Effects of Pollution on the Structure and Physiology of Ecosystems

Changes in natural ecosystems caused by many different types of disturbances are similar and predictable.

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The accumulation of various toxic substances in the biosphere is leading to complex changes in the structure and function of natural ecosystems. Although the changes are complex, they follow in aggregate patterns that are similar in many different ecosystems and are therefore broadly predictable. The patterns involve many changes but include especially simplification of the structure of both plant and animal communities, shifts in the ratio of gross production to total respiration, and loss of part or all of the inventory of nutrients. Despite the frequency with which various pollutants are causing such changes and the significance of the changes for all living systems (*1*), only a few studies show details of the pattern of change clearly. These are studies of the effects of ionizing radiation, of persistent pesticides, and of eutrophication. The effects of radiation will be used here to show the pattern of changes in terrestrial plant communities and to show similarities with the effects of fire, oxides of sulfur, and herbicides. Effects of such pollutants as pesticides on the animal community are less conspicuous but quite parallel, which shows that the ecological effects of pollution correspond very closely to the general "strategy of ecosystem development" outlined by Odum (*1*) and that they can be anticipated in considerable detail.

The problems caused by pollution are of interest from two viewpoints. Practical people—toxicologists, engineers, health physicists, public health officials, intensive users of the environment—consider pollution primarily as a direct hazard to man. Others, no less concerned for human welfare but with less pressing public responsibilities, recognize that toxicity to humans is but one aspect of the pollution problem, the other being a threat to the maintenance of a biosphere suitable for life as we know it. The first viewpoint leads to emphasis on human food chains; the second leads to emphasis on human welfare insofar as it depends on the integrity of the diverse ecosystems of the earth, the living systems that appear to have built and now maintain the biosphere.

The food-chain problem is by far the simpler; it is amenable at least in part to the pragmatic, narrowly compartmentalized solutions that industrialized societies are good at. The best example of the toxicological approach is in control of mutagens, particularly the radionuclides. These present a specific, direct hazard to man. They are much more important to man than to other organisms. A slightly enhanced rate of mutation is a serious danger to man, who has developed through medical science elaborate ways of preserving a high fraction of the genetic defects in the population; it is trivial to the rest of the biota, in which genetic defects may be eliminated through selection. This is an important fact about pollution hazards—toxic substances that are principally mutagenic are usually of far greater direct hazard to man than to the rest of the earth's biota and must be considered first from the standpoint of their movement to man through food webs or other mechanisms and to a much lesser extent from that of their effects on the ecosystem through which they move. We have erred, as shown below, in assuming that all toxic substances should be treated this way.

Pollutants that affect other components of the earth's biota as well as man present a far greater problem. Their effects are chronic and may be cumulative in contrast to the effects of short-lived disturbances that are repaired by succession. We ask what effects such pollutants have on the structure of natural ecosystems and on biological diversity and what these changes mean to physiology, especially to mineral cycling and the long-term potential for sustaining life.

Although experience with pollution of various types is extensive and growing rapidly, only a limited number of detailed case history studies provide convincing control data that deal with the structure of ecosystems. One of the clearest and most detailed series of experiments in recent years has been focused on the ecological effects of radiation. These studies are especially useful because they allow cause and effect to be related quantitatively at the ecosystem level, which is difficult to do in nature. The question arises, however, whether the results from studies of ionizing radiation, a factor that is not usually considered to have played an important role in recent evolution, have any general application. The answer, somewhat surprisingly to many biologists, seems to be that they do. The ecological effects of radiation follow patterns that are known from other types of disturbances. The studies of radiation, because of their specificity, provide useful clues for examination of effects of other types of pollution for which evidence is much more fragmentary.

The effects of chronic irradiation of a late successional oak-pine forest have been studied at Brookhaven National Laboratory in New York. After 6 months' exposure to chronic irradiation from a ^{137}Cs source, five well-defined zones of modification of vegetation had been established. They have become more pronounced through 7 years of chronic irradiation (Fig. 1). The zones were:

1) A central devastated zone, where exposures were > 200 R/day and no higher plants survived, although certain mosses and lichens survived up to exposures > 1000 R/day.

