CHAPTER 28

Environmental Risk Assessment

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28.1 INTRODUCTION

Risk assessment is the process of assigning magnitudes and probabilities to adverse effects associated with an event. The development of risk assessment methodology has focused on accidental events (e.g., an airplane crash) and specific environmental stresses to humans (exposure of humans to chemicals), and thus most risk assessment is characterized by discrete events or stresses affecting well-defined endpoints (e.g., incidence of human death or cancer). This *single stress–single end point* relationship allows the use of relatively simple statistical and mechanistic models to estimate risk and is widely used in human health risk assessment. However, this simple paradigm has only partial applicability to ecological risk assessment because of the inherent complexity of ecological systems and the exposure to numerous physical, chemical, and biological stresses that have both direct and indirect effects on a diversity of ecological components, processes, and endpoints. Thus, although the roots of ecological risk assessment can be found in human health risk assessment, the methodology for ecological risk assessment is not well developed and the estimated risks are highly uncertain. Despite these limitations, resource managers and regulators are looking to ecological risk assessment to provide a scientific basis for prioritizing problems that pose the greatest ecological risk and to focus research efforts in areas that will yield the greatest reduction in uncertainty.

To this end the US Environmental Protection Agency has issued guidelines for planning and conducting ecological risk assessments. Because of the complexity and uncertainty associated with ecological risk assessment the EPA guidelines provide only a loose framework for organizing and analyzing data, information, assumptions, and uncertainties to evaluate the likelihood of adverse ecological effects. However, the guidelines represent a broad consensus of the present scientific knowledge and experience on ecological risk assessment. This chapter presents a brief overview of the ecological risk assessment process as presently described by the EPA.

Ecological risk assessment can be defined as:

> The process that evaluates the likelihood that adverse ecological effects may occur or are occurring as a result of exposure to one or more stressors.

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Estimating the *likelihood* can range from qualitative judgments to quantitative probabilities, though quantitative risk estimates still are rare in ecological risk assessment. The *adverse ecological effects* are changes that are considered undesirable because they alter valued structural or functional characteristics of ecological systems and usually include the type, intensity, and scale of the effect as well as the potential for recovery. The statement that effects *may occur or are occurring* refers to the dual *prospective* and *retrospective* nature of ecological risk assessment. The inclusion of *one or more stressors* is a recognition that ecological risk assessments may address single or multiple chemical, physical, and/or biological stressors. Because risk assessments are conducted to provide input to management decisions, most risk assessments focus on stressors generated or influenced by anthropogenic activity. However, natural phenomena also will induce stress that results in adverse ecological effects and cannot be ignored.

The overall ecological risk assessment process is shown in Figure 28.1 and includes three primary phases: (1) problem formulation, (2) analysis, and (3) risk characterization. Problem formulation includes the development of a conceptual model

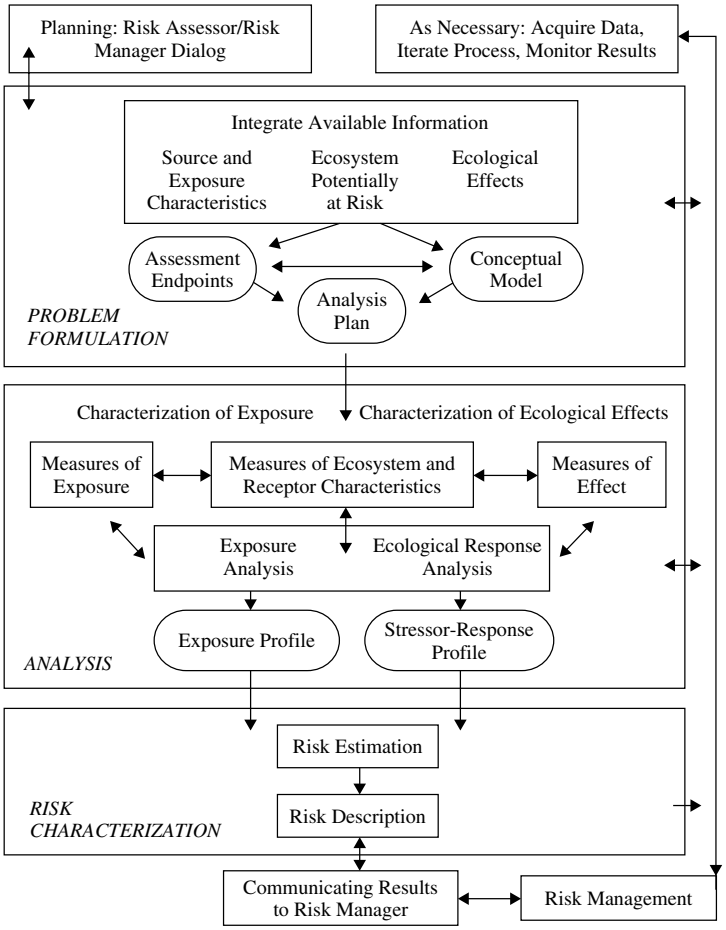

Figure 28.1 The ecological risk assessment framework as set forth by the US Environmental Protection Agency.

of stressor-ecosystem interactions and the identification of risk assessment end points. The analysis phase involves evaluating exposure to stressors and the relationship between stressor characteristics and ecological effects. Risk characterization includes estimating risk through integration of exposure and stressor-response profiles, describing risk by establishing lines of evidence and determining ecological effects, and communicating this description to risk managers. While discussions between risk assessors and risk managers are emphasized both at risk assessment initiation (planning) and completion (communicating results), usually a clear distinction is drawn between risk assessment and risk management. Risk assessment focuses on scientifically evaluating the likelihood of adverse effects, and risk management involves the selection of a course of action in response to an identified risk that is based on many factors (e.g., social, legal, or economic) in addition to the risk assessment results. Monitoring and other data acquisition is often necessary during any phase of the risk assessment process and the entire process is typically iterative rather than linear. The evaluation of new data or information may require revisiting a part of the process or conducting a new assessment.

28.2 FORMULATING THE PROBLEM

Problem formulation is a process for generating and evaluating preliminary hypotheses about why ecological effects have occurred, or may occur, because of human activities. During problem formulation, management goals are evaluated to help establish objectives for the risk assessment, the ecological problem is defined, and the plan for analyzing data and characterizing risk is developed. The objective of this process is to develop (1) assessment end points that adequately reflect management goals and the ecosystem they represent and (2) conceptual models that describe critical relationships between a stressor and assessment end point or among several stressors and assessment end points. The assessment end points and the conceptual models are then integrated to develop a plan or proposal for risk analysis.

