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ASSESSMENT OF ECOLOGIC RISKS RELATED TO CHEMICAL EXPOSURE METHODS AND STRATEGIES USED IN THE UNITED STATES

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1 CURRENT STATUS

At present, the United States has yet to develop government- or agency-wide guidelines for conducting ecologic risk assessments; however, various standard test methods have been developed to provide toxicologic benchmarks. The earliest of these methods measured acute toxicologic effects, but as this field of science progressed, methods to measure chronic effects were also developed. Most recently, research efforts have been directed toward developing test methods that predict chronic and acute toxicologic effects based on results of short-term exposure of organisms during sensitive life stages.

The American Society for Testing and Materials (ASTM) has published many of the earlier methods used in the United States for testing acute and chronic effects. Depending on their scope and level of detail, test procedures are published as ASTM guides, practices, or test methods. A partial compilation of methods developed by the United States Environmental Protection Agency (EPA) or published by ASTM is presented in Tables 5.1, 5.2, and 5.3. These toxicologic methods are grouped according to their use for measuring effects on terrestrial, freshwater, or saltwater organisms.

Ecologic risk assessments performed by the EPA are done primarily by the quotient or ratio method; less frequently used methods include ranking techniques and application factors. The ratio method compares a toxicologic benchmark such as an acute LC_{50} value or a chronic no-effects concentration to a given exposure concentration to provide an estimate of risk. As the ratio for a given species approaches a critical value, a high risk is inferred. Exposures of varying intensities and data on ecologic effects are evaluated depending on the purpose of the assessment and the legal requirements that specify the scope of the assessment.

Table 5.1. Methods for Estimating Toxicologic Effects on Terrestrial Species and Birds of Exposure to Potentially Toxic Chemicals

Method	Reference
Standard Method for Effective Bird Control	ASTM, 1986a
Standard Method for Percutaneous Toxicity	ASTM, 1986b
Standard Method for Subchronic Dermal Toxicity	ASTM, 1986c
Standard Practice for Determining Acute Oral LD_{50} for Testing Vertebrate Control Agents	ASTM, 1986d

Table 5.2. Methods for Estimating Toxicologic Effects on Freshwater Organisms of Exposure to Potentially Toxic Chemicals

Method	Reference
Methods for Acute Tests with Fish, Macroinvertebrates, and Amphibians	U.S. EPA, 1975 ASTM, 1986e
Method for Aquatic Multiple Species Toxicant Testing	Phipps and Holcombe, 1985
Methods for Conducting Effect Studies on Snail (*Aplexa hypnorum*) Embryo through Adult Exposures	Holcombe et al., 1984
Standard Practice for Conducting Static Acute Toxicity Tests on Wastewaters with *Daphnia*	ASTM, 1986f
Standard Guide for Assessing the Hazards of a Material to Aquatic Organisms and their Uses	ASTM, 1986g

2 FUTURE DIRECTIONS

State-of-the-art assessment of risk to the ecosystem is still evolving. Although the single-species tests listed in Tables 5.1, 5.2, and 5.3 have provided valuable information for the assessment of ecologic risk, it is necessary to focus on ecosystems-level tests and analyses. The increasing availability of predictive models makes assessment of risk to the environment, rather than simply to a single species, more possible.

Predicting an ecosystem's response to pollutant stress is difficult because of the large number of dependent and independent variables constituting and inherent to a natural ecosystem. These include population-level factors such as density, immigration, growth, and mortality, and community-level factors such as diversity, relative dominance, trophic structure, and distribution.

Table 5.3. Methods for Estimating Toxicologic Effects on Saltwater Organisms of Exposure to Potentially Toxic Chemicals

