Journal of Hazardous Materials, 35 (1993) 241–253
Elsevier Science Publishers B.V., Amsterdam

Ecological risk assessment: A scientific perspective*

John H. Gentile[1], Mark A. Harwell[2], William H. van der Schalie, Susan B. Norton and Donald J. Rodier

U.S. Environmental Protection Agency, Risk Assessment Forum, Washington, DC 20460 (USA)

Abstract

Ecological risk assessment is becoming an increasingly important tool for ranking, assessing, reducing, and managing environmental risks. To provide Agency-wide guidance in this area in the U.S., EPA's Risk Assessment Forum has begun a multi-year guidelines development program. The first step in this program was the publication of the report "Framework for Ecological Risk Assessment" which describes the principles, concepts, terminology, and structure of ecological risk assessments.

1. Introduction

Since its inception in 1971, the U.S. Environmental Protection Agency (EPA) has had the responsibility for regulating the use of individual and complex mixtures of pollutants entering our air, land and water. The Agency's focus during this period centered primarily on environmental problems attributable to the use of individual toxic chemicals. For example, scientific evidence demonstrated that specific chemicals (e.g., persistent lipophilic organic chemicals such as DDT, PCB's, etc.,) were distributed throughout the biosphere and had accumulated in biological tissues where they posed a substantial risk to the survival, reproduction, and sustainability of susceptible populations (e.g., avian raptors). Recognition of these environmental problems led to legislation, regulations, and research centered on determining chemical specific effects on the responses of individual species. Extensive ecotoxicity and monitoring data bases have been developed to determine the potential

---

* Paper presented at the Symposium on the Role of Environmental (Ecological) Assessment in the Management of Chemical Pollution, American Chemical Society 204th National Meeting, Division of Industrial & Engineering Chemistry, Washington, DC, August 26–28, 1992.

[1] Present address: Environmental Protection Agency, 27 Tarzwell Drive, Narragansett, RI 02882. Fax: (401) 782-3099.

[2] Present address: Rosenthiel School of Marine and Atmospheric Science, University of Miami, Miami, FL.

impacts from chemical contaminants before and after they have been released into the environment. This philosophy has and continues to produce a variety of chemical-specific regulations (e.g. Water and Sediment Quality Criteria, pesticide registrations, toxic substances, etc.) that support "end-of-pipe" control and remediation strategies which have and continue to improve environmental quality [1].

The scope of today's environmental problems are diverse, complex, and will require an integrated scientific and regulatory policy. This policy, while continuing to control new and historical sources of individual chemicals (i.e., "end-of-the-pipe") and remediate existing pollution problems, will have to address the cumulative effects from multiple stresses. In this decade, regional- and global-scale environmental problems are increasing in importance. This is illustrated by: (1) the alteration of freshwater aquatic communities and forests from acid deposition; (2) the effect of chloro-fluorohydrocarbons on the integrity of the planet's stratospheric ozone layer; and (3) the potential alteration of global climates from increased atmospheric concentrations of such common gases as carbon dioxide and methane. In addition, the threat posed by non-chemical stresses (e.g., habitat alteration and fragmentation, species loss and introduction, etc.) presents a substantial ecological risk to the integrity of both specific populations and ecosystems [2].

Risk assessment is the process for determining the probability, with associated uncertainty, of a particular event occurring as the result of the action of a specific agent or stressor [3]. Ecological risk assessment, therefore, can be defined as a process for evaluating the likelihood of adverse ecological effects occurring as a result of exposure to one or more stressors. Ecological risk assessment provides the strategy for integrating sources of environmental pollution with adverse ecological effects and therefore can be expected to play an important role in environmental decision-making. Recently, EPA's Science Advisory Board recommended that the ecological risk assessment process be used both as the corner stone for environmental decision-making within EPA and that it receive equivalent priority to the Agency's health risk assessment program [1]. By adopting these recommendations, EPA will increase the prominence of ecological risk assessment in the regulatory process and require that state-of-the-science guidance be developed for Agency scientists to assure consistency in the conduct and interpretation of ecological risk assessments so that informed decisions can be made by Agency managers [2].

At the present time EPA does not have an Agency-wide strategy or approach for providing consistency in the design, analysis, and interpretation of research information that is to be used in making risk-based decisions for ecological problems. In other words, EPA does not have an ecological analog to its guidelines for conducting human health risk assessments. The need for consistency in ecological risk assessments is particularly important because it assures the environmental manager that the information used to formulate decisions throughout EPA has been acquired and interpreted within a consensus set of guidelines that have been peer-reviewed by the scientific and regulatory communities and the public.

