Endpoints for Regional Ecological Risk Assessments

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ABSTRACT / Ecological risk assessments must have clearly defined endpoints that are socially and biologically relevant, accessible to prediction and measurement, and susceptible to the hazard being assessed. Most ecological assessments do not have such endpoints, in part because the endpoints of toxicity tests or other measurements of effects are used as assessment endpoints. This article distinguishes assessment and measurement endpoints in terms of their roles in risk assessments and explains how the criteria for their selection differ. It then presents critical discussions of possible assessment and measurement endpoints for regional ecological risk assessments. Finally, the article explains how endpoint selection is affected by the goal of the assessment. Generic goals for regional risk assessment include explanation of observed regional effects, evaluation of an action with regional implications, and evaluation of the state of a region. Currently, population level assessment endpoints such as abundance and range are the most generally useful. For higher levels (ecosystems and regions), data are generally not available and the validity of models has not been demonstrated, and for lower level effects (physiological, and organismal) are not relevant. However, landscape descriptors, material export, and other regional-scale measurement endpoints show promise for regional assessments.

Regional ecological risk assessment is concerned with describing and estimating risks to environmental resources at the regional scale or risks resulting from regional-scale pollution and physical disturbance (Hunsaker and others 1989). Examples include acid rain effects, ozone depletion, and pollution of a river basin by multiple-point and nonpoint pollution sources. Because of the apparent increase in the number of regional problems and the recognition of the value of a regional perspective in environmental regulation, the need for regional risk assessment is increasing. If regional assessments are to be performed efficiently and effectively, it is necessary to consider how each of the components of a risk assessment must be adapted to address regional-scale problems. The component addressed in this paper is the endpoints, those characteristics of valued environmental entities that are believed to be at risk.

Ecological risk assessments begin with three activities that define the nature of the problem to be assessed: choosing endpoints, describing the environment, and describing the hazard. These are followed by a formal analysis of the problem which consists of exposure assessment, effects assessment, and integration of the exposure and effects assessments to estimate the probability and level of effects. In a process called risk management, the results of the risk assessment are considered along with economic, technological, and political considerations to arrive at a decision. Each of these component processes should be coordinated. This article describes two different expressions of endpoints, presents criteria for judging endpoints, presents endpoints that are potentially useful in regional risk assessments, judges them by the criteria, and discusses how the nature of the assessment problem affects endpoint choice.

KEY WORDS: Endpoints; Risk; Assessment; Regional; Landscape

Types of Endpoints

Some confusion has occurred in environmental risk assessment because the term endpoint has been used to describe two related but distinct concepts. To avoid this confusion, I have distinguished assessment endpoints from measurement endpoints (Suter 1989) and that distinction has been adopted by the US Environmental Protection Agency's Ecotoxicity Subcommittee (Hinckley 1989). Assessment endpoints are formal expressions of the actual environmental value that is to be protected. The output of a risk assessment is an estimated probability of occurrence of a dichotomous assessment endpoint (e.g., probability of extinction of a species) or an estimated relationship between probability and magnitude of a scalar assessment endpoint (e.g., probability that the number of fishless lakes will be greater than *X*). These expressions of effects on assessment endpoints are the input to the risk-management process. Assessment endpoints must be valued by society, but they are not ultimate values. Rather, they are the highest values that can be assessed formally. In regional risk assessment, the ultimate value is the quality of life provided to the region's inhabitants, which is an indefinable function of the region's ability to provide food, clean water and air, aesthetic experience, recreation, and other services without floods,

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property-damaging fires, and other disservices. Such ultimate values fall in the domain of risk management where risk assessment results are considered along with political, economic, and ethical values.

A measurement endpoint is an expression of an observed or measured response to the hazard; it is a measurable environmental characteristic that is related to the valued characteristic chosen as the assessment endpoint. In the simplest cases, a measurement endpoint is an instrumental reading such as a pH measurement in a lake acidification study. More often, measurements of ecological responses are composed of a complex set of observations, and the measurement endpoints are statistical or arithmetic summaries of the observations that comprise the measurement. Examples are the median lethal concentration (LC_{50}), a point on a regression line fitted to observed mortality rates in sets of organisms exposed to a series of toxicant concentrations, and relative abundance measures such as area of wetland per unit length of coast (WRI/IIED 1986). The term "test endpoint" is used in environmental toxicology, and measurement endpoint is simply an expansion of this concept to include field monitoring studies. In some cases, the measurement endpoint may be the same as the assessment endpoint. For example, if the endpoints for sugar maple decline are increased mortality and decreased sugar production, then sugar maple mortality rates and sugar production can be directly monitored and related to environmental conditions. Because the assessment endpoint may not be observable or measurable or because available or standard data must be used in an assessment, measurement endpoints are often surrogates for the assessment endpoints. For example, if the assessment endpoints are reductions in populations of largemouth bass and the hazard is an effluent containing aniline dyes, then a measurement endpoint might be an aniline LC_{50} for fathead minnows. Alternatively, measurement endpoints may be part of the causal link between a disturbance and the assessment endpoint. For example, one might measure habitat loss and infer effects on a wildlife population.

Although all risk assessments must have assessment endpoints, there may be no measurement endpoints. The assessment may be based on theory or assumptions about the relationship between the hazard and the assessment endpoints. For example, Krummel and others (1984) assessed the sensitivity of plant communities in western Kentucky on the basis of the distribution of SO_2 concentrations relative to the distribution of plant communities. Because they did not have the opportunity to measure SO_2 effects in the various communities and did not feel that the existing phytotoxicity data were adequate, the authors hypothesized two possible threshold concentrations for SO_2 effects and assumed that all communities were equally sensitive. The uncertainty introduced by the absence of effects measurements limited the assessment to suggesting areas that were worthy of study rather than actually predicting effects. In other cases, measurements may be unnecessary or impossible. For example, if the assessment endpoint for an assessment of a proposed power plant is the probability of exceeding an air quality standard, then there is no environmental response to measure and, assuming that good local meteorologic data and source terms are available, models based on atmospheric theory are adequate predictors.

