UNEP/IPCS Training Module No. 3

Section C

Ecological Risk Assessment

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EDUCATIONAL OBJECTIVES

You should understand the fundamental requirements of a natural ecosystem in terms of primary and secondary production and the various levels at which an ecosystem may be affected. You should be familiar with the concepts of food chains and webs and of bio-accumulation, bioconcentration and biomagnification. You should know the main habitat types, how ecosystems may be quantified and what factors, including potential toxicants, may affect their dynamic stability. From the preceding knowledge, you should understand approaches to ecotoxicity testing and ecological monitoring. You should understand the essential concepts of ecological risk assessment and how it is carried out from problem formulation to risk characterization. You should know how ecological systems may respond to stressors, the problems of exposure measurement, and the difference between assessment and measurement endpoints. You should understand how to analyse ecological risk and how to report your assessment to risk managers.

1 INTRODUCTION

This section is based partly on the USEPA document “A Framework for Ecological Risk Assessment” which describes the basics of ecological risk assessment. Two other useful reviews of ecological risk assessment are “Ecological Risk Estimation” by Bartell et al. (1992) describing an integrated approach to the assessment of aquatic ecological systems with an emphasis on simulation modelling and “Ecological Risk Assessment” by Suter (1993) which is an overview with excellent sections on the application of population biology and ecology to risk assessment.

It is important to make clear the relationship between ecology, ecotoxicology and the relevant aspects of risk assessment. Ecology and ecotoxicology are sciences devoted to defining the relationship between chemical exposures and resultant adverse effects on ecosystems and their component organisms. Risk assessment is a management tool used for making decisions, often with a great deal of uncertainty. While the conclusions from ecology and ecotoxicology should be objectively reached, societal perceptions and values often set the criteria applied in risk assessment.

2 ECOLOGY AND ECOTOXICOLOGY

Toxicology is most commonly concerned with effects of toxicants on humans. Ecotoxicology is concerned with effects on organisms other than man. This has three dimensions: toxicity to single species other than man, toxic effects on interrelationships between species, and accumulation of toxicants by organisms and their movement between organisms and species.

Study of ecotoxicology requires basic knowledge of ecology before the toxic effects can be fully understood. Following an introduction to ecology and to the unifying concept of a balanced ecosystem, this chapter examines in general terms the effects of man on ecosystems and the methods for monitoring ecological effects.

To understand ecotoxicology requires knowledge of how organisms interact in nature with each other (the biotic environment) and with the physical and chemical aspects of the environment (the abiotic environment). This is the science of ecology that can be viewed at several levels of organisation, at each of which there can be toxic effects. Examples of these levels in ascending order of complexity are shown in Table 1.

The following account of ecology illustrates how these and other toxic effects can occur and assumes no previous knowledge of biology. It starts from a broad consideration of the sustainability of ecosystems and is based on the review by Wilkinson (1996).

2.1 Understanding how ecosystems work

We can start from the simple assumption that there are two requirements that organisms have from the environment to sustain their life which take precedence over all other requirements:

(i) a supply of carbon to form the organic molecules of which organisms are composed;

(ii) a supply of energy to power the chemical reactions that keep the organisms alive.

Carbon is freely available in the environment as carbon dioxide in the air and as various inorganic forms, including bicarbonate, dissolved in water. However, organisms require organic carbon. Organisms can be divided into two major groups depending upon how they obtain organic carbon, as shown in Table 2. **Autotrophs** are organisms that can make all their chemical constituents from simple inorganic compounds, making their carbon compounds from carbon dioxide. **Heterotrophs** are organisms that require to obtain complex organic molecules in their diet as they are unable to synthesize them from simple carbon compounds like carbon dioxide.

In terms of number of species, autotrophs are very much in the minority, but they are of absolutely crucial importance because they make the organic matter that all organisms need. By far the biggest group of autotrophs, responsible for most of the fixation of inorganic carbon into organic form on the earth, are the plants using the process of photosynthesis, summarised as follows:

$$6CO_2 + 6H_2O + \text{light energy} \text{--->} C_6H_{12}O_6 + 6O_2$$

This equation summarizes many reaction steps but illustrates the basic principle. The other fundamental process, respiration, is a series of breakdown reactions which, unlike photosynthesis, are undertaken by all organisms:

$$C_6H12O_6 + 6O_2 \text{--->} 6CO_2 + 6H_2O + \text{chemical energy available for use in the cell}$$

The living cell couples catabolic (breakdown) and anabolic (synthetic) reactions using energy from breakdown processes to drive synthetic reactions.

Only autotrophs make new organic matter while all organisms consume it. Hence growth of new body matter of autotrophs is called **primary production**. Production of new body matter by heterotrophs that simply recycle already existing organic matter is called **secondary production**. Therefore the production by the autotrophs must be sufficient to meet the needs of both autotrophs and heterotrophs for respiration. Hence in a balanced system there is a balance between production and respiration. The photosynthesis by plants is balanced approximately by the total community respiration.

Energy and carbon alone are not enough for life. About 20 different inorganic nutrient ions are needed because of their roles in biochemical reactions in living cells or because they are components of particular organic compounds e.g. nitrogen in proteins. Plants absorb these from water and soil and they are passed to heterotrophs in the diet.

Table 1. Levels of consideration in ecology

Level of organisation	Description of level	Examples of toxicant effects
1. Individual organism or species	Concerned with how physical and chemical environmental factors control which species can occur in which place.	Alteration of the physical and chemical factors can affect the growth or survival of particular species.
2. Population	A group of individuals of a single species living together and having interrelationships through gene exchange by sexual reproduction.	Effects on population size; adaptation to toxicants by tolerant mutants spreading through population.
3. Community	A collection of populations of different species living together in one place (habitat) giving species assemblages characteristic of particular conditions e.g. oak woodlands.	Changes in species composition owing to selectively different effects of toxicants on different species.
4. Ecosystem	Organisms in a particular habitat considered together with their physical and chemical environment, and the processes linking the organisms and environment such as energy and nutrient flow and biogeochemical cycles. Ecosystems are characterised by a degree of sustainability.	Interference with nutrient recycling; concentration and accumulation of toxic substances in food chains; alteration of productivity; sustainability can be impaired by these alterations.

Table 2. Nutritional types of organism

Type of organism	Means of getting carbon	Means of getting energy
Heterotrophic e.g. animals, fungi, some bacteria	***Ready made organic carbon*** By ingesting ready made organic matter in the form of other living organisms or their waste products. Digestion to smaller molecules provides the building blocks for synthesis of other larger organic molecules using energy from respiration.	***Chemical energy*** By breaking down (catabolism) some of the larger organic molecules ingested in the diet in the process of respiration and applying the chemical energy released to synthesis (anabolism) of other chemicals needed by the organism.
Autotrophic mainly plants but also some bacteria	***Inorganic carbon*** Carbon dioxide (on land) or bicarbonate and other dissolved forms (in water) are reduced to organic carbon, primarily by photosynthesis in plants. Sugars resulting from photosynthesis can then provide an energy source in respiration or be used to synthesise other organic molecules.	***Light energy*** A physical form of energy, freely available in the environment, light, powers the anabolic reactions of photosynthesis in plants and some bacteria (but in a few chemosynthetic bacteria chemical energy from inorganic reactions is used to reduce inorganic to organic carbon).

Some nutrients, e.g. nitrogen and phosphorus, may often be in low concentrations in the environment compared with the amounts needed and so may limit plant growth and primary production. Other nutrients such as various metal ions may be even less abundant but are needed in such smaller amounts. Some trace elements, e.g. copper, may be toxic when available in more than trace quantities but bio-availability in soil or water may be regulated by natural binding agents reducing their effective toxicity.

Organisms can be placed in a chain of dependence, known as a food chain, with several different **trophic levels** (levels at which organisms feed) with plants or primary producers absorbing light, inorganic carbon and nutrients, and passing nutrients and organic molecules with their chemical energy to the higher trophic levels of herbivores and carnivores (Fig. Eco-1).

