Introduction

The purpose of this paper is to develop a decision analytic framework for choosing indicator species for ecological assessments at Superfund sites. The Comprehensive Environmental Response, Cleanup, and Liability Act (CERCLA) amended by the Superfund Amendments and Reauthorization Act (SARA) charges the Environmental Protection Agency (EPA) with ensuring that remediation efforts chosen for a site are protective of human health and the environment.

To ensure that the natural communities in the vicinity of a site are being protected, the Environmental Protection Agency performs an ecological assessment. Indicator Species are used in the ecological assessment method. Indicator species are organisms who by their presence or absence indicate the extent of environmental contamination in natural communities. The Environmental Protection Agency does not currently use indicator species in ecological assessments, but is interested in using them for monitoring cleanup effectiveness after remediation.

Choosing indicator species involves information that is difficult to quantify and the use of expert judgment. Decision analysis structures the decision problem and formally incorporates the expert judgement that is involved in choosing indicator species.

The paper begins with a discussion of the use of ecological assessment by the Environmental Protection Agency and how indicator species may be used. This is followed by a discussion of the history of the indicator species concept and a review of the use of indicator species in terrestrial and aquatic environments. Criteria for choosing indicator species are then summarized. These criteria are then incorporated into a framework for choosing indicator species in the next section. This section includes a sensitivity analysis of the parameters of the problem. The final section of the paper is a case study site which illustrates the application of the framework for choosing indicator species.

Ecological Assessment and Indicator Species

Introduction

The following section is a review of ecological assessment as used by the Environmental Protection Agency (EPA 1984, EPA 1986, EPA 1988, EPA 1989b, EPA 1989c). This review covers the definition of ecological assessment, outlines the regulatory framework for ecological assessment, briefly describes methodologies, and examines the role of indicator species.

Ecological assessment is a single component of a hazardous waste site evaluation. Other areas of evaluation include chemical analyses to establish the fate and distribution of contaminants, and the assessment of threats to human health to the site.

The Environmental Protection Agency's Environmental Monitoring and Assessment Program (EMAP) is developing environmental indicators for a number of areas: near coastal waters, inland surface waters, wetlands, forests, arid lands, and agroecosystems. The EMAP strategy identifies three main types of indicators: 1) response indicators, 2) exposure or habitat indicators, and 3) stress indicators. Indicator species are a response indicator, providing a measure of the overall biological condition of the ecosystem. Although EMAP's focus is on providing policy-relevant ecological monitoring information on regional scales (rather than site-specific information as is needed at Superfund sites), EMAP may provide useful insights into the use of indicator species for ecological assessments.

Statutory and Regulatory Basis of Ecological Assessment

The Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) as amended by the Superfund Reauthorization and Amendment Act of 1986, charges the Environmental Protection Agency with protecting human health and the environment from releases or potential releases of contaminants from abandoned hazardous waste sites. The proposed revision of the National Contingency Plan (NCP) calls for the identification and mitigation of environmental impacts from these hazardous waste sites and the selection of remedial actions that are "protective of environmental organisms and ecosystems." Compliance with these laws may require evaluation of a site's ecological effects and the measures needed to mitigate those effects.

Statutes of CERCLA and SARA require that remediation actions chosen for a site protect both human health and the environment. The Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), as amended by the Superfund Amendments and Reauthorization Act (SARA), requires EPA to protect the environment in terms of the selection of remediation alternatives, and the assessment of the degree of cleanup necessary.

Ecological assessments only need to be performed at sites where there are substantial ecological resources potentially at risk. It would be inappropriate to perform an ecological assessment in areas where the biota is minimal due to urban or residential development. or in areas where only groundwater or geologic strata are contaminated.

Ecological Assessment and Ecological Risk Assessment

Ecological assessment can refer to any type of assessment related to actual or potential ecological effects resulting from human activities. Because ecological impact and risk assessment are emerging fields, the term "ecological risk assessment" has been used in many different ways. Strictly defined, ecological risk assessment refers to a quantitative procedure that estimates the probability of specified levels of ecological effects occurring in an ecosystem or part of an ecosystem due to stress from anthropogenic chemicals. Ecological risk assessment has four components: receptor characterization, hazard assessment, exposure assessment, and risk characterization (ORLN 1986). The Environmental Protection Agency often uses the term ecological risk assessment in reference to many types of ecological assessment which the agency uses to support regulatory decision making that do not involve estimates of risk.

Ecological Assessment is a "qualitative and/or quantitative appraisal of the actual or potential effects of a hazardous waste site (HWS) on plants and animals other than people or domesticated species" (EPA 1989b).

An ecological assessment includes several areas. The current status of selected parts of the biological community are assessed. Then the current level of ecological effects due to contaminants at a site is determined based on selected ecological endpoints. An estimate is made of the extent and variability of toxic effects. Finally, to the extent possible, the Environmental Protection Agency determines the extent to which these effects have been caused by toxic chemicals rather than factors such as habitat disruption or variability of species distribution (EPA 1989c).

Indicator species can be used in a CERCLA Type B Natural Resource Damage Assessment (DOI 1987) where site-specific assessments are performed based on data collected in the field. An assessment using indicator species is performed to determine the present adverse effects of contaminants in an ecosystem and to monitor the success of clean-up after remediation efforts. This type of assessment is more properly referred to ecological assessment than ecological risk assessment. However, the data from ecological assessments of this type may provide valuable case study data for ecological risk assessments.

An ecological assessment is conducted to quantify the ecological effects occurring at a hazardous waste site. Ecological effects refer principally to community-level effects on terrestrial and aquatic organisms and ecological processes. The extent of ecological effects is determined by the evaluation of selected ecological endpoints that are thought to represent reasonably the health of biological populations and communities on and near a hazardous waste site. An ecological assessment does not include the predictions of future ecological effects at a site, an assessment risk at a site, analyses specific to optimizing remedial actions, evaluation of fate and transport of anthropogenic chemicals at a site, or comprehensive ecological studies (EPA 1989C). However, an ecological assessment may contribute to any of these areas.

An ecological assessment may be conducted to:

- Determine actual or potential damage to the ecology of a site to support a proposed remedial action.

- Determine the extent of site contamination and adverse ecological effects of contaminants.

- Develop remediation criteria.

- Determine the ecological effects of various remediation alternatives, as part of a feasibility study. (EPA 1989B)

An ecological assessment provides input into the decision-making process for Superfund sites, including site prioritization, waste characterization, site characterization, cleanup or remediation assessment, and site monitoring (EPA 1989C). In this paper we are concerned primarily with choosing indicator species to monitor the success of remediation efforts at a site.

The results of an ecological assessment are descriptions of the relationship between anthropogenic chemicals and ecological endpoints of interest. In our case this endpoint is mortality for indicator species. A number of different endpoints can be used for indicator species, but mortality is the most common. Different endpoints would require different sets of criteria for choosing indicator species, therefore we will focus on developing a decision framework for the most common usage of the term.

Endpoints

Assessment endpoints are those describing effects that drive the decision making process. They represent socially or ecologically important values. Measurement endpoints are those used in the field to approximate the assessment endpoint when the assessment endpoint is not measurable or observable.

Endpoints can be either structural or functional. Structural endpoints include indicator species, species diversity and abundance, biomass, indices, and guild structure. Functional endpoints such as cellular metabolism, individual or population growth rates, and rates of material or nutrient transfer are less commonly used. They are more difficult to measure and have been more recently developed than structural endpoints.

Chemical analyses, ecological surveys, and toxicity tests are all necessary to establish that a cause-and-effect relationship between toxic chemicals and ecological effects. Chemical analyses of water, air, and soil provide information on the presence, concentrations, and variabilities of toxic chemicals at a site. Ecological surveys establish that adverse effects to biota have occurred at a site. Toxicity tests establish a link between the adverse ecological effects and the toxicity of the wastes. Without these three types of data we could not eliminate other potential causes of ecological decline such as habitat alterations and natural variability. The only capacity in which indicator species have been used in ecological assessments at Superfund sites is as toxicity test species.

Ecological Assessment Methodologies

An appropriate methodology for an ecological assessment should:

- Measure the exposure of biota to contaminants.

- Determine the adverse effects on ecosystems due to contaminants at the organismal, population, and community levels, as well as effects on community processes.

- Select ecological endpoints that characterize ecosystem responses to contaminants.

- Select ecological indicators that measure the state or rate of change of those endpoints.

- Determine the role of uncertainties in environmental decision making (Harwell 1990).

Site-specific characteristics influence the assessment strategy and methods at a site. For example, the potential list of "appropriate, relevant, and applicable regulations" (ARARs) from CERCLA and SARA provide a basis for selecting methods appropriate at a given site (1989C).

A detailed ecological assessment involves the measurement of structural and functional relationships of biota at the levels of individuals, populations, communities, and ecosystems. This is the role of field surveys. Indicator species are a method of field survey. Field surveys have several advantages:

- Organisms at a site serve as continuous monitors of adverse effects, integrating possible fluctuation in exposure over time.

- Organisms at a site directly reflect adverse effects and no laboratory extrapolations are necessary.

- Results of field surveys are directly interpretable since the results are quantified on the resources directly at risk (EPA 1989C).

Indicator species are a population-level assessment. Population-level assessments are generally more useful in an ecological assessment than organismal, community, or ecosystem responses for several reasons:

- Loss of a whole population of organisms has more biological and social importance than the loss of individuals within the population.

- Populations of many species (such as sports fish) have economic, recreational, aesthetic, and ecological significance.

- Methods for evaluating population responses are better developed than those for organismal, community or ecosystem responses. Population responses have been used longer and more research has been done on them than on responses at other levels.