Recently, EPA has published a "Framework for Ecological Risk Assessment" (Framework) that describes the concepts, principles, and proposes a simple, flexible structure for organizing future guidelines [4]. The Framework does not provide, however, the level of detail necessary to serve as a guideline and does not address the larger question of where, in the total set of potential ecological risk issues, the Agency-wide risk assessment guideline should be focused. Each ecological risk assessment has many potential dimensions (space, time, stressors, ecosystems, etc.) for which scientific issues must be resolved before guidance for specific problems (e.g. stressor–ecosystem combinations) can be prepared. These scientific issues, when fully developed, will serve as the bridge between the Framework's general principles and more substantive ecological risk assessment guidelines.

The purpose of this paper is to provide an overview of the scientific principles that are relevant to understanding and conducting ecological risk assessments; the Agency's Framework for ecological risk assessment; the application of the Framework to pro- and retrospective types of assessments; and, some of the scientific issues for which additional information is required before the agency can prepare substantive ecological risk assessment guidance.

2. Scope of ecological risk assessments

Ecological risks result from individual and multiple stressors acting singly or in combination over a wide range of spatial, temporal, and ecological scales. Consequently, stressors often affect one or more ecosystems simultaneously and may require that ecological assessments be made at one or more levels of biological organization. The scale and complexity of ecological systems and their interactions with anthropogenic and natural stresses present a challenge to assessing both risks and recovery in these ecosystems. There are, however, two central aspects to understanding the roles and interactions of a stress in ecological risk assessments: (1) the characterization of the stressor, its distribution in space and time, and co-occurrence experienced by various biological components of the ecosystem; and (2) the characterization of how ecosystems respond to and recover from one or more stressors [5].

Knowledge of the potential interactions of stressors in ecological systems suggests that five variables can be used to define the potential range of ecological risk assessment types. The five variables that describe the ecological risk landscape and capture the essential features of the ecological risk assessment process are: type of stressor, ecological organization, ecosystem type, spatial and temporal scale [6].

- *Stressor.* This refers to the type (chemical, non-chemical), properties (physical and chemical), potential modes of action, scale, intensity/duration/frequency and timing. These characteristics provide insight into potential abiotic and biotic interactions of the stressor and the stressors temporal and spatial co-occurrence with the ecological components of one or more ecosystems that are the focus of the risk assessment.

- *Ecological organization.* Ecological organization represents the level of ecological scale and complexity (for both endpoints and indicators) at which the ecological risk assessment is conducted. In theory, the scale of ecological organization chosen for the ecological risk assessment is dependent upon and must be compatible with both the spatial and temporal scales of the stressor and the ecosystem components co-occurring with and affected by the stressor.
- *Ecosystem type.* Ecological assessments are typically though not necessarily ecosystem specific, that is, assessments describe the risk of ecological effects for aquatic, terrestrial, or wetlands categories of ecosystems and/or their respective subcategories.
- *Spatial scale.* Spatial scale delineates the area over which the stress is operative and within which direct ecological effects may occur. Indirect ecological effects may greatly expand the spatial scale required for the assessment.
- *Temporal scale.* Temporal scale defines the expected duration for the stress, the timescale for expression of direct and indirect ecological effects, and the time for the ecosystem to recover once the stress is removed. The spatial and temporal scale of the stressor are important variables in defining the boundaries of the risk assessment.

These variables provide a multi-dimensional approach to classifying the types of ecological risk assessments and can be used to define the context and potential range of scientific issues needing to be addressed in the conduct of ecological risk assessments. This can be visualized when selected variables are combined into a three-dimensional matrix and displayed graphically as a "Cube" (Fig. 1) [6]. Spatial and temporal scale are acknowledged, implicitly, as being important across all components of the process and for defining the boundaries of the assessment.

This graphic representation is useful because it explicitly shows the relationships between the variables, presents a comprehensive description of the potential types of ecological risk assessments for which guidance will be needed, and suggests the types of scientific issues associated with the risk-based evaluation of environmental problems. However, the "Cube" does not provide: (1) a structure and process that describes how ecological risk assessments are conducted; (2) a detailed description of the specific types of information for each of the five variables that are needed in a risk assessment; and (3) a process for analyzing, integrating and interpreting information in a manner necessary to provide an estimate of ecological risk. What is needed is a structure and process that describes how ecological risk assessments are conducted and that can be applied to any "cell" within the matrix of variables described by the "Cube".