Each trophic level produces waste material (as excretory products and dead matter) and carbon dioxide from respiration. The waste products are broken down by decomposer organisms (bacteria and fungi) which release nutrients back to the environment where they are available for re-use. Thus nutrients cycle between organisms and the environment. This is part of a more complex cyclic system - the **biogeochemical cycle**. For each element utilised by organisms there is such a cycle. The precise details differ between elements depending on the amount of the element available, the uses to which organisms put it, where they store it in their bodies, and the sinks for it in the environment.

All biogeochemical cycles incorporate the idea that, for any essential element at any one time, part of the total naturally occurring amount of the element is in organisms and part is in different components of the natural environment. Individual atoms or molecules move between these compartments but the proportions in the different compartments remain roughly constant. These cycles must continue to function to ensure a supply of nutrients for organisms and to ensure continuing biological productivity.

Some organisms accumulate certain elements and compounds from the environment (**bio-accumulation**) causing them to have very high body loads relative to the outside concentrations (**bioconcentration**), e.g. organochlorines in plant and animal tissues. If the accumulated substance is conserved (not broken down by cellular processes) and stored, then a high dose will be given to the organisms that eat the bio-accumulator.

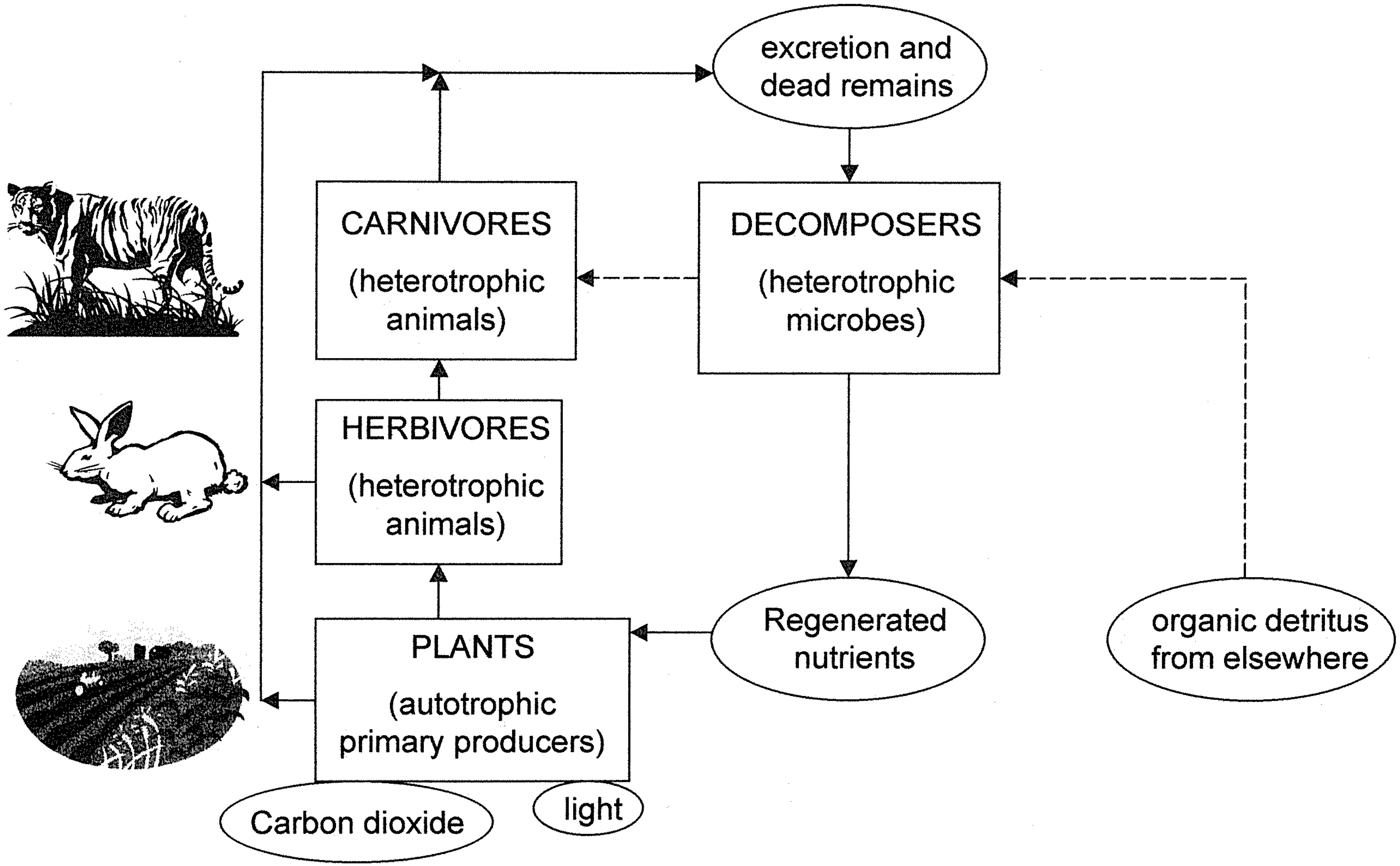

Figure Eco.1 Diagrammatic representation of a food chain. Arrows represent cycling of and pathways for energy, carbon and nutrients (carbon dioxide cycling has been omitted for clarity). The dotted line shows the route for input of energy from organic carbon and nutrients from detritus imported from another ecosystem. Organisms are in boxes and environmental requirements in ovals.

Because of losses of organic matter owing to respiration, each successive trophic level often has a lower area **biomass** (mass of living material in a given area at one time) or productivity than the levels below it. The body concentration of conserved substances passed up the food chain can therefore increase up the chain (**biomagnification**), sometimes resulting in toxic doses to organisms near the top of the chain.

Nutrients and carbon are recycled. The only requirement for life not recycled directly is light energy. Energy is lost to the environment by organisms. Consequently, primary productivity is dependent on the continuous input of energy from the sun.

Primary productivity is also controlled by the availability of all the other requirements for plant growth, carbon dioxide, water and nutrients. Since the availability of all these substances differs between habitats, different levels of primary production are characteristic of different places (Table 3).

The rate of secondary production depends on the availability of energy, carbon, and nutrients from the primary producers. Thus, factors affecting plant growth usually affect total production of the whole system.

An exception to immediate dependence on plant growth is seen in detritus-based systems such as estuaries. In estuaries the hydrographic conditions cause suspended particles from land drainage, the sea and freshwater to accumulate, giving turbid water which restricts light penetration for photosynthesis. The accumulated suspended matter includes much organic detritus that is instead used as a carbon, energy and nutrient source by estuarine heterotrophs. There is so much detritus that there is high secondary production despite restricted photosynthesis in this system. The primary production has been done in other habitats from which the detritus has been transferred

A food web is a more realistic concept than a food chain. Fig. 2 presents a very simple food web based on imaginary species (most natural ones would contain many more species). Even with such a simple one there can be a complex pattern of flow of energy, carbon and nutrients, based on the feeding preferences of different species, as indicated by the lines on the diagram. For any particular habitat there is a degree of stability by which the same assemblages of species are present in a food web in successive years, with the same dominant and rare species, with the same flow pathways important and others less so.