Method	Reference
Sea Urchin DNA-Based Embryo Growth Toxicity Test	Jackim and Nacci, 1984, 1986.
Sea Urchin Sperm Cell Toxicity Test	Dinnel et al., 1983 Beckman, 1982
Bacterial Toxicity Test (Microtox®)	Beckman, 1982 Nacci, 1986
Phorocephalid Amphipod Bioassay	Swartz, 1985
Rhodophyta Life Stages Toxicity Test	Steele and Thursby, 1983
Atherinid Fish Early Life Stage Toxicity Test	Goodman et al., 1985a
Sheepshead Minnows Life Cycle Toxicity Test	Hansen and Parrish, 1977
Cytogenetic Model for Marine Genetic Toxicology	Pesch et al., 1981
Method to Measure Scope for Growth Index for Blue Mussels	Nelson et al., 1985
Method for Measuring AEC as a Test for Stress in Mussels	Zaroogian et al., 1982
Method for Measuring Bioaccumulation of Chemicals in Mussels and Polychaetes	Lake et al., 1985
Method for Measuring Sister Chromatid Exchange in Marine Polychaetes	Pesch et al., 1984
System for Preliminary Evaluation of Infectivity and Pathogenesis of Insect Virus in Shrimp	Couch and Martin, 1984
Tidewater Silversides (Menidia peninsulae) Early Life Stage Toxicity Test	Goodman et al., 1983
Early Life Stage Toxicity Test Using California Grunion	Goodman et al., 1985b

There are ways to simplify the complex structure of an ecosystem. For example, determination and analysis of a key species may facilitate prediction of the effects of pollutant stress on dependent species. In addition, knowledge of physico-chemical parameters of pollutants may make possible the analysis of pollutant fate and transport (see, for example, Chapter 7 of this book). Nevertheless, ecosystem-level analysis is an inherently complex undertaking. Ecosystems may modify the fate and transport of environmental pollutants. In aquatic systems, for example, micro- [illegible] may occur with a subsequent accumulation of neurotoxic methylmercury in fish. A number of the factors to be included in any discussion of ecological risk assessment are discussed below.*

2.1 End Points

A variety of ecotoxicologic end points have been proposed to assess the effects of pollutants on ecologic systems. Potential end points occur at the level of the individual organism, the population, and the ecosystem. In general, end points at lower levels of organization (organism or suborganism levels) have been used more widely because they are simpler, are more rapidly and inexpensively assessed, and are most useful in determining the mechanisms of toxicologic effects. End points at the population or ecosystem levels of organization are more complex and difficult to interpret but are probably ecologically more realistic, because they incorporate the complexity of interactions among organisms and between organisms and their abiotic environment. A major, unresolved question is the extent to which end points at lower levels of organization can be used to predict pollutant impacts at higher levels of organization.

2.1.1 Ecosystem Structure End Points. Measures of ecosystem structure can provide important data for ecosystem risk assessments. Structural changes in stressed ecologic communities may be visualized as an information network reflecting environmental conditions but not demonstrating the external mechanisms or internal interactions that brought about a reorganization in species composition or dominance patterns.

Structural end points such as abundance (McNaughton and Wolf, 1973) and biomass (Clapham, 1973) of communities provide relatively simple, gross measurements of ecosystem stress. Species richness has been shown to be sensitive to the level of stress and can provide a partial picture of changes in community composition which accompany stress (McNaughton and Wolf, 1973).

Combined numerical indices such as similarity (Hellawell, 1977) and ordination (Odum, 1971) measures may be used to track changes in community structure which occur as pollutant concentrations change. Although diversity indices (Odum, 1971; Herricks and Cairns, 1982) have been used widely in hazard assessment studies (see, for example, Chapter 10 of this book), these integrated measures are often insensitive to stress and provide data that are difficult to interpret (Hellawell, 1977). The use of numerical indices exclusive of the biologic data from which they are calculated should be discouraged.

2.1.2 Ecosystem Function End Points. The analysis of functional response end points can provide data on energy flow and nutrient cycles. The functional capability of the ecosystem is, in fact, the ultimate criterion of ecologic success. The effective use of end points in describing impacts is dependent on a theoretical and practical knowledge of ecosystems for proper interpretation, and on collection of sufficient baseline data to establish normal process rates. A history of measuring functional response variables will be necessary to establish threshold values for unacceptable reductions in functional capability.

Primary productivity (McNaughton and Wolf, 1973) provides the energy for the base of the food web. This process has been shown to be sensitive to a variety of pollutants and other forms of stress. Reductions in primary productivity, which are of substantial magnitude and long duration,

*Some of the discussion that follows is taken from material submitted by Technical Resources, Inc., Rockville, MD, for work performed under EPA [illegible] no. 68 02 4100 are unquestionably detrimental to energy processing in exposed ecosystems.