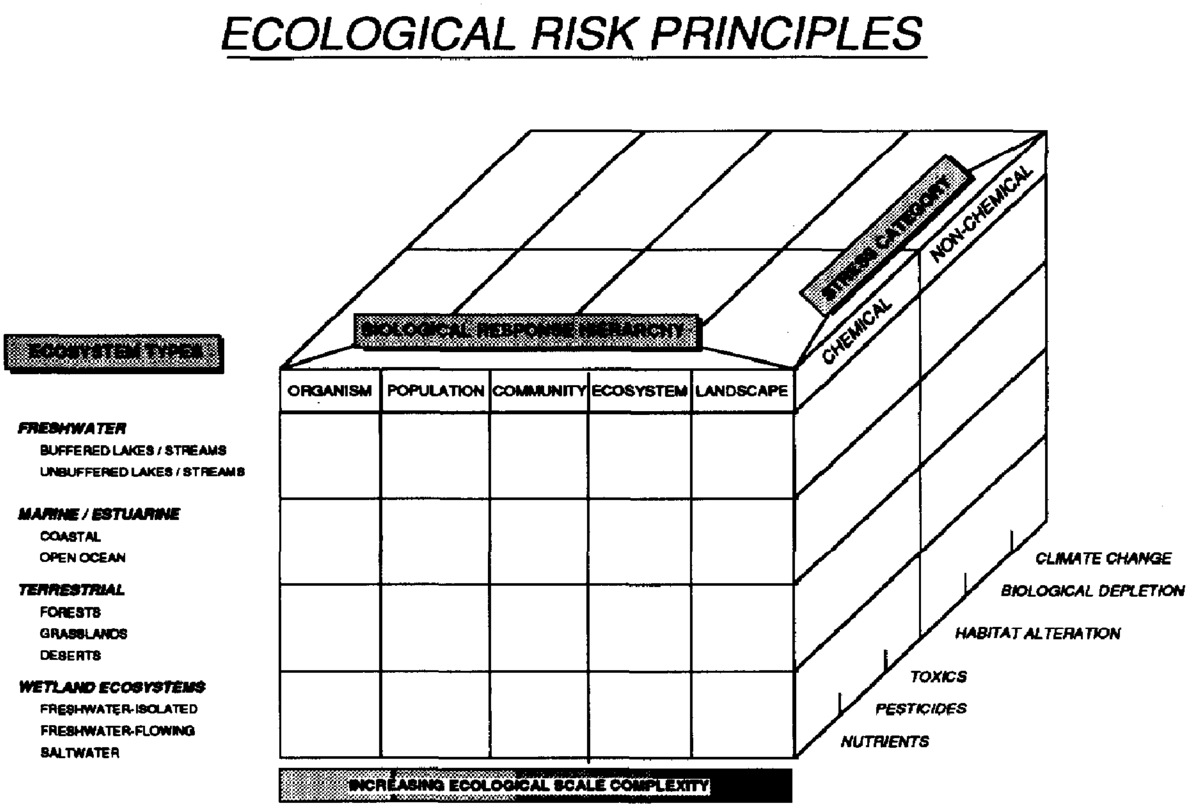

Fig. 1. Three-dimensional matrix of ecological risk organizing principles.

3. Ecological risk assessment framework

Ecological risk assessment is defined as a process for evaluating the likelihood that adverse ecological effects have, are, or will occur as a result of exposure to one or more stressors [4]. Implicit in this definition is that: (l) environmental stressors have the inherent ability to cause one or more adverse effects, and (2) the stressor co-occurs with or contacts an ecological component (i.e., organisms, populations, communities, or ecosystems) long enough and at a sufficient intensity to elicit the identified adverse effect [5]. Consequently, the risk assessment process is based upon two major elements: *Characterization of Exposure* and *Characterization of Ecological Effects*. The following is a brief description of EPA's Framework for Ecological Risk Assessment" that has been proposed as structure for ecological risk assessments.

The Framework is divided into three phases: problem formulation, analysis, and risk characterization (Fig. 2).