2) A sedge zone, where *Carex pensylvanica* (*2*) survived and ultimately formed a continuous cover (> 150 R/day).

3) A shrub zone in which two species of *Vaccinium* and one of *Gaylussacia* survived, with *Quercus ilicifolia* toward the outer limit of the

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circle where exposures were lowest (> 40 R/day).

4) An oak zone, the pine having been eliminated (> 16 R/day).

5) Oak-pine forest, where exposures were < 2 R/day, and there was no obvious change in the number of species, although small changes in rates of growth were measurable at exposures as low as 1 R/day.

The effect was a systematic dissection of the forest, strata being removed layer by layer. Trees were eliminated at low exposures, then the taller shrubs (*Gaylussacia baccata*), then the lower shrubs (*Vaccinium* species), then the herbs, and finally the lichens and mosses. Within these groups, it was evident that under irradiation an upright form of growth was a disadvantage. The trees did vary—the pines (*Pinus rigida*) for instance were far more sensitive than the oaks without having a conspicuous tendency toward more upright growth, but all the trees were substantially more sensitive than the shrubs (*3*). Within the shrub zone, tall forms were more sensitive; even within the lichen populations, foliose and fruticose lichens proved more sensitive than crustose lichens (*4*).

The changes caused by chronic irradiation of herb communities in old fields show the same pattern—upright species are at a disadvantage. In one old field at Brookhaven, the frequency of low-growing plants increased along the gradient of increasing radiation intensity to 100 percent at > 1000 R/day (*5*). Comparison of the sensitivity of the herb field with that of the forest, by whatever criterion, clearly shows the field to be more resistant than the forest. The exposure reducing diversity to 50 percent in the first year was ~ 1000 R/day for the field and 160 R/day for the forest, a greater than fivefold difference in sensitivity (*3*).

The changes in these ecosystems under chronic irradiation are best summarized as changes in structure, although diversity, primary production, total respiration, and nutrient inventory are also involved. The changes are similar to the familiar ones along natural gradients of increasingly severe conditions, such as exposure on mountains, salt spray, and water availability. Along all these gradients the conspicuous change is a reduction of structure from forest toward communities dominated by certain shrubs, then, under more severe conditions, by certain herbs, and finally by low-growing plants, frequently mosses and lichens. Succession, insofar as it has played any role at all in the irradiated ecosystems, has simply reinforced this pattern, adding a very few hardy species and allowing expansion of the populations of more resistant indigenous species. The reasons for radiation's causing this pattern are still not clear (*3, 6*), but the pattern is a common one, not peculiar to ionizing radiation, despite the novelty of radiation exposures as high as these.

Its commonness is illustrated by the response to fire, one of the oldest and most important disruptions of nature. The oak-pine forests such as those on Long Island have, throughout their extensive range in eastern North America, been subject in recent times to repeated burning. The changes in physiognomy of the vegetation follow the above pattern very closely—the forest is replaced by communities of shrubs, especially bear oak (*Quercus ilicifolia*), *Gaylussacia*, and *Vaccinium* species. This change is equivalent to that caused by chronic exposure to 40 R/day or more. Buell and Cantlon (*7*), working on similar vegetation in New Jersey, showed that a further increase in the frequency of fires resulted in a differential reduction in taller shrubs first, and a substantial increase in the abundance of *Carex pensylvanica*, the same sedge now dominating the sedge zone of the irradiated forest. The parallel is detailed; radiation and repeated fires both reduce the structure of the forest in similar ways, favoring low-growing hardy species.