Disruptions in material cycles such as the nitrogen cycle (Westman, 1985; Cook, 1984) can be critical if the effects on cycling processes indirectly inhibit ecosystem production. Material cycles can be upset by pollutant inhibition of the decomposition process, interference with the functional links in specific nutrient cycles, or disruption of nutrient conservation mechanisms. Effects on decomposition can be measured in terrestrial and aquatic ecosystems, and changes in decomposition rate and completeness of mineralization can be related to the level of pollution stress. At present, few data are available on the long-term impacts of reduced decomposition on ecosystem production.

Specific nutrient cycling processes are key to the production efficiency of ecosystems. Identification of the critical cycles in specific ecosystems will be necessary for the selection of appropriate monitoring points.

Nutrient conservation is exceedingly important in terrestrial ecosystems. Evidence of excessive leaching of essential nutrients is a sign of stress. Leaching loss of nutrients has been correlated with reduced nutrient availability in the plant-root zone and reduced plant growth in nutrient-deficient soil (Jackson et al., 1979).

A problem in the use of ecosystem function end points is their relative insensitivity to ecosystem structure. Shifts in species composition to more pollutant-resistant species may or may not result in changes in such functional processes as productivity or nutrient cycling. Thus, an assessment of pollutant effects at the ecosystem level should include both structure and function end points.

Because the factors controlling ecosystem structure and function are numerous and poorly understood, it is difficult to distinguish ecosystem-level effects of pollutants from naturally occurring processes. Many of the ecosystem-level end points depend on the questionable assumption that unpolluted ecosystems are at a stable, undisturbed state.

2.1.3 Population-Level End Points. At the population level, stress response may be monitored in terms of changes in the abundance, distribution, age structure, or gene makeup of exposed populations. The first three end points can be related quite clearly to the overall success of the exposed population. Changes in the gene pool may be related to future adaptability of the population to similar types of stress.

Also in question is the selection of an appropriate population or populations to be monitored in an impact assessment. Quite clearly, monitoring effects on commercially or aesthetically valuable species is important for predicting impacts on those species. More valuable for predicting higher level impacts are population response data on representative and ecologically important species within exposed communities. Included within this category are keystone species that strongly influence the structure of the communities or the functioning of the ecosystem. If there is interest in extrapolating population response to predict ecosystem-level impacts, emphasis should be placed on gathering data on populations from major functional groups, including primary producers, primary, secondary, and tertiary consumers, and decomposers.

A problem in using population-level end points as indicators of the effects of pollution is that the numerous factors regulating population structure are, as yet, poorly understood. This makes it difficult to discriminate pollutant effects from naturally occurring processes. As population structure is influenced by interactions among population members, with other populations, and with the abiotic environment, it becomes necessary to examine effects of pollutants at the ecosystem level.

2.1.4 Physiologic End Points. The physiologic end points most closely related to individual fitness are acute mortality, growth and development, and reproductive success. Acute lethality testing such as LD_{50} or LC_{50} determination is widely used to provide minimal estimates of toxicity. However, such testing is not sufficiently sensitive to assess sublethal or chronic effects that occur at lower toxicant concentrations and that may be of considerable ecologic importance.

Biochemical response end points may provide information on mechanisms of toxic action. Since biochemical processes are in general particularly sensitive to pollutants, biochemical response end points may provide early warning of potential impacts on the individual. However, most biochemical processes also respond to conditions other than pollutant stress, and the response of these end points may be adjusted as an individual acclimates to a stress. Correlations between biochemical response end points and individual success need to be established to enhance the value of these sensitive end points as predictors of higher level impacts.

Osmoregulatory activity is an appropriate end point for assessing impacts on certain freshwater and estuarine fish and invertebrates. Again, the ability of individual organisms to acclimate to osmoregulatory stress must be considered in interpreting osmoregulatory response data. Musculoskeletal end points have also been used to monitor stress responses in fish. Correlations need to be established between abnormalities and the ecologic success of deformed fish.