28.2.1 Selecting Assessment End Points

Assessment end points are *explicit expressions of the actual environmental value that is to be protected* and they link the risk assessment to management concerns. Assessment end points include both a valued or key ecological entity and an attribute of that entity that is important to protect and that is potentially at risk. The scientific basis for a risk assessment is enhanced when assessment end points are both ecologically relevant and susceptible to the stressors of concern. Assessment endpoints that also logically represent societal values and management goals will increase the likelihood that the risk assessment will be understood and used in management decisions.

Ecological Relevance. Ecologically relevant end points reflect important attributes of the ecosystem and can be functionally related to other components of the ecosystem; they help sustain the structure, function, and biodiversity of an ecosystem. For example, ecologically relevant end points might contribute to the food base (e.g., primary production), provide habitat, promote regeneration of critical resources (e.g.,

nutrient cycling), or reflect the structure of the community, ecosystem, or landscape (e.g., species diversity). Ecological relevance becomes most useful when it is possible to identify the potential cascade of adverse effects that could result from a critical initiating effect such as a change in ecosystem function. The selection of assessment end points that address both specific organisms of concern and landscape-level ecosystem processes becomes increasingly important (and more difficult) in landscape-level risk assessments. In these cases it may be possible to select one or more species and an ecosystem process to represent larger functional community or ecosystem processes. Extrapolations like these must be explicitly described in the conceptual model (see Section 28.2.2).

Susceptibility to Stressors. Ecological resources or entities are considered susceptible if they are sensitive to a human-induced stressor to which they are exposed. *Sensitivity* represents how readily an ecological entity responds to a particular stressor. Measures of sensitivity may include mortality or decreased growth or fecundity resulting from exposure to a toxicant, behavioral abnormalities such as avoidance of food-source areas or nesting sites because of the proximity of stressors such as noise or habitat alteration. Sensitivity is directly related to the mode of action of the stressors. For example, chemical sensitivity is influenced by individual physiology, genetics, and metabolism. Sensitivity also is influenced by individual and community life-history characteristics. For example, species with long life cycles and low reproductive rates will be more vulnerable to extinction from increases in mortality than those with short life cycles and high reproductive rates. Species with large home ranges may be more sensitive to habitat fragmentation compared to those species with smaller home ranges within a fragment. Sensitivity may be related to the life stage of an organism when exposed to a stressor. Young animals often are more sensitive to stressors than adults. In addition events like migration and molting often increase sensitivity because they require significant energy expenditure that make these organisms more vulnerable to stressors. Sensitivity also may be increased by the presence of other stressors or natural disturbances.

Exposure is the other key determinant in susceptibility. In ecological terms, exposure can mean co-occurrence, contact, or the absence of contact, depending on the stressor and assessment end point. The characteristics and conditions of exposure will influence how an ecological entity responds to a stressor and thus determine what ecological entities might be susceptible. Therefore one must consider information on the proximity of an ecological entity to the stressor along with the timing (e.g., frequency and duration relative to sensitive life stages) and intensity of exposure. Note that adverse effects may be observed even at very low stressor exposures if a necessary resource is limited during a critical life stage. For example, if fish are unable to find suitable nesting sites during their reproductive phase, risk is significant even when water quality is high and food sources are abundant.

Exposure may take place at one point in space and time, but effects may not arise until another place or time. Both life history characteristics and the circumstances of exposure influence susceptibility in this case. For example, exposure of a population to endocrine-modulating chemicals can affect the sex ratio of offspring, but the population impacts of this exposure may not become apparent until years later when the cohort of affected animals begins to reproduce. Delayed effects and multiple stressor exposures add complexity to evaluations of susceptibility. For example, although toxicity

tests may determine receptor sensitivity to one stressor, the degree of susceptibility may depend on the co-occurrence of another stressor that significantly alters receptor response. Again, conceptual models need to reflect these additional factors.

Defining Assessment End Points. Assessment end points provide a transition between management goals and the specific measures used in an assessment by helping identify measurable attributes to quantify and model. However, in contrast to management goals, no intrinsic value is assigned to the end point, so it does not contain words such as *protect* or *maintain* and it does not indicate a desirable direction for change. Two aspects are required to define an assessment end point. The first is the valued ecological entity such as a species, a functional group of species, an ecosystem function or characteristic, or a specific valued habitat. The second is the characteristic about the entity of concern that is important to protect and potentially at risk.

Expert judgment and an understanding of the characteristics and function of an ecosystem are important for translating general goals into usable assessment end points. End points that are too broad and vague (ecological health) cannot be linked to specific measurements. End points that are too narrowly defined (hatching success of bald eagles) may overlook important characteristics of the ecosystem and fail to include critical variables. Clearly defined assessment end points provide both direction and boundaries for the risk assessment.

Assessment end points directly influence the type, characteristics, and interpretation of data and information used for analysis and the scale and character of the assessment. For example, an assessment end point such as "fecundity of bivalves" defines local population characteristics and requires very different types of data and ecosystem characterization compared with "aquatic community structure and function." When concerns are on a local scale, the assessment end points should not focus on landscape concerns. But if ecosystem processes and landscape patterns are being considered, survival of a single species would provide inadequate representation of this larger scale.

The presence of multiple stressors also influences the selection of assessment end points. When it is possible to select one assessment end point that is sensitive to many of the identified stressors, yet responds in different ways to different stressors, it is possible to consider the combined effects of multiple stressors while still discriminating among effects. For example, if recruitment of a fish population is the assessment end point, it is important to recognize that recruitment may be adversely affected at several life stages, in different habitats, through different ways, by different stressors. The measures of effect, exposure, and ecosystem and receptor characteristics chosen to evaluate recruitment provide a basis for discriminating among different stressors, individual effects, and their combined effect.

Although many potential assessment end points may be identified, practical considerations often drive their selection. For example, assessment end points usually must reflect environmental values that are protected by law or that environmental managers and the general public recognize as a critical resource or an ecological function that would be significantly impaired if the resource were altered. Another example of a practical consideration is the extrapolation across scales of time, space, or level of biological organization. When the attributes of an assessment end point can be measured directly, extrapolation is unnecessary and this uncertainty is avoided. Assessment end points that cannot be linked with measurable attributes are not appropriate for a risk

assessment. However, assessment end points that cannot be measured directly but can be represented by surrogate measures that are easily monitored and modeled can still provide a good foundation for the risk assessment.

28.2.2 Developing Conceptual Models

Conceptual models link anthropogenic activities with stressors and evaluate the relationships among exposure pathways, ecological effects, and ecological receptors. The models also may describe natural processes that influence these relationships. Conceptual models include a set of risk hypotheses that describe predicted relationships between stressor, exposure, and assessment end point response, along with the rationale for their selection. Risk hypotheses are hypotheses in the broad scientific sense; they do not necessarily involve statistical testing of null and alternative hypotheses or any particular analytical approach. Risk hypotheses may predict the effects of a stressor, or they may postulate what stressors may have caused observed ecological effects.