Problem formulation. This first phase of the Framework includes a preliminary characterization of exposure and effects specifically directed toward developing a conceptual model of the risk assessment. The conceptual model is

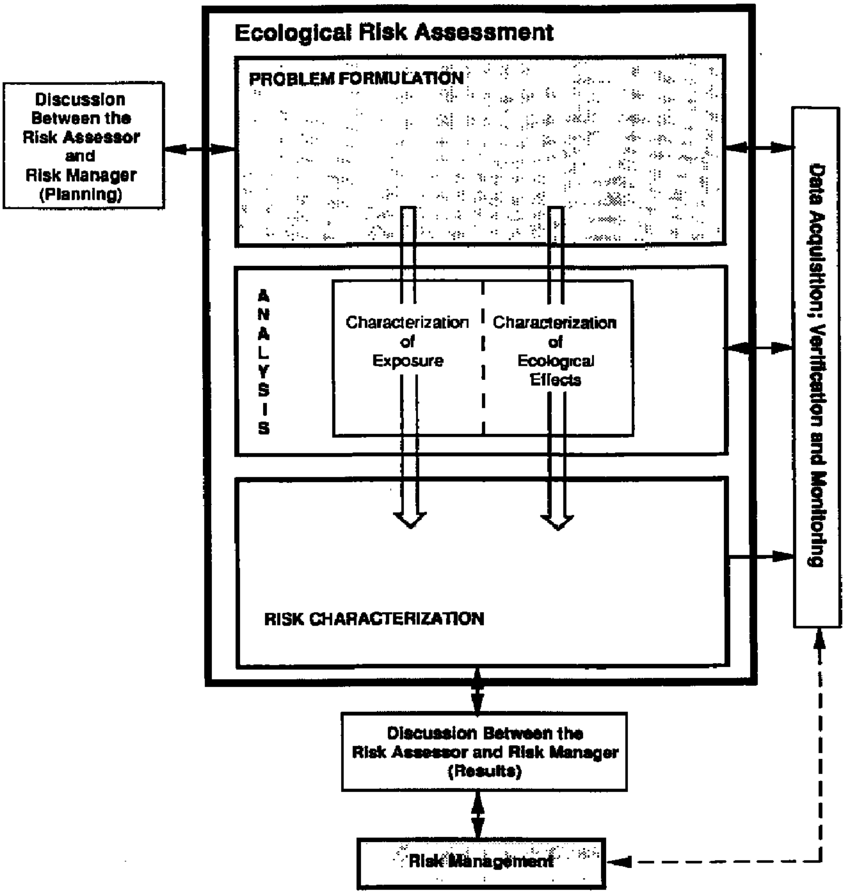

Fig. 2. Framework for ecological risk assessment.

comprised of hypotheses linking the types, actions, and exposure pathways of stressors to: their sources, the ecosystems of concern, and the direct and indirect ecological effects that are the basis of the risk assessment.

Analysis phase. This second phase of the Framework consists of two previously mentioned activities, Characterization of Exposure and Characterization of Ecological Effects. The purpose of Characterization of Exposure is to predict or measure the spatial and temporal distribution patterns of a stressor and its co-occurrence or contact with the ecological components of concern. The purpose of Characterization of Ecological Effects is to identify and quantify the ecological responses elicited by a stressor and, to evaluate the strength of potential cause and effect relationships.

Risk characterization. This third phase of the Framework integrates exposure and ecological effects information to evaluate the likelihood of adverse ecological effects associated with exposure to a stressor. It includes a summary of the assumptions used, the scientific uncertainties, and the strengths and weaknesses of the analyses. Further, the ecological significance of the risk is discussed with consideration of the types and magnitudes of the effects, their spatial and temporal patterns, and the likelihood of recovery. The purpose is to provide a complete picture of the analysis, results, and associated uncertainties of the assessment.

In addition the Framework illustrates the roles of ***Risk Management*** and *Data Acquisition, Verification and Monitoring* in the ecological risk assessment process (Fig. 2). The interface of policy, risk assessment, and risk management is crucial, in all regulatory programs. Social and economic values are reflected in the legislation enacted to protect one or more components of the environment. Those values are important to risk management decisions. Therefore, societal values should be considered early in the risk assessment process (e.g., identifying ecological endpoints of concern) to ensure that the risk assessment will provide relevant information for the risk manager.

Data acquisition provides the information necessary to identify potential environmental problems and to conduct the risk assessment. The verification and monitoring phases are used to: (1) validate specific components (e.g., models) of the ecological risk assessment process; (2) confirm predictions of risk; (3) provide the necessary feedback concerning the effectiveness and practicality of policy decisions.