Unfortunately, in many monitoring programs, clear measurement endpoints are applied to vague assessment endpoints such as "are the things that we are measuring changing?" or "are the things that we are measuring different at these two sites?" Without a clear definition of why measurements are being taken, time and effort are wasted. If one monitors any aspect of the environment long enough, change will be seen, and if any two sites are sampled intensively enough, they will be found to differ. A clearly defined assessment endpoint not only indicates what is worth measuring, but also how intensively it must be measured.

Criteria for Endpoints

Assessment Endpoints

Criteria for good ecological risk assessment endpoints are listed in Table 1. First, an assessment endpoint should have societal relevance; that is, it should be an environmental characteristic that is understood and valued by the public and by decision makers. In local risk assessments the most appropriate endpoints often are effects on valued populations such as crops, trees, or game fish, and these are likely to be important in regional assessments, also. Societal value is emphasized because assessments of risks to nematodes or aphids are unlikely to influence decisions. This is not to say that species and other environmental attributes that are not publicly valued or understood have no place in environmental risk assessment. Rather, if species that are not socially valued are particularly susceptible, then they must be explicitly linked to valued species or other valued environmental attributes.

It is desirable that the assessment endpoint have biological relevance. The biological significance of an effect is a function of its implications for the next higher level of biological organization. For example, the sig-

Table 1. Characteristics of good assessment endpoints.

Social relevance
Biological relevance
Unambiguous operational definition
Accessible to prediction and measurement
Susceptible to the hazard

nificance of infertility of individuals is determined by the resulting population reduction, and the significance of the loss of a major grazing species is determined by the ability of other grazers to substitute functionally for the lost species, thereby sustaining the community structure. Biological significance may not correspond to societal significance. The abundance of bald eagles has clear societal significance and is an important assessment endpoint on that basis alone, but the near extinction of bald eagles in the contiguous United States apparently had no significance for the rest of the biota.

Assessments often fail because their endpoints lack unambiguous operational definitions (Beanlands and Duinker 1983). Phrases such as "ecosystem integrity" and "balanced indigenous populations" adequately express the longing of legislators for a good natural environment, and they are suitable subjects for contemplation by the risk manager, but they are not suitable subjects for assessment because they cannot be measured or modeled from any measurement. Exactly how do we know when an ecosystem has lost its integrity and what do we balance a population against? A complete operational definition of an assessment endpoint requires a subject (bald eagles or endangered species in general) and a characteristic of the subject (local extinction or a percentage reduction in range).

Assessment endpoints should be accessible to prediction and measurement. Prediction requires (1) toxicity tests and statistical models for summarization and extrapolation of test results; (2) measurements of responses of similar systems to similar hazards; or (3) mathematical models of the response of the system to the hazard. For example, sharks are not used in toxicity tests and good fisheries data for sharks are not available, so effects of pollution on sharks are not good assessment endpoints. This may seem inappropriately dismissive of a large group of organisms. However, we cannot assess effects on everything, and, in the absence of a clear hazard with major societal significance that will support an extensive research effort, risk assessments must concentrate on endpoints such as production of teleost fish for which good data and methods exist.

Finally, the assessment endpoints must be susceptible to the hazard being assessed. Susceptibility results from a potential for exposure and responsiveness of the organisms or ecosystem attribute to the exposure. In some cases, susceptibility will be known in advance because observed effects prompted the assessment. In other cases, where a novel hazard is involved or the causal linkage between the putative hazard and the observed damage is unclear, screening assessments may be needed to establish susceptibility before proceeding to assess levels and probabilities of effects. This criterion is as important as the others, but it will not be discussed further because susceptibility is too complex to be treated adequately here.

The seriousness of effects has been suggested as a criterion in other discussions of endpoints (e.g., American Management Systems, Inc. 1987) but is excluded here as inappropriate. This criterion includes severity, reversibility, and extent. If an endpoint has societal and biological significance, then it should not be excluded simply because more serious effects are possible. Rather, both serious but low-probability endpoints and less serious but potentially high-probability endpoints should be assessed so that they can be considered and balanced in the risk management process.

Measurement Endpoints

The criteria for a good measurement endpoint are listed in Table 2. First, a measurement endpoint must correspond to or be predictive of an assessment endpoint. The environmental sciences literature is replete with examples of traits that were measured in the laboratory or field but that could not be explicitly translated into a societally or biologically important environmental value. If a measurement endpoint does not correspond to an assessment endpoint, it should be correlated with an assessment endpoint or should be one of a set of measurement endpoints that predict an assessment endpoint through a statistical or mathematical model. For example, the assessment endpoint, landscape aesthetics, might be a function of two measurement endpoints, a landscape dominance index and the percent of the landscape that is visibly disturbed.

Measurement endpoints should be readily measured. That is, it should be possible to obtain accurate measurements quickly and cheaply using existing techniques.

Measurement endpoints must be appropriate for the scale of the pollution, physical disturbance, or other hazard. It would be inappropriate to measure the outmigration of salmon smolts to determine the effects of an individual waste outfall, but outmigration

Table 2. Characteristics of good measurement endpoints.

Corresponds to or is predictive of an assessment endpoint
Readily measured
Appropriate to the scale of the disturbance/pollution
Appropriate to the route of the exposure
Appropriate temporal dynamics
Low natural variability
Diagnostic
Broadly applicable
Standard
Existing data series

might be appropriate as a measure of the quality in an entire riverine watershed as fish habitat.

Measurement endpoints must be appropriate to the route of exposure. The organisms or communities that are measured should be exposed to the polluted media and should have the same routes of exposure in approximately the same proportions as assessment endpoint organisms or communities. When such matching is not possible, then organisms that have the highest exposure should be used. For example, at sites where soil is contaminated, burrowing rodents have higher exposures than rodents that use surface runs and nests (McBee 1985). As another example, canopy trees have greater exposure to air pollutants than understory trees, and trees on ridge tops have high exposures to regional pollution, while trees on the sides of ridges at the average inversion height have the greatest exposure to local pollutants.