Diagrams can be used to illustrate the relationships described by the conceptual model and risk hypotheses. Conceptual model diagrams are useful tools for communicating important pathways and for identifying major sources of uncertainty. These diagrams and risk hypotheses can be used to identify the most important pathways and relationships to consider in the analysis phase. The hypotheses considered most likely to contribute to risk are identified for subsequent evaluation in the risk assessment.

The complexity of the conceptual model depends on the complexity of the problem, number of stressors and assessment end points being considered, nature of effects, and characteristics of the ecosystem. For single stressors and single assessment end points, conceptual models can be relatively simple relationships. In cases where conceptual models describe, besides the pathways of individual stressors and assessment end points, the interaction of multiple and diverse stressors and assessment end points, several submodels would be required to describe individual pathways. Other models may then be used to explore how these individual pathways interact. An example of a conceptual model for a watershed in shown in Figure 28.2.

28.2.3 Selecting Measures

The last step in the problem formulation phase is the development of an analysis plan or proposal that identifies measures to evaluate each risk hypothesis and that describes the assessment design, data needs, assumptions, extrapolations, and specific methods for conducting the analysis. There are three categories of measures that can be selected. *Measures of effect* (also called *measurement end points*) are measures used to evaluate the response of the assessment end point when exposed to a stressor. *Measures of exposure* are measures of how exposure may be occurring, including how a stressor moves through the environment and how it may co-occur with the assessment end point. *Measures of ecosystem and receptor characteristics* include ecosystem characteristics that influence the behavior and location of assessment end points, the distribution of a stressor, and life history characteristics of the assessment end point that may affect exposure or response to the stressor. These diverse measures increase in importance as the complexity of the assessment increases.

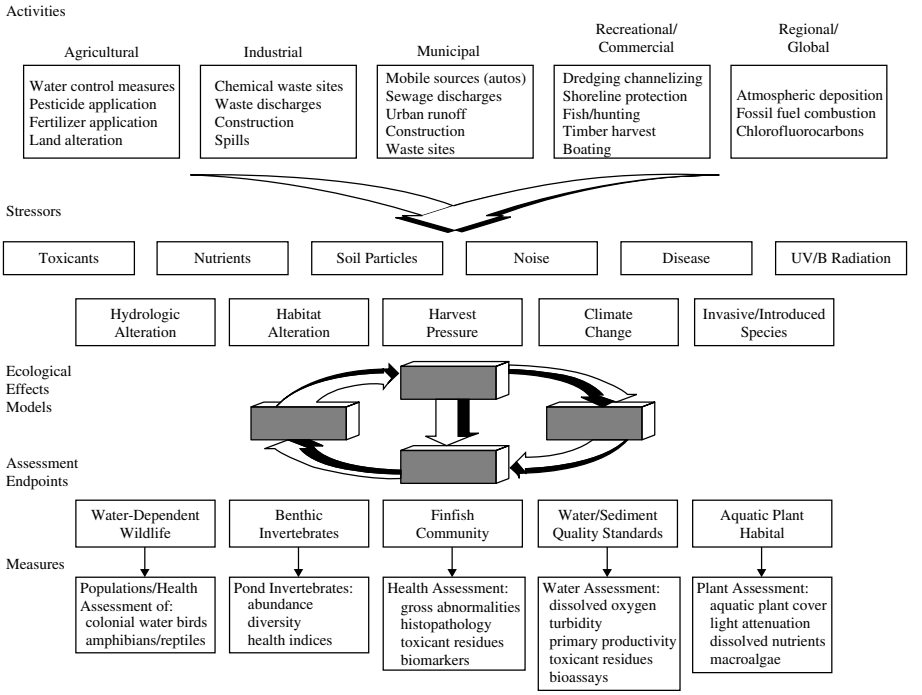

Figure 28.2 An example of a conceptual model for a watershed. Human activities, shown at the top of the diagram, result in various stressors that induce ecological effects. Assessment end points and related measures that are associated with these effects are shown at the bottom of the diagram.

An important consideration in the identification of these measures is their response sensitivity and ecosystem relevance. Response sensitivity is usually highest with measures at the lower levels of biological organization, but the ecosystem relevance is highest at the higher levels of biological organization. This dichotomy is illustrated in Figure 28.3. In general, the time required to illicit a response also increases with the level of biological organization. Note that toxicologists focus on measures at lower levels of biological organization, relying on an extrapolation of the toxicant effects on populations and communities that are initiated at the molecular/cellular level and, if this insult is not corrected for, or adapted to, then effects on physiological systems and individual organisms. For certain toxic modes of action (e.g., reproductive toxicity), this could result in effects at the population and community levels. In contrast, ecologists focus on measures at the population level or higher for obvious reasons of ecological relevance. A combination of measures often is necessary to provide reasonable sensitivity, ecosystem relevance, and causal relationships.

28.3 ANALYZING EXPOSURE AND EFFECTS INFORMATION

The second phase of ecological risk assessment, the analysis phase, includes two principal activities: characterization of exposure and characterization of ecological effects (Figure 28.1).