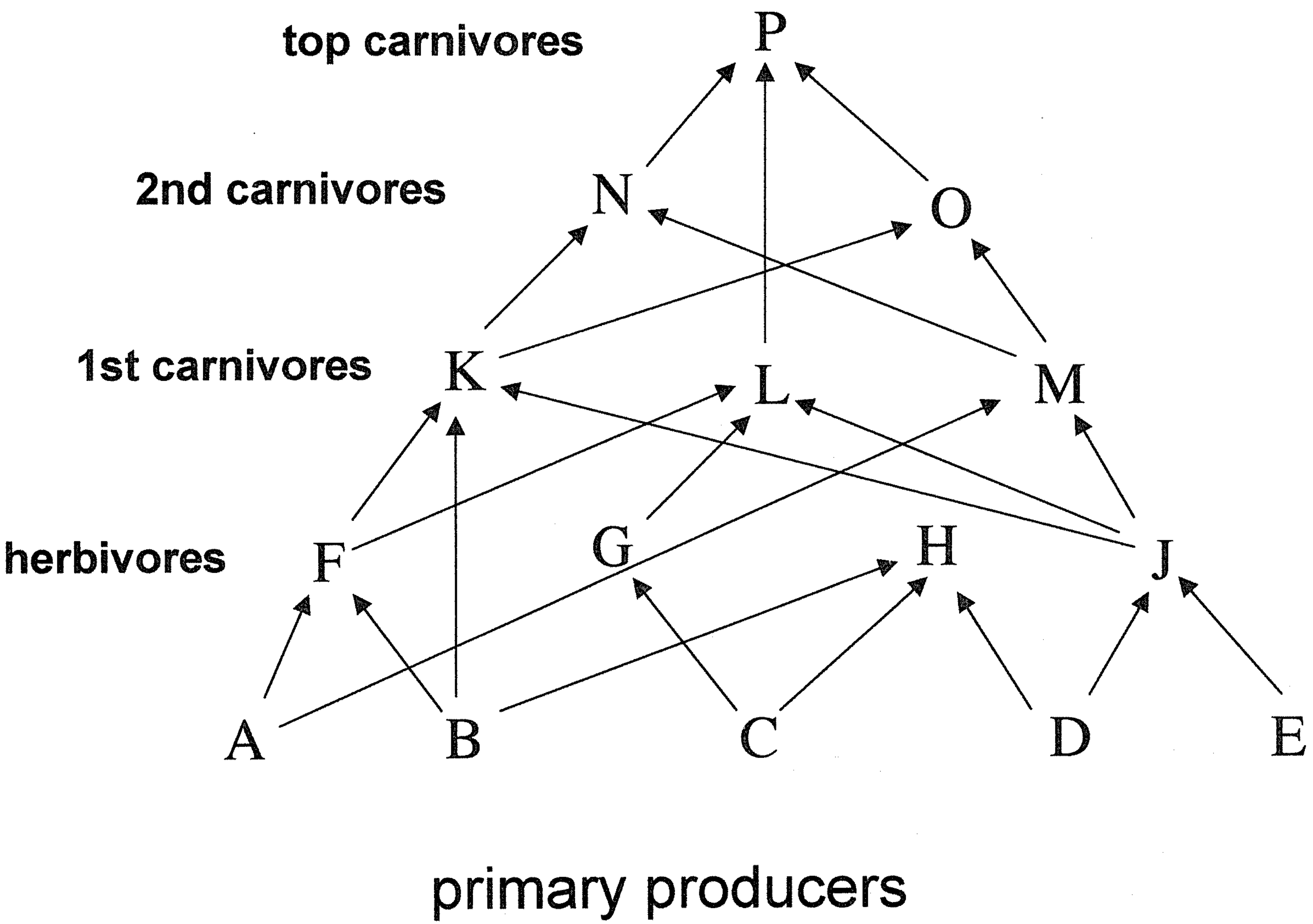

Figure Eco.2

Theoretical food web for a group of imaginary species, indicated by letters (After Wilkinson, 1996). Lines joining the imaginary species indicate feeding relationships and hence pathways for the flow of energy, carbon and nutrients. Note the complexity of the diagram since species have feeding preferences. Some species feed at more than one trophic level.

Organisms do not occur together wholly by chance. A particular habitat has its own set of environmental conditions to which an organism must be tolerant if it is to survive. Different species have different tolerances to physical and chemical environmental factors (**abiotic factors**) e.g. temperature, rainfall, soil nutrient status. The range of abiotic factors tolerated along a gradient of such factors (Fig. 3) can be considered as the "theoretical niche" of the species. In practice, species usually occupy a narrower range of conditions than this - the "realised niche". They do not occur at the extremities of the theoretical range because of interactions there with other organisms (biotic interactions). For example a species will be best adapted to the environment near to the middle of its tolerance range. Towards the extremities it might be under some stress. It will not compete there with other better-adapted species, which are towards the middle of their tolerance ranges.

This leads us to the concept of an ecosystem. An ecosystem consists of all the organisms in a particular place or habitat, their interrelationships with each other in terms of nutrient, carbon and energy flows, and in terms of biotic determinants of community composition such as competition between species, the physical habitat and the abiotic factors associated with it, which also play a role in determining community composition and in determining primary, and hence secondary production

Ecosystems can be quantified, for example, in terms of the fluxes of carbon, energy and nutrients and the productivity of each trophic level. They can be quantitatively modelled using computers to enable predictions to be made about ecosystem performance.

Table 3. Generalized productivity of different habitat types (after Odum, 1985)

Habitat type	**Gross productivity (grams of dry matter per square metre per day) indicative of primary productivity**
Deserts	less than 0.5
Grasslands, deep lakes, mountain forests, some agriculture	0.5 - 3.0
Moist forests and secondary communities, shallow lakes, moist grasslands, most agriculture	3 - 10
Some estuaries, springs, coral reefs, terrestrial communities on alluvial plains, intensive year-round agriculture	10 - 25
Continental shelf waters	0.5 - 3.0
Deep oceans	less than 0.5

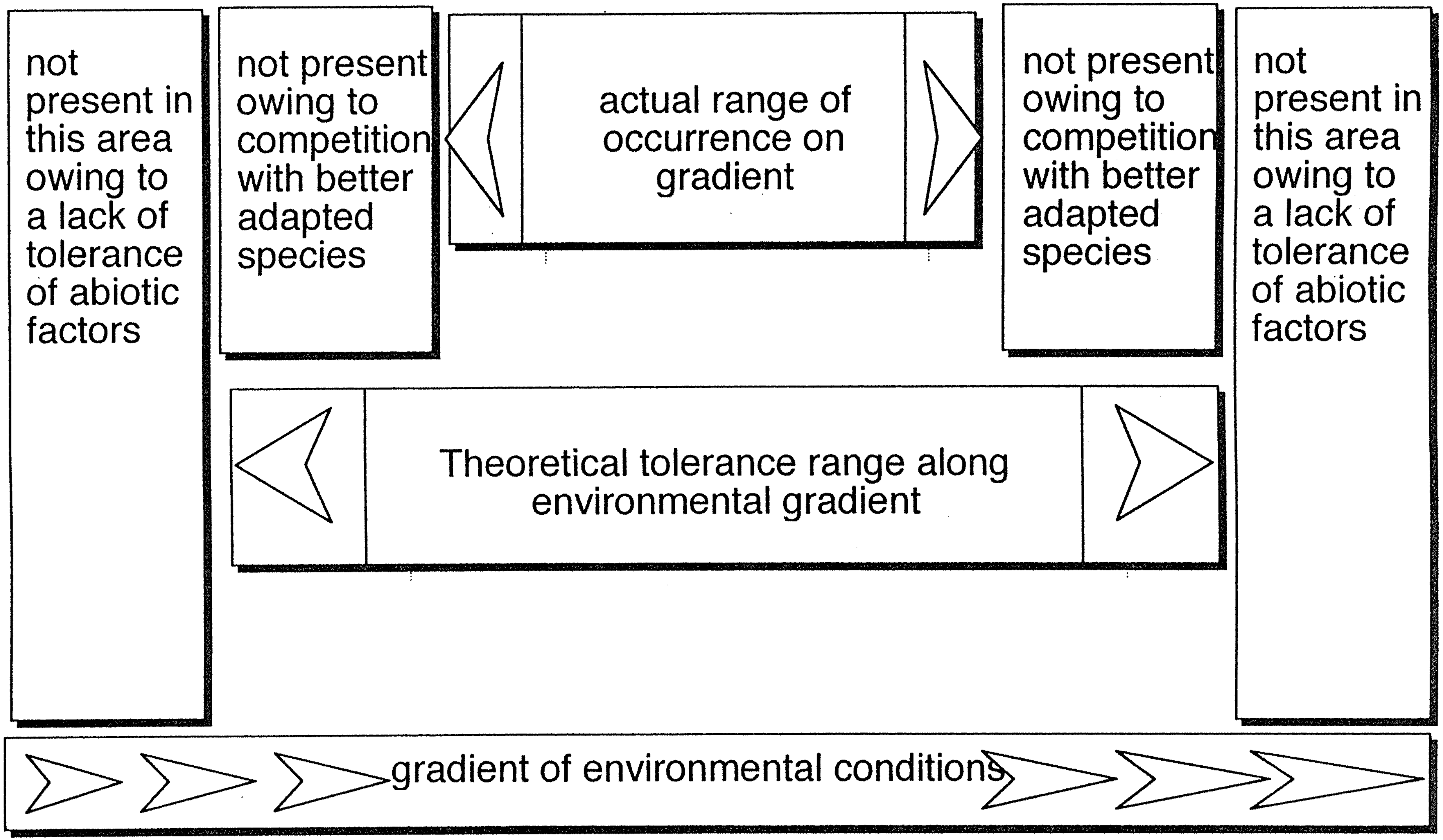

Figure Eco.3 Occurrence of species and its relationship to a stressor environmental gradients.