Measurement endpoints should have appropriate temporal dynamics. If the hazard is episodic, then the measured response should be persistent so that evidence of effects will still be apparent after the event. For example, visible injury of leaves is apparent after air pollution episodes but photosynthetic rates recover rapidly.

Measurement endpoints should have low natural variability. Responses that are highly variable among individuals or across space and time have low signal-to-noise ratios when used to measure pollution effects. As a result, either the effects are masked or large numbers of replicates must be used. The importance of variability depends on the relative scales of the variance and the measurements. For example, most environmental assessments address effects on the scale of years, so diurnal variance is irrelevant and variance resulting from climatic trends on the scale of hundreds to thousands of years is not detected in such assessments.

It is desirable for measurement endpoints to be diagnostic of the pollutants of interest, to the extent that the pollutants have been identified. For example, concentrations of adrenal corticoids are indicators of stress in general, DNA single strandedness is indicative of genotoxins, and DNA adducts of benzo[A]pyrene (BAP) are indicative of DNA damage by BAP.

It is desirable for measurement endpoints to be broadly applicable to allow comparison among sites and regions. For example, armadillos are probably good monitors of soil pollutants because they burrow and feed on soil and litter invertebrates. However, armadillos occur in a small portion of the United States, while mice of the genus *Peromyscus* are ubiquitous.

It is desirable for measurement endpoints to be standardized to allow precise comparisons among sites or tests. Standard methods and endpoints for toxicity testing are readily available for a variety of aquatic organisms, for some terrestrial animals, for a few plant responses, and for a few microcosms and mesocosms. Sources include the American Society for Testing and Materials (ASTM), American Public Health Association (APHA), Organization for Economic Cooperation and Development (OECD), and Environmental Protection Agency (EPA). Standard methods for measuring pollutant concentrations in the environment are available from the same organizations. Methods for biological monitoring are much less standardized and what standards exist (e.g., ASTM 1987) are not as widely used.

Finally, it would be desirable to use a measurement endpoint for which there is an existing time series of data so that background levels, variability, and trends can be estimated. There is the additional advantage that data from an ongoing monitoring or testing program are free. Potential examples are climatic data, air and water quality data, and harvest data for resource species.

Potential Assessment Endpoints

Potential assessment endpoints for ecological risk assessment are listed in Table 3. They are divided into two categories: (1) traditional endpoints that have been used for local environmental risk assessments and may be useful in regional assessments, and (2) endpoints that are characteristic of regions. The listed assessment endpoints are actually classes of endpoints; an endpoint for a real assessment would specify the entity and characteristic (e.g., frequency of kills of more than 100 fish of any species). Even at this level of generality, any list of endpoints will be incomplete. Anyone can imagine other assessment endpoints that may be useful in specific cases. The endpoints listed in Table 3 were chosen to have generic utility.

Table 3. Potential assessment endpoints for regional ecological risk assessments.

Traditional
Population
Extinction
Abundance
Yield/production
Frequent gross morbidity
Contamination
Massive mortality
Community/ecosystem
Market/sport value
Recreational quality
Change to less useful/desired type
Abiotic
Air and water quality standards
Characteristic of Regions
Population/species
Range
Productive capability
Soil loss
Nutrient loss
Regional production
Pollution of other regions
Pollution of outgoing water
Pollution of outgoing air
Susceptibility
Pest outbreaks
Fire
Flood
Low flows
Landscape aesthetics
Climatic changes
Continental glaciation
Sea level rise
Drought
Increased UV radiation

Populations

Population-level assessment endpoints have generally been the most useful in local risk assessments because: (1) responses at lower levels (i.e., organismal and suborganismal) have no social or biological significance; (2) populations of many organisms have economic, recreational, aesthetic, and biological significance that is easily appreciated by the public; and (3) population responses are well defined and easier to predict with available data and methods than are community and ecosystem responses. Clearly, the societal or biological significance of population-level responses depends on the societal or biological importance of the species. Changes of productivity of a soil nematode or a rotifer population would be unnoticed and unmourned by the public and would not have significant biological repercussions in most ecosystems. The remainder of this discussion will be referring to populations of socially or biologically important species.

The most socially and biologically significant population-level effect is extinction. It should be predicted with good success if the hazard is habitat loss and with moderate success for toxic effects. Extinction can be monitored with relative ease for conspicuous species. If we declare a species functionally extinct when it is not sufficiently abundant to fulfill its societal or biological role (e.g., a fish that is too rare to support a fishery or a predator that is too rare to affect prey population size), all extinctions of macroorganisms are easily monitored.

Abundance, production, and yield are expressions of the ability of a population to fulfill a biological or resource role. If the abundance of a valued population, such as a sport fish or song bird declines, the societal significance is obvious. The biological significance of abundance and production depends on the natural variability of the species and its role in the biotic community. Although techniques exist to predict these quantitative population responses, their reliability is not well established. Effects of habitat modification on wildlife can be predicted using, for example, the US Fish and Wildlife Service's habitat evaluation procedure (Division of Ecological Services 1980), and effects of pollutants can be predicted by applying the effects observed in toxicity tests to population models (Barnthouse and others 1987, 1989, Larson and Heck 1984). Abundance is easily measured locally for many species but is difficult to measure over an entire region. Techniques exist for measuring production of most species in the field, but they are more difficult and less accurate than abundance measures. For resource species, regional abundance or yield data are often available from resources agencies.