Respiratory activity has been used as a response end point for a number of species. However, it is difficult to generalize about the patterns of respiratory response to stress. Respiration rates may be elevated or inhibited by pollutants, and ventilation rates in exposed individuals may adjust as acclimation occurs.

Behavioral alterations are appropriate end points for impact assessments if the alterations act either to protect the individual from harm, as in avoidance behavior, or to make the individual more vulnerable to the stress, as in the loss of antipredator behavior. Although behavioral responses are not easy to demonstrate in the laboratory or in the field, these end points, if demonstrated, may be easily extrapolated to predict potential population-level effects.

Genotoxicity and carcinogenicity are end points that provide early warning of stress. Data must be gathered on the natural incidence of mutations and tumors to aid in interpreting the importance of chemically induced mutation and tumor incidence rates.

End points measuring growth, development, and reproductive success of individuals are of most obvious utility in predicting population-level impacts. Because these end points are directly related to population success, their use is recommended in impact studies where single-species test data are extrapolated to predict population-level impacts. These end points have been used less frequently because of the time and expense required to conduct full-life-cycle chronic toxicity tests. However, the more frequently used short-term physiologic and biochemical end points cannot be recommended until their relationships to organismal growth and reproductive success are determined.

A number of studies (Babich and Stotzky, 1980; Lighthart, 1980;

Reinert and Spurr, 1972; Miles and Parker, 1980) have documented interactions between effects of pollutants and abiotic and biotic factors in the environment. These studies illustrate the inadequacy of using laboratory single-species, single-factor testing to estimate all ecologic effects of contaminants, and they point to the necessity of relating ecotoxicologic effects on individual organisms to population- and ecosystem-level effects of pollutants.

2.1.5 End Points and Ecological Risk Assessment. A multilevel ecologic risk assessment, which makes use of a combination of organism, population, and ecosystem-level end points, provides the most effective approach to examining ecosystem stress. Multilevel testing would both enhance the sensitivity of a risk assessment and broaden its scope to include more complex levels of ecologic organization. In contrast, the traditional approach of using only single-species testing is generally inadequate to account for pollutant-induced effects on the complex organization of an ecosystem. Single-species measures can be greatly enhanced by the use of population and ecosystem-level end points.

The precise choice of end points for use in an ecologic risk assessment should be made on a case-by-case basis, depending on both the ecosystem being tested and the nature of the pollutant stressor. Various population- and ecosystem-level end points are potential choices. Many of these end points are readily measurable and are highly sensitive to low levels of pollutant stress. Still inadequate, however, are field data documenting the usefulness of population- and ecosystem-level end points in ecosystem toxicity studies. Future research in this area would facilitate the development of the multilevel risk assessment approach.

2.2 Choice of Species

The choice of species to study in an ecosystem is also important; typically, the focus is endangered or sensitive species. The selection of ecosystem media and interaction of pollutants within these media further complicate ecosystem assessment. Ecosystems incorporate processes that operate on diverse spatial, structural, or temporal scales. The enmeshing of these variables presents difficulties in calculating the effects of localized versus general processes and in integrating key factors such as primary production with seasonal climatic changes and geochemical cycling.

Intermediate between full field tests and single-species laboratory bioassays are microcosm and mesocosm studies. Microcosms and intermediate mesocosms are isolated parts of a naturally occurring system that can be modified to duplicate many features of an intact ecosystem. Microcosms have many limitations including those of spatial scale, number of organisms, species diversity, and physical controlling variables.

2.3 Use of Models

Various models can be used to evaluate ecosystem risk. These include models of fate, transport, exposure, and effects as well as integrative models (see, for example, Chapter 7 of this book). Other ecosystem models focus on population density, food chains, bioenergetics, and toxicokinetics. The diverse models for both individual species and population groups have advantages and disadvantages that must be defined and tailored to specific circumstances. This diversity provides for a wide variety of approaches that can be applied to the problems encountered in ecologic risk assessment.

Succession models take on a wide range of mathematical forms. Their richness in formulation originates to an extent in the specific objectives and training of the model designer. These differences frequently imply different theoretical constructs as to what is important in the functioning of a given ecosystem. In this sense, the models represent a complex set of a priori hypotheses about the function and behavior of ecosystems.