The value of the risk assessment framework lies in its utility as a process for ordering and analyzing exposure and effects information, and in its flexibility for describing both past, present, and future risks. Risk assessment, therefore, can predict the likelihood that an effect will occur given exposure to a stressor (prospective) and can evaluate the likelihood that a specific stressor is responsible for observed ecological effects (retrospective). Prospective analysis generally refer to *a priori* predictions of ecological risks (e.g., pre-manufacture pesticide risks) that are inferred from the characteristics and properties of the stressor. These types of risk assessments are used by EPA's program offices to evaluate the potential risk of adverse ecological effects from pesticides and toxic chemicals prior to their release and use in the environment. Retrospective analyses are *a posteriori* determinations of the likelihood that observed ecological effects (e.g., fish kills, declines in resources, etc.) have been caused by one or more stressors already present at that time in the environment. In retrospective analyses the intent is to develop evidence on the likelihood that observed ecological effects are linked to one or more existing stressors in the environment (e.g., RCRA, CERCLA, etc.). Retrospective studies often use an eco-epidemiological approach for diagnosing and identifying potential causal relationships.

The development of a quantitative stressor–response relationship is essential for two reasons. First, determination of stressor–response relationship provides important evidence for inferring potential causal, relationships that are necessary for implementing management control strategies. Second, stressor–response relationships premit the prediction of incremental risks from different exposures. The predictive capability of the risk assessment process, of obvious use in prospective assessments, is also important in retrospective studies for setting remediation goals and for evaluating management options.

From the perspective of the Framework, only the initial information available in the problem formulation phase differs in the two types of assessments, being source–stressor driven in prospective analyses and effects driven retrospective studies. Once the ecosystem potentially at risk and the endpoints for the assessment have been identified, the types of information and process used for determining past, present, and future risks are essentially the same in prospective and retrospective studies [4, 6].

4. Scientific issues in ecological risk assessment

Throughout the development of the Framework Report, case studies, and EPA sponsored workshops [7] and colloquia [8], a series of scientific issues have emerged that are critical to the conduct and interpretation of ecological risk assessments. These issues are important to the development of future guidelines because they expand upon important principles introduced but not discussed in detail in the Framework Report. These issues represent scientific aspects of the risk assessment process for which improved technical information is needed before comprehensive guidance can be developed. Because these issues are related directly to specific elements of the risk assessment process described in the Framework, they also serve as a bridge linking the Framework and future guidelines. The following nine issues illustrate, in part, the scientific issues that have been identified.

1. Scale and complexity in ecological risk assessments. The scale and complexity of ecological systems and their interactions with anthropogenic and natural stresses present a challenge to preparing guidance that can be used for assessing risk and recovery in ecosystems [6]. Three categories of scale have been highlighted in discussions: spatial scale, temporal scale, and ecological scale. Spatial scale delineates the area over which the stress is operative and where direct ecological effects may occur. Temporal scale defines the expected timing and duration of the stressor, the time-scale for expression of direct and indirect effects, and the time for the ecosystem to recover once the stress is removed. Ecological scale refers to level of ecological organization and complexity (e.g. organisms, populations, etc.) for which endpoints must be selected. These three aspects of scale are interdependent. For example, the scale of ecological organization chosen for the risk assessment is dependent on both the spatial and temporal scales of the stressor. In addition, the occurrence of indirect effects (e.g., effects on the food or habitat of the ecological component of interest) can expand all three aspects of scale. Because additional uncertainties are introduced in extrapolating between dissimilar scales, it is important that all three scales be compatible in an ecological risk assessment.