The use of methods such as indicator species is a toxicity-based approach to ecological assessment. This is the approach most commonly used. It is also possible to perform an ecological assessment using a chemical-based approach such as chemical analyses and laboratory-generated water quality criteria to estimate toxicity. If concentrations in air, water, or soil exceed the criteria limits, then the concentrations are considered to be toxic.

Terrestrial and Aquatic Indicator Species

The Indicator Species Concept

Indicator Species Definition

An indicator is "an organism or ecological community so strictly associated with particular environmental conditions that its presence is indicative of the existence of these conditions" (Morrison 1986). The presence or absence of indicator species is commonly used to assess adverse impacts on ecological communities. Indicator species are organisms that are selectively adapted to certain pollution conditions, either heavily polluted or clean. The term "indicator species" has also been applied to organisms that bioaccumulate toxic substances in their tissues that are present in trace amounts in the environment. These organisms are more properly referred to as "chemical monitor species" (Connell and Miller 1984). It has also been used to describe organisms in a healthy or stressed state under a given set of environmental conditions. These different types of indicator species would have different objectives they are being used to fulfill. The problem that I am addressing is the choice of indicator species that reflect environmental contamination through their presence or absence.

Indicator species can be divided into two types, class I and class II (Ryder and Edwards 1985):

Class I Indicator Species. Class I indicator species are specialized organisms that have narrow tolerances for most environmental properties. These are stenoecious organisms (organisms that have evolved to be specially adapted to pristine conditions). Selected attributes of Class I indicator organisms may serve as early warning indicators of perturbations such as chemical stress from a hazardous waste site. The attribute most often chosen is population decline. Class I organisms tend to signal environmental degradation earlier than Class II organisms. Class II organisms fill the niches which are emptied by the decline of class I organisms.

Class II Indicator Species. Class II indicator species are less specialized organisms that have relatively broad tolerances for many environmental properties. These organisms are euryoecious (not evolved to fill a highly specialized niche) and are outcompeted by stenoecious organisms in the environments to which the latter are specially adapted. Class II organisms therefore tend to be present in low numbers in healthy ecosystems. However, tolerant organisms are better adapted to the degraded conditions of a stressed system. Thus an increase in the populations of Class II organisms can signal the degradation of environmental conditions.

History of the Indicator Species Concept

Community composition has been proposed to assess the effects of organic pollution on aquatic ecosystems (Kolkowitz and Marrson 1908). They developed lists of organisms associated with various zones of pollution, differentiated according to the degree of organic matter in the saprobian spectrum. These zones range from the polysaprobic (large amount of decomposable organic matter and a low dissolved oxygen concentration) through the alpha and beta zones of recovery, to a clean water oligosaprobic zone. As we move from the polysaprobic to the oligosaprobic zone, decomposable organic matter decreases and dissolved oxygen increases. Zones are the "centers for optimum growth and development" for the organisms associated with them. An investigator collects and identifies the organisms at a location, and compares them with a list to determine the level of organic pollution.

This system was refined by various scientists in Europe (Sladecek 1965, Thomas 1975). However, this system relied on species sensitivity to dissolved oxygen content in water and did not take into account the toxic pollutants present today. The importance of the saprobien system is its introduction of the indicator species concept.

Chemical Stress and Indicator Species

For areas such as hazardous waste sites the emphasis on indicator species needs to be shifted from dissolved oxygen sensitivity to toxic substance sensitivity. For toxicants, there are large differences in susceptibility among species (Sloof and De Zwart 1983). Differences in susceptibility of species occupying key places in the food web may have drastic consequences for the structure and function of an ecosystem. Changes in chemical conditions can result in the appearance of characteristic taxa, although these often represent large population increases in previously inconspicuous taxa rather than colonization (Ford 1989).

Changes in species composition may involve the elimination of only one of the most sensitive species. This species may be of minor ecological importance or concern. However, if this is a major species such as a fish or an important fish-food organism, this may give rise to a great deal of concern (Hawkes 1982). More intense chemical stress may affect large numbers of organisms in an ecological community. Chemical stress can result in individual species replacements when stress-tolerant species replace stress-sensitive ones. Other effects on species are more common than straight-forward mortality. Sensitive species losses may not be directly attributable to the chemical stress, but the stress may leave the organism open to other threats such as fungal or insect attacks, or failure in pollination due to deleterious effects on honey bees or other sensitive animals (Borman, 1983). Activities such as resource gathering and reproduction may also be affected. Shifts in dominance may occur at different trophic levels.

Increased levels or duration of chemical stress not only cause the disappearance of Class I indicator species, but lead to increases in the numbers of Class II indicator species. Blooms of opportunistic species normally controlled by competition or predation appear. Blooms create new food supplies for decomposer species, and can lead to a temporary increase in decomposer species (Ford 1989).

The ecosystem response to a chemical stress depends upon the place of the affected species in the food web. A proper ecological assessment based on indicator species requires a thorough knowledge of the relationships between the type of stress and the response of the system. When dealing with disturbance caused by toxic chemicals, knowledge is often insufficient and environmental assessment is seriously hampered (Sloof and De Zwart 1983).

Advantages of the Indicator Species Approach.

The Indicator species approach has many advantages:

- Indicator species are a relatively easy, inexpensive and accurate ecological measure if chosen correctly.

- Indicator species serve as continuous monitors of pollution at a hazardous waste site, integrating fluctuations in exposure over time. Indicator species can also demonstrate when conditions are returning to normal.

- Indicator species are a direct measure of the effects on the ecology of an area. There is no need to extrapolate from laboratory tests.

- Effects on indicator species populations are easily understood by managers, regulators, and the general public.

- Indicator species are useful in identifying specific species at risk (EPA 1989b).

Karr (1986) writes that indicator species are a useful measure of the biotic integrity of an area. He defines biotic integrity as the ability to support and maintain "a balanced, integrated, adaptive community of organisms having a species composition, diversity, and functional organization comparable to that of the natural habitat of the region." Systems with biotic integrity can withstand natural and human-induced stresses or rapidly recover from these stresses when they are removed. Systems without biotic integrity are often already degraded and when further perturbed are likely to change rapidly to even more degraded states. Karr uses the "index of biotic integrity" he developed as applied to fish to determine perturbations to aquatic ecosystems.

Disadvantages of the Indicator Species Approach.

In recent years there has been a growing dissatisfaction among scientists with the use of indicator species (Cairns 1986, Ford 1989). Ecologists have been pushing for a whole ecosystem approach. A whole ecosystem approach involves measurements of interactions between species and the health of the entire ecosystem rather than measurements on populations of species. The health of these populations is used to extrapolate the health of the ecosystem as a whole. Whole ecosystem studies are a great deal more costly and time consuming. They also require even greater knowledge than the indicator species approach. The arguments against indicator species are outlined below:

- No single taxa have emerged as the accepted standard among all biologists (Cairns 1974).

- Anthropogenic chemicals may cause stress to exposed organisms that leads to gradual degradation and cumulative changes rather than immediate loss of organisms (Weinstein and Birk 1988).

- Absence of indicator species may be due to factors other than anthropogenic chemicals, such as competition, predation, lack of colonization potential, inadequate sampling intensity, and chance. Presence of indicator species can also be misleading as they may be present in low numbers in undisturbed systems.

- The signal of the response to chemical stress may not be discernable from natural variations in species populations (Kelly and Harwell 1989).

- If an ecosystem is subject to more than one chemical stress, as is often the case at hazardous waste sites, the indicator species concept may be difficult to apply as different species respond differently to various sets of stresses (Ford 1988). A variety of toxic chemicals will result in a non-specific decrease of species richness and population size (Sloof and De Zwart 1983).

- Although many indicator species are common, many other are uncommon or rare in a community, and their presence and especially their absence may be difficult to demonstrate. Under ideal circumstances, a biological monitoring program would include many taxa on different trophic levels, but time and money do not usually allow this (Cairns 1974).

Conclusion

Whether or not species are strongly associated with specific environmental conditions and share these associations with others is currently under debate (Mannan et al. 1984). The use of indicator species has not been critically evaluated. The circumstances under which plants or animals may provide insight into environmental degradation, or the specific organisms that may best serve as the indicators of degradation have not been well defined (Morrison 1986). The following two sections of this paper will briefly outline what information is available for plant and animal indicator species in aquatic and terrestrial ecosystems. The value of the indicator species approach is low in the absence of other supporting data. But careful choice of indicator species applied to well-defined problems may be useful in detecting regional and site-specific contamination. The value of the indicator species approach is enhanced if groups of indicator species are used. It is particularly useful if they are chosen from different guilds or trophic levels (Kelly et al. 1988). If groups of indicator species all begin to show large population changes then it is more likely that these declines are caused by chemical stress.

Terrestrial Organisms

Aquatic Versus Terrestrial Organisms

Indicator species have been much more extensively used for aquatic ecosystems than they have for terrestrial ecosystems. In forest ecosystems, the dominant producers are trees. Trees reproduce and grow slowly. If they are killed it may be years before they are replaced. A gradual movement from pollution-sensitive to pollution-resistant species occurs in both terrestrial and aquatic ecosystems. This trend is much slower in terrestrial ecosystems. The turnover time for terrestrial ecosystems may be years or centuries instead of days. Therefore changes are not detectable nearly as early in terrestrial ecosystems as they are in aquatic ecosystems. However, it will also take a lot longer for a terrestrial ecosystem to recover so detection of perturbation may be even more important in terrestrial ecosystems (Schindler, 1987). Terrestrial soils tend to concentrate pollutants, thus exposing the primary producers to toxic chemicals. In aquatic ecosystems the key primary producers are phytoplankton. They are exposed to toxic pollutants only if those pollutants are water soluble.