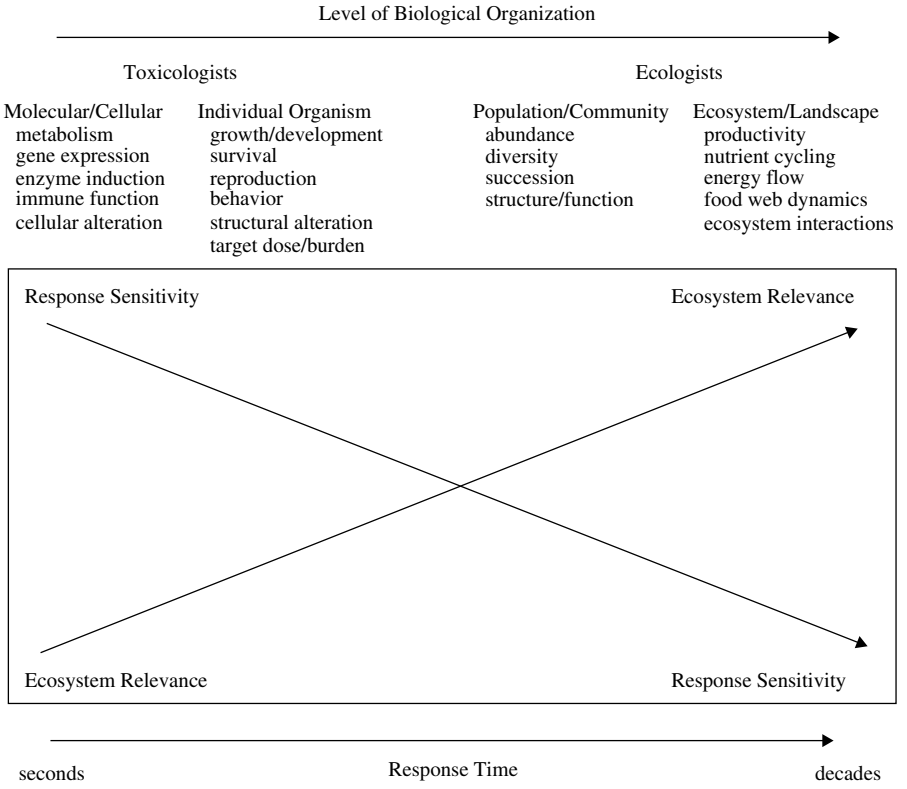

Figure 28.3 The response time and sensitivity of an ecological receptor is a function of the level of biological organization. Higher levels of organization have greater ecosystem relevance. However, as the level of biological organization increases, response time increases, sensitivity decreases, and causal relationships become more uncertain. Ecological risk assessments must balance the need for sensitive, timely, and well-established responses with ecological relevance.

28.3.1 Characterizing Exposure

In exposure characterization, credible and relevant data are analyzed to describe the source(s) of stressors, the distribution of stressors in the environment, and the contact or co-occurrence of stressors with ecological receptors. An exposure profile is developed that identifies receptors and exposure pathways, describes the intensity and spatial and temporal extent of exposure, describes the impact of variability and uncertainty on exposure estimates, and presents a conclusion about the likelihood that exposure will occur.

A source description identifies where the stressor originates, describes what stressors are generated, and considers other sources of the stressor. Exposure analysis may start with the source when it is known, but some analyses may begin with known exposures and attempt to link them to sources, while other analyses may start with known stressors and attempt to identify sources and quantify contact or co-occurrence. The source description includes what is known about the intensity, timing, and location of the stressor and whether other constituents emitted by the source influence transport, transformation, or bioavailability of the stressor of interest.

Many stressors have natural counterparts and/or multiple sources that must be considered. For example, many chemicals occur naturally (e.g., most metals), are generally widespread due to multiple sources (e.g., polycyclic aromatic hydrocarbons), or may have significant sources outside the boundaries of the current assessment (e.g., regional atmospheric deposition of PCBs). Many physical stressors also have natural counterparts such as sedimentation from construction activities versus natural erosion. In addition human activities may change the magnitude or frequency of natural disturbance cycles such as the frequency and severity of flooding. Source characterization can be particularly important for new biological stressors (e.g., invasive species), since many of the strategies for reducing risks focus on preventing entry in the first place. Once the source is identified, the likelihood of entry may be characterized qualitatively.

Because exposure occurs where receptors co-occur with or contact stressors in the environment, characterizing the spatial and temporal distribution of a stressor is a necessary precursor to estimating exposure. The stressor's spatial and temporal distribution in the environment is described by evaluating the pathways that stressors take from the source as well as the formation and subsequent distribution of secondary stressors. For chemical stressors, the evaluation of pathways usually follows the type of transport and fate modeling described in Chapter 27. Some physical stressors such as sedimentation also can be modeled, but other physical stressors require no modeling because they eliminate entire ecosystems or portions of them, such as when a wetland is filled, a resource is harvested, or an area is flooded.

The movement of biological stressors have been described as diffusion and/or jump-dispersal processes. Diffusion involves a gradual spread from the site of introduction and is a function primarily of reproductive rates and motility. Jump-dispersal involves erratic spreads over periods of time, usually by means of a vector. The gypsy moth and zebra mussel have spread this way; the gypsy moth via egg masses on vehicles and the zebra mussel via boat ballast water. Biological stressors can use both diffusion and jump-dispersal strategies, which makes it difficult to predict dispersal rates. An additional complication is that biological stressors are influenced by their own survival and reproduction.

The creation of secondary stressors can greatly alter risk. Secondary stressors can be formed through biotic or abiotic transformation processes and may be of greater or lesser concern than the primary stressor. Physical disturbances can generate secondary stressors, such as when the removal of riparian vegetation results in increased nutrients, sedimentation, and altered stream flow. For chemicals, the evaluation of secondary stressors usually focuses on metabolites or degradation products. In addition secondary stressors can be formed through ecosystem processes. For example, nutrient inputs into an estuary can decrease dissolved oxygen concentrations because they increase primary production and subsequent decomposition. A changeover from an aerobic to an anaerobic environment often is accompanied by the production of sulfide via sulfate-reducing bacteria. Sulfide can act as a secondary stressor to oxygen-dependent organisms, but it also can reduce exposure to metals through the precipitation of metal sulfides (see Chapter 27).

The distribution of stressors in the environment can be described using measurements, models, or a combination of the two. If stressors have already been released, direct measurements of environmental media or a combination of modeling and measurement is preferred. However, a modeling approach may be necessary if the assessment is intended to predict future scenarios or if measurements are not possible or practicable.

28.3.2 Characterizing Ecological Effects

In ecological effects characterization, relevant data are analyzed to evaluate stressor-response relationships and/or to provide evidence that exposure to a stressor causes an observed response. The characterization describes the effects that are elicited by a stressor, links these effects with the assessment endpoints, and evaluates how the effects change with varying stressor levels. The conclusions of the ecological effects characterization are summarized in a stressor-response profile.

Analyzing Ecological Response. Ecological response analysis has three primary components: determining the relationship between stressor exposure and ecological effects, evaluating the plausibility that effects may occur or are occurring as a result of the exposure, and linking measurable ecological effects with the assessment end points.

Evaluating ecological risks requires an understanding of the relationships between stressor exposure and resulting ecological responses. The stressor-response relationships used in a particular assessment depend on the scope and nature of the ecological risk assessment as defined in problem formulation and reflected in the analysis plan. For example, a point estimate of an effect (e.g., an LC50) might be compared with point estimates from other stressors. The stressor-response function (e.g., shape of the curve) may be critical for determining the presence or absence of an effects threshold or for evaluating incremental risks, or stressor-response functions may be used as input for ecological effects models. If sufficient data are available, cumulative distribution functions can be constructed using multiple point estimates of effects. Process models that already incorporate empirically derived stressor-response functions also can be used. However, many stressor-response relationships are very complex, and ecological systems frequently show responses to stressors that involve abrupt shifts to new community or system types.

