EFFECTS OF TOXICITY ON ECOSYSTEMS

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1. Definition of ecosystem

The purpose of this paper is to put the proposed epidemiological study of pollution effects into an ecological perspective. Before discussing effects of toxicity on ecosystems, I need to define a few terms. The term *ecosystem* was introduced by Tansley in 1935 [25] and its applicability to general ecological study was argued by Evans in 1956 [8]. An ecosystem is the sum of the organisms and the nonliving environment in a given area. A particular ecosystem can be as large as the whole earth or as small as the protozoa living in the gut of a termite; its actual size depends on the ecological questions being asked. In the study of an ecosystem as in the study of any other system, the functional pathways linking components and the interactions among the components are stressed. To a greater and greater extent, the methods and generalizations of systems analysis that have been developed in other fields are being brought to bear on the study of ecosystems [27], [28], [29].

A critical aspect of the description of an ecosystem is the delineation and study of its boundaries. All natural ecosystems are more or less permeable, that is, various substances cross the defined limits of the system and may have significant effects on its components. For example, a stream ecosystem receives water, dissolved substances, dead plant material, and numerous organisms from the land and radiant sunlight from above. Many organisms spend from a few moments to most of a life cycle within the stream, returning later to the land. There is extensive output from the system as it flows into the sea or some other body of water. Man removes water from the system for drinking and for various agricultural and industrial purposes and may return the water in a greatly altered form. He dumps various additional materials into the system at innumerable points. Thus, the study of what is going into and coming out of the system is almost as complicated as determining what is going on within the system itself.

2. Toxicity effects on the ecosystem

Toxicity effects on an ecosystem are chemical or radiation effects on a species or group of species that result in the reduction or elimination of these components through death or sterility. Toxicity effects are to be distinguished from nontoxic, but perhaps equally disasterous, effects. Such nontoxic effects would include abnormal climatic patterns, man's mechanical removal of vegetation prior to cultivation, *eutrophication* (the addition of nitrates, phosphates, and other limiting substances to aquatic ecosystems producing increased growth of algae and other plant species), over harvesting of particular species, and so forth. The toxicity effects may generate a series of additional changes, and they may significantly interact with each other and with the nontoxic effects.

It should be stressed that not all toxic effects on ecosystems are caused by man's activities. Many plants release *phytotoxins* into the environment that give them an advantage over competing species, a phenomenon called *allelopathy* [17], [31]. Considerable interest has developed around the discovery that plants produce insecticides and other deterrent chemicals that protect them from herbivorous insects [6], [31]. Many potentially toxic substances, such as arsenic and other heavy metals, may enter terrestrial and aquatic ecosystems through natural weathering processes. Perhaps the most striking example of toxicity effects on an ecosystem in which man plays no apparent role is the red tide, in which one or more species of dynoflagellate algae become temporarily extremely abundant and produce such a high concentration of toxic chemicals that huge numbers of other organisms in the area are killed [4], [9]. Man himself may be poisoned by eating shellfish containing the dynoflagellate [3], [20].

3. Monitoring the ecosystem

Numerous problems are associated with the simple description of ecosystems. Adequate description of them requires monitoring all the essential components and all the relevant input and output of the system. Any ecological study, whether at the ecosystem level or at the population level, faces the basic problem of determining how many organisms of each kind are present in the environment. This problem is complicated by the fact that many organisms have a clumped distribution in nature, necessitating more extensive sampling than if the distribution were random or regular. Changes in the system may be associated with changes in the values of a number of abiotic factors, such as temperature, relative humidity, concentration of particular chemical substances, solar radiation, and so forth. Since any of the components may be changing rapidly, frequent monitoring of them is required. Even if human, technological, and financial requirements for complete monitoring of the ecosystem could be met, there is the real possibility that something approaching the uncertainty principle exists in ecology, namely, that by the very process of frequently measuring all of the components, the system will be altered. The samples removed and the other perturbations produced by monitoring may partly determine the particular output observed and the interactions discovered.

4. Ecosystem dynamics and model building

At this point, I want to draw a very strong distinction between the simple description of an ecosystem and the functional analysis of that ecosystem. The simple description would require enumerating the species present, determining who eats whom, and, for a particular toxin or set of toxins, determining their concentration in each species and in the various parts of the environment.