Frequent gross morbidity (tumors, lesions, and deformities) or mass mortality (fish kills and tree die-offs) are societally significant because they are aesthetically unappealing and because mortality diminishes the availability of resources. Morbidity and mortality are also significant because the public has come to interpret them as signs of pollution that may constitute a human health threat. Gross morbidities have little biological significance per se, but mass mortalities can be highly significant and can be translated into monetary values (Economic Analysis, Inc. 1987). Mass mortality is relatively easily predicted if good exposure estimates are available because the most common toxicological endpoints represent laboratory mass mortalities (i.e., LC_{50}s and LD_{50}s). Gross morbidity is not presently predictable, although deformities are observed in reproductive toxicity tests. Mass mortality of fish is readily apparent in inland waters, and state agencies often keep records of fish kills. Mass mortality of trees and coastal marine mammals is also apparent. Mass mortality of most other organisms is likely to go undetected. Gross morbidity is more readily measured because the conditions persist and can be evaluated by inspection of a sample of organisms.

Contamination of populations by pollutants has societal significance if the organisms provide human food. This endpoint is well defined for many chemicals by the FDA action levels. It is readily predicted for aquatic organisms from concentrations in water but not for terrestrial plants or wildlife. Contamination is easily measured and is already monitored in commercial foods.

Population-level endpoints are appropriate to regional assessments under three circumstances. (1) If the subject of the assessment is a jeopardized species, such as an endangered species, or a declining species, such as the black duck, then population endpoints must be evaluated at a regional scale where the region corresponds to the range of the species or the portion of the range where the decline is occurring. (2) Population-level endpoints are appropriate when the abundance or other characteristics of a species characterize the perceived value of a region. For example, preservation of old-growth forest in northern California, Oregon, and Washington has been an issue for decades but the issue has been largely expressed in terms of preservation of populations. First there was "save the redwoods," which meant save the oldest age classes of redwoods. More recently, saving the spotted owl has been an assessment endpoint that also expresses a desire to save the old-growth coniferous forest community type (Simberloff 1987). (3) Population-level endpoints could be used to characterize the state of a region by selecting a suite of species whose status would serve to integrate the physical and chemical disturbance of a region. These might include classic indicator species (e.g., sludge worms and mayflies for polluted and clean aquatic environments, respectively), endangered or declining species, and commercial or recreational species.

Community and Ecosystem

Changes in the character of a biotic community can have major societal implications. If the market or sport value of a community changes, as from a fish community dominated by pelagic species such as lake trout or striped bass to one dominated by benthic species such as carp and suckers, the societal implications are obvious. Similarly, community changes such as severe eutrophication can diminish the recreational value of the community. Changes of community type that do not directly involve commercial, sport, or recreational values are also likely to be regarded as changing the utility or desirability of the community. However, the definition of what constitutes a significant negative change in a community type is often ambiguous. A moderate increase in the trophic status of a lake may increase production of desirable fish species but diminish the value for swimming, boating, and aesthetic enjoyment, particularly in an oligotrophic lake such as Lake Tahoe, California.

A change in community type is likely to have biological significance because large numbers of species and large areas are potentially involved. However, whether a particular change is biologically significant depends on the particular change and the community function evaluated. For example, conversion of a mixed forest to a pine plantation would decrease the number of animal species supported but could increase habitat for the endangered red-cockaded woodpecker.

Endpoints for most significant community transformations can be given good operational definitions. Examples include the conventional classification of lake trophic states and classifications of vegetation types.

Prediction of community changes resulting from physical disturbances (e.g., conversion of forest to pasture or filling of wetlands) is a trivial assessment problem if we know what types of communities will inhabit the sites. Effects on communities of additions of nontoxic pollutants (e.g., organic matter and nutrients) are reasonably predictable in aquatic systems, and there is a growing body of information on sludge and wastewater disposal in terrestrial systems that can provide a basis for prediction. Effects on communities of toxic chemicals are not directly predictable. They can be inferred from information on toxicity to component taxa and knowledge of the relationship between taxa (O'Neill and others 1982, 1988, West and others 1980, Dale and Gardner 1987), but there is not sufficient experience with this approach to evaluate its predictive power. Microcosms and mesocosms are an alternate means of assessing toxic effects in communities, but their utility is not well established.

Community transformations that take the form of changes in vegetation are easily measured from satellite and aerial images or ground surveys. Monitoring changes in terrestrial animal communities and in aquatic communities requires greater effort in sampling or observation but present no conceptual problems.

At a regional scale, the appropriate expressions of community-level endpoints are frequency of changes of community type or changes in the area of community types. Examples include changes in the frequency of unacidified lake communities and reduced area of old-growth forests. These may be assessed directly by characterizing the communities or, as mentioned above, indicator populations may be assessed. In the lake acidification example, one can predict the presence of a salmonid-dominated community by assessing effects of pH and aluminum on trout (Christensen and others 1988) or by assessing landscape characteristics that lead to high exposures to acidity and aluminum (Hunsaker and others 1986).

Air and Water Quality Standards

Although the derivation of air and water quality criteria and standards is a difficult and complex process, use of standards as assessment endpoints is simple. It is assumed that exceedence of standards is both societally and biologically significant. Standards are completely and precisely defined and measurable and can be predicted by standard models of pollutant transport and fate. Their chief limitations are that they have no meaning outside the legal regulatory context (i.e., knowing that a standard is exceeded tells you something about legal consequences but nothing about environmental consequences), and they only protect those environmental values that were included in the standard setting process. Sensitive responses, such as reduction in plant growth by ozone or material damage by sulfates, may be neglected in favor of human health. Poorly understood mechanisms (e.g., behavioral effects) are left out of the estimation of criteria and standards, and poorly understood effects (e.g., effects of acid deposition on trees) are left out of the standard-setting process entirely.

Regional Populations

The range of a population or species is the lowest-level endpoint that is characteristic of the regional scale (Table 3). Range is socially significant to people at the edge of a species' range who may lose the benefits of the species. Range reductions are biologically significant in that the functional properties of the species are lost in the former range and in that the species may become more susceptible to extinction. Range can be readily measured for macroscopic species. Range reductions that are due to local hazards that cause local extinctions are generally predictable, but range reductions resulting from a regional hazard (e.g., shrinkage of the range of a tree species because of the combined effects of regional air pollution and suboptimal habitat at the periphery of its range) are not readily predicted.

