CHAPTER 15

Ecosystem Response to Pollution

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15.1. INTRODUCTION

The effects of pollutants on plants and animals at the individual and population levels have been discussed in the preceding chapters. Moving one step up the integration scale of natural systems, consideration should be given to the implications of the introduction of chemical and physical agents for ecosystems as a whole. Changes specific to this level of organization find their mechanistic explanations in processes at the levels below, i.e. population and individuals.

Ecosystems are environmental units comprising the communities of living organisms and the abiotic components in a given volume of space (habitat). They are characterized by a defined structure and function, which result from the complex interactions between their components. The organisms may be grouped typically into producers (photosynthetic and chemosynthetic plants), consumers (animals), and decomposers (mostly bacteria and fungi), whereas the abiotic components are the soil and the atmosphere for terrestrial ecosystems, sediment, water, solutes, and suspended matter for aquatic ecosystems. Energy flows unidirectionally through the ecosystem while matter is recycled within its boundaries, although energy may be recycled, in chemical form, to a small extent, and nutrients may leave or enter the system in variable amounts.

The complex interrelations between its numerous components determine the structure of the ecosystem and contribute to its stability. This homeostasis or the ability to reestablish the initial state after disturbance, results from the interplay of various adaptive, feedback or damping mechanisms in the functioning of the system. It does not, however, prevent long-term evolutionary changes. The degree of homeostasis, which seems to depend on certain characteristics of the ecosystem, is obviously of major importance in determining the response to a stress, whether natural or man made. Disturbances may be of many kinds -- climatic (extreme heat or cold, drought or flooding), geomorphologic (landslides, erosion, silting), man-related (land clearing for agriculture, grazing, fishing, road building, urbanization, fertilization, pollution, etc.). Only the last will be discussed here, i.e. the effects at the ecosystem level of chemical and physical (ionizing radiation, waste heat) pollutants, although it is probably safe to say that responses of ecosystems to these types of insult do not differ essentially from those to other kinds of disturbances.

Response of the system as a whole to pollution is considered here while the transfer pathways of pollutants in the environment leading to man as a target are discussed elsewhere (Chapters 4 and 5).

15.2 METHODS OF STUDYING ECOSYSTEM RESPONSE

The qualitative and quantitative evaluation of the responses of whole ecosystems to disturbances is fraught with difficulties, not the smallest of which is the insufficient understanding of the mechanisms of operation of 'normal', undisturbed ecosystems. Other problems are related to the estimation of exposure dose, the incomplete knowledge of toxicity of the pollutant at the species level, the relative uniqueness of every ecosystem, the difficulty of experimenting on real-life ecosystems, as well as the logistics and costs involved.

It should also be noted that a pollutant may act directly on the organisms (e.g. a selective herbicide on specific plant taxa) or indirectly through alteration of the physical environment (e.g. by reducing the pH of a water body, as in the case of acid rain).

What is known today about ecosystem response has been revealed either by observation of systems subjected to unintentional exposure or by experimentation with ecosystems deliberately exposed to chemical or physical agents.

To the first approach belong case studies pertaining to major pollution occurrences, e.g. oil spills in the sea, atmospheric emissions around power-generating or industrial plants, release of industrial wastes in rivers or lakes, nuclear explosions, etc.

Experimentation on ecosystem response has been carried out rather exceptionally on life-size systems (e.g. the chronic gamma irradiation of a forest). Most of the data available were obtained by treating small parts of ecosystems (such as plots of agricultural land, or confined volumes of water in lakes) or by establishing model systems, or microcosms (e.g. artificial streams, microorganisms in chemostats) and subjecting them to various stresses.

Although they were originally designed to study basic ecosystem processes, microcosms have received increased attention recently as test systems for investigating the impact of chemical pollution and the screening of potentially hazardous chemicals (Draggan, 1976). A distinction should be made here between artificial food chain models, such as those consisting of an alga, a zooplankton, and a fish which are useful to trace the fate and transport of pollutants in the environment (Cole *et al.*, 1976), and real microcosms which should have achieved a certain balance between producers, consumers, decomposers and their physical-chemical environment. In such a system including algae, grazers, and bacteria, Taub (1976) showed that low levels of pesticides and heavy metals drastically altered trophic relationships.

The major problem with microcosm studies is that of extrapolating their results to natural ecosystems. There are also technological difficulties in the establishment and balancing of such microcosms.