In simple cases the response will be one variable (e.g., mortality) and quantitative univariate analysis can be used. If the response of interest is composed of many individual variables (e.g., species abundances in an aquatic community), multivariate statistical techniques must be used. Multivariate techniques (e.g., factor and cluster analysis) have a long history of use in ecology but have not yet been extensively applied in risk assessment. Stressor-response relationships can be described using any of the dimensions of exposure (i.e., intensity, time, space). Intensity is probably the most familiar dimension and is often used for chemicals (e.g., dose, concentration). The duration of exposure also can be used for chemical stressor-response relationships; for example, median acute effects levels are always associated with a time parameter (e.g., 24 h, 48 h, 96 h). Both the time and spatial dimensions of exposure can be important for physical disturbances such as flooding. Single-point estimates and stressor-response curves can be generated for some biological stressors. For pathogens such as bacteria and fungi, inoculum levels may be related to the level of symptoms in a host or actual signs of the pathogen. For other biological stressors such as introduced species, developing simple stressor-response relationships may be inappropriate.

Causality is the relationship between cause (one or more stressors) and effect (assessment end point response to one or more stressors). Without a sound basis for linking cause and effect, uncertainty in the conclusions of an ecological risk assessment will be high. Developing causal relationships is especially important for risk assessments driven by observed adverse ecological effects such as fish kills or long-term declines

in a population. Criteria need to be established for evaluating causality. For chemicals, ecotoxicologists have slightly modified Koch's postulates to provide evidence of causality:

1. The injury, dysfunction, or other putative effect of the toxicant must be regularly associated with exposure to the toxicant and any contributory causal factors.
2. Indicators of exposure to the toxicant must be found in the affected organisms.
3. The toxic effects must be seen when normal organisms or communities are exposed to the toxicant under controlled conditions, and any contributory factors should be manifested in the same way during controlled exposures.
4. The same indicators of exposure and effects must be identified in the controlled exposures as in the field.

While useful as an ideal, this approach may not be practical if resources for experimentation are not available or if an adverse effect may be occurring over such a wide spatial extent that experimentation and correlation may prove difficult or yield equivocal results. In most cases extrapolation will be necessary to evaluate causality. The scope of the risk assessment also influences extrapolation through the nature of the assessment end point. Preliminary assessments that evaluate risks to general trophic levels, such as fish and birds, may extrapolate among different genera or families to obtain a range of sensitivity to the stressor. On the other hand, assessments concerned with management strategies for a particular species may employ population models.

Whatever methods are employed to link assessment end points with measures of effect, it is important to apply the methods in a manner consistent with sound ecological and toxicological principles. For example, it is inappropriate to use structure-activity relationships to predict toxicity from chemical structure unless the chemical under consideration has a similar mode of toxic action to the reference chemicals. Similarly extrapolations from upland avian species to waterfowl may be more credible if factors such as differences in food preferences, physiology, and seasonal behavior (e.g., mating and migration habits) are considered.

Finally, many extrapolation methods are limited by the availability of suitable databases. Although these databases are generally largest for chemical stressors and aquatic species, even in these cases data do not exist for all taxa or effects. Chemical effects databases for mammals, amphibians, or reptiles are extremely limited, and there is even less information on most biological and physical stressors. Extrapolations and models are only as useful as the data on which they are based and should recognize the great uncertainties associated with extrapolations that lack an adequate empirical or process-based rationale.

Developing a Stressor-Response Profile. The final activity of the ecological response analysis is developing a stressor-response profile to evaluate single species, populations, general trophic levels, communities, ecosystems, or landscapes—whatever is appropriate for the defined assessment end points. For example, if a single species is affected, effects should represent appropriate parameters such as effects on mortality, growth, and reproduction, while at the community level, effects may be summarized in terms of structure or function depending on the assessment end point. At the landscape level, there may be a suite of assessment end points, and each should be addressed separately. The stressor-response profile summarizes the nature and intensity of effect(s),

the time scale for recovery (where appropriate), causal information linking the stressor with observed effects, and uncertainties associated with the analysis.

28.4 CHARACTERIZING RISK

Risk characterization is the final phase of an ecological risk assessment (Figure 28.1). During risk characterization, risks are estimated and interpreted and the strengths, limitations, assumptions, and major uncertainties are summarized. Risks are estimated by integrating exposure and stressor-response profiles using a wide range of techniques such as comparisons of point estimates or distributions of exposure and effects data, process models, or empirical approaches such as field observational data. Risks are described by evaluating the evidence supporting or refuting the risk estimate(s) and interpreting the adverse effects on the assessment end point. Criteria for evaluating adversity include the nature and intensity of effects, spatial and temporal scales, and the potential for recovery. Agreement among different lines of evidence of risk increases confidence in the conclusions of a risk assessment.

28.4.1 Estimating Risk

Risk estimation determines the likelihood of adverse effects to assessment end points by integrating exposure and effects data and evaluating any associated uncertainties. The process uses the exposure and stressor-response profiles. Risks can be estimated by one or more of the following approaches: (1) estimates based on best professional judgment and expressed as qualitative categories such as low, medium, or high; (2) estimates comparing single-point estimates of exposure and effects such as a simple ratio of exposure concentration to effects concentration (quotient method); (3) estimates incorporating the entire stressor-response relationship often as a nonlinear function of exposure; (4) estimates incorporating variability in exposure and effects estimates providing the capability to predict changes in the magnitude and likelihood of effects at different exposure scenarios; (5) estimates based on process models that rely partially or entirely on theoretical approximations of exposure and effects; and (6) estimates based on empirical approaches, including field observational data. An example of the first approach, using qualitative categorization, is shown in Figure 28.4.

28.4.2 Describing Risk

After risks have been estimated, available information must be integrated and interpreted to form conclusions about risks to the assessment endpoints. Risk descriptions include an evaluation of the lines of evidence supporting or refuting the risk estimate(s) and an interpretation of the adverse effects on the assessment end point. Confidence in the conclusions of a risk assessment may be increased by using several lines of evidence to interpret and compare risk estimates. These lines of evidence may be derived from different sources or by different techniques relevant to adverse effects on the assessment end points, such as quotient estimates, modeling results, field experiments,