2. Selection of endpoints. The identification and selection of endpoints for use in ecological risk assessments must consider and represent specific properties of the ecosystem that are deemed to be at risk. These properties, if sufficiently altered, will constitute a fundamental change in the ecosystem that is of ecological or societal importance. Two categories of endpoints are identified in the Framework Report; *assessment endpoints* which are explicit expressions of the environmental values that are to be protected; and *measurement endpoints* which are measurable ecological characteristics that are related to the assessment endpoints [9]. Considerable discussion on this topic has led to the identification of the following issues: (1) the use of both structural (e.g., community diversity) or functional (e.g., rates of primary production) ecosystem properties as endpoints; (2) relevancy, that is, the endpoint must have either ecological importance (e.g., keystone species, ecologically important processes) or societal importance (e.g., economically important, endangered, or aesthetic species); (3) criteria for selecting and linking assessment and measurement endpoints from different levels of biological organization (e.g., organism, population, community, and ecosystem); (4) endpoints that can discriminate between types of stressors or their signatures (e.g. toxics, nutrients, habitat loss, etc.); (5) the natural variability of candidate endpoints; and (6) comparability of endpoints with other ecological risk assessments (e.g., using some endpoints in common to different systems or different stresses) [10]. It is likely that a suite of both assessment and measurement endpoints will be required to assure that the full range of ecosystem values are evaluated. If this is true then the issue of weighing and interpreting the relative value of each assessment endpoint's contribution to the risk assessment will have to be considered.

3. Exposure characterization. This is a broad topic containing several issues not the least of which is terminology (e.g., stress, stressors, exposure, etc.). Our current understanding of exposure concepts and principles is based on experience with chemicals, specifically toxic chemicals. At issue is how applicable are these concepts, models, and methods to different categories of stressors. This issue is particularly important since the Agency must be prepared to deal effectively with important non-chemical stressors such as physical and biological stressors. Issues for non-chemical stressors include understanding the nature and form of the physical stress–response relationships, and approaches for quantifying the intensity, duration, and extent of stressors. Chemical stressor issues include: (1) information on the nature, transformations and interactions of stressors with both biotic and abiotic components in the environment; (2) the bioavailability of chemical stressors; and (3) co-occurrence of anthropogenic stressors with natural environmental variables and critical periods of biological activity [4]

4. Stressor–response relationships. Many of the methods for estimating exposure and stressor–response relationships were developed for assessing chemical risks to individual organisms and species. At issue is whether the same concepts and/or methods can be applied to higher levels of biological organization and to non-chemical stressors such as physical perturbations or introduced species. Issues that need to be discussed include: (1) evaluating the applicability of stress–response relationships developed for chemical stressors and organism level responses to non-chemical stressors (e.g. physical perturbations) and to higher levels of ecological organization; (2) determining the feasibility of stress–response models for communities, ecosystems, and biomes; (3) examining the utility of unique forms of stress–response expressions (e.g. non-linear, step-functions, etc.); (4) selecting the most appropriate expressions of stress-response relationships for non-chemical stressors (e.g. habitat alteration, introduced species, etc.); and (5) describing which approaches and methods are most appropriate for including indirect effects, recovery, and cumulative impacts in estimates of the stress–response relationships.

5. Cumulative impacts. Cumulative impacts can result from the incremental effects of multiple stressors acting over large spatial and long temporal scales. Issues include: (1) how to determine the response to mixtures of chemicals and combinations of chemical and non-chemical stressors; (2) how to combine the effects of both anthropogenic and non-anthropogenic stressors; and (3) how to integrate ecological effects at different spatial scales.

6. Ecosystem recovery. Ecosystem recovery has been identified as an important issue area for which guidance will be needed in the future. Central to understanding the role of recovery in ecological risk assessments is knowledge of the following: (1) definition of "disturbance", "recovery" and the selection of appropriate indicators; (2) the particular qualities and novelty of the stressor, (3) the intensity, duration, and frequency of the stressor; (4) the role of life-history and behavioral characteristics; (5) the availability and size of refugia and corridors for immigration; (6) natural successional patterns and the temporal scales of colonizing biota; (7) the "reversibility" of the effects; (8) biological and physical scaling, and (9) spatial and temporal heterogeneity and variability of recovery [11, 12].

7. Ecological significance. It is generally recognized that the interpretation of environmental problems involve scientific, policy and societal components. Discussion of ecological significance within the context of ecological risk assessment requires clearly defining several scientific concepts and issues. For example: (1) determining what constitutes a significant change in one or more assessment endpoints; (2) determining implications and significance of a change in the assessment endpoint(s) within a broader ecological context (ecosystem, watershed, landscape, etc.); (3) understanding the changes within the context of natural selection processes and time scales; (4) knowledge of natural variability, be that temporal (e.g. seasonal cycles of abundance), spatial (e.g. the spatial heterogeneity of communities) and/or biological (e.g. differential sensitivity of life stages, physiological races, etc.); (5) understanding the role of recovery in ecological significance; and (6) the role of societal values and their juxtaposition with ecological values. In addition, recent discussions on the interpretation and communication of ecological significance have emphasized the importance of issues of spatial and temporal scale, indirect effects (e.g., food or habitat), discriminating changes in endpoints due to natural variability from anthropogenic causes, and understanding the relationship between the scope of measured changes and the broader ecological context within which the risk assessment resides as critical to determining ecological significance.