Regional Productive Capability

Productive capability has clear societal and biological significance, but that significance is discounted relative to current production. Productive capability is difficult to define, predict, or measure, and realized regional production is a crude estimate of productive capability. The processes of soil and nutrient loss imply loss of productive capability if they exceed soil formation and nutrient input. Soil and nutrient loss can be readily measured in effluent rivers; losses in air are more difficult to measure but are much smaller in most of the United States. Production of resource species can be estimated from agricultural, forestry, and wildlife statistics. Prediction of soil loss is routine on the scale of individual fields (Wischmeier and Smith 1978), but no good methods are available for predicting regional soil or nutrient loss. Prediction of agricultural and forestry production relies primarily on economic models rather than environmental models because of the importance of management and land conversion.

None of these indicators of productive capability is easily or reliably interpretable. The problem is in large part a matter of spatial aggregation and of aggregation of distinct processes. Soil export from a region does not indicate how soil might be moved around within a region, such as from fields to riparian lowlands or to the bottoms of reservoirs. Similarly, soil loss from agricultural fields has different implications than loss from a construction site that will no longer produce crops or forests. Erosion control at a construction site will improve water quality but has no implications for future terrestrial production. Increased nutrient export may reflect a loss of productive capability or may reflect increased fertilizer use and increased sewage disposal. Increases in realized production may reflect a genuine improvement in productive capability or simply more intensive management, such as irrigation or conversion of mature natural forests to tree plantations. Conversely, some management practices, such as herbicide use and treatment of water to reduce nutrient content, are intended to reduce total production. If productive capability is to be assessed, it may be necessary to address soil and nutrient loss at a smaller scale than a region or to address realized production in terms of specific valued species such as crops and timber trees, preferably normalized to input of land, fertilizer, water, and energy. Brown (1987) suggested ecologically deflated production as an indicator of productive capability. It is calculated as realized agricultural production minus production from unsustainable practices such as tillage of highly erodible land. Clearly, endpoints for regional productive capability are still a subject for research.

Pollution of Other Regions

The amount of pollution exported by a region is an indicator both of damage done to adjoining regions and of the amount of pollutant chemicals in the regional environment. Pollution export is easily measured in outflowing rivers but not in air. It is predictable for both air and water for point sources and for those pollutants specified in effluent permits. Pollution export is only crudely predictable for nonpoint sources and for noncriterion pollutants.

This endpoint is most useful and reliable as an indicator of relationships between regions such as pollution of estuaries by upstream regions. As an indicator of pollution of the exporting regions, it suffers from aggregation error resulting from retention of pollutants where they were deposited or transfer between compartments within a region. Thus, pollution export may underestimate an increase in regional pollution load.

Susceptibility

Pest outbreaks, property-damaging fires and floods, and stream flows that are inadequate to provide for dilution of effluents, consumptive uses, or navigation have clear societal and biological significance. Characteristics of a region can make it more or less susceptible to these events, and those susceptibilities are potentially important regional assessment endpoints. These susceptibilities can be defined and measured in terms of frequencies of occurrence of events greater than a certain magnitude (e.g., fires burning more than 100 ha). It is much more difficult to predict how changes in a region will affect susceptibility, although development of such capabilities is an active area of research.

Landscape Aesthetics

Although the aesthetic implications of changes in regional landscapes have social significance, they have no biological significance and are difficult to define clearly. Perception of the beauty of a landscape is highly variable because of the critical role of culture, personal values, and prior experience. The Englishman's pleasure in a "land parceled and pieced" contrasts with the Westerner's love of "wide open spaces." Survey procedures are used to establish the reaction of user groups to a specific landscape change, such as construction of a power plant, and specific valued views can be identified for protection, but it is difficult to define a priori the extent to which regional-scale changes in a landscape will constitute a risk to the aesthetic experience of its visitors and inhabitants. The loss of small farms in the southeastern United States has resulted in an increase in woodlands and a decrease in fields and barns that has drastically changed the landscape. The aesthetics of that change depend on the observer's feelings about farming and on the observer's awareness that the woodlands have expanded at the expense of small farms. Aesthetics may even be in conflict with biologically based environmental values. For example, the aversion to swamps has contributed to their destruction. In sum, landscape aesthetics may be a useful endpoint in specific instances where a consensus on the aesthetic implications of an action can be identified by opinion surveys, but regional aesthetics cannot be given a clear operational definition a priori.

Climatic Change

In the last two decades, concerns have been raised about modification of the global climate or regional climates by fossil fuel combustion, release of chlorofluorocarbons, release of particulates, nuclear war, deforestation, and devegetation. These could cause glaciation, sea-level rise, drought, or biological damage by ultraviolet radiation, all endpoints that have greater social and biological significance than any of those previously discussed. These endpoints are obviously measurable but only after long periods of observation because of the large background variance. Prediction of regional and global climatic effects is a major activity, but the validity of the models used is questionable. The implications of climatic change are grossly predictable by identifying the communities that occur now or occurred in the past in areas that have or had climates similar to the predicted climate. Although agriculture and commercial forestry are relatively adaptable, the modern circumstance of isolated fragments of natural communities precludes the assumption that communities or species will move to their appropriate habitats.

Measurement Endpoints

Potential measurement endpoints for regional risk assessment are listed in Table 4. As with the assessment endpoints, they are divided into those that are traditional and those that are characteristic of regions. As with the assessment endpoints, these are classes of endpoints. For example, actual measurement endpoints for individual mortality include median lethal dose, the highest dose at which no deaths occurred, and the number of dead individuals observed fol-

Table 4. Potential measurement endpoints for regional ecological risk assessments.