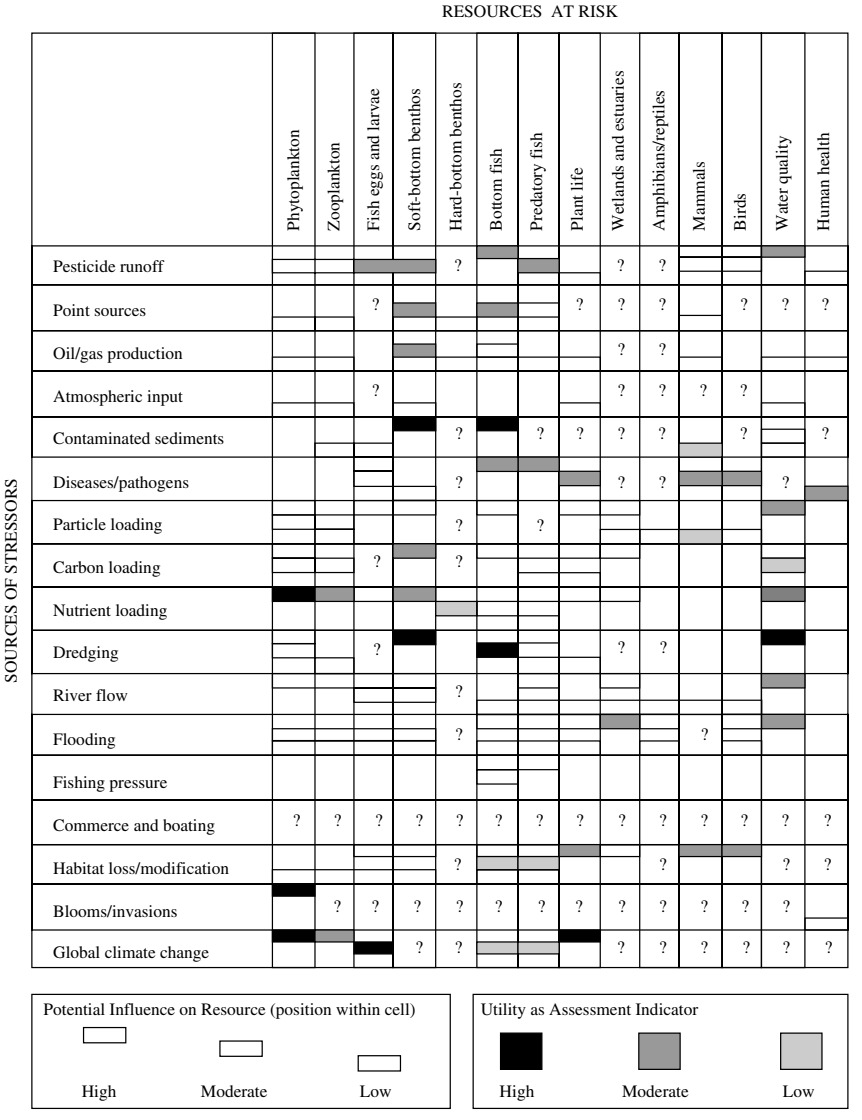

Figure 28.4 An example of a qualitative categorization of ecological risk for a hypothetical matrix of stressors and resources at risk.

or field observations. Some of the factors to consider when evaluating separate lines of evidence are:

- Relevance of evidence to the assessment end points.
- Relevance of evidence to the conceptual model.
- Sufficiency and quality of data and experimental designs used in supporting studies.
- Strength of cause/effect relationships.
- Relative uncertainties of each line of evidence and their direction.

At this point in risk characterization, the changes expected in the assessment end points have been estimated and described. The next step is to interpret whether these changes are considered adverse and meaningful. Meaningful adverse changes are defined by ecological and/or social concerns, and thus usually depend on the best professional judgment of the risk assessor. Five criteria have been proposed by EPA for evaluating adverse changes in assessment end points:

1. Nature of effects
2. Intensity of effects
3. Spatial scale
4. Temporal scale
5. Potential for recovery

The extent to which the five criteria are evaluated depends on the scope and complexity of the ecological risk assessment. However, understanding the underlying assumptions and science policy judgments is important even in simple cases. For example, when exceedence of a previously established decision rule such as a benchmark stressor level or water quality criterion is used as evidence of adversity, the reasons why exceedences of the benchmark are considered adverse should be clearly understood.

To distinguish ecological changes that are adverse from those ecological events that are within the normal pattern of ecosystem variability or result in little or no meaningful alteration of biota, it is important to consider the nature and intensity of effects. For example, an assessment end point involving survival, growth, and reproduction of a species must consider whether predicted effects involve survival and reproduction or only growth. Or if survival of offspring are affected, the relative loss must be considered.

It is important to consider both the ecological and statistical contexts of an effect when evaluating intensity. For example, a statistically significant 1% decrease in fish growth may not be relevant to an assessment end point of fish population viability, and a 10% decline in reproduction may be worse for a population of slowly reproducing marine mammals than for rapidly reproducing planktonic algae.

Natural ecosystem variation can make it very difficult to observe (detect) stressor-related perturbations. For example, natural fluctuations in marine fish populations are often very large and cyclic events (e.g., fish migration) are very important in natural systems. Predicting the effects of anthropogenic stressors against this background of variation can be very difficult. Thus a lack of statistically significant effects in a field study does not automatically mean that adverse ecological effects are absent. Rather, factors such as statistical power to detect differences, natural variability, and other lines of evidence must be considered in reaching conclusions about risk.

Spatial and temporal scales also need to be considered in assessing the adversity of the effects. The spatial dimension encompasses both the extent and pattern of effect as well as the context of the effect within the landscape. Factors to consider include the absolute area affected, the extent of critical habitats affected compared with a larger area of interest, and the role or use of the affected area within the landscape. Adverse effects to assessment end points vary with the absolute area of the effect. A larger affected area may be (1) subject to a greater number of other stressors, increasing the complications from stressor interactions; (2) more likely to contain sensitive species or

habitats; or (3) more susceptible to landscape-level changes because many ecosystems may be altered by the stressors.

Nevertheless, a smaller area of effect is not always associated with lower risk. The function of an area within the landscape may be more important than the absolute area. Destruction of small but unique areas, such as submerged vegetation at the land-water margin, may have important effects on local wildlife populations. Also, in river systems, both riffle and pool areas provide important microhabitats that maintain the structure and function of the total river ecosystem. Stressors acting on some of these microhabitats may present a significant risk to the entire system. Spatial factors also are important for many species because of the linkages between ecological landscapes and population dynamics. Linkages between one or more landscapes can provide refuge for affected populations, and species may require adequate corridors between habitat patches for successful migration.

The temporal scale for ecosystems can vary from seconds (photosynthesis, prokaryotic reproduction) to centuries (global climate change). Changes within a forest ecosystem can occur gradually over decades or centuries and may be affected by slowly changing external factors such as climate. The time scale of stressor-induced changes operates within the context of multiple natural time scales. In addition temporal responses for ecosystems may involve intrinsic time lags, so responses from a stressor may be delayed. Thus it is important to distinguish the long-term impacts of a stressor from the immediately visible effects. For example, visible changes resulting from eutrophication of aquatic systems (turbidity, excessive macrophyte growth, population decline) may not become evident for many years after initial increases in nutrient levels.