Introduction

When examining terrestrial ecosystems, an investigator needs to know ecosystem properties such as soil type, slope, precipitation (amount and distribution), and soil permeability to water and air. When a terrestrial ecosystem is exposed to a xenobiotic (human introduced) chemical, many organisms are likely to be sensitive to the chemical, Evolution would not have had time to eliminate sensitive species. Various organisms in a terrestrial ecosystem are differentially susceptible to toxic compounds. Microorganisms capable of detoxifying and breaking down xenobiotics are not likely to have developed significant population sizes, if they exist at all. Studies by Sheehan and Winner (1984) found that pollutants tend to affect species composition and succession by replacing advanced communities with species of earlier seral (successional) stages (see also Woodwell 1983, Odum 1985).

Plants

Early use of indicator species primarily took the form of plants used to identify habitat types. Dominant autotrophs largely determine ecosystem structure, so much has been done to study changes in these organisms (Weinstein and Birk 1988). Plants have been used in studies of both soil and air pollution (Jones and Heck 1981, Martin and Coughtrey 1982, Dewit 1983, Eijsackers 1983, Ernst 1983). Ten Houten (1983) found that plants are generally more suitable for air pollution studies than animals because they "ask less attention and react frequently with characteristic symptoms to low concentrations of specific air pollutants". Air pollution from volatile organics is an important consideration when determining ecological damage at Superfund sites.

Plants have several advantages and disadvantages as indicator species:

Advantages:

- Sedentary.

- Easy to identify and usually do not need to be collected.

- Ubiquitous occurrence.

Disadvantages:

- There is not a great deal of data about plant sensitivity to toxic chemicals. The focus of most research has been on animal species.

- Do not bioaccumulate hydrophobic chemicals and therefore are not useful when monitoring for these compounds (Farrington 1989).

- May react less rapidly than animals (Eijsackers 1983).

Plants may take up chemicals with low log P values through their roots (A log P value is the logarithm of the octanol-water coefficient (K_{ow}) that predicts bioaccumulation of compounds in the oils of fish and fat of animals) (EPA 1989B). Plants can't transport significant amounts of compounds with high molecular weights or high log P values. Plants may become contaminated by soil or water, or by the volatilization (into the air) of chemicals at a site.

Patton (1987) claims that plants are the best indicators of environmental change. Plants are non-mobile, easy to count, and indicate change through their presence or absence with a high degree of certainty. Perennial plants are the best plant indicators because repeated measurements can be made at the same location.

Hutton (1984) examined the impacts of airborne metal contamination on a deciduous woodland system. He examined two species, the grass Holcus lanatus and dog's mercury Mercurialis perennis that display tolerance to cadmium contamination. These species showed a strong correlation between abundance and degree of metal contamination. These species were useful in this situation because there was data available on the tolerance of these plants to cadmium and because the substance was not a hydrophobic bioaccumulating compound.

Invertebrates

Terrestrial invertebrates have been used to some extent, but not to the overwhelming extent they have been in aquatic environments. Rosenburg (1986) reviewed the use of terrestrial insects in monitoring studies. Soil is the major terrestrial sink for pollutants, so invertebrates are often heavily exposed to contaminants. Invertebrates have many advantages and disadvantages implicit in their use:

Advantages:

- High species diversity.

- Ubiquitous occurrence.

- Often abundant and easily sampled.

- Potentially rapid response.

- Ecological and economic importance for decomposition of organic matter; provision of food for wildlife (Rosenburg et al. 1986).

Disadvantages:

- Small and cryptic in coloration and behavior -not as easily observed as birds or mammals.

- Identification and analysis of samples is time consuming and expensive.

- Species level taxonomic data are often lacking (Whitby and Hutchinson 1974).

- Soil types need to be characterized to determine whether a species should be present or absent.

Decomposer organisms in the litter layer appear to be relatively sensitive to metals because of their intimate exposure to them (Hutton 1984). For example, earthworms are efficient accumulators of both metals and organochlorine compounds, and give a measure of the relative amounts entering the foodchain. The species Allobophora calliginosa has been shown to be especially sensitive in studies with copper, cadmium, zinc, fly ash, and sewage sludge (Eijsackers 1983). Earthworms burrow through the upper soil layers (20-100 cm) thus integrating the toxic components of these different layers. Organisms that are soil ingestors like earthworms are particularly useful because they are highly exposed to pollutants in soil. Soil organisms are not useful however, when the contaminant is not trapped by soil particles. Terrestrial invertebrates have not been used extensively as indicator species, and data are often lacking. However, there is sensitivity information on this species of earthworm, which makes it a useful indicator.

Vertebrates

Vertebrates have not been used extensively to monitor for environmental contaminants.

Advantages:

- High ecological, economic, and social value.
- Conspicuous and easily observed.
- Extensive taxonomic, life history and chemical sensitivity information.
- Upper trophic level organisms which are especially susceptible to bioaccumulating compounds.

Disadvantages:

- Effects of environmental contaminants occur relatively late when compared with smaller organisms with higher turnover rates.
- Populations tend to be small and absence may be due to demographics or inadequate sampling.

Birds are the most extensively used vertebrate indicator species (Roberts 1985, Block et al 1986, Block et al 1987). Birds are often the most conspicuous organisms within ecosystems (Morrison 1986). They also appear to be more sensitive to environmental contaminants than other vertebrates (Stickel 1975, Grue et al 1983). Rats, mice, and rabbits are other vertebrates that have frequently been favored as indicator species. This is not because of their inherent sensitivity but because of the wealth of laboratory data available which aids in correlating population decreases with the presence of environmental contaminants. Sylvia Talmage (1989) assessed the merits of using small mammals as monitors for environmental contaminants. There was a correlation between the amount of contaminants in the soil and in small mammals. The concentration of contaminants generally increases with higher trophic level organisms.

Morrison (1986) reviews the use of birds for monitoring ecological effects of DDT on British peregrines (Falco peregrinus). Upper trophic level species such as peregrines are especially useful for hydrophobic bioaccumulating compounds such as DDT. However, care must be taken in their use because their numbers are small relative To lower trophic level species, and sampling error may account for population fluctuations.

Aquatic Organisms

Introduction

The use of indicator species is more prevalent in aquatic than in terrestrial ecosystems (Phillips 1978, Angermeier and Karr 1986, Peterson 1986, Courtemanch and Davies 1987, Klerks and Levington 1989). This is because aquatic ecosystems have been the traditional receptors for municipal and industrial waste. Most of the work that has been done with indicator species has been in regard to municipal sewage. However, organisms respond very differently to sewage than they do to toxic chemicals. High concentrations of poorly treated sewage favor organisms that can survive in environments with a low dissolved oxygen content. Toxicity is the main concern with chemical compounds at hazardous waste sites.

In contrast to the relatively slow reactions of terrestrial ecosystems, aquatic systems are very dynamic. Heterogeneity is a particularly severe problem in aquatic ecosystems (Ford 1989). It is often difficult or impossible to measure the variability of a system. This is particularly important in weighing the presence or absence of a species. Even normal seasonal successional changes are more variable than in terrestrial systems (Ford 1989). The large numbers of chemicals and ecosystem types make the two very difficult to match in terms of expected effects and changes.

Large lakes are temporally stable physiochemical environments that can also be surprisingly patchy and changing in terms of community structure. Stratification and mixing lead to differences in species abundance and ecosystem structure. The sampling intensity necessary to account for ecosystem variability can be great.

Rivers and streams are at the other extreme from lake ecosystems. Lotic systems are temporally variable and a longer monitoring period may be necessary to characterize lotic systems than non-moving systems. This can be overcome, however, by monitoring a section of stream upstream from the site as well as a section that is being affected by the site (Stauffer and Hocutt 1980). This allows for comparison between the two sections. Care must be taken that the ecosystem types of the two sections and extraneous factors are not significantly different.

For aquatic systems it is necessary to determine ecosystem properties such as dissolved oxygen, substrate, flow, and temperature. In most aquatic ecosystems the best indicators of stress include changes in sensitive short-lived species and changes in community structure resulting from the elimination of keystone predators (Schindler 1987).

Periphyton

Periphyton are complex assemblages comprised of autotrophs (algae) and heterotrophs (fungi, bacteria, or protozoa) attached to substrates in lotic environments. They are sometimes are sensitive indicators of environmental contaminants in lotic (river and stream) ecosystems (Lewis et al 1986). Non-diatom species predominate in polluted and recovering areas. Studies have shown declining species diversity and species richness which demonstrate a loss of sensitive species with a concurrent increase of more resistant species (Crossey and La point 1988, Steinman and McIntire 1990).

Advantages:

- Small and rapidly reproducing, are among the first organisms affected (EPA 1989C)

- Ubiquitous occurrence

- Easy to collect

- Ecological importance i.e. a food source for higher trophic level organisms

Disadvantages:

- Relatively little information available on species sensitivity (EPA 1989C)

- Difficult to identify

- Little taxonomic data available

Crossey and LA Point (1988) examined periphyton community structural and functional responses to heavy metals. They found that diatom cell abundances increased significantly in contaminated sites relative to control sites, but diatom diversity was significantly lower. This indicates a decline in community complexity where non-diatom species predominate. There is presently little information on periphyton, but as more research is performed on them they should become more useful indicator species.

Phytoplankton

Phytoplankton have not been used extensively as indicators of chemical contaminants (Shubert 1984). Changes in phytoplankton species composition are thought to be among the most sensitive indicators of ecosystem stress, but collection and identification problems have kept phytoplankton from being used (Schindler 1987). Patrick and Strawbridge (1963,1964) examined effects of contaminants on diatoms.

Advantages:

- Among the first organisms to show changes in species dominance because they are small, rapidly reproducing, and disperse widely (Shubert 1984).