A purely theoretical approach has also been used to predict the effect of disturbances on the structure and stability of mathematical models of ecosystems.

In the remainder of the chapter a number of approaches to assess the response of ecosystems to pollution will be reviewed before attempting the generalizations given at the end of the chapter.

15.3. ASSESSMENT OF LEVELS OF POLLUTION

(i) Qualitative

It may be possible to detect a polluted environment by visual observation; although not quantitative the results may nevertheless form a valid assessment. Three examples will be given.

The existence of air pollution will be evident from the presence in the air of solid particles (soot or dust) or of photochemical smog. Alternatively, some of the effects may be visible, e.g. damage to vegetation.

Oil spills give rise to visible pollution. It has been estimated that about 2.5 million tons of oil per year escape at sea, or are discharged, from ships or from underwater wells. This threatens birds and fisheries and is especially harmful to larval forms of marine organisms. Even if not lethal, the oil may lower resistance of organisms to disease and other stresses. Senses of smell and taste may be impaired thus interfering with normal functioning. Drifting to shore, oil is deposited along the shoreline where the shoreline ecosystems are then subjected to a new environmental factor with which they have not evolved. Furthermore, economic, aesthetic, and recreational damage may be considerable in coastal resort areas (Devanney, 1974). Detergents used to clear up oil pollution have proved to be more damaging than oil itself, as clearly shown in the detailed study of the Torrey Canyon accident (Smith, 1968).

Another form of visible pollution is the accumulation of sediments on the bottoms of lakes, streams, or estuaries. One example is cellulose fibres discharged from pulpmills. Another is dead algae from algal blooms, which decay and settle to the bottom of the stream or lake. The deposition of these and other sediments, especially from silt in run-off, modify the habitat, often making it unsuitable for the natural fauna. The rocky beds of many streams are rendered unsuitable for organisms to cling to, and breeding sites of aquatic insects are often buried. The sludge eliminates the niche for mayflies, gaddisflies, and stone flies, important aquatic food sources. They are often replaced by sludgeworms and mosquito larvae.

(ii) Quantitative

An obvious measure of the state of the environment can be obtained by measuring the amount of pollutant in environmental media (air, water, soil) or in some biological material. Indications of the biota to be analysed may come from signs of adverse effects. Such analyses are in the beginning exploratory as opposed to the routine analyses conducted in a monitoring programme. When a polluted ecosystem or a source of pollutant has been identified it may become necessary to keep the situation under continued surveillance by instituting regular analyses in a monitoring programme. The monitoring should be related as closely as possible to the source, to the route of transport to the critical receptors and to the doses received by these receptors. These principles are elaborated in a SCOPE Report (1977). Four examples of the monitoring that may be carried out for environmental assessment follow.

Integrative measurements of airborne metals were made by enclosing clean and dry samples (1.5 g) of an epiphytic moss *Hypnum* in nylon mesh bags and exposing these at sites of interest (Goodman and Roberts, 1971). These showed elevated levels of metals in the air downwind from smelters in Wales. Studies to correlate the analysed levels on the moss with emission rates and doses to receptors, are continuing (Swansea, 1975).

Oxides of sulphur are major contaminants released into the atmosphere from power plants burning fossil fuels and from smelters. Sulphur dioxide is converted to sulphuric acid and sulphates. Most of this settles to the ground but before doing so may be transported great distances.

In the area around a nickel smelter at Sudbury, Ontario, Gorham and Gordon

(1963) have found a sharp rise in sulphate concentrations in lakes within 6.4 to 8 kilometres of the source. Recent evidence shows that some of this sulphur drifts for hundreds of kilometres and is deposited on ecosystems far from its origin (Odum, 1975). Such is the case with atmospheric sulphur released in the United Kindom and Central Europe some of which deposited in Scandinavian countries.

When deposited on the earth, largely in precipitation, the sulphurous or sulphuric acid enters a number of pathways potentially altering the normal sulphur and acid balance of ecosystems. The effect of this 'acid rain' is most evident so far in aquatic ecosystems. The lakes in many parts of southern Norway and Sweden are on igneous bedrock with a very low buffering capacity. Therefore, they are especially sensitive to additions of acids. The strong acids are principally sulphuric and nitric. An increase of 0.5 ppm of SO_4, as occasionally demonstrated in the precipitation, would be sufficient to increase the hydrogen ion concentration an order of magnitude, from pH 5.6 to 4.6. The increasing acidity of lakes in the south and west of Sweden and in southern Norway is consistent with the atmospheric fall-out of acids (Braekke, 1976).