The similarity of response appears to extend to other vegetations as well. G. L. Miller, working with F. McCormick at the Savannah River Laboratory, has shown recently that the most radiation-resistant and fire-resistant species of 20-year-old fields are annuals and perennials characteristic of disturbed places (*8*). An interesting sidelight of his study was the observation that the grass stage of long leaf pine (*Pinus palustris*), long considered a specific adaptation to the fires that maintain the southeastern savannahs, appears more resistant to radiation damage than the mature trees. At a total acute exposure of 2.1 kR (3 R/day), 85 percent of the grass-stage populations survived but only 55 percent of larger trees survived. Seasonal variation in sensitivity to radiation damage has been abundantly demonstrated (*9*), and it would not be surprising to find that this variation is related to the ecology of the species. Again it appears that the response to radiation is not unique.

The species surviving high radiation-exposure rates in the Brookhaven experiments are the ones commonly found in disturbed places, such as roadsides, gravel banks, and areas with nutrient-deficient or unstable soil. In the forest they include *Comptonia peregrina* (the sweet fern), a decumbent spiny *Rubus*, and the lichens, especially *Cladonia cristatella*. In the old field one of the most conspicuously resistant species was *Digitaria sanguinalis* (crabgrass) among several other weedy species. Clearly these species are generalists in the sense that they survive a wide range of conditions, including exposure to high intensities of ionizing radiation—hardly a common experience in nature but apparently one that elicits a common response.

With this background one might predict that a similar pattern of devastation would result from such pollutants as oxides of sulfur released from smelting. The evidence is fragmentary, but Gorham and Gordon (*10*) found around the smelters in Sudbury, Ontario, a striking reduction in the number of species of higher plants along a gradient of 62 kilometers (39 miles). In different samples the number of species ranged from 19 to 31 at the more distant sites and dropped abruptly at 6.4 kilometers. At 1.6 kilometers, one of two randomly placed plots (20 by 2 meters) included only one species. They classified the damage in five categories, from "Not obvious" through "Moderate" to "Very severe." The tree canopy had been reduced or eliminated within 4.8 to 6.4 kilometers of the smelter, with only occasional sprouts of trees, seedlings, and successional herbs and shrubs remaining; this damage is equivalent to that produced by exposure to 40 R/day. The most resistant trees were, almost predictably to a botanist, red maple (*Acer rubrum*) and red oak (*Quercus rubra*). Other species surviving in the zones of "Severe" and "Very severe" damage included *Sambucus pubens, Polygonum cilinode, Comptonia peregrina*, and *Epilobium angustifolium* (fire weed). The most sensitive plants appeared to be *Pinus strobus* and *Vaccinium myrtilloides*. The pine was reported no closer than 25.6 kilometers (16 miles), where it was chlorotic.

This example confirms the pattern

of the change—first a reduction of diversity of the forest by elimination of sensitive species: then elimination of the tree canopy and survival of resistant shrubs and herbs widely recognized as "seral" or successional species or "generalists."

The effects of herbicides, despite their hoped for specificity, fall into the same pattern, and it is no surprise that the extremely diverse forest canopies of Viet Nam when sprayed repeatedly with herbicides are replaced over large areas by dense stands of species of bamboo (*11*).

The mechanisms involved in producing this series of patterns in terrestrial ecosystems are not entirely clear. One mechanism that is almost certainly important is simply the ratio of gross production to respiration in different strata of the community. The size of trees has been shown to approach a limit set by the amount of surface area of stems and branches in proportion to the amount of leaf area (*12*). The apparent reason is that, as a tree expands in size, the fraction of its total surface devoted to bark, which makes a major contribution to the respiration, expands more rapidly than does the photosynthetic area. Any chronic disturbance has a high probability of damaging the capacity for photosynthesis without reducing appreciably the total amount of respiration: therefore, large plants are more vulnerable than species requiring less total respiration. Thus chronic disturbances of widely different types favor plants that are small in stature, and any disturbance that tends to increase the amount of respiration in proportion to photosynthesis will aggravate this shift.