Probably the most important characteristic of ecosystems is their **dynamic stability**. They remain broadly constant over time in species composition and abundance and in the magnitudes of processes despite environmental variations. Although the climate fluctuates from year to year, the structure of the ecosystem tends to be stable within limits, and therefore it is sustainable.

An example of dynamic stability is in population sizes. Man's population does not fluctuate wildly from year to year because the generation time is about 20 years and several generations are overlapping. A contrast is in many insects where reproduction occurs every year and the life span is only one year or less. There can be fluctuations of several orders of magnitude in population size over several years but they fluctuate around a mean value. This may result from density-dependent factors, environmental factors whose intensity or effect depends on the population density. For example, at high density, food may be short giving a population crash, while at low density, the abundance of food may allow population size to increase, thus fluctuating over several years about a mean.

Ecosystem stability is not rigid. Some systems change naturally - hence the dynamic nature of the stability. On a short time scale this happens with winter and summer aspects of a community in a temperate climate. On a longer time scale there is **ecological succession** where one community naturally replaces another on an area of land or water, usually as a result of the modification of the habitat conditions by the organisms that are replaced so that it is no longer suitable for their own survival. This happens particularly where an open area of land or water is available for colonisation.

An example of ecological succession is the formation and growth of maritime sand dune systems. Near the high tide mark on a beach is an inhospitable environment for plants, windswept with high water loss by evaporation and with sand abrasion, high sand surface temperatures in summer, and a low nutrient and highly saline soil, subject to erosion by waves and wind. Only a few species, the dune-building grasses, can tolerate this environment, forming an open community where, unusually, most ground area is not colonised. These grasses grow best through depositing sand that they stabilise, so building up dunes. The dune soil becomes less saline due to leaching by rainwater, nutrients accumulate from the grass litter aided by nitrogen-fixing bacteria associated with their roots, and the growing dunes provide shelter. Going inland the habitat becomes progressively more normal, less inhospitable, and there is a progressive replacement of the dune building grasses by a wider range of more normal, less tolerant plants. Ultimately a closed (complete ground coverage) **climax community** is achieved in equilibrium with the climate and with any local conditions such as soil type.

Mature stable ecosystems are characterised by a preponderance of organisms referred to as **K-strategists**, species which succeed by being well adapted to their environment. Earlier stages in a succession may have a greater proportion of **r-strategists**, organisms with wide environmental tolerance which do not survive so well in stable habitats in competition with more precisely adapted K-species. By contrast r-strategists are highly reproductive, flooding the environment with their propagules, ready to colonize opportunistically any habitat space which may become available. In stressful environments, either man-made stress or naturally harsh conditions, tolerance to abiotic factors becomes a greater determinant of community composition than biotic interactions, and r-strategists predominate.

The above description of the ecosystem concept stresses the ability of such systems to remain stable within limits in various ways. Maintenance of this stability is the key to understanding ecotoxicology and the effects on ecosystems caused by pollutants.

2.2 Human effects on ecosystems

Human beings affect the dynamic balance of ecosystems in two ways, by pollution and by physical disturbance. Here we are concerned with toxic effects and so will only consider pollutants. **Pollutants** are substances which potentially can have an impact on ecosystems either because they are novel chemicals synthesised by man which normal decomposer organisms are not accustomed to dealing with, or because they are discharged in unusually high amounts and/or to a system from which they did not come e.g. human waste from food grown on land discharged in concentrated form through sewer outlets to rivers or the sea.

Ecosystems become unbalanced through pollutant (toxicant) effects. The stability is disturbed and the productivity and recycling reduced meaning that they are no longer sustainable systems. This results from the selective action of toxicants, affecting different species in different ways, or to different extents, or at different concentrations. There may be lethal effects where species are killed but more commonly there are sublethal effects where species remain alive but with reduced growth or reduced reproductive ability or modified development, all leading to ecosystem alteration. A summary of ways in which toxic pollutants may affect

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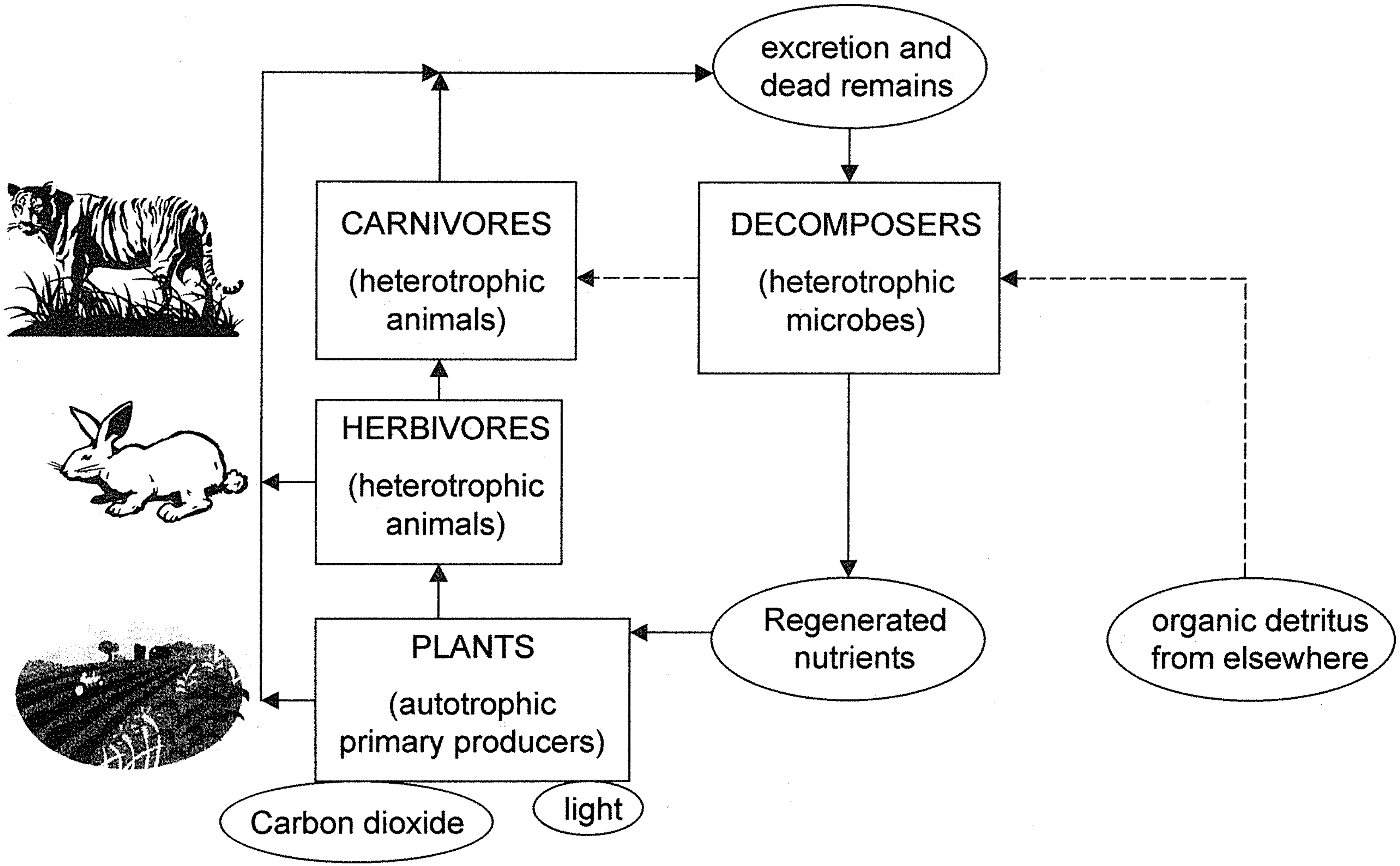