Four hundred of some 3,000 lakes in the west coast region of Sweden were investigated from 1970 to 1972 (Almer, 1974). Half of these lakes had pH values below 6.0. In the autumn and spring, 36 and 22 per cent of the lakes, respectively, had pH values below 5.0. These are the periods of spawning and hatching when the greatest stress to the fish population occurs. It is in the autumn that frequent rains add to the acidity and in the spring that the melting snow releases the accumulated pollution of a winter's deposition. Comparisons of early pH measurements with recent data indicate a 30- to 60-fold increase in acidity since 1941 in 21 lakes and streams in east-coast Norway. Data from 14 lakes in southwestern Sweden show a similar rate of acidification. The increase is attributed to inputs of acid precipitation. The yearly mean pH in precipitation has been 4.3 to 4.4. Since the 1930's the pH has dropped as much as 1.8 pH units. The sulphate and nitrate contents have increased proportionately indicating a low biological activity. Zinc, copper, and lead in the precipitation have also increased.

The release of radioactive iodine from nuclear installations provides a good example of environmental contamination and its monitoring. The food chain to the receptor (air – grass – cow – milk – child) is sufficiently well quantified (see Chapter 5) that monitoring of release rates will permit calculation of the dose to the thyroids of the affected children. Monitoring of the levels in milk gives data leading to more certain estimates.

The fourth example of monitoring for environmental quality is concerned with the pollution of an aquatic ecosystem with mercury (see pages 109–110). The most relevant measurements of food-chain contamination are the methylmercury content of fish muscle. Other measurements for the assessment of past environmental contamination are of the methylmercury content of birds' (especially fish-eating birds) feathers.

15.4. ASSESSMENT OF EFFECTS ON ECOSYSTEMS

Effects at the ecosystem level may be detected by visual semiquantitative observations or by more quantitative measurements. A few examples are briefly described hereafter.

(i) Eutrophication

Chemicals may adversely affect aquatic ecosystems which they can reach by direct aqueous discharges or by way of ground-water after discharge to the atmosphere and deposition on land. Similarly, nutrients applied as fertilizer or arising as farm sewage may enter aquatic ecosystems by run-off. Incompletely treated urban sewage may make a similar contribution. It was recognized early in the nineteenth century that the addition of excess nutrients to lakes accelerated aging (eutrophication). The excessive algal blooms observed in many European lakes were becoming common with the development of sewage systems in the larger cities that piped sewage directly into lakes and streams plus the normal nitrogen-rich run-off from nearby farms (Rolich, 1969).

More intensive farming plus denser populations along the shore began to contribute more nitrogen in the run-off than the lake water could assimilate without alteration of its aquatic ecosystem. As the algal blooms flourished, the dissolved oxygen content of the water diminished, and the populations of sensitive fish species were reduced. Similar situations have occurred in lakes around the world whenever the nutrient balance has been disturbed.

(ii) Acid Rain in Lakes

The effects of such rain on the lake ecosystems are considerable. Most diatoms and green algae species disappear below pH 5.8; among the zooplankton, most daphnians disappear below pH 6.0. Fish reproduction and populations are affected below pH 5.5. Minnow, arctic char, and trout have disappeared from acidified waters. Shifts have been observed from higher aquatic plants towards mosses, which will also influence nutrient exchange with the sediments. In lakes around Sudbury, Ontario, which may also be affected by direct deposition, the numbers of aquatic plant species were inversely proportional to the concentration of dissolved sulphates.

(iii) Oil Spills in the Marine Environment

The study of the impact of oil on microbial populations has generally concentrated on biodegradation phenomena. As stated by Colwell and Walker (1977) there is not enough information about the effects on the autotrophic microbes involved in the main biogeochemical cycles, nor on viruses, fungi, and yeasts. Reasons for concern are the resistance to biodegradation of the more toxic aromatic components of oil, the heavy oxygen demand of oil biodegradation, and the ability of oil to concentrate heavy metals and chlorinated hydrocarbons.