8. Uncertainties. The complexities inherent in ecological risk assessments are the source of several types of uncertainty. One of the goals of risk assessments is the clear delineation of both individual sources of uncertainty and the propagation of those uncertainties to provide a composite estimate of the total uncertainty of the assessment. Some if the issues relative to this topic include: (1) the theoretical considerations in characterizing uncertainty; (2) model uncertainties (incorrect model, excluded variables, abnormal conditions, etc.); (3) parameter uncertainties; (4) natural variability and stochasticity; (5) extrapolation uncertainties (spatial, temporal, and ecological scales, endpoints, taxa, etc.); (6) decision-rule uncertainties (the measure to describe risk summary statistic, etc.); (7) methods for expressing and estimating uncertainty; (8) techniques for quantifying and propagating uncertainty; and (9) presenting and communicating uncertainty [13, 14]. Although a wide variety of models are available, criteria will be need for selecting and using the appropriate models within an ecological risk assessment context.

9. Biological stressors. The Framework report does not discuss accidentally or deliberately introduced species or genetically engineered organisms. There is considerable scientific evidence of the impacts from biological stressors on both terrestrial and aquatic environments, there has not been a systematic examination of whether the principles of ecological risk assessment, developed for other categories of stressors (e.g. toxic chemicals, nutrients, etc.), are applicable to introduced species. While the general principles described in the Framework may be useful in addressing risks associated with biological stressors the capacity of these organisms for reproduction and interaction introduces additional issues. The following questions illustrate the problem. What is the nature of biological stressors, including conceptual differences from chemical and physical stressors? What are the appropriate levels of ecological organization for selecting endpoints for determining the risks from biological stressors? How is the concept of exposure applied to biological stressors? What attributes of a biological stressor should be considered to determine the likelihood of transport by a particular pathway? Addressing the scientific issues illustrated by these questions will be essential to developing guidance

The intent of the Agency is to develop comprehensive, state-of-the-science, guidance relevant information on each of these issues to serve as a bridge between the Framework and substantive Agency-wide ecological risk assessment guidelines

5. Future directions: Plans for agency guidelines

The form and content of the Agency's future ecological risk assessment guidelines has been discussed by EPA scientists and managers [4, 8], scientific experts [6, 7], and the SAB [15]. While the Framework Report describes the general structure for organizing individual risk assessments, the "Cube" attempts to address the larger question of where, in the total set of ecological risk issues, should EPA begin writing Agency-wide risk assessment guidelines. Initially, EPA assumed that scientific experts would recommend one or two of the five potential organizing principles (e.g., type of stressor, type of ecosystem, or level of ecological organization) as the basis for ecological risk assessment guidelines.

When presented to a guidelines strategic planning workshop, however, the expert panel recommended that future guidelines follow the principal components of the risk assessment process now described in the Framework Report [6] while acknowledging that the Framework Report, in its current form, does not provide the level of detail necessary to serve as a guideline. Organizing the guidelines according to the risk assessment process takes advantage of many elements and approaches that are common to all types of ecological risk assessments. The panel identified several scientific issues (i.e. those discussed above) related to the ecological risk assessment process that they felt must be resolved before guidance for specific problems (e.g. stressor–ecosystem combinations) could be developed. The panel also recommended that comprehensive, state-of-the-science reports be developed for each of these issues that would as resources for the risk assessor. Finally, the panel unanimously recommended that case-studies be used to illustrate the ecological risk assessment process for a variety of environmental problems. Having completed the Framework for Ecological Risk Assessment, the Risk Assessment Forum is preparing a series of comprehensive, peer-reviewed scientific papers on several of the ecological risk assessment issues discussed above and developing peer-reviewed case studies that represent a range of ecological risk assessment types.