- Are sensitive to a large number of compounds: organochlorines such as DDT and PCBs, and trace elements such as copper, zinc and mercury (Schindler 1987).

Disadvantages:

- Difficult to obtain and sort samples i.e. species identification (Schindler 1987).

- Rapid species succession can cause acute responses to be masked -little time integration (Schindler 1987).

- Have not been used extensively i.e data are lacking.

Macroinvertebrates

Aquatic macroinvertebrates are the most commonly used organisms for the ecological assessment of environmental contaminants (Resh and Unzicker 1975). Many studies have been performed using aquatic macroinvertebrates (Lenat et al. 1983, Schaeffer et al. 1985, Hilsenhoff 1988). Because pollutants are generally more concentrated in sediments than in the water column, benthic macroinvertebrates are exposed to greater concentrations of pollutants than pelagic or planktonic organisms. Thus benthic organisms are the macroinvertebrates most commonly chosen (Morse 1983). Many benthic organisms are among the most sensitive higher aquatic species, even to pollutants such as acids which are not concentrated in sediments (Schindler 1987).

Aquatic macroinvertebrates exhibit a steady, predictable response to heavy metals and other compounds. In streams extensively polluted with heavy metals, all species except for tubificid worms and chironomids were virtually eliminated (Winner et al. 1980). Mayflies were found to occur only at the least polluted areas while heavily polluted areas were dominated by midges. Chironomids comprise a very small fraction of the fauna in unpolluted streams in North America, but comprise 40-75% of the fauna in streams contaminated with heavy metals. Caddis flies were eliminated at the most seriously polluted parts of streams but were co-dominant with chironomids in moderately polluted parts of streams (Sheehan and Winner 1984).

Macroinvertebrates are the most extensively used indicator species, but species indentification is sometimes a problem. For example, a species-level identification of chironomids requires dissection and examination of mouth parts of the organism under a microscope.

Advantages:

- Large enough for easy collection.

- Are not mobile enough to leave an area of pollution rapidly.

- Can be studied in labs easily.

- Exist in all aquatic environments.

- Life cycle is short enough that short term effects of pollutants will not be overcome until the following generation (EPA 1989c).

- Communities heterogeneous, several phyla usually represented, therefore chances are high that some groups will respond to environmental contaminants (Hellawell 1986).

Disadvantages:

- Quantitative samples may be difficult to obtain because of spatial heterogeneity.

- Species that drift may be found in areas where they normally don't occur (Lenat et al. 1983).

- Sorting and identifying species may be time-consuming and expensive (Berkman 1986).

- Species level taxonomic and life stage information may be lacking.

- Chemical sensitivity data are often lacking.

- Under certain circumstances benthic macroinvertebrates may not be affected by pollution discharges of short duration that may affect organisms in the water column (Hawkes 1982).

Fish

Fish are commonly used as bioassay organisms, but they have rarely been used in comprehensive monitoring studies. Fish are becoming more popular as indicator species. Many scientists have decided that the advantages of fish as a monitoring species outweigh the disadvantages (Karr 1981, Hocutt 1981).

When there are many non-migratory species of various ages and normal growth rates, then pollution has not likely occurred recently. The presence of fish is more useful than their absence because of their motility (Goodnight 1973). Karr (1986) has found both the proportion of omnivores and presence of top carnivores to be important in determining pollution levels. Omnivores constitute less than 20% of the fish in an unpolluted ecosystem. A proportion of omnivores of greater than 45% indicates gross pollution. Presence of top carnivores indicates a relatively healthy and trophically diverse ecosystem.

Advantages:

- Commonly used as a bioassay organism; there is a great deal of data on chemical sensitivity.

- Economic, recreational, and aesthetic value.

- Identification is relatively easy compared to smaller organisms.

- Much information available on the environmental requirements and life histories of fish (Karr 1986).

- Fish are "integrators" of lower trophic levels (Hendricks et al 1980).

- Long lived i.e. temporal integration.

- Species occupy many trophic levels.

- Most species reproduce once a year leading to stable populations in the summer when most sampling occurs (Hocutt 1981).

- Contain upper trophic level species which will bioaccumulate hydrophobic compounds.

Disadvantages:

- Mobile and can move away from contaminated areas.

- Numbers are fewer than with smaller organisms, leading to a greater chance of sampling error being responsible for presence or absence. It may also cause sampling to affect the success of a species at the site.

- Quantitative samples are difficult to obtain.

- Have rarely been used; They are not tried and tested.

Karr (1981) developed the "Index of Biotic Integrity," an index of fish community structure, to monitor the health of an aquatic ecosystem. At Black Creek in Allen County, Indiana, he found a correlation between the trophic structure of the fish community and the amount of environmental contaminants. He notes, however, that fish have not been used extensively in biological monitoring, and sampling must be extensive to avoid sampling error.

Conclusion

In terrestrial environments, the use of indicator species has been sparse relative to aquatic environments. Plants are useful indicators of substances of herbicides and substance with low log P values. Soil dwelling macroinvertebrates are useful indicators of contaminants that tend to be trapped by sediments. Vertebrates are the most useful indicators of bioaccumulating substances.

In aquatic environments, the use of indicator species has been extensive. When an ecologist conducts a field survey in a lotic habitat, fish or invertebrates are most commonly used. In standing water, the gradual decrease in effects further from the site is more difficult to detect. In standing water, a fish residue or toxicity test utilizing water or sediments from the site is often more useful than monitoring for presence or absence of species (EPA 1989C). It is difficult to recommend a specific trophic level to focus on because of site-specific and contaminant-specific differences. However, in certain situations specific types of indicators species are superior.

Macroinvertebrates are most often used for several reasons: they are ubiquitous; they are easily sampled; and in most cases they can be quickly identified by an expert.

There are some situations where fish are better indicator species than macroinvertebrates. Fish are good measures bioaccumulators substances. Fish are often important when social (i.e. sportsfish) or economic (i.e. commercial fishery) issues are involved.

In many cases neither macroinvertebrates nor fish experience significant population increase or decline due to nutrient enrichment or herbicides. The use of periphyton or phytoplankton is then recommended.

Criteria For Choosing Indicator Species

Introduction

The selection of a suitable organism is one of the first and most important tasks in environmental assessments once the decision to use indicator species has been made. An incorrect decision at this stage may render the ecological assessment useless. The species choice will be influenced by the needs of the survey as well as by site-specific characteristics of the hazardous waste site. The choice of the site should reflect the aquatic and terrestrial resources at risk.

Two different branches of the federal government have already developed criteria for choosing indicator species. The United States Fish and Wildlife Service (USFWS 1980a,b,c) and the United States Forest Service (Code of Federal Regulations 1985) have developed criteria for choosing indicator species. The United States Fish and Wildlife criteria are as follows:

Ecological Criteria:

- Sensitivity to specific environmental factors.
- Keystone species (exert a major influence on the community).
- Single species representative of a guild.

- Socioeconomic Criteria:

  - High public interest value.
  - High socioeconomic value.

The United States Forest Service has developed criteria for choosing "management indicator species":

- Recovery species; those identified by state or local government as threatened, endangered, or rare.

- Featured species; those of high socioeconomic value.

- Sensitive species; those identified by regional foresters as having habitat requirements particularly sensitive to management activities.

- Ecological indicators; those used to monitor the state of environmental factors, population trends of other species, or habitat conditions.

Specific goals, objectives, and standards for management indicator species appear in each National Forest Plan that the United States Forest Service is required to develop (Code of Federal Regulations, 1985). These criteria were developed to monitor the impact of management activities on federal land rather than to monitor for ecological contamination with toxic chemicals.

Confounding Factors

Introduction

Choosing indicator species is a difficult task. A number of factors confound the choice of an indicator species. Species may be present or absent due to factors other than chemical contamination.

Even well-defined ecosystem types have a variety of redundancy characteristics. One organism may provide an irreplaceable food source for a number of species, or there may be other organisms that could take its place. Key species and processes may also vary (Ford 1989). Thus different species are important in different ecosystems and these species can vary widely in their sensitivity to a number of chemical contaminants present at a hazardous waste site. Several floral and faunal groups should ideally be incorporated into an integrated ecological assessment. (Roberts 1985). Practical consideration such as time and money often require that a single species be used. This makes the choice of a proper species crucial.

It is difficult to choose between monitoring for the presence of a tolerant species or the absence of an intolerant one to determine environmental degradation through chemical contamination. An ecologist at a site must be concerned with sampling error that may cause an indicator species to appear to have a higher or lower population than it actually does. Having a sensitive species appear present or a tolerant species appear absent when the opposite is true would constitute a false negative for ecological damage. Having a sensitive species appear absent or a tolerant species appear present when the reverse is true would constitute a false positive for ecological damage. Monitoring for indicator species that have large populations would minimize the risk of false positives and false negatives. Sensitive species with large populations must decline in abundance before the less competitive tolerant species can increase in abundance. Thus sensitive species are an earlier indicator of environmental degradation. However most scientists use the presence of a tolerant species in determining chemical contamination. However, tolerant species are not always present at a site. Organisms have a wide range of tolerance to pollution conditions. Therefore absence of non-tolerant species is of greater significance than the presence of tolerant species (Lenat et al 1983). Absence cannot always be determined for a species because it may be present in low numbers but appear absent.

Cairns (1974) however, has a different point of view. He notes that the presence of a species indicates that certain minimal environmental conditions have been met. The absence of a species is the more risky choice because of possible confounding factors:

- The environmental conditions are unsuitable.
- The species has not had a chance to colonize the area but would do so if introduced.
- Another species has assumed the functional niche.