(iv) Detergents in Sewage

A unique example of interaction from land to sea to air to trees was shown to be taking place in an area near Sidney, Australia (personal observation, Treshow). Norfolk Island pines (*Araucaria excelsa* R. Br.) grown in the area for many years to enrich the beauty of the popular nearby beaches were slowly dying. None of the usual fungus or insect pests was involved; virus diseases seemed unlikely, and air pollution in the area had not reached toxic levels. The species was not out of place, as it had evolved along the neighbouring shores dotting the South Pacific. But near Sidney, a new component had been added to the ecosystem: sewage. Sewage wastes were not released immediately to sea but pumped 300 yards out from land in a large pipe. Here, apparently, detergents in the sewage floated to the surface to be whipped into the air and drift on the winds, often onshore. The detergent spray then settled on the foliage and entered the leaf in amounts sufficient to disrupt the normal waxy layer of the cells that protected the trees from salt injury. With the protective coating gone, the salt spray could penetrate and damage the plant cells to an extent leading to the slow death of the trees.

A more refined assessment of the condition of an ecosystem and the amount of deviation from 'baseline' conditions requires a quantification of the kind of visual observations described above.

(v) Ecosystems with Algal and Protozoan Communities

Ecosystems in which the living components are mostly algae (for effects of pollution on algae, see Chapters 11 and 12) and protozoa exhibit a fairly rapid response to pollution stress. From observations and experiments it has been shown that the imposition of such a stress results generally in a reduction of the number of species present, an increase in the range of numbers of individuals per species, and a shift in dominance favouring some species over others. In fact the change in species diversity may be used as an indicator of pollution. The overall response is usually a reduction in the complexity of the living communities. The total number of species is reduced but there are also greater differences in the numbers of individuals per species which in undisturbed systems often exhibit a log-normal distribution (see Figures 15.1 and 15.2). This is due to the fact that as pollution stress increases, species are eliminated or strongly reduced in numbers while other, more tolerant, species become more abundant under conditions of reduced competition. Of course as pollution increases further, more and more species are affected and diminish in numbers and eventually disappear.

There is thus a pattern of dose-response of the community showing a zone of 'no

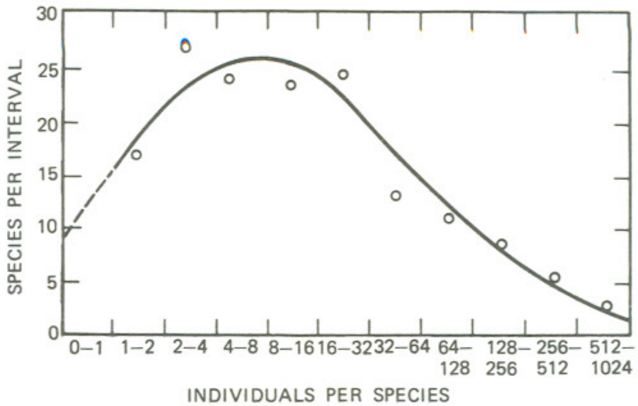

Figure 15.1 Diatom population in a stream not adversely affected by pollution (Ridley Creek, Pennsylvania, U.S.A., November 1951). (Reproduced by permission of John Wiley & Sons, Inc., from Cairns and Lanza, 1972)

detectable' effect, a range of graded response, and a zone of constant response as the pollutant concentration keeps increasing (Cairns and Lanza, 1972). The graded response to increasing pollution stress exhibited by such communities of algae may be used in practice to assess the degree of pollution in streams.

For practical purposes pollution may be said to be any environmental change which alters the species diversity more than a fixed percentage, say 20%, from the empirically determined level for a particular biotope.

As examples of the response of these communities to various types of pollution, one may mention:

(a) for non-toxic organic and inorganic substances: the well-known process of eutrophication (see above) accompanied by increased biomasses, caused by increased levels of nutrients (N,P,C), shift toward blue–green algae and other less oxygen-demanding groups of organisms. In flowing waters, the replacement of the communities by others more tolerant to oxygen depletion or more adapteu to mineralizing organic matter results in an increase of the heterotrophic part of the biocenosis and leads to the self-purification process which exemplifies the homeostatic character of such systems.

(b) for thermal pollution: successive replacement of diatom communities by green algae and by blue–green algae, reduction of species diversity of protozoa after a thermal shock, followed by recovery in a few days or hours.