In contrast to this, a functional analysis of the ecosystem would require discovering the rates at which energy and various substances are flowing through the system. It would require determining the consequences of removing particular species or groups of species from the system, of altering the reproductive dynamics of particular species, of so altering the environment that particular exotic species move in, and so forth. In particular, a functional analysis would permit prediction of future ecosystem performance under a variety of possible management decisions; a descriptive analysis merely tells us what is there now and perhaps what appears to be going on now. A functional analysis requires model building and sensitivity analysis, followed by experimental manipulations to verify the predictions of the model and of the sensitivity analysis of the model.

Ideally, any experimental manipulation of an ecosystem, whether it is intentional or accidental, should have an associated control so that the effects of the particular manipulation can be distinguished from effects that would have occurred in its absence. But a control for any particular study is very difficult to find. No two large natural ecosystems are exactly alike; they differ with respect to the levels of abiotic components and species composition. Neither is it completely satisfactory to do "before and after" studies of the same ecosystem, since some of the ecosystems studied to date are capable of changes in structure and species composition in the absence of obvious external manipulation [23], [7]. Furthermore, most of the ecosystems of interest to us in any toxicity study have not been adequately studied prior to their alteration by an influx of toxic substances. For example, the decline in productivity of a coastal marine fishery has no control ecosystem for comparison, so it is possible that the decline is due to an influx of various toxins, or to erosion of the shoreline and silting of the bays, or to over exploitation of the fishery by man, or to natural cycles of abundance of predators and prey, or to some combination of these and/or other factors. Perhaps our only hope at present for such systems is to design statistical studies that will discover correlations between concentrations of particular toxins and unusual structural properties or states of components in the ecosystem. We can hope that future studies and experiments will demonstrate the causal relationships (if any) involved. But such purely statistical studies will not allow us to make firm predictions of the consequences of various management decisions.

One possible alternative to a control for our experiments is to develop a general model for the kind of ecosystem we are studying, and then see how our abused system differs from this general model. At present no sufficiently complete and detailed model for a natural ecosystem exists. However, one of the goals of the Analysis of Ecosystems section of the US International Biological Program (IBP) is the construction of an ecosystem model for each of six of the major biomes of the world. The models, if successfully constructed, would predict *primary productivity* (the rate at which plants produce material that is potentially available as food for other organisms) as a function of the values of the other components, and will functionally relate primary productivity to as many of the other factors and properties of the system as possible. As an integral part of the program, changes in all major components of the system will be monitored and correlated with changes in other components and parameters. Experimental manipulations of replicas of the systems are being performed, including watering, grazing, fertilizing, and so forth. A large team of researchers works on each project, with each researcher or group of researchers responsible for the study of one component or set of components of the system. It is hoped that the results obtained will be integrated into a coherent and robust model, using all the modern techniques of systems analysis. The model will then be simulated, and its more interesting and promising predictions will be tested by further experimentation. The models from the different ecosystems will be compared to discover their common properties and particular differences. An outline of a Canadian approach to the design and initiation of an IBP ecosystem study has been presented by Coupland and co-workers [5]. The major problems encountered in planning the study were location of an adequate study area, recruitment of competent researchers, and individual adherence to the group's research goals.

It will be at least a few years before these studies are complete enough to provide us with workable models for the study of toxicity and other effects on large ecosystems, although preliminary models are currently being circulated among participating researchers in the program. The progress of the US/IBP Analysis of Ecosystems section should be carefully followed. We should attempt to profit from their mistakes, and, where possible, should incorporate their results and progress into our experimental design.

5. Pollutant pathways in the food web

Given that our knowledge of ecosystems is very incomplete and is based largely on simplistic and incomplete models and theory, on causal inferences from observed correlations, and on studies of small subsets of ecosystems, what relevant generalizations are possible concerning ecosystems, and how do these generalizations relate to toxicity effects on ecosystems?