From the temporal scale of adverse effects we come to a consideration of recovery. Recovery is the rate and extent of return of a population or community to a condition that existed before the introduction of a stressor. Because ecosystems are dynamic and even under natural conditions are constantly changing in response to changes in the physical environment (weather, natural catastrophes, etc.) or other factors, it is unrealistic to expect that a system will remain static at some level or return to exactly the same state that it was before it was disturbed. Thus the attributes of a "recovered" system must be carefully defined. Examples might include productivity declines in an eutrophic system, re-establishment of a species at a particular density, species re-colonization of a damaged habitat, or the restoration of health of diseased organisms.

Recovery can be evaluated despite the difficulty in predicting events in ecological systems. For example, it is possible to distinguish changes that are usually reversible (e.g., recovery of a stream from sewage effluent discharge), frequently irreversible (e.g., establishment of introduced species), and always irreversible (e.g., species extinction). It is important to consider whether significant structural or functional changes have occurred in a system that might render changes irreversible. For example, physical alterations such as deforestation can change soil structure and seed sources such that forests cannot easily grow again.

Natural disturbance patterns can be very important when evaluating the likelihood of recovery from anthropogenic stressors. Ecosystems that have been subjected to repeated natural disturbances may be more vulnerable to anthropogenic stressors (e.g., overfishing). Alternatively, if an ecosystem has become adapted to a disturbance pattern, it may be affected when the disturbance is removed (fire-maintained grasslands). The lack of natural analogues makes it difficult to predict recovery from novel anthropogenic stressors such as exposure to synthetic chemicals.

The relative rate of recovery also can be estimated. For example, fish populations in a stream are likely to recover much faster from exposure to a degradable chemical than from habitat alterations resulting from stream channelization. It is critical to use knowledge of factors such as the temporal scales of organisms' life histories, the availability of adequate stock for recruitment, and the interspecific and trophic dynamics of the populations in evaluating the relative rates of recovery. A fisheries stock or forest might recover in several decades, a benthic infaunal community in years, and a planktonic community in weeks to months.

28.5 MANAGING RISK

When risk characterization is complete, a description of the risk assessment is communicated to the risk manager (Figure 28.1) to support a risk management decision. This communication usually is a report and might include:

- A description of risk assessor/risk manager planning results.
- A review of the conceptual model and the assessment end points.
- A discussion of the major data sources and analytical procedures used.
- A review of the stressor-response and exposure profiles.
- A description of risks to the assessment endpoints, including risk estimates and adversity evaluations.
- A summary of major areas of uncertainty and the approaches used to address them.
- A discussion of science policy judgments or default assumptions used to bridge information gaps, and the basis for these assumptions.

After the risk assessment is completed, risk managers may consider whether additional follow-up activities are required. Depending on the importance of the assessment, confidence level in the assessment results, and available resources, it may be advisable to conduct another iteration of the risk assessment in order to facilitate a final management decision. Ecological risk assessments are frequently designed in sequential tiers that proceed from simple, relatively inexpensive evaluations to more costly and complex assessments. Initial tiers are based on conservative assumptions, such as maximum exposure and ecological sensitivity. When an early tier cannot sufficiently define risk to support a management decision, a higher assessment tier that may require either additional data or applying more refined analysis techniques to available data may be needed. Higher tiers provide more ecologically realistic assessments while making less conservative assumptions about exposure and effects.

Another option is to proceed with a management decision based on the risk assessment and develop a monitoring plan to evaluate the results of the decision. For example, if the decision is to mitigate risks through exposure reduction, monitoring will help determine whether the desired reduction in exposure (and effects) is being achieved. Monitoring is also critical for determining the extent and nature of any ecological recovery that may be occurring.

Ecological risk assessment is important for environmental decision making because of the high cost of eliminating environmental risks associated with human activities and the necessity of making regulatory decisions in the face of uncertainty. Ecological risk assessment provides only a portion of the information required to make risk

management decisions, but this information is critical to scientifically defensible risk management. Thus ecological risk assessments should provide input to a diverse set of environmental decision-making processes, such as the regulation of hazardous waste sites, industrial chemicals, and pesticides, and improve the management of watersheds affected by multiple nonchemical and chemical stressors.

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PART VIII

SUMMARY

CHAPTER 29

Future Considerations for Environmental and Human Health

ERNEST HODGSON

29.1 INTRODUCTION

Since the publication of the second edition of this textbook there has been rapid, and in some cases dramatic, progress not only in toxicology but in the sciences that contribute methods and insights to toxicology. However, it is still true that speculation concerning future developments in toxicology can be made only against an assessment of where the science has come from and its current status. Toxicology, despite its use of many state-of-the-art techniques and explorations of the most fundamental molecular mechanisms of toxic action, is, at its heart, an applied science serving the needs of society. Society is served in two principal ways: the protection of human health and the protection of the environment. In both of these aspects two avenues are explored: studies of chemicals in use and the development of new chemicals that are both safe and effective. These studies range from studies of the mechanisms of toxic action to in vivo toxicity testing, but the ultimate goal is a meaningful assessment of risk resulting from exposure to the chemicals in question.

The vast increase in public awareness of the potential of chemicals to cause harmful effects and the propensity of the print and electronic media to fan the flames of controversy in this area make certain the continued need for toxicologists. We need to ask what they will be doing during the next few decades compared to what they have been doing in the immediate past.

Through the 1950s and 1960s toxicology tended to be a largely descriptive science, relating the results of in vivo dosing to a variety of toxic end points, in many cases little more that the medial lethal dose (LD50) or median lethal concentration (LC50). However, ongoing studies of xenobiotic-metabolizing enzymes were attracting more attention and techniques for chemical analysis of toxicants were starting to undergo a remarkable metamorphosis. The 1970s were most remarkable for developments in metabolism and the beginnings of a boom in mode of toxic action studies, whereas the 1980s and 1990s saw the incorporation of the techniques of molecular biology into many aspects of toxicology, but perhaps to greatest effect in studies of the mechanisms of chemical carcinogenesis and the induction of xenobiotic-metabolizing enzymes.

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It should be emphasized that all of these activities proceed simultaneously, and that increased emphasis and interest in any particular area is often preceded by the development of new techniques—for example, the tremendous increase in specificity and sensitivity of chemical methods has proceeded simultaneously with the introduction of molecular biologic techniques into studies of mechanisms of toxic action.