Thus it is essential to use an orderly, justifiable process in developing and selecting an appropriate ecosystem model. Refining and improving available models are critical aspects of developing precise models for each particular situation in nature.

One of the most pressing needs in environmental management is for evaluation of models used routinely in assessment of environmental exposure and impact. Many models are being used for situations where they are of questionable validity. In particular, models should not be applied to environments outside the range for which they have been calibrated and tested. Although this may seem obvious, oftentimes models are used to predict impacts for changing conditions that are appreciably different from those for which the models were originally developed and calibrated.

With regard to population modeling, although current work on mathematical models of individuals and populations shows great promise, insufficient scrutiny to date has precluded a general consensus on approach. Most rudimentary population models have been developed from a retrospective viewpoint with biologic data, but few biologic principles, as a focus. Such models are useful for risk assessment only from a qualitative perspective. However, discrete age- or stage-structured population models offer a well-developed theory and a reasonable computational scheme.

Another significant problem in current ecosystem risk assessment is the paucity of toxic effects models and of predictive methods. Validation of methods to predict ecosystem response is difficult because of the absence of empirical data in many areas. Generation of data, development of models, and validation of methods are current projects of the EPA's Office of Environmental Processes and Effects Research.

2.4 Resilience and Recovery

Factors that influence recovery of an ecosystem from environmental stress include severity of the stress, reversibility of effects, rate and effectiveness of stress removal, frequency and duration of ecosystem disturbance, resilience of ecosystem structure and function, extent of alteration, compensatory interaction of multiple species, kinetic balance of the system, complexity of the system, temporal and spatial variability, availability of regenerating units, and rate of reestablishment of the biologic and physical habitat.

The resilience of ecologic systems and their resistance to natural and anthropogenic forms of disturbance have been measured in field and laboratory studies. Of necessity, these studies have been of long duration. In most cases, natural ecosystems have not been shown to be displaced to the extent that recovery is not possible when the disturbance abates (Sheehan, 1984). The availability of colonizers to the disturbed ecosystem and the existence of biogeochemical feedback loops are cited as factors important to the rapid recovery of disturbed ecosystems. Functional redundancy of species is cited as important to the resistance of ecosystems to disturbance. Loss of individual populations may not in itself be an adequate measure of the stability of the structure and function of a disturbed ecosystem.

Resistance and resilience are appropriate response variables for impact assessment. These stability criteria represent integrated measures of system breakdown and recovery. In future studies, measurement of amplitude will be essential to establish measurable threshold levels of disturbance which may be indicative of permanent changes in stressed ecosystems.

2.5 Development of Surrogate Systems

One potential tool for quantification of health and environmental effects is the classification of well-described ecosystem types for use as surrogates for candidate ecosystems. Establishment of such surrogate systems would simplify evaluation without excessive loss of accuracy.

Screening methodologies can be used for certain classes of chemicals to predict chemical persistence and the potential for bioaccumulation based on physico-chemical properties and quantitative structure-activity relationships. On the basis of screening results, biologic testing may be recommended. Further assessment with integrated exposure/effects models, microcosm/mesocosm experiments, or field studies are logical extensions of such screening efforts.

2.6 Uncertainty

The uncertainty associated with ecosystem risk analysis can arise from a variety of different sources and in a number of different ways that affect the calculation of risk. Perhaps foremost among these is that the response of ecosystems, or their components, to anthropogenic stress involves numerous factors. Each of these factors incorporates physical or biologic mechanisms that in turn vary in degree of scientific characterization, availability of data sets, and sources and levels of uncertainty. Thus, natural complexity and stochasticity contribute to the uncertainty associated with models. Because ecosystem risk analysis typically includes a mathematical or statistical model, lack of correspondence between the model and the modeled ecosystem leads to model error. Errors in parameter estimates resulting from experimental measurement error, approximation and extrapolation of experimental results, and solution techniques also contribute uncertainties to ecologic risk assessment (see also Chapter 2 of this book).

2.7 Integrated Strategy

An integrated strategy including single-species bioassays, microcosm and mesocosm experiments, and models for exposure and toxic effects allows an estimate of the biologic effects of a physical or chemical stress. If model parameters can be obtained from actual test data, then model accuracy can be improved by stepwise calibration of models to microcosms and mesocosms. Thus, variable natural conditions can be represented more realistically and ecologic risk estimated with fewer uncertainties.

