outline of the conflict between our economic system and the ecosphere were given in President Nixon's 1970 State of the Union address as follows:

> We can no longer afford to consider air and water common property, free to be abused by anyone without regard to the consequences. Instead we should begin to treat them as scarce resources which we are no more free to contaminate than we are free to throw garbage into our neighbor's yard. This requires comprehensive new regulations. It also requires that to the extent possible the price of goods should be made to include the costs of producing and disposing of them without damage to the environment.
>
> Now, I realize that the argument is often made that there is a fundamental contradiction between economic growth and the quality of life, so that to have one we must forsake the other.
>
> The answer is not to abandon growth but to redirect it. For example, we should turn toward ending congestion and eliminating smog the same reservoir of inventive genius that created them in the first place.
>
> Continued vigorous economic growth provides us with the means to enrich life itself and to enhance our planet as a place hospitable to man.[6]

In other words, we must change our attitudes toward the environment (air, water, and land), but we cannot afford to change our attitudes toward continuing economic growth. We must somehow find regulatory and technological means of solving environmental problems made severe enough to constitute a crisis by the unregulated population growth and unrestrained economic growth which were made possible and have been accelerated by clever technological advances. At our present stage of cultural evolution, it appears that the fundamental conflicts between ecosystems and economic systems can be alleviated only by demonstrating that continued growth in rates of resources utilization, production and consumption, and restoration or maintenance of high environmental quality can be achieved simultaneously. To say the very least, this will be a tough job. With no restraints on either economic or population growth, it may well prove to be impossible.

Since the National Environmental Policy Act of 1969 went into effect on January 1, 1970, all agencies of the Federal Government have been required to consider routinely the effects of recommended legislation or other major actions on "the quality of the human environment." Numerous bills and resolutions pertaining to environmental problems ranging from air pollution to urban noise have been introduced in the Senate and/or the House of Representatives. Executive measures have been taken to reorganize various agencies of the federal government, to establish an Environmental Protection Agency and other new agencies responsible for environmental questions, and to mobilize the nation's resources for a concentrated effort to resolve or "get rid of" our environmental problems. Because of these and related actions both in and out of the government, I think it is reasonable to expect a marked stimulation, within a year or two, of ecological and other kinds of research related to environmental problems. It also seems reasonable to anticipate that most of these initial efforts will be directed toward the symptomatic treatment of environmental ills and not toward the underlying causes of the ecological crisis because the former can be attacked without delay while we are not yet prepared to do anything effective about the latter.

The basic scientific information and technological know-how required to reduce many symptoms of the ecological crisis (air and water pollution for example) are available right now, but only a fraction of this information is being used to establish management policies and only a fraction of the know-how is being implemented to reduce pollution. Much of the apparent reluctance of government and industry to apply existing knowledge in the "ecologically right way" appears to be based primarily on pragmatic economic and political considerations. In other words, the measures that could be taken would cost money. They would also require changes in the status quo, and they might stir up controversy and opposition. However, many politicians are confident that as soon as the public indicates its willingness to pay the price for cleaner air and water and as soon as the public's desire for improved environmental quality begins to be expressed in the voting booths around the country, these economic and political barriers will give way to positive, effective actions on the part of both industry and government.

With sufficient public and government backing and commitment, most of our nation's problems with respect to environmental pollution could be markedly reduced or even eliminated in less than a decade. This most probable course of action would not resolve the ecological crisis, but it would certainly demonstrate our ability to make progress in the right direction. It would contribute to the restructuring of social insitutions, decision-making processes, and attitudes toward environmental resources. It would provide time for research needed to understand better the functioning and interactions of both the ecosphere and our social systems and to develop the policies, mechanisms, and management tools required to apply that understanding. Most important of all, it would prepare us to attack the real problems with reasonable confidence in our ability to solve them.

The real problems, in my estimation, are population growth and economic growth, both of which tax the ability of the ecosphere to continue producing food, degrading toxic waste products, and recycling essential materials. If the simple concepts I have presented to illustrate the salient features of these complex problems are essentially correct, the important points of this paper can be bluntly summarized as follows:

1. Unregulated population growth will, if it has not already done so, produce more people than the earth can feed. People in excess of the earth's long-term carrying capacity will lead miserable lives if, when, and wherever neglect of birth control and other population control measures should lead to natural balancing of the population growth equation by means of famine, disease, and other causes of premature death.

2. Unrestrained economic growth and exploitation of natural resources (air, water, soil, plant and animal life, minerals, etc.) will lead sooner or later to disastrous changes in the biogeochemical cycles upon which both man and the ecosphere depend. Such changes in the balance of nature could render the planet, or large parts of it, unfit for human habitation.

3. Technological innovations have slowed or temporarily reversed these trends and can still continue to do so; but until the laws of conservation of matter and energy are repealed, no amount of technological cleverness can halt them permanently in the face of continued population and economic growth. The only rational solution to the ecological crisis requires the balancing of population and economic

growth rates against the rates of energy flow and materials cycling in the ecosphere. Although we have greatly modified the ecosphere, we cannot rebuild it entirely to our own specifications, nor can we afford to continue ignoring the natural constraints on environmental management. We cannot control all aspects of nature, but we may be able to control ourselves. If we really try, we may be able to restructure our social system and redirect our economic system, making both compatible with the ecosphere and the highest of mankind's aspirations.

Perhaps the real problems are too difficult and too charged with emotion to be tackled effectively and immediately, but there is no technological panacea, no ecological incantation, no political magic that will make them go away. The simple concepts I have described of exceedingly complex problems and processes are not adequate for the task ahead, but they provide a place to begin, a foundation upon which to begin to build a more substantial framework of concepts, a beachhead from which to expand the area of our knowledge of how ecosystems and social systems work and interact with one another. Frequent reference to these and similar, admittedly oversimplified but nonetheless unifying, concepts may help us to avoid overemphasizing the strictly symptomatic or episodic approach to environmental problems and to keep at least a part of our attention focused on the basic problems which may be too tough to solve right now but could become quite easy once the groundwork has been laid.

Since it requires no more effort to be optimistic than it does to be pessimistic, I believe man will continue evolving culturally (and this includes the evolution of ethical beliefs suitable to the occasion) and that he will go on winning, perhaps by an uncomfortably narrow margin, the struggle to live with himself.

NOTES

1. LaMont C. Cole, "The Ecosphere," *Scientific American* 198 (1958): 83–92.
2. Thorstein Veblen, *The Theory of the Leisure Class* (New York: Modern Library, 1934).
3. T. R. Malthus, *An Essay on the Principle of Population as It Affects the Future Environment of Society* (London: Johnson, 1798), first and second chapters reprinted in Edward J. Kormondy, ed., *Readings in Ecology* (Englewood Cliffs, N.J.: Prentice-Hall, Inc., 1965), p. 63.
4. Cole, p. 90.
5. L. B. Slobodkin, "Energetics in *Daphnia pulex* Populations," *Ecology* 40 (1959): 232–43.
6. Richard M. Nixon, State of the Union address delivered before joint session of Senate and House of Representatives, January 22, 1970, House Document, 91st Congress.