Traditional	Characteristic of regions
Individual	Landscape descriptors
Death	Fractal dimension
Growth	Contagion
Fecundity	Dominance
Overt symptomology	Diversity
Biomarkers	Area of ecosystem/use classes
Population	Rate of movement of ecotones
Occurrence	Length of ecotone/edge
Numbers/density	Populations/species
Age structure	Range
Reproductive performance	Material export
Yield/production	Soil export
Frequency of gross morbidity	Nutrient export
Community	Pollutant chemical export
Number of species	Susceptibility
Species evenness	Frequency of pest outbreaks
Species diversity	Frequency/area of fires
Market/sport value	Frequency/severity of floods
Saprobic index	Frequency/severity of low flows
Other indices	Hydrologic variables
Ecosystem	Regional production
Biomass	
Productivity	
Nutrient export	
Abiotic	
Pollutant concentrations	
Physical state variables	

lowing a pollution episode. It is more difficult to generalize about the utility of measurement endpoints than about assessment endpoints because the ability to measure an environmental characteristic and its relation to the hazard are situation specific.

Individual

The endpoints of nearly all laboratory toxicity tests are summaries of responses of individual organisms. For example, the LC_{50} is a statistical estimate of the concentration at which the median individual dies. Death, reproduction, and growth can be related to population- and ecosystem-level assessment endpoints through the use of population and ecosystem models (see above). In addition, regulatory agencies have developed safety factors for interpretation of these standard test endpoints (e.g., Urban and Cook 1986). Overt symptomology (visible effects such as spinal deformities in fish and chlorosis of plant leaves) and biomarkers (biochemical, physiological, and histological indicators of exposure or effects) are potentially diagnostic. Handbooks are available for attributing visible plant injury to specific pollutants (Jacobson and Hill 1970, Malhotra and Blauel 1980), and many biomarkers are diagnostic of classes of chemical (e.g., metalothioneins for metal exposure) or of specific chemicals (e.g., DNA adducts of specific mutagenic chemicals). Overt symptomology, biomarkers, and behavioral responses currently cannot be used to predict assessment endpoints even though they have clear implications for the health and survival of organisms. There are currently no models that relate symptoms, biomarkers, or behavior to higher-level effects. In general, individual responses are difficult to measure in the field, but there are exceptions, such as the responses of individual trees.

Population

The conventional population parameters (occurrence, abundance, age structure, birth and death rates, and yield) are poor subjects for laboratory tests but are popular components of ecological field studies. They are directly interpretable in terms of assessment endpoints for valued populations. Occurrence and abundance are easily measured, but age structure, birth rates, death rates, and yield are difficult to estimate for many species. The scale of population responses of large vertebrates is appropriate for regional risk assessments. Population responses have good temporal dynamics in that they integrate chronic and acute exposures. However, they are not diagnostic and may be quite variable. Methods for population surveys are not standardized, but generally accepted methods are available for most species.

The frequency of mass mortalities and the frequency and nature of overt morbidity correspond to assessment endpoints. Overt morbidity is readily measured in the field for most vertebrates but natural variability is high. Care must be taken in diagnosis of lesions and tumors to distinguish effects of parasites or mechanical injury. These endpoints are not standardized and, with the exception of fish kills, there is unlikely to be existing data.

Community

The most commonly used community characteristics in environmental monitoring are the number of species, species evenness, and species diversity. They are popular because they conveniently summarize the data generated by biotic surveys. They are easily measured for macroorganisms and temporally integrate acute and chronic exposures. For most macroscopic flora and fauna, they have reasonably low variance, but the evenness and diversity of invertebrates tend to be highly variable. Community endpoints are broadly applicable but not diagnostic or well standardized although some standards for community sampling exist (APHA 1985, ASTM 1987). The problem comes in relating these numbers to assessment endpoints. If the nature and aspect of the community has not been affected, then changes in number, evenness, and diversity must be interpreted in terms of the species that have appeared, disappeared, or changed in relative abundance as a result of the presence of the pollutant. In other words, the effects must be assessed at the population level because the number and diversity of species is no longer believed to confer stability or any other value on the community. Certainly the increase in species number and diversity that results from colonization of disturbed areas by weedy species is not valued or of great consequence. If the nature and aspect of the community has been changed, then number, evenness, and diversity are simply adjuncts to the description of the changed community type.

Indices of community quality may be indicative of pollution effects or of habitat quality in general. The best example of a community pollution index is the saprobic index (Hynes 1960). This index arrays aquatic communities, with respect to conventional organic pollution (i.e., sewage and similar effluents), that predictably replace one set of species with another. Indices of generic community quality, such as the index of biological integrity (IBI) (Karr and others 1986), show promise as indicators of the state of communities. The IBI provides an indication of the physical and chemical quality of streams based on the species composition, trophic composition, abundance, and condition of fish. Community quality indices, like diversity indices, are statistically intractable and greatly reduce the information obtained from a biotic survey by reducing it to one number. However, if an index is well characterized for a region, as the IBI is for the north central states, it can be used to indicate how far communities have diverged from an undisturbed state. For most regions and community types, appropriate indices and baseline data are not currently available.

The indicator-species concept is a reduced form of the community index. The presence or abundance of a species that is thought to be either pollution sensitive or tolerant is used to indicate the status of a community. Like the saprobic index, indicator species have been effective in assessing oxygen-demanding pollution but not for other types.

To be relevant to regional assessments, community responses need to be scaled to the regional level. The community properties and indices discussed above are intended to characterize a particular site. Regional assessments need a measure of the state of the individual community types in the region or a means of integrating measurements from individual sites. These measures could be as simple as percentages of sites below some threshold value (e.g., streams with fewer than three species of fish or forests less than 100 years old), but more sophisticated measures can be easily imagined. The chief limitation is the lack of consistent measurements of community properties from sites distributed across a region.