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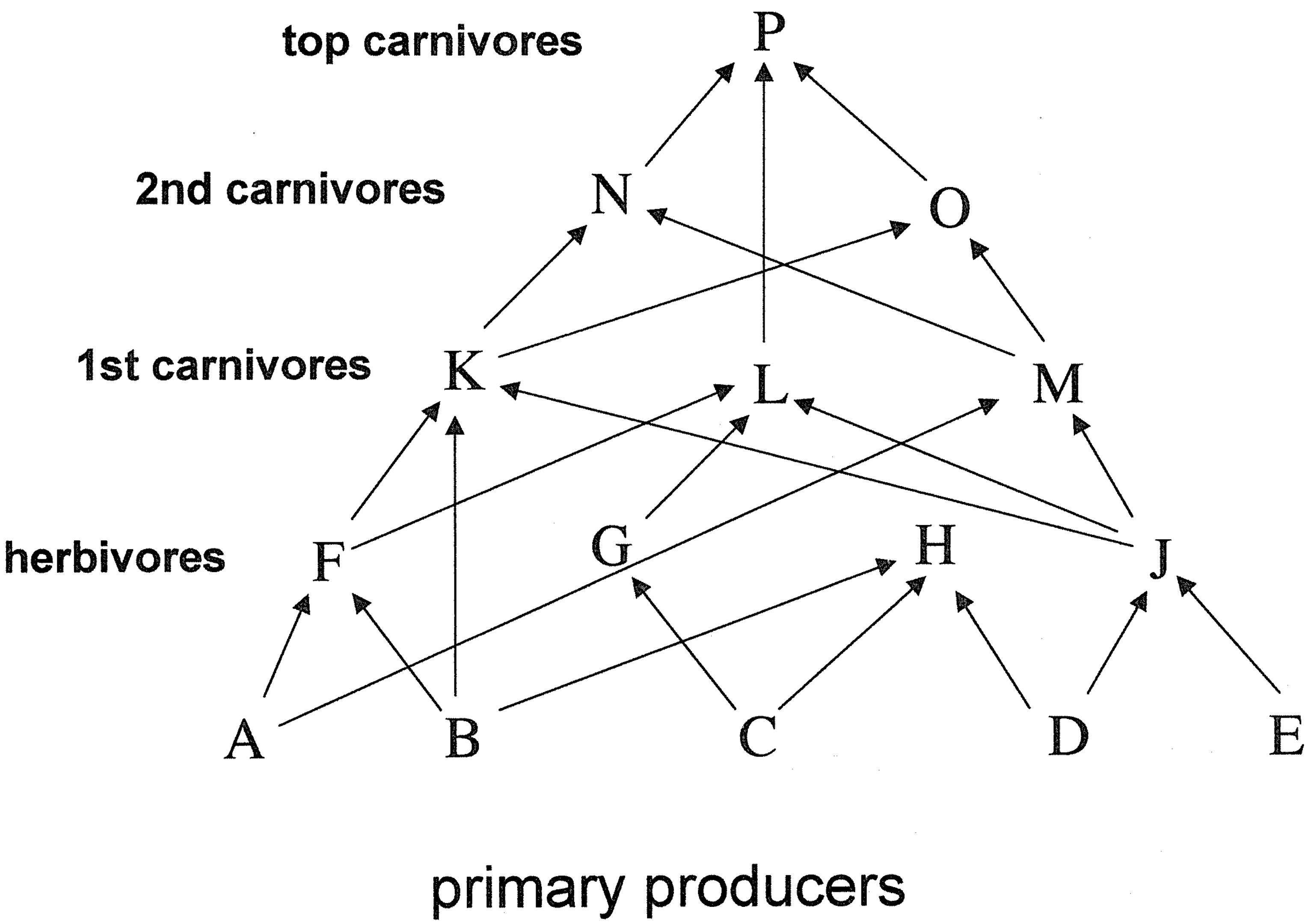

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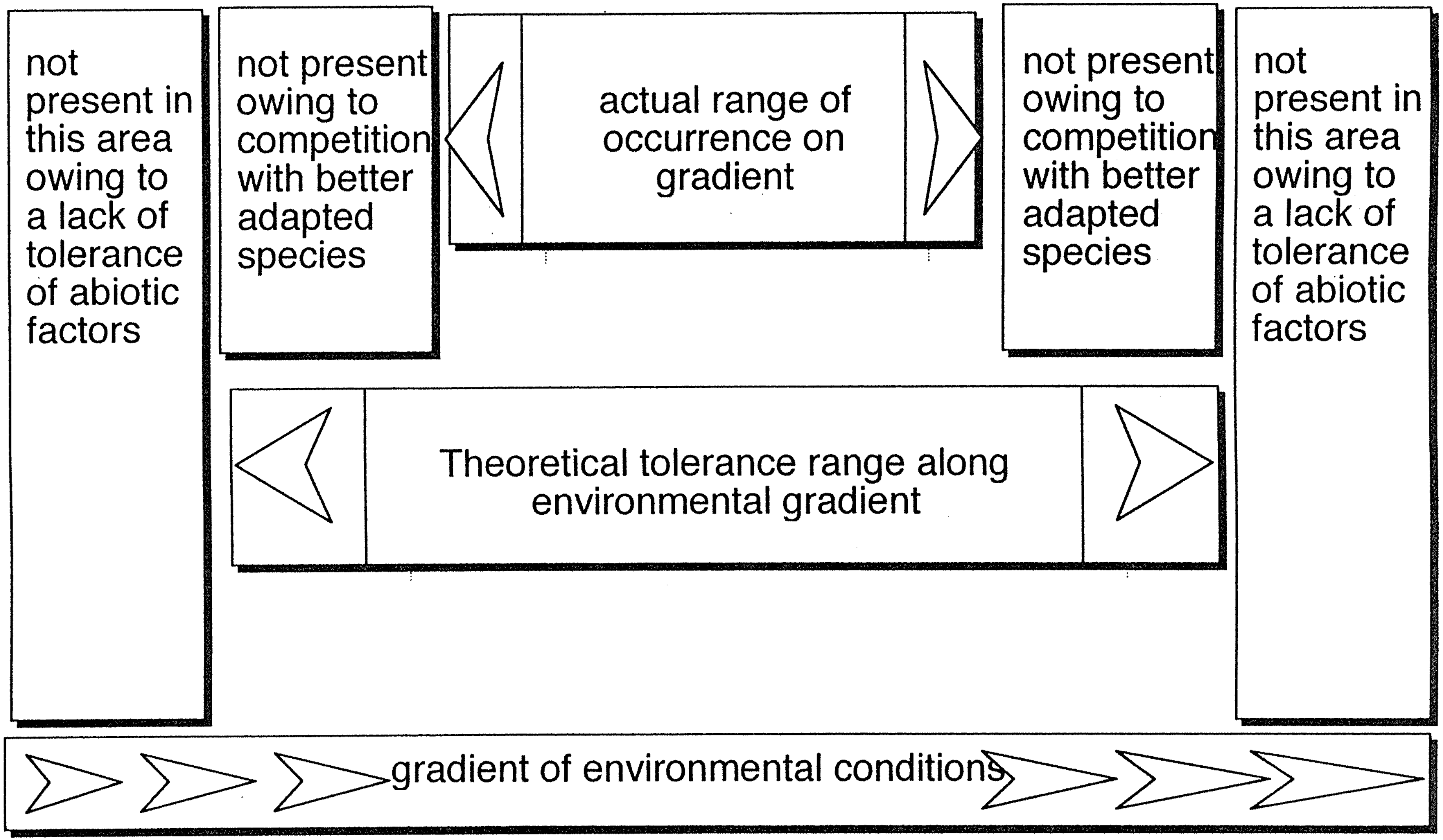

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At an ecosystem level the above effects can give rise to various symptoms of stress in the system. However stress can be due not only to toxicants but also to non-toxic pollutants, to physical disturbance, and to natural stress in extreme habitats. Part of the art of measuring biological effects of pollution (summarised later) is in distinguishing man-made from natural stress effects. The symptoms of stress in ecosystems are given below in Table 4.

