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ECOTOXICOLOGY

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Ecotoxicology is concerned with describing, understanding, and predicting the effects of chemicals used by people, either from natural sources (such as metals) or from synthetic processes (agrochemicals, pharmaceuticals, industrial chemicals), on ecological systems. It provides the basis for ecological risk assessment, predicting likely impacts of chemicals on ecological systems, and is an important contributor to environmental protection legislation.

THE CONCEPT

First defined explicitly by Truhaut in the 1970s, ecotoxicology was specified somewhat broadly as “the study of toxic effects, caused by natural or synthetic pollutants, to the constituents of ecosystems, animal (including human), vegetable and microbial, in an integral context.” But the field soon became more focused and sought to study the effects of chemicals on individuals and their systems (biochemistry, physiology, cells) in a few widely tested species. More recently, attention has returned to broader ecological concerns, with a realization that individual-level responses may not translate straightforwardly into population and ecosystem effects. Homeostatic responses might dampen individual responses, or indirect effects (i.e., loss of predators, prey, or competitors through toxic effects leading to changes in interspecies interactions) might serve to magnify them for populations and ecosystems. Thus, extrapolation—e.g., from test species to nontested species, from toxicological effects to ecological impacts, from laboratory to field—is an important element of ecotoxicology.

Organisms can be exposed to chemicals in the environment through various routes, namely, water, air, sediment/soil, and food. An important challenge is to relate chemical concentrations in these environmental compartments to a toxicologically relevant dose. For practical reasons, ecotoxicological tests are most often carried out at high concentrations over short periods of time (acute exposures), and yet chemicals in nature often occur at low concentrations, with organisms exposed for long periods of time (chronic exposures). It is assumed that toxicological responses to acute, high-concentration

exposures give some insight into responses to chronic, low-concentration exposures.

At the toxicological level, chemicals can have different modes of action. Some may target very specific metabolic sites or processes (e.g., insecticides that specifically inhibit chitin synthesis and hence molting in arthropods), whereas others may exhibit nonspecific modes of action (e.g., narcotics that impair overall membrane function). Regardless of toxicological mode of action, the effects of chemicals at the ecological level only become relevant when they impact the structure and dynamics of populations, mediated through effects on survival, reproduction, and growth.

Ideally, chemical effects ought to be studied on either natural populations/ecosystems or isolated subsets of them (micro- and mesocosms). But generally, such studies are neither practicable nor desirable. Yet because society obtains great benefits from chemicals in terms of agricultural production, medicine, and general well-being and lifestyle, the pressures to assess chemicals for risks to human health and the environment are enormous. One common tendency, therefore, has been to base risk assessments on worst-case responses from ecotoxicology and to use large uncertainty factors to add a margin of safety to observed effects. In this context, chemicals that are likely to bioaccumulate to high levels or persist for long times in the environment, as well as those that have a high toxicity, are prioritized for management. However, this might lead to overly conservative assessments and hence increased costs to producers and users without commensurate benefits.

THE THEORY

Ecotoxicology is an applied science. It has no definitive theory as such, but instead it relies on theory from environmental chemistry, toxicology, and ecology to develop an understanding of the fate and effects of chemicals in ecological systems.

Theory from environmental chemistry provides a basis for using chemical structure and properties to predict the fate of chemicals in the environment and their uptake by organisms. For example, quantitative structure activity relationships (QSARs) aim to predict chemical behavior from structural attributes. Other models use physico-chemical characteristics to make predictions about reaction products (e.g., chemical speciation) and environmental distribution.

Historically, the most important theoretical concept in toxicology is that the effects of chemicals depend on dose and duration of exposure. There is a substantial body

of theory on dose-response and time-response relationships that seeks to provide mechanistic understanding and analytical tools. Typically, the dose-response curves for chemicals are monotonic (continuously increasing or decreasing with increasing dose). However, there are cases for which the dose-response may show a non-monotonic pattern. For example, some chemicals that act as if they were hormones in organisms can have more effect at low concentration than at high concentration. Similarly, some chemicals seem to show stimulatory effects at low doses but then increasingly adverse effects as dose increases. This is known as hormesis.

Another important issue arising from toxicological theory is how chemicals interact in mixtures to have their effects on organisms. Given that organisms in natural ecosystems are exposed to a complex soup of chemicals from natural and synthetic sources, it is important to have an understanding of possible additive, antagonistic (less-than-additive), or synergistic (more-than-additive) interactions among chemicals. Toxicological models exist to distinguish among these different types of interactions, but mixture toxicity continues to pose challenges for ecotoxicology.

There is now considerable ecological theory that relates individual responses to environmental factors to population structure and dynamics and changes in population dynamics to ecosystem structure and processes. This is increasingly being used to address the extrapolation challenges for ecotoxicology.

At the individual-to-population interface, there are three broad classes of relevant models. The first class, demographic models, describes individuals in terms of their contribution to recruitment and their survivorship. All individuals may be treated as identical (unstructured), or they can be separated into different size or age classes (structured). Spatial structure may also be included, as in metapopulation models, and stochasticity can also be included to represent both demographic and environmental characteristics. The second class of models, energy budget models, are similar to the first in treating all individuals as the same, but they represent the responses of individuals in terms of intakes and outputs of energy that relate to individual growth performance and reproductive output. A third class of models, individual-based models (IBMs), represent each individual in a population as being distinct and describe individual responses with more or less detail.

Species sensitivity distributions aim to bring the effects on different species populations together to predict likely ecosystem effects. They make three key

presumptions that are not necessarily valid: (1) that the species included in the distribution are representative of the ecosystem to be protected; (2) that toxicological sensitivity is predictive of ecological sensitivity; and (3) that protecting structure (i.e., species composition) protects ecological function. Ecological theory indicates that the relationship between species composition and ecosystem stability is complex and that some species may be more important than others in both maintaining the structure and the processes within ecosystems. These features have yet to be incorporated into ecotoxicological work except insofar as the precautionary approach of attempting to protect all through protecting the most (toxicologically) sensitive species is applied.

Trophic transfer models and food web models have been used to chart the movement of chemicals through ecological communities, and hence the possibility of bioaccumulation and biomagnification. Food web models have also been useful in demonstrating indirect effects and their consequences for ecosystem structure and processes.

Finally, evolutionary theory predicts that toxic chemicals will act as selection pressures. Classical examples include resistance of pest organisms to pesticides and the evolution of heavy metal-tolerant plants growing in soils contaminated with mine waste. The implication of this adaptation is that some species may become less sensitive to chemicals over time. Another possibility, however, is that selection for tolerance to chemicals may reduce genetic variability and thus the capacity for populations to respond to other forms of stress, whether artificial or natural.

CONCLUSIONS AND FUTURE DEVELOPMENTS

Theoretical models have an important part to play in ecotoxicology, because it is extremely difficult to predict the likely effects of chemicals in complex ecological systems simply on the basis of observation. Ecological models that incorporate mechanistic understanding of the appropriate processes and linkages are particularly useful. An important issue to be addressed in this context is how much complexity needs to be incorporated in models to make them suitably predictive for their application in risk assessment and environmental protection. More generally, effort needs to be put into developing methods for assessing how chemicals impact ecosystem processes that have consequences for valued ecosystem services. Finally, there is as yet little understanding of how evolutionary adaptation should be addressed in risk assessment, and this needs further study.

SEE ALSO THE FOLLOWING ARTICLES

Ecosystem Ecology / Food Webs / Individual-Based Ecology / Metapopulations / Population Ecology / Stochasticity, Demographic / Stochasticity, Environmental

FURTHER READING

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