The shift in the structure of terrestrial plant communities toward shrubs, herbs, or mosses and lichens, involves changes in addition to those of structure and diversity. Simplification of the plant community involves also a reduction of the total standing crop of organic matter and a corresponding reduction in the total inventory of nutrient elements held within the system, a change that may have important long-term implications for the potential of the site to support life. The extent of such losses has been demonstrated recently by Bormann and his colleagues in the Hubbard Brook Forest in New Hampshire (*13*), where all of the trees in a watershed were cut, the cut material was left to decay, and the losses of nutrients were monitored in the runoff. Total nitrogen losses in the first year were equivalent to twice the amount cycled in the system during a normal year. With the rise of nitrate ion in the runoff, concentrations of calcium, magnesium, sodium, and potassium ions rose severalfold, which caused eutrophication and even pollution of the streams fed by this watershed. The soil had little capacity to retain the nutrients that were locked in the biota once the higher plants had been killed. The total losses are not yet known, but early evidence indicates that they will be a high fraction of the nutrient inventory, which will cause a large reduction in the potential of the site for supporting living systems as complex as that destroyed—until nutrients accumulate again. Sources are limited: the principal source is erosion of primary minerals.

When the extent of the loss of nutrients that accompanies a reduction in the structure of a plant community is recognized, it is not surprising to find depauperate vegetation in places subject to chronic disturbances. Extensive sections of central Long Island, for example, support a depauperate oak-pine forest in which the bear oak, *Quercus ilicifolia*, is the principal woody species. The cation content of an extremely dense stand of this common community, which has a biomass equivalent to that of the more diverse late successional forest that was burned much less recently and less intensively, would be about 60 percent that of the richer stand, despite the equivalence of standing crop. This means that the species, especially the bear oak, contain, and presumably require, lower concentrations of cations. This is an especially good example because the bear oak community is a long-lasting one in the fire succession and marks the transition from a high shrub community to forest. It has analogies elsewhere, such as the heath balds of the Great Smoky Mountains and certain bamboo thickets in Southeast Asia.

The potential of a site for supporting life depends heavily on the pool of nutrients available through breakdown

Fig. 1. The effects of chronic gamma radiation from a 9500-curie ^{137}Cs source on a Long Island oak-pine forest nearly 8 years after start of chronic irradiation. The pattern of change in the structure of the forest is similar to that observed along many other gradients, including gradients of moisture availability and of exposure to wind, salt spray, and pollutants such as sulfur dioxide. The five zones are explained in the text. The few successional species that have invaded the zones closest to the source appear most conspicuously as a ring at the inner edge of zone 2. These are species characteristic of disturbed areas such as the fire weed, *Erechtites hieracifolia,* and the sweet fern, *Comptonia peregrina*, among several others. [The successional changes over 7 years are shown by comparison with a similar photograph that appeared as a cover of *Science* (*16*)].

of primary minerals and through recycling in the living portion of the ecosystem. Reduction of the structure of the system drains these pools in whole or in part; it puts leaks in the system. Any chronic pollution that affects the structure of ecosystems, especially the plant community, starts leaks and reduces the potential of the site for recovery. Reduction of the structure of forests in Southeast Asia by herbicides has dumped the nutrient pools of these large statured and extremely diverse forests. The nutrients are carried to the streams, which turn green with the algae that the nutrients support. Tschirley (*11*), reporting his study of the effects of herbicides in Viet Nam, recorded "surprise" and "pleasure" that fishing had improved in treated areas. If the herbicides are not toxic to fish, there should be little surprise at improved catches of certain kinds of fish in heavily enriched waters adjacent to herbicide-treated forests. The bamboo thickets that replace the forests also reflect the drastically lowered potential of these sites to support living systems. The time it takes to reestablish a forest with the original diversity depends on the availability of nutrients, and is probably very long in most lateritic soils.

In generalizing about pollution, I have concentrated on some of the grossest changes in the plant communities of terrestrial ecosystems. The emphasis on plants is appropriate because plants dominate terrestrial ecosystems. But not all pollutants affect plants directly; some have their principal effects on heterotrophs. What changes in the structure of animal communities are caused by such broadly toxic materials as most pesticides?