As mentioned above, not all pollutants are directly toxic. Nonetheless some of the non-toxic ones are relevant to this account because they can have a secondarily toxic effect. An example is enrichment of a water body with plant nutrients such as nitrogen and phosphorus (**eutrophication**) which can enter as pollutants from sewage, fertiliser run-off or some industry.

Assuming adequate supplies of carbon and light, plant growth will be limited by nutrients. Nutrient pollution can have a fertilising rather than a toxic effect. Considerable enrichment can give massive unchecked growth of plants which outstrips the ability of herbivores to graze on it. The decay of the excess plant biomass by bacterial activity then creates a demand for oxygen for bacterial respiration that may exceed its rate of supply from the overlying atmosphere. The resulting de-oxygenation of water can have a lethal effect on aquatic animals since most animals require respiratory oxygen more than plants which can produce their own oxygen by photosynthesis. Some of these effects on ecosystems can be used in biological measurement of pollution. The next section gives an overview of such techniques.

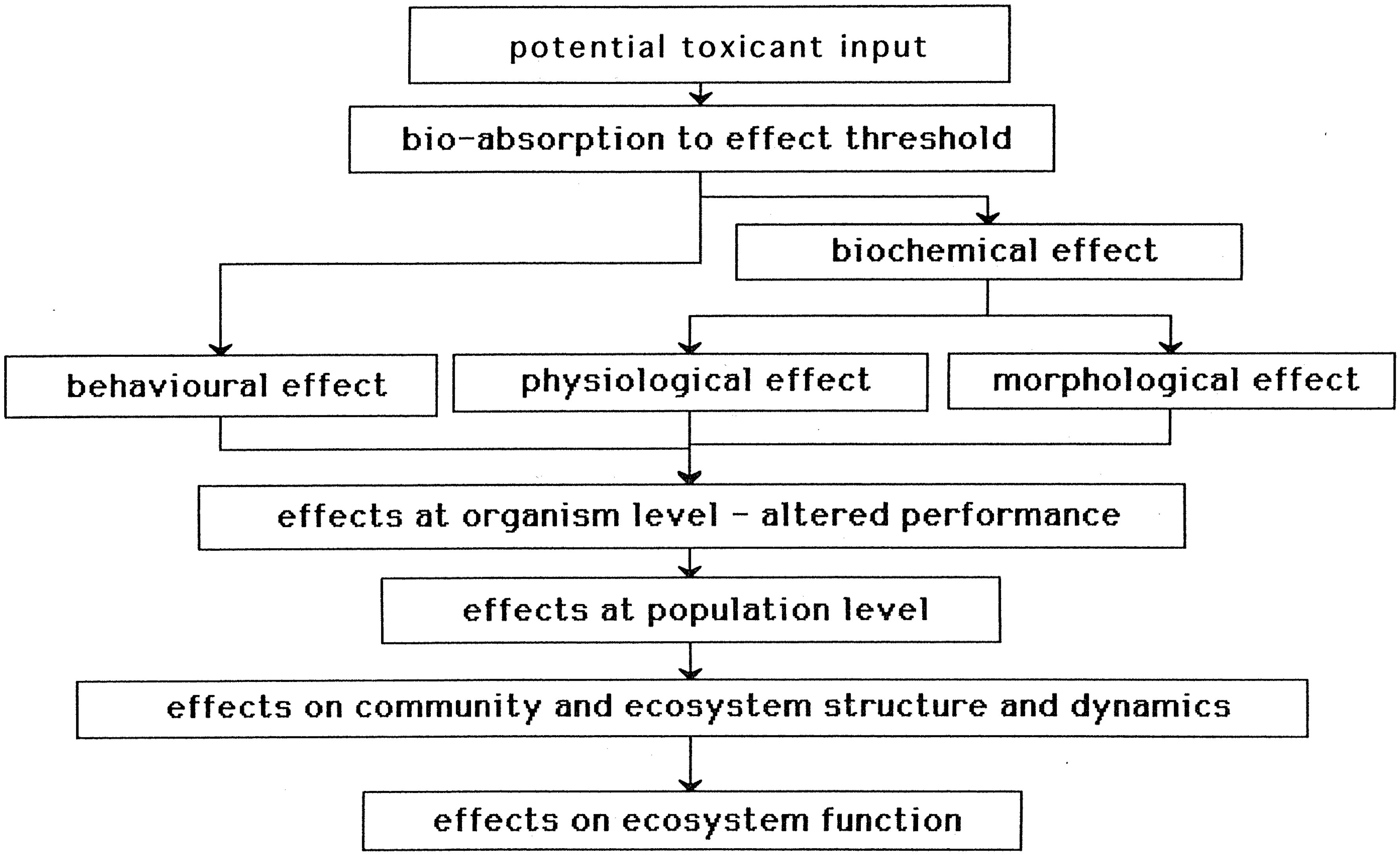

Figure Eco.4 Flow chart to show the various levels at which potentially toxic substances can affect natural ecosystems (after Sheehan et al, 1984).

Table 4. Trends expected in stressed ecosystems (after Odum, 1985)

Energetics

1. Community respiration increases
2. Production to respiration ratio becomes unbalanced
3. Primary production exported to other systems or remaining unused increases

Nutrient Cycling

4. Nutrient turnover increases
5. Horizontal transport of nutrients (i.e. to other systems) increases
6. Vertical cycling (i.e. internal recycling) of nutrients decreases
7. Nutrient loss increases

Community Structure

8. Size of organisms decreases
9. Life spans decrease
10. Species diversity decreases and dominance increases
11. Food chains become shorter

Ecosystem-level Trends

12. Ecosystem becomes more open (i.e. more space available for colonisation)
13. Successional trends reverse
14. Efficiency of resource use decreases

2.3 Measurement of toxic effects on organisms and ecosystems (Fig. Eco.5)

Measurement can be made by direct toxicity assessment or by assessment of ecosystem effects (ecological monitoring).

Direct measurement or toxicity testing is a laboratory procedure carried out with a single species using toxicants as single chemicals or as effluents before or after mixing with the receiving environment. The organism is incubated under standard conditions for a fixed time in various dilutions or with various doses of the toxicant and with controls with no added toxicant. The concentration that brings about death of 50% of the individuals in the test population is the **LC50**. Alternatively the single added dose that brings about 50% mortality is the LD50. Such lethal toxicity tests are popular because they are straightforward to carry out but they do not reflect what happens under normal conditions.

Most toxic effects are sublethal and so sublethal tests should be used as much as possible. This can be done in terms of an **EC50**. This is the concentration of added toxicant that in the given time under the given conditions brings about a 50% specified sublethal response, such as a 50% reduction in growth rate relative to a control with no added toxicant. It could also be a 50% change in any sublethal measurement of a physiological process, such as a 50% reduction in photosynthetic or respiratory rate relative to a control, or a 50% change in a developmental process such as the formation of reproductive bodies. A more relevant measure for environmental protection is the **NOEC** or no observed effect concentration. This is the highest concentration of added toxicant that has no measurable inhibitory sublethal effect on the test organism under the specified conditions in the prescribed time.

Regulators use the results of toxicity tests because they give easily determined and repeatable numerical measures, but they should not be extrapolated out of context. Problems exist in the selection of suitable test organisms and in the extrapolation of toxicity test results to field conditions.