The success of the project to describe the human genome along with progress in the definition of polymorphisms in human xenobiotic-metabolizing enzymes and other proteins will certainly lead to the ability to define populations and individuals at increased risk from a particular chemical insult. This ability will be extended and put on a more mechanistic basis by advances in the new disciplines of proteomics and metabonomics.

The future, both immediate and long term, will provide important information an all aspects of toxic action and the role of toxicology in public life will mature as the importance of toxicology is perceived by the population in general, first in developed countries and ultimately around the world. The fundamental role of the toxicologist, namely the acquisition and dissemination of information about all aspects of the deleterious effects of chemicals on living organisms, will not change; however, the manner in which it is carried out will almost certainly change. The next several decades will be exciting times for toxicologists, and those in training at this time have much to anticipate.

Change can be expected in almost every aspect of both the applied and the fundamental aspects of toxicology. Risk communication, risk assessment, hazard and exposure assessment, in vivo toxicity, development of selective chemicals, in vitro toxicology, and biochemical and molecular toxicology will all change, as will the integration of all of these areas into new paradigms of risk assessment and of the ways in which chemicals affect human health and the environment.

The importance of a new group of potential toxicants, genetically modified plants (GMPs) and their constituents, has emerged in the last decade. Potentially a boon to the human race, they have already generated considerable controversy. While these products of applied molecular biology appear to be relatively harmless, both to human health and to the environment, they will need to be monitored as they increase in number and complexity.

29.2 RISK MANAGEMENT

Public decisions concerning the use of chemicals will continue to be a blend of science, politics, and law, with the media spotlight continuing to shine on the most contentious aspects: the role of the trained toxicologist to serve as the source of scientifically sound information and as the voice of reason will be even more critical. As the chemist extends our ability to detect smaller and smaller amounts of toxicants in food, air, and water, the concept that science, including toxicology, does not deal in certainty but only in degrees of certitude must be made clear to all. Although this concept is easy for most scientists to grasp, it appears difficult, even arcane, to the general public and almost impossible to the average attorney or politician. Risk will have to be managed in the light of our new found ability to identify individuals and populations at increased and to accommodate new legislation such as the Food Quality Protection Act.

29.3 RISK ASSESSMENT

In the past, risk assessment consisted largely of computer-based models written to start from hazard assessment assays, such as chronic toxicity assays on rodents, encompass the necessary extrapolations between species and between high and low doses, and then produce a numerical assessment of the risk to human health. Although the hazard assessment tests and the toxic end points are different, an analogous situation exists in environmental risk assessment. A matter of considerable importance, now getting some belated attention, is the integration of human health and environmental risk assessments.

Although many of these risk assessment programs were statistically sophisticated, they frequently did not rise above the level of numbers crunching, and more often than not, different risk assessment programs, starting with the same experimental values, produced very different numerical assessments of risk to human health or to the environment. Although having risk assessment become more science based has been a stated goal of regulators for decades, its scientific basis has not been advanced significantly. The need to incorporate mechanistic data, including mode of action studies and physiologically based pharmacokinetics, has been realized to some extent. Apart from epidemiology and exposure analysis, human studies have not, despite the fact that many such studies can now be performed in noninvasive and ethical experiments.

The immediate future in risk assessment will focus on the difficult but necessary task of integrating experimental data from all levels into the risk assessment process. A continuing challenge to toxicologists engaged in hazard or risk assessment is that of risk from chemical mixtures. Neither human beings nor ecosystems are exposed to chemicals one at a time, yet logic dictates that the initial assessment of toxicity start with individual chemicals. The resolution of this problem will require considerable work at all levels, in vivo and in vitro, into the implications of chemical interactions for the expression to toxicity, particularly chronic toxicity.

29.4 HAZARD AND EXPOSURE ASSESSMENT

The enormous cost of multiple-species, multiple-dose, lifetime evaluations of chronic effects has already made the task of carrying out hazard assessments of all chemicals in commercial use impossible. At the same time, quantitative structure activity relationship (QSAR) studies are not yet predictive enough to indicate which chemicals should be so tested and which chemicals need not be tested. In exposure assessment, continued development of analytical methods will permit ever more sensitive and selective determinations of toxicants in food and the environment, as well as the effects of chemical mixtures and the potential for interactions that affect the ultimate expression of toxicity. Developments in QSARs, in short-term tests based on the expected mechanism of toxic action and simplification of chronic testing procedures, will all be necessary if the chemicals to which the public and the environment are exposed are to be assessed adequately for their potential to cause harm.

29.5 IN VIVO TOXICITY

Although developments continue in elucidating the mechanisms of chemical carcinogenicity, much remains to be done with regard to this and other chronic end points,

particularly developmental and reproductive toxicity, chronic neurotoxicity, and immunotoxicity. The further utilization of the methods of molecular biology will bring rapid advances in all of these areas. It will be a challenge to integrate all of this information into useful paradigms for responsible and meaningful risk assessments.

29.6 IN VITRO TOXICITY

In vitro studies of toxic mechanisms will depend heavily on developments in molecular biology, and great advances can be expected. Many of the ethical problems associated with carrying out studies on the effects of toxicants on humans will be circumvented at the in vitro level by the use of cloned and expressed human enzymes, receptors, and so on, although the integration of these data into intact organism models will still require experimental animals. High-throughput technology in genomics, proteomics, and metabonomics will greatly facilitate these studies.

29.7 BIOCHEMICAL AND MOLECULAR TOXICOLOGY

As indicated previously, contributions to all aspects of the mechanistic study of toxic action from the use of biochemical and molecular techniques can be expected. No doubt new techniques will be developed, answers will be found to many questions that did not yield to earlier techniques and new questions will be raised. The challenge, as always, will be to integrate the results form these studies—and reach new levels of sophistication—into useful and productive approaches to reduce chemical effects on human health and the environment.

29.8 DEVELOPMENT OF SELECTIVE TOXICANTS

Almost all aspects of contemporary human society depend on the use of numerous chemicals. Except in the unlikely event that society decides to return to a more simplistic and, in fact, more primitive, more unhealthy, and more demanding lifestyle, the challenge is in learning how to live with anthropomorphic chemicals, and not in learning how to live without them. In many aspects, such as the production of food and fiber and the maintenance of human health, the development of selective pesticides, drugs, and so on, is needed. New techniques in molecular biology, in particular, the availability of cloned and expressed human enzymes and receptors and new knowledge of human polymorphisms, will make this task easier, as will similar knowledge of target species, including microorganisms causing human disease, and insects and weeds affecting the production of food and fiber, and so on.

High-throughput techniques will not only speed up the search, but in this area, as in other aspects of toxicology, bioinformatics will be necessary, not only for correlating the data from many sources but also for reducing it for practical applications.