Summary and conclusions

Ecological risk assessment is becoming an increasingly important tool for ranking, assessing, reducing, and managing environmental risks. To provide Agency-wide guidance in this area, EPA's Risk Assessment Forum has begun a multi-year guidelines development program. The first step in this program was the publication of the report "Framework for Ecological Risk Assessment" which describes the principles, concepts, terminology, and structure of ecological risk assessments. The Framework structure includes three phases (problem formulation, analysis, and risk characterization) and is flexible enough to include both prospective and retrospective studies as well as a wide range of stressors, ecosystems, and scales of effects (ecological, temporal, and spatial). Substantive guidance for ecological risk assessments will require additional information and discussion of several scientific issues (e.g. scale, endpoints, recovery, significance, uncertainty, etc.) which will be developed in peer-reviewed issue papers and illustrated by case studies. The Framework, issue papers and case-studies will form the scientific foundation for the future ecological risk assessment guidelines.

References

1 U.S. EPA, Reducing Risk: Setting Priorities and Strategies for Environmental Protection, Report of the Science Advisory Board Relative Risk Reduction Strategies Committee, SAB-EC-90-021. U.S. Environmental Protection Agency, Washington, DC, 1990, 26 pp.
2 U.S. EPA, Reducing Risk, Appendix A, Report of the Ecology and Welfare Subcommittee, Relative Risk Reduction Project, SAB-EC-90-021A. U.S. Environmental Protection Agency, Washington, DC, 1990, 77 pp.
3 R. Wilson and E.A.C. Crouch, Risk/Benefit Analysis. Ballinger Publishing Company, Cambridge, MA, 1982, 218 pp.
4 U.S. EPA, Framework for Ecological Risk Assessment, EPA/630/R-92/001. Risk Assessment Forum, U.S. Environmental Protection Agency, Washington, DC 02640, 1992.
5 M.A. Harwell, C.C. Harwell, D.A. Weinstein and J.R. Kelly, Characterizing ecosystem responses to stress, Pages 91–115, In: W. Grodzinski, E.B. Cowling and A.I. Breymeyer, with A.S. Phillips, S.I. Auerbach, A.M. Bartuska and M.A. Harwell (Eds.), Ecological Risks: Perspectives from Poland and the United States. National Academy Press, Washington, DC, 1990, 415 pp.
6 U.S. EPA, Report on the Ecological Risk Assessment Guidelines Strategic Planning Workshop, EPA/630/R-92/002. U.S. Environmental Protection Agency, Washington, DC, 1992.
7 U.S. EPA, Peer Review Workshop Report on a Framework for Ecological Risk, EPA/625/3-91/022. U.S. Environmental Protection Agency, Washington, DC, 1992.
8 U.S. EPA, Summary Report on Issues in Ecological Risk Assessment, EPA/625/3-91/018. U.S. Environmental Protection Agency, Washington, DC, 1991.
9 G.W. Suter II, Ecological endpoints, In: W. Warren-Hicks, B.R. Parkhurst and S.S. Baker, Jr. (Eds.), U.S. EPA. Ecological Assessments of Hazardous Waste Sites: A field and laboratory reference document, EPA 600/3-89/013, Washington, DC, 1989.
10 J.R. Kelly and M.A. Harwell, Indicators of ecosystem response and recovery, In: S.A. Levin, M.A. Harwell, J.R. Kelly and K.D. Kimball (Eds.), Ecotoxicology: Problems and Approaches (pp. 9–35). Springer-Verlag, New York, 1989, 547 pp.
11 J.A. Gore, J.R. Kelly and J.D. Yount, Application of ecological theory to determining recovery potential of disturbed lotic ecosystems: Research needs and priorities, Environ. Manage., 14(5) (1992) 755–762.
12 J.R. Kelly and M.A. Harwell, Indicators of ecosystem recovery, Environ. Manage., 14(5) (1992) 527–545.
13 D. Hattis and J.A. Smith, Jr., What's wrong with quantitative risk assessment?, In: R.F. Almeder and J.M. Humber (Eds.), Biomedical Ethics Reviews. The Humana Press, New York, 1986.
14 A. Tversky and D. Kahneman, Judgement under uncertainty: Heuristics and biases, In: D. Kahneman, P. Slovic and A. Tversky (Eds.), Judgement Under Uncertainty: Heuristics and Biases, Cambridge University Press, New York, 1982, pp. 3–20.
15 U.S. EPA, An SAB Report: Review of the Process and Rationale for Developing Ecological Risk Assessment Guidelines, EPA-SAB-EPEC-92-023. Prepared by the Ecorisk Subcommittee of the Ecological Processes and Effects Committee, U.S. Environmental Protection Agency, Washington, DC, 1992.