Test organisms should be chosen to represent all of the main trophic levels - a plant (autotroph), a herbivore and a carnivore. Fulfilling these criteria alone is not enough. The particular species chosen should be appropriate to the environment at risk where the toxicant is to be discharged. There is a tendency to use a restricted

- biochemical effect
  - changes in enzyme activity, activation ad suppression of metabolic pathways, mutation of DNA
- physiological effect
  - respiration, excretion, feeding, digestion, ionic balance, osmotic balance, nitrogen fixation, photosynthesis
- morphological effect
  - tumours, deformity, histological changes in cells and tissues
- behavioural effect
  - avoidance behaviour
  - predator/prey interactions
  - reproductive behaviour
- effects at organism level - altered performance
  - growth, development, recruitment, reproductive success
- effects at population level
  - reduced abundance, altered gene pool, change in distribution
- effects on community and ecosystem structure and dynamics
  - population extinction, changes in species composition, changes in diversity and dominance of species, changes in successional patterns
- effects on ecosystem function
  - reduced organic decomposition, alterations in nutrient cycles, reduced primary productivity

Figure Eco.5. Examples of effects that may be observed at various levels in an ecosystem.

range of species strains that can be found in culture collections. These strains may have evolved over long periods of repeated subculturing so as to have different responses from the original organisms isolated. An extreme example of an inappropriate choice that has occurred was the use of the marine oyster embryo bioassay to test a substance to be discharged to a freshwater river.

Otherwise ecologically inappropriate tests may have their uses as a standard reference tests to rank the general toxicity of many different chemicals. This may permit the choice of the least toxic substance for given process.

What cannot be done easily from laboratory tests is prediction of effects on the structure or functioning of ecosystems. It is inherent in the nature of a toxicity test that it is done under constant laboratory conditions that cannot mimic the complex and fluctuating field environment and the biotic interactions that occur.

One approach being taken to remedy the lack of relevance of laboratory tests to real ecosystems is the development of tests that are carried out in the field. The organism is grown captive in a polluted location and some measure of its growth, physiology, biochemistry or survival is compared to similarly treated captive organisms in a similar but less polluted control environment. These methods are in their infancy and do not always find favour because of the undefined nature of the conditions and uncertainty that the control environment is similar to the test environment in all features except the pollution.

Recently the British water industry has started to build toxicity criteria into consents given to discharge liquid effluents into watercourses or coastal waters. Previously the consents contained only physical and chemical limits on effluent composition. The addition of toxicity criteria makes them more effective for complex effluents where there might be synergistic effects between components or where there might be so many components that they were not all regulated in the consent. It is the total toxicity of the effluent that is assessed rather than its composition of specific chemicals.

Enforcement of toxicity criteria in consents to discharge could be a problem. While toxicity tests are attractive to some because of their ease and simplicity, routine application of tests on a wide range of organisms with a large number of effluents could be very costly, especially if vertebrates such as fish are used, since they require expensive facilities and government approval. An alternative quick screening technique has been devised based on bacterial luminescence, of which Microtox is one proprietary test. This is based on light emission by a culture of luminescent bacteria. When the bacteria are in toxic solutions, their light emission is reduced relative to identical uncontaminated solutions. Hence an EC50 can be calculated in terms of a 50% reduction in luminescence relative to the control. This might be thought to be an example of an inappropriate test organism but it is used as a screening test. If serious toxicity is shown in the relatively quick and cheap Microtox test then more relevant but time consuming and expensive tests with the full range of organisms can be carried out.

Ecological monitoring is a broader assessment of the ecological effects of toxicants than is given by toxicity testing. It is defined as the assessment of effects of toxicants and pollutants in an ecological context, either by means of their accumulation in organisms other than man, or by looking for abnormal ecological effects at the level of species, community or ecosystem. It performs a different role from that of chemical analysis of toxicants in the environment. Chemical analysis usually relies on occasional instantaneous sampling. It does not necessarily indicate average, maximum or minimum environmental values of the toxicant. Ecological monitoring avoids the very frequent chemical sampling necessary to get over this problem. Indigenous organisms integrate concentrations of toxicant over time. Furthermore they show what chemical sampling cannot do - the effects of the toxicants on natural communities. Ecological methods do not give numerical estimates of toxicant concentrations, so both chemical and ecological approaches are necessary.

Ecological monitoring can use naturally occurring organisms in the field or organisms transplanted to the field for the purpose, and may be supported by laboratory tests. Table 5 presents an illustrative selection of approaches to ecological monitoring, with a bias towards aquatic assessment where these approaches have been most highly developed.

2.4 Conclusion

Toxicants can disturb the sustainability of natural ecosystems by a variety of effects on species, populations, communities and ecosystem processes. Hoxever, such systems have some capacity to absorb potentially toxic substances because of their "dynamic stability". Toxicity testing has limitations in predicting ecological effects and chemical measurement of environmental toxicants must be accompanied by ecological monitoring. Specialist knowledge is needed to distinguish between ecological effects due to the effects of pollution and those due to naturally-occurring environmental conditions that impose severe stress.

Table 5. An overview of selected measures used in ecological monitoring

1. Assessments carried out in the field

Using organisms occurring naturally in the environment	Pollutant accumulation by organisms (bio-accumulation monitoring)	Some organisms accumulate metals, radionuclides and some hydrocarbons to high levels in their tissues in proportion to the external concentration. Gives higher more detectable concentrations. Integrates concentration through time. May indicate biologically active fractions of the substance.
		Algae may indicate dissolved fraction while animals feeding on suspended matter (e.g. mussels) may indicate particulate fraction.
	Assessments using single species	Presence or absence of indicator organisms There are few genuine indicators solely by presence so must be used with care.
		Biochemical measurements on single species - measurement of activity or amount of substances induced by presence of pollutants e.g. enzymes or metal-binding proteins.
		Pathology - presence of tumours induced by pollutants
	Assessments using communities and populations	Age structure - in a species that can be aged and which recruits annually, abnormal age structure may indicate a failure to recruit in one year due to pollution or to natural climatic factors. Life-forms and successions - successions regressed to earlier stages with abnormal abundance of opportunists may indicate stress.

Table 5 (continued)

1. Assessments carried out in the field

	Numerical structure (i) Species richness - fewer species may occur under stress (ii) Diversity - there are many numerical indices which are mathematical formulations of species number, numbers of individuals, and the distribution of individual numbers between species. Used as general assessments of community structure in ecology but variations from expected values can indicate toxicant induced stress. Also specially developed indices such as the Trent Biotic Index which indicates degree of sewage stress on animal communities in rivers based on numbers of taxa and presence of key species or groups
Using organisms planted out at test site	In-situ toxicity assessment using measurements of the growth of organisms at a test site compared with a control site. Colonisation of artificial substrata - provides a uniform substratum that can be compared between different sites using numerical indices (see above) of the communities of small organisms that develop. Colonisation of cleared natural substrata - again using numerical indices of community structure may also show whether an alternative community can develop under pollutant influence when the established one is dislodged. Bio-accumulation monitoring using monitors artificially placed at a variety of test sites to permit comparison.

3. Laboratory-to-field extrapolation - relationship of the estimate of toxicity gathered in the laboratory to the effects expected in the field situation. Laboratory situations are kept simple compared to the reality of the field and are designed to rank toxicity rather than to mimic the field situation. Laboratory tests strictly control the route of exposure and limit the behaviour of organisms. In the field there are no such restrictions.

4. Field to field (or habitat to habitat) extrapolation - relationship of one field or habitat to another. It is most unlikely that any two habitats can be identical. Streams on one side of a continental divide tend to have flora and fauna that are different from those in comparable streams on the other side. Even controlled field studies are difficult to replicate. The qualitative effect of a toxicant may be the same but the quantitative relationship may be very different.

5. Indirect effects - the toxicant effects due to the disruption of the ecosystem in addition to direct impacts on ecosystem components. The elimination of photosynthetic organisms in a pond by a herbicide will eventually eliminate invertebrate herbivores and the fish that rely upon them as a food source.