The general pattern of loss of structure is quite similar, although the structure of the animal communities is more difficult to chart. The transfer of energy appears to be one good criterion of structure. Various studies suggest that 10 to 20 percent of the energy entering the plant community is transferred directly to the animal community through herbivores (*14*). Much of that energy, perhaps 50 percent or more, is used in respiration to support the herbivore population; some is transferred to the detritus food chain directly, and some, probably not more than 20 percent, is transferred to predators of the herbivores. In an evolutionarily and successionally mature community, this transfer of 10 to 20 percent per trophic level may occur two or three times to support carnivores, some highly specialized, such as certain eagles, hawks, and herons, others less specialized, such as gulls, ravens, rats, and people.

Changes in the plant community, such as its size, rate of energy fixation, and species, will affect the structure of the animal community as well. Introduction of a toxin specific for animals, such as a pesticide that is a generalized nerve toxin, will also topple the pyramid. Although the persistent pesticides are fat soluble and tend to accumulate in carnivores and reduce populations at the tops of food chains, they affect every trophic level, reducing reproductive capacity, almost certainly altering behavioral patterns, and disrupting the competitive relationships between species. Under these circumstances the highly specialized species, the obligate carnivores high in the trophic structure, are at a disadvantage because the food chain concentrates the toxin and, what is even more important, because the entire structure beneath them becomes unstable. Again the generalists or broad-niched species are favored, the gulls, rats, ravens, pigeons and, in a very narrow short-term sense, man. Thus, the pesticides favor the herbivores, the very organisms they were invented to control.

Biological evolution has divided the resources of any site among a large variety of users—species—which, taken together, confer on that site the properties of a closely integrated system capable of conserving a diversity of life. The system has structure; its populations exist with certain definable, quantitative relationships to one another; it fixes energy and releases it at a measurable rate; and it contains an inventory of nutrients that is accumulated and recirculated, not lost. The system is far from static; it is subject, on a time scale very long compared with a human lifespan, to a continuing augmentive change through evolution; on a shorter time scale, it is subject to succession toward a more stable state after any disturbance. The successional patterns are themselves a product of the evolution of life, providing for systematic recovery from any acute disturbance. Without a detailed discussion of the theory of ecology, one can say that biological evolution, following a pattern approximating that outlined above, has built the earth's ecosystems, and that these systems have been the dominant influence on the earth throughout the span of human existence. The structure of these systems is now being changed all over the world. We know enough about the structure and function of these systems to predict the broad outline of the effects of pollution on both land and water. We know that as far as our interests in the next decades are concerned, pollution operates on the time scale of succession, not of evolution, and we cannot look to evolution to cure this set of problems. The loss of structure involves a shift away from complex arrangements of specialized species toward the generalists; away from forest, toward hardy shrubs and herbs; away from those phytoplankton of the open ocean that Wurster (*15*) proved so very sensitive to DDT, toward those algae of the sewage plants that are unaffected by almost everything including DDT and most fish; away from diversity in birds, plants, and fish toward monotony; away from tight nutrient cycles toward very loose ones with terrestrial systems becoming depleted, and with aquatic systems becoming overloaded; away from stability toward instability especially with regard to sizes of populations of small, rapidly reproducing organisms such as insects and rodents that compete with man; away from a world that runs itself through a self-augmentive, slowly moving evolution, to one that requires constant tinkering to patch it up, a tinkering that is malignant in that each act of repair generates a need for further repairs to avert problems generated at compound interest.

This is the pattern, predictable in broad outline, aggravated by almost any pollutant. Once we recognize the pattern, we can begin to see the meaning of some of the changes occurring now in the earth's biota. We can see the demise of carnivorous birds and predict the demise of important fisheries. We can tell why, around industrial cities, hills that were once forested now are not; why each single species is important; and how the increase in the temperature of natural water bodies used to cool new reactors will, by augmenting respiration over photosynthesis, ultimately degrade the system and contribute to degradation of other interconnected ecosystems nearby. We can begin to speculate on where continued, exponential progress in this direction will lead: probably not to extinction—man will be around for a long time yet—but to a general degradation of the quality of life.