The presence of an indicator species is generally more useful, but the absence of species can be equally useful if a number of species which are all sensitive to the chemical experience population decline.

Species present/absent due to factors other than tolerance/intolerance. Species may be present or absent due to a number of factors. Species are affected by many factors such as fire or drought, extreme weather conditions, or unknown conditions in areas such as migration routes or wintering grounds. Natural variability and successional changes within the ecosystem may cause changes in species composition over time.

Competition, predation, and disease are factors which can cause the presence or absence of a species. These three factors, however, are in turn affected by environmental contaminants. Chronic exposure to toxic chemicals can lead to weakness or behavioral abnormalities in organisms. This can cause a species to lose its ability to compete with other organisms or escape a predator. A predator may be affected by a chemical compound and be killed or unable to catch prey as successfully. This could lead to a shift in the competitive balance of lower trophic levels. Toxic chemicals may also make a species more susceptible to disease. It is important to try to separate out the influence of these factors while at the same time evaluating how much toxic chemicals contribute to the presence or absence of species.

Differences in comparing one site to another. An indicator that is appropriate in one area may not be appropriate in another area. Even adjoining areas may appear similar but have subtle differences. These differences can occur in the dominant or subdominant species of plants and animals, and/or in species performing vital ecosystem functions. There can be different natural disturbances in the areas, and habitat and resource patchiness. A species living in one ecosystem may not be a resident species in the second ecosystem.

Ambiguous, and ill-defined criteria. Criteria for choosing indicator species need to be unambiguously and explicitly defined (Landres et al 1988). A species used to fill one criterion should not be used to fulfill a second criterion unless it explicitly meets the needs of the second criterion. For example, a species with a high socioeconomic value will sometimes be used to fulfill an ecological criterion. This is not appropriate unless it fulfills both criteria. Species should not be used for multiple roles unless research has verified that the species is appropriate for both criteria. The reasons for having each criterion should be explicitly stated.

Sources of subjectivity. All of the sources of subjectivity in selecting indicator species must be identified and defined. These sources will vary depending on the attributes of the site and the ecosystem and species types found on the site. All assessments and technical decisions inherently contain value judgments which should be discussed so that the merits and difficulties of each may determined.

Criteria For Choosing Indicator Species

When using the criteria, candidate organisms may be arranged by taxonomic class for ease of comparison and organization. An ideal organism would fulfill all of the following criteria. However, the following criteria are extensive, and it may be difficult or impossible to find one organism that fulfills all the criteria. However, several organisms taken together should be able to fulfill the criteria and provide important information for an ecological assessment. These criteria were identified through a literature review of criteria that have been used to choose indicator species. The following criteria will be incorporated into a decision framework for choosing indicator species in the next section of the paper.

Species Sensitivity to the Contaminant. Indicator Species should be chosen based on their sensitivity to the specific environmental contaminants which must be monitored. Sensitivity to toxic chemicals is a crucial element in choosing an indicator species. Those species that are most sensitive to contaminants potentially make the best indicator species (Szaro and Balda 1983). Sensitivity is often measured in terms of LC50 values (the amount of a chemical necessary to cause 50% mortality in a species in a given time period). Organisms differ in their relative abilities to take in, accumulate, metabolize, distribute , and eliminate contaminants. Together, these attributes result in often extreme differences in species' relative sensitivities to environmental contaminants (see Table 1). However, these attributes can differ dramatically from chemical to chemical. Consequently, exposure to two different chemicals can produce two markedly different responses. It is important to determine the contaminants of concern at a site and to match these contaminants with species that are relatively sensitive or insensitive to them.

The organism chosen should be at one end of the range, either extremely sensitive or extremely insensitive to toxic chemicals. It may also be useful to choose species that by themselves or in conjunction with one another will exhibit a graded response to a range of increasing levels of environmental contamination. For example, Sheehan and Winner (1984) report that in streams polluted with heavy metals, mayflies were a significant part of the insect community only at the unpolluted sites. Caddis flies were co-dominant with chironomids at moderately polluted sites while they were eliminated at the most grossly polluted sites. Chironomids were most abundant at the most grossly polluted sites. Thus the level of contamination could be roughly determined by the relative proportions of the three types of insects.

Sensitivity to the contaminants of concern should have a direct cause and effect relationship, rather than a correlation. This can be determined by toxicity tests that clearly demonstrate that a species' population decline is due to the contaminant in question. Otherwise the effect of contaminants on populations may not be separable from other regulating factors such as competition, predation, and disease (Landres et al. 1988).

Sensitive organisms have a relatively rapid response to environmental contaminants. The length of time it takes for a species to be affected by toxic chemicals depends on both species sensitivity and exposure.

Paleoecological studies are becoming more important in determining species sensitive to pollutants (Schindler 1987, Ford 1989). They offer the opportunity to examine changes in community structure at sites that have already experienced chemical stress.

Temporal Continuum of Reproducing Stocks. A species which has been a part of the ecological community at a site for a long time and has several generations existing at once serves a number of purposes. It assures that the organism is a permanent part of the ecosystem which is unlikely to increase or disappear for other reasons. It also allows for continued monitoring of successive generations to determine improvement or further degradation at the site (Ryder and Edwards 1985). The organism should be sufficiently long lived for the examination of more than one year class if desired (Ryder and Edwards 1985). This may be confounded by reproductive toxicity in a species.

High Reliability and Specificity of Response. The organism should exhibit high reliability and specificity of response (Landres et al 1988). In order for this to be happen, several factors must hold true. The population increase or decline due to the chemical stress must be large in comparison to normal population fluctuations. Alternatively, the contribution from each significant source of variation must be identified (Sloof 1983).

Wide Distribution. Potential indicator organisms should be widely distributed in the area. This will allow for comparison with other sites in the area. Candidate species should be screened for organisms whose geographic range does not include the area of the hazardous waste site or who require special habitat features not found at the site (Fry et al 1986). The species should also be abundant enough to be easily found. This minimizes the risk that a species will be misclassified as present or absent. It also minimizes the risk that the populations will be affected by any samples taken.

Residency Status. When monitoring for the absence of an intolerant indicator species it is important for the organism to be indigenous and stable component of the ecosystem. Such an organism will be adapted to relatively unperturbed conditions (only for absence). Indicator species should be permanent residents of the site. Migrating species are affected by many offsite factors. However, migrating species are often included for other reasons such as socioeconomic factors (Landres et al. 1988).

Exposure to Environmental contaminants. Exposure to environmental contaminants is an extremely important consideration when choosing indicator species. It is important to pick the species which is highly exposed to the contaminated media. The primary uptake routes of the organism should be considered. Because organochlorines tend to be associated with particulate matter, a soil organism or filter feeder should be chosen (Phillips 1980). Synthetic organics such as poly-chlorinated biphenyls and dioxin are soluble in fat and thus a species with a large proportion of body fat would be appropriate (Farrington 1989). Trace metals such as cadmium exist almost totally in solution so an organism that exists in the pelagic zone of an aquatic ecosystem would be appropriate. Landres et al (1988) cautions that metal pollution in organisms may result from mobility and transport of the pollutant within the ecosystem rather than being directly related to pollution concentration in the environment. Therefore it is often important to consider species uptake and metabolism, although such information is often limited.

Water soluble compounds should be investigated for potential exposure routes to aquatic species. Water soluble compounds may also move through the aqueous phase of some soils, increasing the likelihood of exposure to soil organisms.

Compounds with low water solubility may be trapped in soil particles and may affect organisms living on or in the ground. Contaminants trapped in soil particles may also be carried by erosion to aquatic or other terrestrial sites. Hydrophobic compounds tend to bioaccumulate and an upper trophic level organism may be appropriate (Farrington 1989).

Dose is an important element of exposure when looking at indicator species. Dose can be high for a short duration (acute exposure) or low for a long duration (chronic exposure). A high dose or acute exposure will induce mortality rapidly. A low dose or chronic exposure will impair the functioning of some biological process within the organism (Weinstein and Birk 1988).

The species chosen should preferably be sedentary at most stages of its life cycle and especially at the life stage of interest. The organism will be more representative of the site the site if it does not spend part of its time off-site. An organism that spends part of its life off-site will not be as fully exposed to the contaminants at the hazardous waste site as an organism which is sedentary. Once the medium which will yield the greatest contaminant exposure has been determined, a sedentary organism in that medium should be chosen to ensure the greatest possible exposure.

Easily and Accurately Collected and Monitored. It is important to use a species that can be collected and measured easily to determine the standing stock in terms of numbers and biomass. This will decrease the time and cost expenditures of the environmental assessment and increase the accuracy of the results (Berkman 1986). In order for a species to be easily collected and monitored it must have a fairly high population density. Organisms with a low population density lead to sampling problems which may make an accurate assessment impossible despite the organism being a good indicator in other ways. Long-term research is needed on each indicator species to assess natural variation in population density not related to environmental contaminants which may confound results. Population density must be balanced with species sensitivity however Freckman et al (1980) showed that less abundant species are relatively sensitive to adverse influences. Szaro and Balda (1983) said that organisms with the following three attributes were relatively easy to monitor:

- Conspicuous by sight and sound.
- Easy to recognize in the field without the observer having to capture the species to identify it.
- Active during daylight hours.

Suitable for Laboratory Experiments. The organism should be suitable for laboratory experiments, especially those designed to investigate cause and effect relationships. Most ecological assessments need a combination of field observation and laboratory experiments of organisms. It is essential to quantify species sensitivity to an environmental contaminant in a laboratory setting.