6. Organizational levels - the transmission of effects up and down levels of biological organization. A decline in reproductive success at the individual organism level may decrease the rate of growth of a population. Conversely, a toxicant which causes the decrease in a herbivore (plant eating) population, eliminating much of the top-down control at community level, will allow plant populations to increase even if the toxicant reduces the maximum rate of plant growth.

7. Spatial and temporal scales - exist in a variety of dimensions relating to the life span and size of the organisms and systems under investigation. One day and 10 m^3 may represent several generations and the entire world of many micro-organisms, but have no relevance to a Californian redwood tree. Heterogeneity of both of these variables contributes to the diversity of species and genotypes.

8. Recovery - the rate at which a system can be restored to its original state. If recovery does occur, it generally depends upon the ability of colonizing organisms to become established upon the impacted site and therefore the

isolation of the damaged ecosystem is important. Initial conditions are extremely important since several new steady states can be reached from similar initial conditions. Recovery to the initial state may be improbable and a more realistic goal may be a new steady state appropriate to the factors selected as assessment endpoints.

4.1.2.4 Stressor-response profile

The stressor-response profile is analogous to a dose-response curve in that it corresponds to a single species toxicity test expanded to the community and ecosystem level. It is important to define the uncertainties, qualifications, and assumptions made at each step.

One of the difficulties in the quantification of the stressor-response profile is that many of the extrapolations are essentially qualitative. Phylogenetic extrapolations are rarely quantified.

Laboratory organisms are generally healthy and laboratory conditions do not mimic availability of micronutrients, behavioural opportunities, and other factors important in an ecosystem. Field studies include many climatalogical and structural stressors that are independent of the introduced stressor. In addition, there is unlikely to be an ecosystem within range of a laboratory that has not been subjected to an anthropogenic stressor which may confound even the best designed study.

4.1.2.5 Data acquisition, verification, and monitoring

Basic research on the effects of stressors on ecosystems, improvement in test methods, knowledge of molecular mechanisms, and improvements in modelling provide critical input to this stage of risk assessment.

5 ECOLOGICAL RISK CHARACTERIZATION

Risk characterization is the final stage of the risk assessment process. This aspect of a risk assessment is comprised of risk estimation and a risk description. The overall process is a correlation of the ecological effect with the environmental concentration to provide a likelihood of effects given the distribution of the stressor within the system.

Assessing the probability of toxic impacts is analogous to the weather forecaster's prediction of rain. If the forecaster says that today there is a 50% chance of rain in the local area, this means that, given the conditions observed, the chance is that rain will occur in 50 out of 100 observations. Similarly, ecotoxicology attempts to make predictions regarding the risk (probability) of an effect of a given substance on an ecosystem, given knowledge of its concentration and the nature of the ecosystem. Because this is still a developing science, ecological predictions of this kind may be less reliable than weather forecasts!

5.1 Integration

Relating exposure to toxicity is not easy. A fish LC_{50} value tells nothing about the loss of nitrogen fixation from an ecosystem. The most widely used method of estimating ecological risk is the quotient method, simply dividing the expected environmental concentration by the hazard (compare Part B, "Environmental Risk Assessment").

Risk quotient = Expected environmental concentration / Concentration producing an unacceptable environmental effect

This is a qualitative expression of risk without regard to the probability distributions of the chemical concentrations or the effects. Distributions of each can be plotted and the distribution of expected effects can be calculated.

The quality and source of the data used in risk assessment contributes to its uncertainty. Toxicological data vary according to the strain or test organism used. Field studies are noted for the difficulty of interpretation. Many multispecies tests and field studies are designed to look at only a few populations or other attributes of the ecosystem. For example, a standardized aquatic microcosm may contain 16 species that are initially inoculated into the system. However, in reporting results for publication, the dynamics and interactions of all species are not reported because it would be cumbersome and expensive. Only the dynamics of the organisms and interactions that are the apparently critical components are reported.

Anecdotal data from field or multispecies tests are also difficult to interpret. Omission or inclusion of information in a report may reflect more the nature of the researcher than the presence or absence of an effect.

5.2 Risk description

There are two aspects to this - ecological risk summary and the interpretation of ecological significance.

The ecological risk summary summarizes the risk estimation results and its uncertainties. The crucial decision concerns the accuracy of the risk estimation. This depends upon:

- Sufficiency of data
- Corroborative information
- Evidence of causality

Sufficiency of the data relates to the quality of the data and its completeness.

Corroborative information is data derived from similar studies with similar stressors that tend to support the conclusions of the risk assessment. However, lack of similarity to previous conclusions or ecological theory does not mean that the current study is in error. It may mean that some fundamental assumption has to be re-assessed.

Evidence of causality, if available, is the most important aspect of the data assessment process. However, correlational data may be all that are available for impacts at the level of interspecies interactions. Correlation does not denote cause and effect. In a complex system, correlations due to chance may occur.

If additional data or reformulation of the conceptual model is required, the assessment process returns to data acquisition, verification, and monitoring, and a further attempt is made to obtain a usable and accurate risk assessment.

5.3 Interpretation of ecological significance

Finally, an interpretation of ecological significance is produced that details the expected size, variation in time and space, and probability of each significant effect. Judgment may have to be made about the recovery potential of the affected ecosystem. This requires a decision as to whether the ecosystem can regain the properties that are regarded as valuable. These properties will have been defined by the assessment endpoints.

5.4 Discussion between the risk assessor and risk manager

The risk manager needs to know the range of impacts, uncertainties in the data, the probabilities of effects, and the stressor-response function. These factors can then be taken into account alongside social, economic and political realities and risk/benefit assessment in selecting management options.

5.5 Data acquisition, verification, and monitoring

The importance of the data acquisition, verification, and monitoring process in the development of accurate risk assessments has been emphasized. Models, no matter how sophisticated, are simply attempts to understand processes and codify relationships. Only the reiteration of the predictive (risk assessment) and experimental (data acquisition, verification, and monitoring) process can bring models close to being a true picture of reality.

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6 SELF ASSESSMENT EXERCISES

1. What are the two fundamental requirements for sustaining life?
2. What are autotrophs, how do they obtain carbon, and how do they obtain energy?
3. What are heterotrophs, how do they obtain carbon, and how do they obtain energy?
4. What are primary production and secondary production?
5. What are the levels of consideration in ecology and what toxicant effects may be observed at these levels?
6. What is a typical food chain and what are the associated trophic levels? How does a food chain relate to a food web?
7. What are bio-accumulation, bioconcentration and biomagnification?
8. What are the 6 main habitat types?
9. What is a tolerance range and what defines it?
10. What is an ecosystem and how may ecosystems be quantified?
11. What is dynamic stability in an ecosystem?
12. What characterizes a mature stable ecosystem?
13. What are pollutants and how can they unbalance ecosystems?
14. What trends are to be expected in stressed ecosystems?
15. How can a nutrient indirectly cause toxicity in an ecosystem?
16. What methods are available for toxicity testing of potential ecological toxicants?
17. What approaches may be used in ecological monitoring for possible damage by pollutant substances?
18. Define ecological risk assessment, stressor, hazard, and exposure?
19. Briefly define problem formulation, hazard assessment, exposure assessment, and risk characterization?
20. Stresses can be of what three categories? What five characteristics can stressors have that are derived in part from use patterns?
21. What are some possible interactions between the stressor and the ecological system?
22. What is an assessment endpoint? What is a measurement endpoint?
23. What factors make risk assessment a "scientific process"?
24. What is the goal of the exposure analysis?
25. How may exposure be measured?
26. What is the most critical aspect of the risk assessment process?

27. What are the criteria used to judge the importance of data when characterizing ecological effects?
28. Describe the eight possible relationships between assessment and measurement endpoints.
29. What is one of the difficulties in evaluating the stressor-response relationship?
30. Describe risk characterization.
31. What is the quotient method of estimating risk? What is a weakness of this analysis.
32. List the three general aspects of the analysis for the ecological risk summary and describe each.
33. What question should be borne in mind in the interpretation of ecological significance of data?
34. List the most important factors in a report to the risk manager.