Ecosystems

Ecosystem properties relate to the exchange of energy and nutrients among functionally defined groups of organisms and between organisms and the environment. The most commonly measured ecosystem properties are biomass of the system or its components, productivity of the system or its components, and nutrient dynamics. These do not correspond to any assessment endpoint but all relate to productive capability. In particular, the realized productivity of an ecosystem is an estimator of its productive capability. Ecosystem properties tend to vary with climatic conditions and are not diagnostic, but they are broadly applicable. There are no standard methods for measuring toxic effects on ecosystem processes in the field, but the EPA has recently adopted laboratory microcosm protocols that include some measurements of ecosystem processes (Office of Pesticides and Toxic Substances 1987).

Properties of individual local ecosystems, like those of communities, must somehow be related to a regional scale. The potential approaches would be the same, and consistent data from the ecosystems in a region is equally lacking. In addition, the individual ecosystem properties have no inherent social value and must be interpreted in terms of the ability to produce resources, sustain desired community types, or other assessment endpoints.

Abiotic

Measurements of pollutant concentrations, pH, dissolved oxygen, suspended solids, temperature, and other abiotic properties of environmental media are readily performed, and there are standard procedures for many analyses. If a criterion or standard is the assessment endpoint, then ambient concentrations are the measurement endpoints. For noncriterion chemicals, the assessment endpoints must be an effect that is associated with predicted or measured concentrations.

Landscape Descriptors

The landscape descriptors produced by the new and growing field of landscape ecology (O'Neill and others 1988, Forman 1986) are appealing as potential measurement endpoints because they describe characteristics of a region as a whole. They are relatively readily measured because of the abundance of high-quality satellite and aerial imagery and recent advances in image analysis and geographic data analysis. They also have low natural variability, are broadly applicable, and historic aerial photos may allow extension of a landscape data series back for 40 years. However, efforts are only beginning to relate them to assessment endpoints. For example, Franklin and Forman (1987) modeled the effects of clear-cutting pattern on landscape descriptors (length of edge, patch size, and proportions of uncut, cut, and interior uncut) and on the amount of nonhuman forest harvesting (fire, blowdown, insect and fungal outbreaks, and landslides). Another example is the attempt to relate abundance of wildlife, particularly birds, to patch size (Freemark and Merriam 1986, Orians 1986), to relative amounts of edge and interior (Kroodsma 1984a, b), and to the availability of corridors between patches (Henderson and others 1985). The proportion of a landscape disturbed by human development is more comprehensible to the public than other landscape descriptors and has been used as an assessment endpoint (e.g., Walker and others 1987), but it should be related to some regional value or utility. All of these landscape descriptors have been designed to quantify physical disturbance in the terrestrial environment; their applicability to toxic effects and aquatic ecosystems is problematic.

Species and Populations

The range of a species or population is an intrinsically regional measure and corresponds to the assessment endpoint discussed above. The range of a species usually has low variability and determinations of changes in range can often draw on existing data series. It is applicable to hazards that encompass all or most of the range of a species or of a spatially distinct population.

Material Export

Export of materials relates to the productive potential of a region and pollution of other regions. It is readily measurable in water, and the natural variability is due primarily to climatic and hydrologic factors that can be corrected for. It is diagnostic for xenobiotic pollutants, is broadly applicable, measurement methods are standardized, and existing data sets can be used.

Susceptibility

Use of frequencies and intensities of pest outbreaks, fires, floods, and low flows to estimate susceptibility of a region to these events amounts to regional-scale epidemiology. The problems are the same as in prospective epidemiology, using small samples of past events to estimate the probability of future events. The samples are small because the frequencies of severe events are low, making it difficult to reliably detect changes in frequencies resulting from regional changes. The solution is to develop regional indicators of susceptibility to severe events. For flood and low flows, this is a matter of extrapolating to extreme events the hydrologic parameters that describe the retention of water by a watershed. For example, Gosselink and Lee (1987) suggested assessing the effects of lost riparian wetlands on flooding by using the heights of discharge curves and the water residence times (stored volume at flood stage/discharge at flood stage). Additional parameters are needed to describe the role of uplands in water control (Forest Service 1980). Fire susceptibility is predictable from species composition, fuel loads, and dryness.

Regional Production

As discussed above, realized regional production can be used as an estimate of productive capability. Crop and forest production statistics can be obtained from the US Department of Agriculture's Crop Reporting Service and Forest Service. These are accurate, free, provide long data series, and have general applicability. Primary production of other community types must be estimated from assumptions and literature values (Turner 1987), but these estimates are not useful for assessment since assumptions and literature values do not respond to hazards. Monitoring programs to determine the production of communities other than crops and forests would be expensive relative to the utility of the data in regional risk assessments. Aggregating crop and forest yield as an estimate of regional production would simply obscure the responses of the individual crops, tree species, and forest community types.

Assessment Goals and Assessment Endpoints

It is not always possible for an assessment endpoint to satisfy all the criteria in Table 1, and it is nearly impossible for a measurement endpoint to satisfy all the criteria in Table 2. The relative importance of the criteria depends in part on the type of assessment. Three general goals of regional assessments are discussed below: explanation of observed effects, evaluation of actions with regional implications, and evaluation of the state of a region.

Explanation of Observed Regional Effects

Certain regional-scale environmental effects are observed before their causation is understood. Examples include the decline of the peregrine falcon and the decline of high-elevation forests in the Appalachians. In these cases, the purpose of assessment is to establish causation and the assessment endpoint is provided by the assessment topic. The measurement endpoints must have close causal links to the assessment endpoint and must be diagnostic of the mechanism involved in at least one causal link. They must also have appropriate spatial scale and temporal dynamics. Examples include concentrations of xenobiotic chemicals in falcons that fail to reproduce and doses causing effects in reproductive toxicity tests. It is less important that measurement endpoints be easily and cheaply measured; when a serious problem is known to exist, there is public support for spending money on measurement, and a program focused on a single problem can expend more effort and money on each of a few pertinent measurements. Similarly, broad applicability, use of existing standard methods, and use of methods that have generated existing data are less important then standardizing the measurements that are most applicable to assessing the identified problem.