Historical Information. Species should be chosen based on the information available on the species' history in the ecosystem. Information is necessary on the species' natural baseline condition and its range of variation in the ecosystem. This information is often available for sports fish. The species should have one or more historic data series for comparison with the present. The data should show quantifiable evidence for the relative abundance or scarcity of an indicator species during a period of relatively little contamination. However, this information is often lacking. Information on the species at the site can be supplemented with information from previous studies on the species in similar ecosystems. By comparing present population levels with historical population levels, an ecologist can determine whether a species' population level may have been affected by chemical contamination at a site. An alternative to this is to have a similar site for comparison with the contaminated site, but if this is done care must be taken to consider confounding factors, i.e., differences in food web structure, nutrient abundance, disease incidence, habitat type.

Available Information and Data. The biology of the species should be known in detail. This should include life history and interactions with other species. This will aid in the evaluation of an organism's response. The organism's physiological responses to a wide range of environmental conditions should also be known (Lenat et al 1983). This will help ensure that environmental factors other than chemical sensitivity will not be responsible for an the presence of a tolerant species or the absence of an intolerant species. Niche requirements and habitat characteristics should be known and supported by adequate scientific information. This will allow the investigator to determine that the organism's absence is not due to unmet niche needs or unsuitable habitat at the site.

Using quantity of available information as a selection criterion reduces time and costs in terms of additional research that may have to be done on the organism (Landres et al 1988). This often has the drawback of reducing the relevance of the organism for an ecological assessment. Little information may exist for a relatively sensitive indicator while a great deal of information exists for a less sensitive one. The less sensitive indicator may be chosen although the more sensitive species is the better indicator of environmental conditions. This criterion must be used carefully and in conjunction with the relative sensitivity of the organism.

Maximize Usefulness of Information Gathered. Species should be chosen in such a way that they complement the other information used in the ecological assessment (Ryder and Edwards 1985). Different indicators should reflect different trophic levels. A certain amount of redundancy in information is useful in confirming ecological damage, but this must be balanced with the need to characterize the state of the natural communities at a site to the greatest extent possible. It is desirable to determine if several species on the same trophic level being affected because this would confirm that significant damage is being done to this trophic level. However, information needs to be gathered for other trophic levels of the ecosystem also.

Critical Species. In order to assess whether the ecosystem is being adversely affected by chemical contaminants, the indicator organism should be a critical species. A critical species is a species that performs a vital ecosystem function in the cycle of biological processes in an ecosystem (Weinstein and Birk 1988). A critical species helps maintain the cycle which provides all organisms in the community with sufficient energy and nutrients. As a result, a disruption in these species would result in a disruption of energy and nutrient pools. For example, Sheehan (1984) noted a buildup of soil litter at sites contaminated with heavy metals. This was due to the loss of critical litter-decomposing organisms and led to a blockage of the flow of energy and nutrients to the biota in the ecosystem. Ecosystem stability and viability depends upon the continued success of critical species. Ecosystem decline will be signaled by the decline of these species. Recovery of ecosystems is also closely linked with the recovery of critical species (Weinstein and Birk 1988). Critical species also include top predators which keep populations under control and maintain species diversity.

When looking at critical species, it is often useful to look at shifts in the dominant species in an ecosystem. These shifts tend to be more ecologically damaging than changes to less dominant species (Ford 1989).

The critical species concept applies to tolerant as well as intolerant species. The relative abundance of species with short life cycles changes to favor those that can maintain critical ecosystem functions in the early stages of ecosystem stress. Such organisms are valuable indicators of stress and may serve as an early warning of contaminant problems (Schindler 1987). The critical species criterion is sometimes difficult to apply because few critical species have been identified although research is continuing.

Low Redundancy and Immigration. The species should occupy a place in the food web where both redundancy (number of species performing an important ecosystem function) and immigration are low. These are the species that are most important to community structure and stability. If few other species perform the species' ecosystem function (such as litter decomposition) and immigration is unlikely to occur, then adverse effects to the organism could significantly effect the food web.

Life Stage. When choosing an indicator species it is important to consider the life stage of interest. A species may have a life stage that is particularly vulnerable to environmental contaminants. For example, adults of a species may withstand a short-term discharge of a contaminant, but this discharge may kill all of the juveniles of a species. To cause injury, chemical exposure must occur at a vulnerable location during a vulnerable period (Weinstein and Birk 1988). The life stage of interest may cover any one of a number of areas:

-Reproductive success as measured by the survival of gametes, larva, juveniles, or embryos.

-Longevity of adults.

-Incidence of disease, including physiological and behavioral abnormalities (EPA 1989b).

Ecosystem Integration. The organism chosen should display at least a moderate level of ecosystem integration. It should interact with many other natural components of the community. An organism which interacts with many other parts of the community will generally have more importance to the system and therefore more relevance in measuring the degradation of the ecosystem. For example, an omnivorous predator that feeds on a large number of lower trophic level organisms would have high ecosystem integration. However a parasitic species that feeds on only one species would have low ecosystem integration. Ecosystem integration is qualitatively rather than quantitatively determined. An important consideration when determining ecosystem integration is that the more an organism is studied, the more ecologists will recognize a species' interactions with other species.

Social Value. It is often helpful to reduce the number of possible species by looking at those which are important to humans. The species may be valuable for aesthetic, economic, educational, scientific, or sporting reasons. These include threatened and endangered species which appear on current state and federal lists. Species important for hunting, fishing, and trapping can be determined using lists obtained from state departments of fish and game. Species of high social value are the species for which we have the most information. They are also the species we are most concerned with protecting against the deleterious impacts of environmental contaminants. Social value has often been the primary criterion when choosing indicator species (Landres et al. 1988).

Alternatively, organisms which are a vital food source for an organism of social value may be chosen. The species may also be one which has a breeding habitat at the site or which uses the site as part of its migration route. The problem with migrating species however is they are affected by many off-site factors.

Framework For Choosing Indicator Species

Introduction

Decision analysis has not been previously been applied to choosing indicator species for ecological assessments at Superfund sites. It has not applied to ecological problems to a great extent, although there are some examples in the literature (Maguire 1986, Keeney 1977, Hilborn and Walters 1977).

When choosing indicator species, the decision maker is faced with a complex problem involving value tradeoffs between conflicting objectives. A great deal of the information concerning the objectives is difficult to quantify and involves expert judgement. Decision analysis structures the decision problem and formally incorporates the expert judgement that is involved in the decision of choosing indicator species. A person not familiar with decision analysis techniques may find this formal structure difficult to use. There are a number of books on decision analysis for further reading (Keeney and Raffia 1976, von Winterfeldt and Edwards 1986, French 1986, Clemen In Publication).

The decision analytic framework which I will lay out in this section of the paper is purposefully general in order to be applicable to a large number of Superfund sites. It may be altered to fit the characteristics of a specific site or the preferences and values of a specific decision maker. This framework includes a number of steps:

1. Creating an objectives hierarchy
2. Choosing attributes for objectives
3. Assessing single attribute value functions
4. Assessing scaling constants
5. Screening potential indicator species
6. Aggregation into model
7. Evaluating candidate species

The Problem

The problem which I am addressing in this paper is to think systematically about ranking a set of indicator species when each individual indicator species is described in terms of performance values on many attributes.

The Decision Maker

The decision maker in the problem is an ecologist experienced with the biota at a Superfund site who is responsible for choosing indicator species and then justify them to EPA. The decision maker may want to consider all species of plants and animals at a site, or after a site visit the decision maker may have already informally narrowed the list down to a limited number of candidate species that he or she wishes to choose among.

The Objectives Hierarchy

The objectives hierarchy is the first step along the way in the decision analytic framework. An objective has two features: 1. It identifies a general concern; and 2. It establishes an orientation for preferences (seeking to either maximize or minimize the objective). The objectives are then structured in an objectives hierarchy that encompasses all of the important elements in the decision. The hierarchy starts with an overall objective at the top, and lists more specific objectives at each lower level. The major objectives provide a basis for defining the lower level objectives. Attributes only need to be identified for the level of the hierarchy the decision maker wishes to evaluate in making his or her decision. The objectives hierarchy for a problem is not unique. A different decision maker may have a different objectives hierarchy. So long as everything of importance to the decision maker is included, the form is not important.

The objectives hierarchy I have developed is for choosing indicator species which demonstrate environmental contamination through their presences or abscence (see Table C). Indicator species used for other purposes would have different objectives hierarchies.

The highest level of the hierarchy is the A level in which I identify the overarching goal of choosing the "best" indicator species for a Superfund site. From this overall goal, I identified five areas of concern that comprise the B level of the hierarchy: signal to noise ratio, rapid response, ease and economy of monitoring, ecological importance, and social value. These five categories can then be further broken down into the C level objectives. These objectives are described in detail in pages 30-43 of the paper.

In this hierarchy there are sixteen lowest level objectives with associated attributes $C_1, \ldots, C_{16}$ (see Figure 1). Thus a given candidate species could be described using a 16-part value function. But this would be too burdensome for evaluating a number of indicator species, and it is not necessary to do this in order to proceed. In this problem we will quantify preferences at a higher level of the objectives hierarchy. We can work with the objectives B_1-B_5 rather than the lowest level of the hierarchy C_1-C_{16}. Each B is a subjectively assessed composite of its lower level objectives C. Even though we are working on the B level, it is useful to continue the hierarchy down to the C level because the qualitative structuring of the lower level objectives associated with B_1-B_5 will help the decision maker think more clearly about B_1-B_5. The hierarchy at the C level serves as a qualitative checklist of things to consider. For many of the objectives on the C level, it is often impractical or impossible to gather the necessary information. Thus it is useful to consider these objectives as qualitative parts of a larger objective which the decision maker assesses.

The above objectives will all meet the requirements for inclusion in the objectives hierarchy in most cases. To be included, there must be a difference to which an objective is achieved by at least two different species, and this difference must be significant relative to other differences between the species. At a specific site however, the species being evaluated may all be very similar in achieving a given objective, and that objective may be dropped from the hierarchy in that situation.