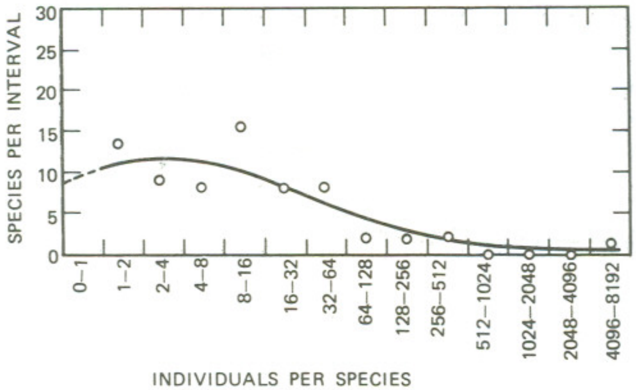

Figure 15.2 Diatom population in a polluted stream (Lititz Creek, Pennsylvania, November 1951). (Reproduced by permission of John Wiley & Sons, Inc., from Cairns and Lanza, 1972)

(c) for toxic chemicals and radioisotopes: large bioconcentration in the unicellular organisms with high surface-to-volume ratios and thus a greater effect on individuals and populations than in larger, more complex organisms. In general, species diversity is reduced, as well as numbers of individuals, although some tolerant species may proliferate; recovery can take place only if the toxin is diluted, or altered to less noxious compounds.

(vi) Rivers and Lakes

To assess the impact of effluents from a chemical factory on a lake (Beak *et al.*, 1959) and on a river (Cooke *et al.*, 1971) the number of freshwater molluscs per unit area of bottom mud were counted. Counts were made at 3-month intervals beginning before manufacturing operations, at various distances from the outfall and upstream of the factory on the river. The results at any one sampling point were plotted on industrial quality control charts to detect significant variations caused by the industrial effluents.

(vii) Estuarine Ecosystems

Even though much information is available on the impact of organic micropollutants on species living in estuaries (Lincer *et al.*, 1976), effects at the community and ecosystem levels have received much less attention.

Here also, loss in species diversity and shifts in dominant taxa have been demonstrated, even at very low pollution levels. Thus estuarine communities dominated by arthopods are replaced, when exposed to 1 to 10 ppb of PCB, by communities poorer in phyla, species and individuals, dominated by tunicates and other chordates. Analogous shifts occur in mixed algal cultures. For instance, when grown together under controlled conditions, a marine diatom (*Thalassiosira pseudonata*) and a green alga (*Dunaliella tertiolecta*) experienced a change in dominance from the former to the latter if exposed to low concentrations (ppb range) of DDT and PCB, which have no apparent effect on single-species cultures (Mosser *et al.*, 1972).

(viii) Coral Reefs

This very specialized ecosystem in which the main primary producers are intimately associated with the consumers has proved to be sensitive to pollution: in areas polluted with sewage, coral may be overcome and replaced by a community dominated by an alga (*Dictyosphaeria cavernosa*), and the coral may be killed if thermal pollution results in an increase of not more than 4°C above ambient temperature (Johannes and Betzer, 1975).

(ix) Mangrove Ecosystems

The responses of mangrove ecosystems to environmental stress are far from uniform: this ecosystem is quite resistant to oxygen depletion or increased turbidity in the water such as might result from sewage outfall (and in fact has been considered as a potential natural sewage treatment system) but it is very vulnerable to oil pollution (Odum and Johannes, 1975). It is also extremely sensitive to defoliants as has been shown in Vietnam. Mangrove response to defoliant has been a reduction in species diversity, loss of productivity, and a reduced inventory of mineral nutrients (Westing, 1971).

(x) Terrestrial Ecosystems

(a) Pesticides

Considering particularly the impact of pesticides in terrestrial ecosystems, Pimentel and Goodman (1974) outline as follows the course of events which has been observed in many instances: the number of species is reduced, which may lead to instability and subsequent population outbreaks of some species. This occurs because the normal check-balance structure of the system has been disrupted, as when a predator or parasite is strongly reduced or eliminated. If, thereafter, the chemical disappears, some species in the lower part of the food chain (e.g. herbivores) may increase to outbreak proportions, hence a new disruption of the system. It is also clear that organisms at the top of food chains are very susceptible to the loss of a species or to wide fluctuations of species populations lower in the food chain.