A common generalization is that the organisms in an ecosystem can be represented as a series of trophic levels, typically green plants, herbivores (which feed on the green plants), carnivores (which feed on the herbivores), secondary carnivores (which feed on the carnivores), and decomposers (which feed on the dead bodies, excretions, and other remains of the other organisms) [14]. In reality, the feeding relationships among the organisms are extremely complex, often vary during the life of the individual, and cannot be easily reduced to a simple trophic structure. For greater precision they should be represented as a food web or food net, in which all of the feeding relationships among species are shown. Whether trophic levels or food webs are used to represent feeding relationships among species in the system, the basic concept is extremely important for any study of direct toxic effects on man. Such a study would require following a toxic substance through the feeding relationships among the species and evaluating its residence time, concentration, and physiological effects in each species. The sampling methods and experimental design are relatively straightforward and have been applied to the study of dichloro diphenyl trichloroethane (DDT) and other chlorinated hydrocarbons and to radioactive substances in particular. For example, dichlorodiphenyl dichloroethane (DDD) (or tetrachlorodiphenylethane, TDE) was applied in 1949, 1954, and 1957 to Clear Lake, north of San Francisco, to kill the aquatic larvae of the midges, which are nuisance insects as adults [12]. Subsequent studies [16], [30] indicated that DDD had become extremely concentrated in numerous organisms in the lake, and the fatty tissues of fish contained 40 to 2500 ppm DDD. The concentration was its highest in the fat of the predatory fishes, which man prefers for sport and food. The flesh of the fish contained less DDD than the fatty tissues, but, for most fish, still exceeded the maximum tolerance level of 7 ppm set by the FDA for DDD residues in marketed foods [30]. A really thorough study of the toxicity effects on this ecosystem, including man as one of the consumers of fish, would involve periodic samples of all of the abundant species in the system to determine the concentration of DDD and its breakdown products, feeding observations and experiments to determine how DDD is flowing through the system, and detailed studies of its distribution in the bottom mud and other parts of the abiotic environment. Samples of the organisms should be tested periodically for sensitivity to DDD and these sensitivities compared with those of populations from areas less exposed to DDD to determine the degree of evolution of resistance to DDD. The third spraying of Clear Lake produced less kill of midges, implying evolution of resistance to DDD, at least on the part of the midges. The Clear Lake ecosystem would be an excellent one to study now, since there has been no deliberate input of DDD since 1957, and sampling of organisms for DDD concentration was stopped in 1965. A similar experimental design would be applied to the study of any other toxin in any other system.

A second generalization about ecosystems is that we know least about the decomposer portion of ecosystems. The bacteria and fungi are responsible for breaking dead plant and animal material down into simple substances that can be reused by the plants. The decomposers are assisted by numerous other organisms that also feed on dead organic matter and on the decomposers themselves. Very little is known about their abundance and detailed function in nature. Yet these are the very organisms that are basic to the detoxification of many toxins, and, in the case of elemental mercury, to the increase in its toxicity in an ecosystem [13]. The decomposers will pose as basic a problem to a study of the toxicity effects on an ecosystem as they do for any other ecological study: we just don't know enough about them and don't have the methodology to deal with the problem.

6. Factors affecting ecosystem stability

Another generalization about ecosystems is that diverse ecosystems are more stable than simple ecosystems. A diverse ecosystem is one composed of a large number of fairly abundant species. It is normally assumed that diverse ecosystems have more complex feeding relationships among the organisms and a greater number of pathways through which food energy can flow. From this it is assumed that more diverse systems are more stable. However, ecologists use the term stability in at least two different ways: (i) to mean constancy of numbers of individuals, and (ii) to mean constancy of species composition. A system in which all the species persist through time would be one in which no species becomes extinct and no species becomes so abundant that it competitively reduces some other species toward extinction. Such a system might be called a system with *protected diversity*, analogous to the term protected polymorphism recently introduced into the population genetics literature [19]. Increased diversity of itself does not always increase stability [10], [29]; it depends on where in the system the diversity is added. But, in the great majority of cases studied, increased diversity produces increased stability in one or both senses of the word, and greater simplification of the system produces greater fluctuations in numbers of individuals and greater probability of extinction. The simplest of man-made ecosystems are the mono-crop agricultural systems, which are very vulnerable to extensive defoliation by pests and to decimation by diseases.

Woodwell [32] has recently argued that ionizing radiation, persistent pesticides, and eutrophication each produce the same kind of simplifying effects on ecosystems. The nuclide, cesium 137, gamma radiation experiments conducted at Brookhaven indicated that at high doses of radiation the trees were eliminated, stronger radiation eliminated the tall shrubs, still stronger radiation eliminated the low shrubs and herbs, and the highest levels of radiation eliminated the lichens and mosses. This is the same order of susceptibility found in studying the effects of fire, exposure on mountains, salt spray, and water availability. The response of the vegetation to oxides of sulphur near the smelters in Sudbury, Ontario, was also similar: first the sensitive tree species were eliminated; then the whole tree canopy, leaving resistant shrubs and herbs widely recognized as characteristic of the development from open field to forest.

Extensive loss of nutrients from the system may accompany loss of the trees, as is illustrated by Bormann's study [2] in the northeastern U.S. in which he cut down a portion of a forest, left the dead vegetation in place, and followed the nutrient concentration and stream flow in the streams draining the area.