The solution? Fewer people, unpopular but increasing restrictions on technology (making it more and more expensive), and a concerted effort to tighten up human ecosystems to reduce their interactions with the rest of the earth on whose stability we all depend. This does not require foregoing nuclear energy; it requires that if we must dump heat, it should be dumped into civilization to enhance a respiration rate in a sewage plant or an agricultural ecosystem, not dumped outside of civilization to affect that fraction of the earth's biota that sustains the earth as we know it. The question of what fraction that might be remains as one of the great issues, still scarcely considered by the scientific community.

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Advanced Composite Materials

The mechanical characteristics, constituent materials, and fabrication techniques are reviewed.

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Extensive research and development efforts have produced high-strength, stiff, light-weight "advanced composite materials" (*1*) that are now being used in aircraft systems. Such efforts were originally sponsored by the Air Force Materials Laboratory, but interest and activity gradually spread throughout the aerospace industry. In addition, the Army, the Navy, and NASA are now actively concerned with the development of these materials for use in structural components of aerospace vehicles.

These composites are all combinations of a matrix or binder material and some type of reinforcement, either particles or fibers (*2*). The matrix serves to transfer loads between the reinforcements. The overall properties of the composite are a function of many variables, including the amount and type of reinforcement and matrix, the orientation of the reinforcing particles or fibers, the processing methods used in fabricating the composite, and so on. Some of these materials show isotropic mechanical behavior, others show anisotropic behavior. A concrete block is a particle-reinforced composite that shows isotropic behavior under load—that is, behavior independent of the orientation of the load. The fiber-reinforced composites, such as those used for rocket-motor cases and for some structural components of aircraft, show anisotropic behavior—behavior dependent on the orientation of the load.

Most metal alloys are homogeneous and isotropic. Up to the present, the metal alloys have been the only materials used for primary structural components of aerospace vehicles. Glass-fiber-reinforced composites have, for years, had a wide variety of structural applications. Of major current interest is their use in rocket motor cases for the Minuteman, Polaris, and Poseidon missiles and their use for many secondary structural components of aircraft, such as radomes and aerodynamic fairings. They have been used very little for primary load-carrying structures. The reasons for the wide variation in the uses to which the metal alloys and the glass-fiber-reinforced composites are put is best understood from a comparison of their mechanical properties.

In Fig. 1 the specific tensile strength (tensile strength relative to density) is plotted as a function of the specific tensile modulus of elasticity (tensile modulus relative to density) for a variety of materials—both composites and metal alloys—used in structural components of aerospace vehicles. Theoretically, the more ideal a material's mechanical properties are, the more closely it will approach the upper right-hand corner of the graph, combining high strength and stiffness with low density. To illustrate, 2024 aluminum (an alloy) has a tensile strength of 49.2 kg/mm^2, a modulus of 7500 kg/mm^2, and a density of 2.77 g/cm^3—that is, a specific strength of 17.8×10^6 millimeters and a specific modulus of 25×10^8 millimeters. Values for stainless steel 301 [containing chromium (18 percent), nickel (8 percent), and carbon (<0.15 percent)] and for titanium 6-4 [containing aluminum (6 percent) and vanadium (4 percent)] have been plotted to show the range of the properties of metallic materials in current use in the aerospace industry.

From Fig. 1 it is apparent that, though glass-fiber-reinforced composites are definitely stronger than any conventional structural material, they are not much stiffer. Similarly, beryllium provides greater specific stiffness but very little more specific strength than conventional structural metals.

From these considerations it is apparent that an ideal material would have the properties of high strength, high stiffness, and light weight. The need for a real material with these characteristics provided the impetus for developing the advanced composite materials. These new materials have already demonstrated the combination of greater strength and stiffness and lighter weight than any conventional structural metals.

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