Evaluation of an Action with Regional Implications

Another goal of regional assessment is predicting the regional implications of environmental decisions. Examples include: (1) licensing a pesticide for use on corn that can be expected to be used at approximately the same time on thousands of fields all across the corn belt, and (2) permitting a new sewage outfall in a river that is already subject to anoxic conditions during low flows. The assessment endpoints in these cases are likely to be scaled-up versions of the endpoints used in local-scale assessments. For example, in a local assessment of a new pesticide, an assessment endpoint might be the expected number of birds killed or the probability that birds will be killed, whereas a regional assessment would use effects on the abundance of a regional avian population. In most cases no new measurements would be available for regional assessments, so the same measurement endpoints would be used in an assessment model with a regional scope. In the pesticide example, the same avian LD_{50} or field test results as are used in local-scale assessments would be used in a model of avian population dynamics in a regional-scale mosaic of habitats, some of which are being sprayed.

In many cases, regional effects of decisions are not simply scaled-up local effects. A conspicuous example is the transformation of pollutants from numerous individual sources into new regional pollutants, including generation of ozone from hydrocarbons and oxides of nitrogen and generation of sulfate aerosols from local SO_2 emissions. Such emergent properties of regional-scale disturbances often are not predicted, but they may be detected by assessments of changes in the state of regional environments.

Evaluate the State of a Region

A third purpose of regional assessment is to evaluate the state of regions so as to (1) determine whether regulatory actions are improving environmental quality or (2) determine whether some hazard that is not being addressed is having environmental effects. In the first case, the assessment program is a validation of the regulatory assessments, so the assessment endpoints that were used in the regulatory actions should be used in the validation. Measurement endpoints should be clearly representative of those assessment endpoints, should be sensitive to the hazard being regulated, and should be readily measured, broadly applicable, and standard so that the effectiveness of actions can be evaluated in a comparable manner at sites within and among regions. In the second case, it is desirable to consider all endpoints so that nothing will be missed. It is obviously impossible to monitor everything adequately, but the number and severity of surprises can be reduced.

The development of endpoints for assessing the state of regions constitutes a difficult research problem. As Dayton (1986) points out, most purely observational studies have had little utility because the complexity of causal factors creates variance that is perceived as noise. This noise results in a high probability of type II error (i.e., missing real effects), which is particularly difficult to overcome if the goal is to detect sensitive early indications of effects. As a result, "credible early warning signals have been the succubus of most pollution workshops . . ." (Dayton 1986).

One possible solution is to use multiple types of endpoints with complementary qualities. One type of measurement endpoint would be summarizations of data from existing environmental, resource, and economic monitoring programs. Because the data are essentially free and are likely to cover a variety of species and other relevant regional characteristics, they need not be perfectly appropriate but they must be reasonably well standardized and should not have extreme natural variability at the time scales of interest. A second type of measurement endpoint addresses specific areas or entities within a region that have regional importance and are thought to be particularly vulnerable to a broad class of pollutants or other hazards. Sensitive, low-variance measurement endpoints with appropriate spatial and temporal scales might be used in those locations. For example, a variety of persistent hydrophobic pollutants accumulates in the sediment of estuaries, so their effects might best be monitored in benthic organisms with a suite of biomarkers, such as the alkaline unwinding assay, that are not chemical specific but indicate a mode of toxic action. Another example might be movement of ecotones (boundaries between types of communities) in response to climatic change or similar stress. Finally, if endpoints can be developed that integrate stress on a region, even if they are not terribly sensitive or diagnostic, they could be used as a general warning that something is changing. For example, frequency of observed fish kills is a rather crude indicator of the general water quality in a river basin.

The difficulty of regional monitoring of environmental quality is reflected in the fact that tens of millions of dollars spent on monitoring the chemical quality of surface water in the United States has not satisfactorily answered questions about trends or the efficacy of current regulatory strategies (GAO 1986, NRC 1987). Biological monitoring presents additional serious challenges.

Conclusions

Because the term endpoints has been used to describe the numeric results of toxicity tests and field monitoring programs as well as to describe the object of an environmental assessment, measurement endpoints have been used as de facto assessment endpoints. Once the distinction between these endpoints is made, it becomes clear that the object of environmental risk assessments is not to predict the probability of occurrence of fathead minnow LC_{50}s in rivers or of changes in fractal dimensions of landscapes. A major task of risk assessors is extrapolating from these measurement endpoints to the assessment endpoints (e.g., to fish abundance in rivers or the productive capability of a region). In many cases the necessary extrapolation models do not exist, and in some cases the conceptual bases for such models do not exist. Regional-scale measurements and indices need to be related to regional values. Methods need to be developed to estimate effects on regional populations and communities from toxicity test endpoints and measured local effects. Relationships need to be developed between body burdens, biomarkers and other symptomology used in biological monitoring programs and effects on populations. These needs must be met by new research.

Regional risk assessments have a particular need for data bases of spatially and temporally extensive and consistent measurement endpoints. Long time series of data are particularly valuable and difficult to come by. All of the assessment goals described above could be enhanced if regional risk assessors could consider trends rather than regional snapshots. In particular, if trends in regional state variables were assessed, then deterioration in environmental values could be identified earlier than if the deterioration must be apparent in temporal isolation. Unfortunately, few monitoring programs are sustained beyond a few years, and environmental data bases often are not sustained and updated after they are created.

Finally, regional-scale assessment endpoints are much less readily identified than are local-scale endpoints. At regional scales it is particularly apparent that we cannot track all of the components of the environment that we care about. In addition, the relative utility to regulators of the various whole-region descriptors that are being developed is not apparent without guidance concerning the regulators' values. Therefore, it will be important for risk assessors and risk managers to identify the regional values that have greatest importance so that efforts can be directed to developing the data and assessment tools needed to assess risks to those endpoints.

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