By creating an objectives hierarchy for our problem, we ensure that no large holes will occur at the different levels of the objective hierarchy. One level follows clearly from the next and any major gaps at lower levels would be obvious. Redundancy can also be easily identified. This hierarchy provides a basis for developing and evaluating screening criteria which will be discussed later in the paper.

An ecologist at a Superfund site may, because of personal preference or site characteristics, choose somewhat different objectives. The decision maker would then create a different objectives hierarchy to schematically represent these objectives.

Single Attribute Value Functions

Now that the objectives hierarchy has been established, and we have decided on a level of the objectives hierarchy to use in evaluating alternative species, we need to establish attributes for this level of the hierarchy. In choosing attributes, we need to keep in mind that these attributes should:

- Completely cover all aspects of the problem
- Be useful in choosing and justifying a decision
- Reduce the complexity and focus the analysis
- Avoid redundancy
- Reduce the time and cost necessary for the study

For the five objectives, we will measure Signal to Noise Ratio in terms of proxy attributes, High Exposure to the Environmental Contaminant and Ease and Economy of Monitoring in terms of with a direct attribute, and Ecological Importance and Social Value in terms of qualitative scales.

The Signal to Noise Ratio category contains five elements:

1) High Species Sensitivity to Pollutant (p.43)
2) Long Temporal Continuum of Reproducing Stocks (p.45)
3) High Reliability and Specificity of Response (p.45)
4) Wide Spatial Distribution in the Region (p.46)
5) High Residency Status at the Site (p.46)

Because there are five elements to the objective there is not one scale we can use to measure the objective. Of these five elements, sensitivity is by far the most important. Sensitivity can be used as a proxy attribute for Signal to Noise Ratio. A proxy attribute uses a scale that relates to the achievement of the objective, but does not directly measure it. Sensitivity can be estimated in terms of LC50 values for a species in a lab (this is the ug of substance that causes 50% mortality in a species in a lab). We will use sensitivity as a proxy attribute for Signal to Noise Ratio. It makes up a large part of the Signal to Noise Ratio, but the signal to noise ratio may vary slightly up or down because of the other factors involved (Kelly and Harvell 1989). This variation could be accounted for using a probability distribution. The decision maker could judge how likely it is that a given score on a proxy attribute approximates true value of the objective. For example, the decision maker may decide that there is a 20% chance that $B_1 = 0.4$, a 50% chance that $B_1 = 0.5$, and a 30% chance that $B_1 = 0.6$. This would give a combined value of $B_1 = 0.2(0.4) + 0.5(0.5) + 0.3(0.6) = 0.51$.

High Exposure to the Environmental Contaminant is an important consideration when choosing indicator species (p.47). The exposure should be large and early for an indicator species relative to the other organisms in an ecosystem. A species with a high exposure to the contaminant will generally respond more rapidly than a species with lower exposure. Concentration can be measured in many ways, such as organism body burdens or water and sediment concentrations. The measurement used will depend on the decision maker's preferences and the information available to him or her.

Ease and Economy of monitoring incorporates four factors:

1) Minimize Informational Overlap (p.52)

2) High Collection or Monitoring Ease (p.49)

3) High Suitability for Laboratory Experiments (p.49)

4) Extensive Historical Information (p.50)

5) Extensive Available Information and Data (p.51)

These factors can all be translated into the costs of monitoring a particular species. The decision maker can assign a dollar value estimate for the collection and monitoring of a particular species and compare it with the costs for monitoring other species.

Ecological importance contains five categories:

1) Highly Critical Species (p.52)

2) Low Redundancy and Immigration (p.53)

3) Examine Most Affected Life Stage (p.54)

4) High Ecosystem Integration (p.54)

When choosing indicator species, we wish to choose indicator species that have high ecological importance. Because no natural scale exists for ecological importance, we will use a qualitative scale based on expert judgement.

Social value does not contain any lower level objectives (p.55). Like ecological importance, social value does not have a natural scale. We will also use a qualitative scale for this attribute based on expert judgement.

Assessing Single Attribute Value Functions

We need to assess the value functions for the various attributes. These assessments will vary from site to site and decision maker to decision maker. For attributes B_1, B_2, and B_3, we will use the bisection method (see von Winterfeldt and Edwards 1986). These three attributes represent continuous and easily quantifiable scales that lend themselves well to the bisection method. In the bisection method, the decision maker assigns the endpoints of the scale values of 0 and 1. Then the decision maker is asked to find the point that is halfway between the two endpoints in terms of value. Continued subdivision leads to refinement of the value scale. Then the decision maker finds the point on the scale that is equivalent to a value of 0.50. Next he or she determines the point on the scale that is equivalent a value of 0.75. A third point determined for the value of 0.25. By continued bisection additional points can be plotted until the value function curve can be drawn (see Figure 2).

We perform this for the three attributes B_1, B_2, B_3. For example, we measure the first attribute B_1, signal to noise ratio, in terms of sensitivity (See Figure 2). This is done in terms of LC50 values. This is the ug (per liter of water or kg of sediment) of substance that causes 50% mortality in a species in the lab in a given time period. The decision maker determines that for a given chemical, sensitivity for different species ranges from almost 0.1 to 100 ug. For simplicity, we will set the lower end of the scale at 0.1.

The more sensitive to a chemical a species is the greater its value as an indicator species. Therefore we will assign 100 ug a value of zero and 0.1 ug a value of 1. We begin with the midpoint of the scale and ask the decision maker if the first 50 ug increase in benefit of the attribute is equal to the increase in benefit of the second 50 mg. This is determined using expert judgement. We keep questioning the decision maker until we find the point where the first x amount of the scale is equal to 100 - x amount. Suppose we find this value to be 60 mg. The first 60 mg of is equal to the last 40 in terms of value. The value of 60 is halfway between the value of 0 and 100. If we define the midpoint of between 0 and 100 mg as $m_{0,100}$ then:

$$v(m_{0,100}) = v(60) = 0.5v(0) + 0.5v(100) = 0.50$$

We can then find the midpoints between 0 and 60 and between 60 and 100. Suppose upon questioning the decision maker, we find that the midpoint between 0 and 60 is 40 and the midpoint between 60 and 100 is 85, then:

$$v(m_{0,60}) = v(40) = 0.5v(0) + 0.5v(60) =0.75$$

and

$$v(m_{60,100}) = v(85) = 0.5v(60) + 0.5v(100) = 0.25$$

With these three points we are then able to plot the value function for the attribute. Further bisection can be performed if necessary to refine the shape of the curve.

Once we have used attributes B_1, B_2, and B_3 in the screening process, we will determine values for the remaining candidate species for attributes B_4 and B_5. In evaluating species on attributes B_4 and B_5, we will employ a direct rating method. Direct rating is useful on small sets of alternatives such as we have when we've screened species list down to a list of candidate species. Direct rating is easy to use and works well with attributes that do not have a natural scale. In direct rating we do not explicitly construct an attribute scale but directly assign single attribute values to the candidate species. There are four steps in the process:

1. When using direct rating, the decision maker first uses expert judgement to choose the best and worst species in terms of a given attribute. These species then become the endpoints of the scale.

2. The decision maker then ranks the species from best to worst between the two extremes.

3. Next the decision maker must change qualitative information in terms of the attribute into a quantitative value scale. To accomplish this, the decision maker performs a numerical rating on a scale. The scale has two endpoints in the best and worst species, with the worst assigned a value of 0 and the best assigned a value of 1. The remaining alternatives are rated in between. The decision maker carefully considers the relative spacing of the candidate species, because the relative spacing reflects the strength of preference of one species over another.

4. Finally the decision maker needs to perform a series of consistency checks. These checks are to make sure that the relative spacing of the candidate species does in fact reflect the decision maker's relative strength of preference for one species over another. The decision maker may ask himself if the difference between A and B on an attribute is really greater than the difference between C and D. Consistency checks may leads to revisions in the relative spacing of candidate species. The scale construction process stops when the decision maker is comfortable with the assessments.

Attribute Weights

Once the single attribute values have been determined for the candidate species, we need to assign weights to the various attributes before we can aggregate them in a model. Weight assessment is necessary because we assigned equal endpoints in value (0 and 1) to each attribute. If we did not have weights for the attributes, we would be implying that increases in strength of preference from the worst to best levels of an attribute are the same for all attributes. In most cases this is not true.

We will use cross-attribute strength of preference to weight the attributes (see von Winterfeldt and Edwards 1986). The decision maker compares his or her relative strength of preference of b_i^* over b_{i*}, the best over the worst attribute level across attributes. Assuming all attributes are at their lowest levels, we ask the decision maker which attribute he or he would like to raise to its best level. Then we ask which attribute he or she would like to raise next, and so on until we can order the attributes from most important to least important. The most important attribute will have the largest weight and the least important will have the smallest. Let's assume the decision maker determines an order of $b_1 > b_2 > b_3 > b_4 > b_5$ (most important objective to least important objective).

To determine how much larger b_4 is than b_5, the decision maker reduces b_4^* to an intermediate level of b_4' and keeps adjusting the value of b_4' until he or she is indifferent between raising b_{4*} to b_4' and raising b_{5*} to b_{5*} with all other attributes assumed to be at their lowest levels. This indifference implies that $w_4v_4(b_4') = w_5v_5(b_5^*)$. By rearranging the equation we get $w_5/w_4 = v_4(b_4')$. By comparing all the other attributes to the least important attribute b_5 in this way, we determine the relative weights for the attributes, generating equations of the form $w_i/w_5 = v_i(x_i')$, where i equals attributes 1 through 4. This requires only four comparisons for the five attributes, but more can be performed as consistency checks. To determine the exact values of the weights, assuming the weights add up to one, we can solve the equation:

$$w_i = \frac{v_i(x_i')}{\text{sum } v_i(x_i')}$$

This can be done for all five attributes.