3 ECOLOGICAL RISK ASSESSMENT GUIDELINES

Ecosystem risk assessment appears to be a feasible undertaking when its limitations are clearly delineated. The EPA's Office of Health and Environmental Assessment is currently developing guidelines that will provide a general approach for conducting ecologic risk assessments. The guidelines will help the assessor identify the pathways and mechanisms by which chemicals reach nonhuman populations; from an understanding of the chemical effects, the assessor will then develop an assessment of risk. The guidelines will help the assessor to determine which aspects of the ecosystem to emphasize and whether available data are adequate to estimate exposure and effects of concern. The risk manager will then have a basis for deciding what constitutes an unreasonable ecologic risk.

The guidelines will discuss the fundamental principles governing the response of the environment to stress not only for individual organisms but also for populations of organisms. Discussion will include current, acceptable methods for testing effects of pollutants on single and multiple species; biologic, molecular, and physiologic indicators of toxicity; pharmacodynamic and environmental mechanisms of toxic effects; and ecosystem-level functions such as nutrient processing, productivity, and diversity as indicators of toxic effects.

The guidelines will allow the risk assessor to consider the following questions when developing an ecologic exposure assessment: how does the ecosystem modify the fate and transport of the toxicant; how is the contaminant distributed within the ecosystem; what are the residence times; what are the sites of retention or deposition; what fate and transport models would be helpful in determining environmental concentrations; is it possible to combine bioassay data with models, microcosm studies, and field-study methods to determine transport, fate, and potential exposure; what is known about the natural dynamics of the ecosystem; what is the extent and duration of exposure for the biota; does the ecosystem recover from the stress, and how is recovery measured; and are any sensitive or endangered species, or species at vulnerable life stages, present in the ecosystem being studied?

The guidelines will help the assessor develop an ecologic hazard assessment. Elements that may contribute to a hazard assessment include factors that affect the toxicity of the chemical; parent, metabolite, or degradation products responsible for the toxic effects; selection of models based on an intent to study effects on individual species, certain population groups, or the ecosystem as a whole; comparison of changes that occur in the environment in the absence of stress with changes that occur in the presence of stress; identification of ecologically important species; possible synergistic mechanisms; intent to study acute or chronic effects or both; appropriateness of laboratory-to-field extrapolations; availability of appropriate benchmark compounds; availability of applicable retrospective cases; appropriateness of an approach involving a surrogate species or ecosystem; and presence of ecologic indicators in the air, water, soil, and ecosystems.

The guidelines will help the assessor choose the best monitoring system for the assessment, design the sampling plan, determine the role of models, and decide whether a tiered testing approach is necessary to predict higher-order effects.

Finally, the guidelines will help the assessor to develop a risk assessment that integrates the exposure and hazard assessments. Key elements that should be considered for inclusion in the risk assessment include selection of end points, description of the reference environment, identification of sources, assessment of exposure and effects, integrated risk assessment, and evaluation of uncertainty.

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16. ABSTRACT

The state-of-the-art assessment of risk to the ecosystem in still evolving. Although single-species tests have provided valuable information for the assessment of ecologic risk, it is necessary to focus on ecosystems-level tests and analyses. The increasing availability of predictive models makes assessment of risk to the environment, rather than simply to a single species, more possible. The United States has yet to develop government- or agency-wide guidelines for conducting ecologic risk assessments although the U.S. Environmental Protection Agency currently has efforts underway to develop such guidelines in the Office of Health and Environmental Assessment. However, various standard test methods have been developed to provide toxicologic benchmarks primarily for the measurement of acute toxicological effects. Recent research efforts have been directed toward developing test methods that predict chronic and acute toxicologic effects based on results of short-term exposure to organisms during sensitive life stages. This paper presents a partial compilation of methods used in performing ecological risk assessments developed by the U.S. Environmental Protection Agency or published by the American Society for Testing and Materials and looks at the future directions of the U.S. EPA in the development of new ecological risk assessment methodologies and approaches.

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