The greater simplification of ecosystems associated with toxicity effects has the potential for producing greater instability. This possibility should be thoroughly investigated in any study of toxicity effects on ecosystems, although the lack of an adequate control is a very serious limitation. The instability would presumably result from basic alterations in the structure of the system due to the elimination of a number of components and the possible introduction of additional components. In this sense, an ecologist does not care *how* something dies, but that it dies; and the consequences of its death for the ecosystem as a whole are what concern him most. The consequences may include greater fluctuations in abundance of species of interest to man, as in the case of a marine fishery; an increase in abundance of various species man considers undesirable; or the breakdown of a vital function of the system, such as the water-holding capability of a forest ecosystem. In any case, the loss of a species will probably produce an ecosystem that is less aesthetically pleasing to man.

There is considerable circumstantial evidence that extensive use of certain pesticides in agricultural systems can so alter the structure of the system that subsequently a more extensive use of pesticides is required, resulting in newer and more serious problems [21], [24]. The following pattern may develop: a pest is particularly abundant late in the growing season of a crop, so the farmer sprays to kill the pest. But at the same time, he kills a number of the parasites and predators of the pest, due to greater sensitivities, concentrating effects, or peculiarities of their life cycles. The system may then enter the next growing season with fewer predators and parasites, allowing the pests to achieve high densities earlier in the next season. The farmer sprays earlier and more often this next season, thereby setting up greater problems the following season. This positive feedback system may proceed until the predators of an organism that has never achieved pest densities before are killed, and this secondary pest emerges early in the season and causes extensive damage. If this secondary pest is one for which little chemical control is yet possible, as was the case for mites for a while [18], the farmer has no choice but to postpone his time of treating for a number of years until the system reestablishes more of a state of stability. The farmer suffers considerable economic loss in the process. Thus, in a really effective program of toxicity study it would be desirable to follow the actual structural changes in the ecosystem caused by the toxic substances so that the consequences of reducing toxic inputs could be foretold as well as the consequences of continued or increased toxic input. It may be that by trying to act on the basis of too little knowledge of ecosystem function and structure, we will cause greater problems than if we fail to act.

As an example of this latter possibility, considerable debate has developed around the feasibility and desirability of reducing the phosphate content of detergents [1], [11], [26]. Ryther and Dunstan [22] have studied this problem from the standpoint of the coastal marine phytoplankton, the single celled algae that are the base of the food chain of the ocean. They demonstrated, by some convincing observations and experiments, that nitrogen, not phosphorus, is the critical factor limiting coastal marine phytoplankton. About twice the amount of phosphate as can be used by the algae is normally present in polluted waters. This is a result of the nitrogen to phosphorus ratio in the input to marine environments and to the greater rate of recycling of phosphorus compared with nitrogen. They conclude that removal of phosphate from detergents is therefore not likely to slow the eutrophication process in costal marine waters, and its replacement with nitrogen containing nitrilotriacetic acid will only accelerate the problem.

Although eutrophication is not a toxicity effect on an ecosystem as I have defined the term, it may interact significantly with toxicity effects, as is suggested by Wurster [33] in his study of DDT sensitivity of algae from coastal marine waters. He found very significant reductions in photosynthesis for laboratory stocks of four very different species of marine algae at fairly low concentrations of DDT. Since eutrophication favors the development of certain species of algae and greatly alters the relative abundance of the trophic levels, its interaction with DDT inhibition could produce significant changes in the structure of the marine environment. But our knowledge of that ecosystem, as well as most others, is too incomplete to predict the form of the structural changes.

A fundamental problem in the study and description of changes in an ecosystem is to determine the amount of dimensionality necessary to describe the responses of the system. Lewontin [15] has recently discussed this problem and suggests that if the unaccounted for dimensionality is treated as a random variable, we may be able to generate a stochastic model that will adequately describe the state of the system. The only problem we may face in this connection is the possibility that the structure of the system is not very stable: it is possible that changes in values of parameters unaccounted for in the model will produce very different performances of the system. As Lewontin points out, this is very well illustrated by the classical predator-prey equations of Lotka and Volterra, in which the basic model predicts undamped oscillations, but the addition of density effects for each population produces damped oscillations.

7. Summary

In summary, any epidemiological study of pollution effects must concern itself with description of the concentrations in and pathways through the components of the ecosystems involved. But if the study is to have any predictive value and to form the basis for any intelligent management decisions with respect to environmental quality, the study must also include the functional analysis of these ecosystems. It must produce realistic and testable models that adequately represent the nature and consequences of the interrelationships of ecosystem components.