Pesticides must be used in agriculture because the very much simplified ecosystems created to produce food are especially subject to perturbation. When plant species over a given area are reduced to one, as is the aim in most agricultural and many forestry situations, any adverse stress which the crop cannot tolerate will inevitably cause some disruption. This has always been true where some disease or insect pest has become prevalent and ruined a crop. Since the advent of agriculture, farmers have attempted to manage their land for maximum productivity. So when insects threaten to reduce yields, the natural expediency is to try to reduce the numbers of insects. During the past century, chemical controls of insects have become increasingly effective, but the chemicals often have had effects reaching beyond the agricultural ecosystem. Pesticides, notably insecticides, kill more than the target species. Thus in an agricultural situation, desirable insects such as bees, as well as insects that are parasitic or predatious on the pest species are killed. In this way, the natural biological control, or population balance, of insects is disrupted (Rudd, 1964).

The agricultural crops themselves, like any ecosystem, are also subject to toxic doses of the chemicals used to control pests. The concentrations may be immediately toxic, or they may accumulate in the soil over a period of years. This subject has been thoroughly treated by Rudd (1964) and others, so will be discussed here only briefly to show the interplay of chemicals among different communities in the ecosystem.

The above discussion of pesticide use in farming is also relevant to forest management, where the greatest damage comes from native insects. Their numbers are kept in balance by natural factors. But the fluctuations of their populations are great around a 'norm' and their density may become far greater than forest managers would like. To limit losses, pesticides are then applied. Rather than control the pest, however, they may further disrupt the system. Pesticides sprayed over forests to control spruce budworm or other pests may reduce the pest populations, but they sometimes kill their parasites and predators. The pest species often build back much more rapidly than their predators so that the long-term balance of the system is upset and the damage may become increasingly severe.

It is important to recognize that half or more of the pesticide applied may never reach the target species or even the forest canopy. A significant fraction is picked up by air currents, circulated through the lower troposphere and ultimately deposited on the ground in precipitation, often in areas remote from that where the application was made. If the chemical is persistent and stable (and fat-soluble) as is DDT, it may build up in food chains many miles distant from where it was released and accumulate to toxic levels in top carnivores. For a discussion of global contamination with DDT, see Woodwell *et al*. (1971).

(b) Acid Rain in Terrestrial Ecosystems

Acid precipitation may increase soil acidity (Schofield, 1975) resulting in the likelihood that ions such as aluminium, manganese, or iron, might become more mobile, be leached form the soil system and thereby accumulate in toxic concentrations. The presence of these ions and possibly even the lower pH alone, could alter the soil microfauna and flora present, as well as injure higher plant species in both terrestrial and aquatic systems. Aluminium and iron might have secondary effects in interfering with phosphorus transport in germinating seedlings.

The release of other minerals might also be accelerated. Nitrogen, for example, might become more available, enhancing plant growth in the short term, but becoming deficient in the long run as it becomes bound in perennial vegetation.

The acid rain absorbed into the bark of trees has the further potential of changing the reaction of the bark thus placing a stress on the lichen species growing on this bark (Staxang, 1969; Johnsen and Söchting, 1973). Since certain lichens play a role in absorbing nitrogen from the atmosphere and making it available to the plants, the nitrogen balance of the ecosystem could be adversely altered. Other biogeochemical cycles might also be affected, such as the build-up of sulphur in some ecosystems as it is deposited from industrial processes elsewhere.

It should be stressed, however, that it has not been possible to demonstrate these, or many other effects sometimes postulated, in the field. If they are already occurring, either the effects are balancing each other out, or they are not of sufficient magnitude to measure.

(c) Metals

Heavy metals provide yet another example of the transfer of chemicals from one system to another. When ores, coal or other materials are burned, the unwanted or waste materials are generally released into the atmosphere. Particulate materials containing such heavy ions as lead, zinc, arsenic, cadmium, and copper, tend to settle out of the air within a few hundred yards of the source where the concentrations may build up in the soil to increasingly toxic amounts. The chemicals may then leach into the ground-water to a slight extent, but mostly they remain in the soil where they influence the composition of the plant community – some plant species or ecotypes being more tolerant of the toxic ions than others.

Thus for instance, *Agrostis tenuis* in western Europe, which is quite tolerant to zinc and cadmium as well as to acidity tends to replace the pre-existing vegetation around zinc smelters (Denaeyer-De Smet and Duvigneaud, 1974).

A further threat to the ecosystem arises when the metal ions are taken up by the plants. A build-up in the leaves could be harmful to animals feeding upon them, including humans. This possibility has been suggested for vegetable crops grown near smelters where the chemicals have been accumulating for perhaps a hundred years. Fortunately, the uptake of these ions by the roots of plants is very limited but foliar deposition must always be considered.