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Discussion

Question: John R. Goldsmith, Environmental Epidemiology, California Department of Public Health

In considering the analogy of ecology and epidemiology there may be merit in considering how epidemiologists deal with the problem of the extremely large number of variables which may affect health. The most vital technique is the classification of variables, followed by choice of an index (or more than one) for each class.

By such methods, which should be applicable as well to ecology and epidemiology, one can then choose a specific hypothesis of association for testing. In a way, formulating such a hypothesis is the second vital step in epidemiology. Testing such a hypothesis is the third crucial step.

Reply: R. Gill

Your comment is well taken, in that ecologists are often overwhelmed by the complexity of the systems they study. Perhaps such an epidemiological approach to ecological systems would yield considerable understanding of them.

Question: B. E. Vaughan, Ecosystems Department, Battelle Memorial Institute, Richland, Wn.

Would you elaborate on monitoring and the statistical design needed for adequate monitoring? Are we at a point where we can formulate an adequate approach to sampling in yet poorly studied systems? Dr. Sterling yesterday described teratogenic considerations about 2,4,5-T. When 2,4,5-T is used for forest management purposes, does anyone here know, for example, (1) what concentrations in runoff water are typical? (For example, how do these concentrations compare to teratogenic levels?) (2) How tightly does 2,4,5-T bind to soil? Can you elaborate on this or analogous problems from the standpoint of better monitoring or sampling approaches?

Reply: R. Gill

To answer the last part of your question first, the work that has been done up to 1967 on ecological effects of herbicides and their movement through ecosystems has been summarized in W. B. House, *et al.*, *Assessment of Ecological Effects of Extensive or Repeated Use of Herbicides: Final Report,* Midwest Research Institute, Kansas City, Missouri, 1967. This report contains discussion of a number of somewhat superficial studies that indicate 2,4,5-T is retained in the soil longer than 2,4-D is; from three months to perhaps a year, depending on climate and soil conditions. I don't know of any studies in which the distribution and concentration of 2,4,5-T in a whole ecosystem were adequately measured. Further, I don't think we know enough about 2,4,5-T's teratogenic properties in the organisms of the system to put the concentrations into a teratogenic perspective, once they are measured.

With respect to the rest of your question, monitoring within a given ecosystem would require following introduced toxic substances through the ecosystem until they were transported out of the system or rendered nontoxic. For widely used substances that are transported considerable distances, such as the chlorinated hydrocarbons, this would mean worldwide monitoring.

In general, I think we are at the point of formulating some, but not all, of the necessary aspects of the monitoring design for any given system. For the physical environment it must involve sampling of surface water, ground water (where possible), soil, and air (to test for possible codistillation, for example). It must involve enough stations to detect patterns of movement of the substances through the physical environment. Dr. Behar, for instance, worked with 20 sampling stations in his study of oxidants in the air of the Los Angeles basin, and this seems to me to be the bare minimum number of stations to get an effective picture of the formation and movement of oxidants in the air of the basin.

But in addition, there must be sampling of the organisms in the system that are exposed to the toxin, to determine their sensitivity to the toxin and the concentration of the toxin within them, if they retain it.

Particularly relevant to the problem of monitoring design is the possibility that monitoring from the standpoint of ecosystem structure and function may dictate a very different design from that dictated solely by consideration of human exposure to the pollutants. If pollutants are accumulating in the soil or in certain organisms, a monitoring system focusing on human exposure to pollutants will not detect this, but will produce strange and confusing results every time the pollutants are released from these ecological reservoirs. I have tried to point out that the presence of toxins in the ecosystem can have far reaching human effects due to alterations in ecosystem structure and function, and these effects might not be explicable from the results of a monitoring system built solely to consider human exposure problems.

Question: Unidentified discussant

Would you comment on the minimum number of components of an ecosystem that should be established to yield an adequate description of reality?

Reply: R. Gill

This varies with the system and the purpose of the study. If you are willing to establish a somewhat artificial set of black box categories, involving such concepts as trophic levels, 10 or 15 categories might produce some meaningful results. For more realistic categories, perhaps 50 components would be necessary. Dr. Vaughan, would you like to comment on this question?

Reply: B. E. Vaughan

I greatly disagree with generalized black box building. With due respect to the last questioner, the question (of how simple an ecosystem needs to be for adequate description of a real system) is badly framed. It is not a matter of how many boxes are strung together, but rather a judgmental matter of how representative a schema may be. It takes a great deal of ecological experience to judge the adequacy of an ecosystem model. You referred to the trophic level concept, which may be quite misleading for the multiply interconnected food web of an estuarine ecosystem. In such web systems, even a few interconnected boxes can be made to demonstrate some very remarkable properties.