Population modifications also influence species diversity as the numbers of sensitive individuals are reduced and the tolerant individuals thrive. An extreme example of this occurred in the area immediately surrounding an aluminium reduction plant near Zwollen in Czechoslovakia (personal observation, Treshow). Within a few years of operation, the native conifers and oaks were killed along with much of the understory, and the plant populations closest to the industry were reduced almost solely to a single species, *Conium macrophylla.*

(d) Ionizing Radiation

Studing the response of a pine–oak forest to gamma radiation, Woodwell (1967) found that diversity expressed as the number of species per unit area was reduced in a continual gradient up to 1,000 roentgens per day. A dose of 160 roentgens per day reduced the diversity to 50 per cent of that of the unirradiated community. The reduced diversity was accompanied by a reduced cover, but the more tolerant species, particularly *Carex* spp. soon expanded over the open land to become dominant. This illustrates the potential importance of less common species in maintaining the stability of the overall community following periods of stress. The productivity along the gradient as measured by total dry weight of plants changed initially very little since the space and energy resources available became used by the more tolerant species. Thus diversity was initially a far more sensitive index of impact than productivity or biomass.

After a few months of exposure to the gamma source, several well-defined vegetation zones were established as a function of the exposure dose. Trees were eliminated first, then the tall shrubs, the low shrubs, the herbs, and finally the lichens and mosses. Parallel changes were observed with respect to diversity, primary production, total respiration, and nutrient inventory. In this case as well as in others involving different stresses (toxic chemicals, fire, etc.) the more hardy species, whether animal or vegetable, were the 'generalists'.

Other terrestrial ecosystems (tropical forest, grassland, etc.) have been acutely or chronically irradiated. One of them is a Mediterranean forest with subtypes dominated respectively by *Quercus pubescens* and *Quercus ilex*. There also, chronic exposure to gamma radiation increased leaching of mineral and organic compounds from litter and soil (Saas *et al.*, 1975).

15.5 CONCLUSIONS AND PREDICTIONS

In the preceding section, case studies of the response of various types of ecosystem to pollution have been described briefly. In attempting to draw general conclusions on this subject, one must refer to current concepts in basic ecological theory.

(i) Diversity, Stability, Maturity of Ecosystems

As mentioned in the Introduction, ecosystems are characterized by structure and function. Function relates to energy and material flows and involves such concepts as productivity (primary and secondary) and the biogeochemical cycles of chemical elements. Structure may be described in terms of trophic levels and ecological 'pyramids' of population and biomass. It also involves such concepts as diversity, stability, and maturity which are less precisely defined.

Diversity is often determined by the number of species per unit area or volume. A variety of indices have been proposed to express it, such as the reciprocal Simpson Index used by E. Odum (1975), which is equal to $1 - \Sigma(P_i)^2$, where P_i is the probability for the occurrence of each species in terms of the ratio of its importance to the total of importance values. Importance is usually based on numbers of individuals but may also be calculated in terms of biomass.

Diversity may also be expressed in terms other than species e.g. life-forms for plants (phanerophytes, geophytes), or subspecific units such as human population groups included in a consideration of an ecosystem, as advocated by Jacobs (1975).

Diversity contains in fact two notions, (a) that of richness or number of species (or other groups), and (b) that of evenness of distribution or the relative abundances of the individuals within each species (or group). It never concerns whole ecosystems but only certain components thereof and is assumed to be a reflection of multiple, dynamic functions in the system (Jacobs, 1975).

Stability is the tendency of a system to remain near an 'equilibrium' condition or to return to it after a disturbance. This concept may imply the ideas of constancy (lack of change), persistence (referring to survival time), inertia (ability to resist external perturbations), elasticity (speed with which a system returns to its former state following a perturbation), amplitude (amount of perturbation from which recovery is possible). Cyclical stability is the property of the system to cycle or oscillate around a central point (e.g. predator–prey systems), whereas trajectory stability refers to the property of moving towards a final end-point despite differences in starting points, such as in plant succession towards a climax (Orians, 1975). A listing of environmental factors and species characteristics which increase the various kinds of stability is given by the same author.

Even though stability (as expressed by constancy) is often found to be positively correlated with diversity, the assumption of any general relationship between these two attributes is not warranted. Much depends on the adaptive characteristics of the organisms present, which are determined in turn by their environment, the past experiences with perturbations, and the continual evolution of species.

The concept of practical stability has been introduced by Harte and Levy (1975) to account for the fact that disturbed ecosystems do not return to precisely their previous states. They may be considered as practically stable if the initial perturbation (which is finite) is not sufficient to push the system beyond tolerable limits. Practical stability lends itself to mathematical treatment by the Liapunov Direct Method (Lasalle and Lefshetz, 1961). Thus these authors have shown theoretically that increasing the number of trophic levels has no effect on stability – except if the biomass pyramid is inverted – and that increasing the number of species at each trophic level leads to a decreasing domain of stability. They also discovered that damage to the decomposers or to the organic or inorganic nutrient pools is a potentially stronger cause of instability than disturbances of the predator–prey components of the system.

Maturity applies to the successional stage of an undisturbed ecosystem approaching a more or less stable climactic stage (Jacobs, 1975). It is associated with an increase in internal effective links, making the system less dependent on inputs from outside. A stabilizing factor in ecological succession is the increasing importance of species which extend their connection in space and time ('K-strategists'). Another feature of succession is a progressive decrease in the ratio of primary productivity to biomass, thus a slowing down of turnover, at least in relatively closed systems, receiving, e.g. only radiation from the outside (Margalef, 1975).

Diversity increases generally with succession, at least in the early stages. Afterwards it may still increase, due to increases in richness or evenness but it may also decrease as observed for instance when single-species, very stable phytocoenoses become established.

(ii) Effects of Pollution on Ecosystem Characteristics

The estimation of doses has been discussed in Chapter 5, and the relations between doses and effects in Chapter 6. When these are used in conjunction with models described in Chapter 4, some predictions of the effects of releasing a pollutant into the environment may be possible. Unfortunately most of the available information is about individual species. Because of a lack of knowledge about fundamental ecosystem ecology and its responses to chemical and physical agents the predictions possible in the present state of knowledge are severely limited. Although it is impossible to make any sweeping generalizations, some tentative statements are presented here.

(a) Acute, accidental exposures to a pollutant often bring succession back to a previous stage, generally, but not always, of lower diversity, i.e. through a decrease in richness of species, or in evenness. Similar effects may be induced by other types of drastic disturbance such as fire.

    The resistance of ecosystems to these disturbances is not, however, related to their complexity. In fact, quite simple systems, especially if they have evoked in a stressing environment, may be more able to withstand an acute insult. On the other hand, very complex systems survive strong disturbances of the kind they may encounter under 'natural' conditions.

(b) Chronic exposures to chemicals, or ionizing radiation, or warm effluents, bring about gradual modifications of ecosystem structure to adapt it to the new prevailing conditions. Species, or ecotypes, are replaced by others that can survive and compete under the new set of environmental factors, thereby altering the physiognomy of the biocoenosium (e.g. suppression of the tree stratum in irradiated areas). Trophic functions may shift in importance (e.g. increased heterotrophy in organically polluted rivers, with sometimes a reduction in self-purification resulting from heavy metal poisoning of heterotrophic organisms). Primary productivity of terrestrial systems may be reduced but standing crop will be reduced even more, with a subsequent reduction in the turnover of nutrients. Increased leakage of nutrients may occur as a consequence of the decrease in standing crop.

By and large, one may agree with Woodwell's statement (1970) that pollution in general, although there are exceptions, brings about a simplification of the ecosystem structure and shifts the ratio of gross production to total respiration.

There is a trend from highly specialized species to 'generalists', a reduction in diversity and increase in monotony, a depletion of nutrients in terrestrial system coupled with an excessive input of these in aquatic systems.

The large-scale (i.e. of an order of magnitude similar to that of natural phenomena: e.g. heat release in a city in relation to solar radiation balance, dispersion of metals by industrial and power-generation activities as compared with the natural sedimentary cycle) introduction of pollutants into the environment has also the consequences of bringing down the barriers between natural ecosystems, enhancing exchange of energy and materials and, in a way, making them subsystems of a larger ecosystem in which man must be included.

In view of this, and considering the many uncertainties which still prevail, one should try to minimize the interferences of human ecosystems with 'natural' systems, upon which the balance of the biosphere depends, through the use of 'clean' technologies, recycling, economizing materials. Until we know better, every species should be saved, and one should keep in mind the aphorism of the great conservationist Aldo Leopold: 'The first rule of intelligent tampering is to save all the pieces'.

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