Screening Process

Sometimes because previous work at similar sites, the ecologist at a site will already have in mind a number of candidate indicator species which are few enough in number that they can be evaluated fully without paring down the list. Also, the number of potential indicator species at a site may be small enough that species do not need to be screened out. In either of these cases, the ecologist could skip the screening procedure directly evaluate the species. However, in most cases, the ecologist at the site is going to have to cut down the list of potential indicator species to a manageable number of candidate species that can be fully evaluated. For this elimination process, we will use a decision analytic screening model.

The screening process allows the decision maker to rapidly focus on the best possible candidate species in areas of high species diversity. It can also help a decision maker determine if there is a worthwhile candidate species at a site with low species diversity.

There are a great number of species at any given site that may be potential indicator species. Many, and often most of the species can be eliminated as inappropriate for a variety of reasons. Some can easily be eliminated from further consideration because they are dominated by other species in terms of every attribute. Often however, after the easy cases are eliminated, there are still too many potential indicator species to evaluate thoroughly. The decision maker must reduce the number of potential indicator species to a manageable number of candidate species which will then be thoroughly evaluated. The decision maker must balance the advantages and disadvantages of the screening procedure. A thorough screening procedure can greatly simplify the task of choosing indicator species by weeding out the inferior candidates. This must be balanced however, against the likelihood that extensive screening procedures may inadvertently eliminate some or all of the best indicator species. We will eliminate this possibility by using a decision analysis screening procedure.

There are several important considerations that are not addressed in most screening models. All assumptions in the screening process must be clearly stated. There is the assumption that all species achieving the same attribute level are equal. Cutoff levels must be carefully determined. Consistency among screening criteria must also be addressed (a cutoff level on one criterion should be equal to a cutoff level on another attribute). Also, a value tradeoffs mechanism needs to be addressed in terms of one attribute compensating for another.

When using a decision analysis screening model the concerns stated above are all addressed. Value judgments are clearly stated, explicit, and quantified. Scales and cutoff levels are clarified and justified.

The screening process is conducted attribute by attribute, with species being eliminated from consideration if they fall below the cutoff level on a given attribute. We make a large assumption in eliminating species that fall below a cutoff level. We may eliminate species that are adequate with respect to several criteria but fall just short of the cutoff values on one or two. However, this approach provides a mechanism for rapidly focusing attention on candidate species that have a higher probability of being the best indicator species. The advantages in terms of time saved when applying each criterion individually outweigh the disadvantages of possible elimination of some legitimate candidate species.

A screening criterion is made up of two parts, the attribute and its cutoff level. The attribute is necessary to determine how well a particular indicator species fulfills the decision maker's objectives. The cutoff level is used to determine what is an acceptable value for a candidate species in terms of an attribute and what is not. In order for the screening procedure to be efficient, it should be easy to determine whether a potential indicator species does or does not satisfy the particular criterion. Proxy attributes are often used as screening criteria (Keeney 1980).

In carrying out the screening procedure, the decision maker starts with the most important criterion and eliminates all of the species that fall below the cutoff level. Then the decision maker moves on to the second most important criterion, and so on, until the list is reduced to a reasonable number of candidate species that can be evaluated fully.

The ordering of the screening criteria should be based on the importance of the criterion and how many species can be screened out as a result of the data. Finally, there should be a clear relationship between the screening attribute levels and the objectives. Based on these considerations, I chose to use the attributes created for single attribute value functions (step 3. in the framework) as screening attributes so that their relationships with the objectives would be clear.

Let's suppose that when weighting the attributes, the decision maker determined that the order of the screening criteria from most important to least important is $B_1>B_2>B_3>B_4>B_5$. By choosing the most important attributes as screening criteria, we can narrow down the number of species that need to be evaluated. If the decision maker feels that the number of potential indicator species is small enough, then he or she can move on to evaluating the candidate species in steps 6. and 7.

Suppose the decision maker judges that because of the number of potential indicator species it is necessary to screen them using three screening criteria. The decision maker chooses the three most important attributes, B_1, B_2, and B_3. As the first step in the screening process, we will develop a value function for the three attributes:

$$v(b_1,b_2,b_3) = w_1v_1(b_1) + w_2v_2(b_2) + w_3v_3(b_3)$$

where $v(b_1^*, b_2^*, b_3^*) = 1$ and $v(b_{1*}, b_{2*}, b_{3*}) = 0$
b^* refers to the highest score among the potential indicator species and b_* refers to the lowest score among the potential indicator species. Based on the above equation, the combined screening scores of any one species evaluated on the attributes will be bounded between 0 and 1. The above equation is based on the additive model (see von Winterfeldt and Edwards 1986). If the decision maker determines that the objectives do not satisfy the conditions of additive independence then the multiplicative or multilinear models can be employed (see von Winterfeldt and Edwards 1986).

An example will illustrate the screening process. Keeney (1980) developed a screening model for sites for an energy facility which can be easily applied to screening indicator species. The following value function will serve as our screening model.

Suppose $v(b_1, b_2, b_3) = 0.6v_1(b_1) + 0.3v_2(b_2) + 0.1v_3(b_3)$ where v_1, v_2, and v_3 are value functions scaled from 0 to 1 and where $v_i(b_i^*) = 1$ and $v_i(b_{i*}) = 0$ and $i = 1,2,3$.
The value judgments of the decision maker at the site are used to choose the aggregation model, and to assess the value functions and scaling constants. Let's suppose the decision maker determined that B_1 was the most important screening criterion, followed by B_2 and B_3 We begin by collecting data on the most important attribute (B_1) for all of the potential indicator species. Let us suppose that the highest scoring species has a level b_1' of objective B_1 such

that $v_1{'}(b_1) = 0.90$. For this species, the minimum possible overall score would be:

$v(b_1{'}, b_{2*}, b_{3*}) = 0.6(0.90) + .3(0) + 0.1(0) = 0.54$

A species with a b_1 level of B_1 such that $v_1(b_1) < 0.23$ will have an overall value less than 0.54, since even with attributes B_2 and B_3 at their best levels:

$v(b_1, b_2^*, b_3^*) = 0.6(0.23) + 0.3(1) + 0.1(1) = 0.54$

Therefore, any species below a level of b_1 such that $v_1(b_1)$ < 0.23 can be eliminated from further consideration.

The next phase of the screening process begins with the attribute B_2. Only the species not screened in terms of B_1 will be considered in terms of B_2. Suppose that the species with the best level of B_2 is $b_2{''}$ such that $v_2(b_2{''}) = 0.95$. Usually the species that has the best score on B_1 will not have the best score on B_2. Suppose the species that scores highest on B_2 has a value of B_1 such that $v_1(b_1{''}) = 0.6$ Also suppose that the species scoring highest on B_1 ($v_1(b_1)$ $= 0.90$) has a level of B_2 such that $v_2(b_2) = 0.5$.

Then the minimum overall values for the two species would be:

$v(b_1{'}, b_2{'}, b_{3*}) = 0.6(0.9) + 0.3(.50) + 0.1(0) = 0.67$

$v(b_1{''}, b_2{''}, b_{3*}) = 0.6(0.6) + 0.3(0.95) + 0.1(0) = 0.65$

we would then check to see if there is a higher scoring species on the two criteria combined. Suppose when doing this we find a species that has a level of B_1 such that $v_1(b_1) = 0.75$ and a level of B_2 such that $v_1(b_1) = 0.80$. This would give the species a minimum possible score of

$0.6(0.75) + 0.3(0.8) + 0.1(0) = 0.69$. This new value of 0.69 allows us to raise the cutoff level of B_1 such that $v_1(b_1) = 0.48$ because even with B_2 and B_3 at their optimal levels, $0.6(0.48) + 0.3(1) + 0.1(1) = 0.69$. We can then check to see if we can screen by B_2 alone. If we assume the maximum values for B_1 and B_3 then we get $0.6(1) + 0.1(1) = 0.70$. Since this is higher than .69, a species could potentially have a value of 0 for B_2 and we cannot yet screen by B_2 alone.

Finally, we collect data for attribute B_3 for the species that have not yet been screened out. Suppose the species with the highest level of B3 has a value such that $v_3(b_3) = 1.0$. Suppose that the highest overall score for the remaining species turns out to be $v(b_1, b_2, b_3) = 0.76$. On the last screening criteria, we do not want to use the highest overall value because this could eliminate all but one of the remaining species. We may therefore use a slightly lower cutoff value to leave us a number of species to evaluate fully. Suppose we choose a cutoff value of $v(b_1, b_2, b_3) = 0.71$. We can check to see if we can screen by B_3. If we take the highest levels of B_1 and B_2 we get $0.6(0.9) + 0.3(0.95) = 0.83$ Since this is higher than our overall cutoff level of 0.71, we can't screen by B_3 alone. Next we can raise the cutoff level of B_1 to $v_1(b_1) = 0.54$ because:

$v(b_1, b_2, b_3) = 0.6(0.54) + 0.3(0.95) + 0.1(1) = 0.71$.

We can now also establish a cutoff level for B_2 of 0.23. We can do this because even if B_1 and B_3 are at their highest levels, B_2 would have to equal 0.23 to achieve the highest overall value:

$$v(b_1, b_2, b_3) = 0.6(0.9) + 0.3(0.23) + 0.1(1) = 0.71$$

If further reduction of candidate species is needed, we can screen using pairs of attributes. Any species with a combination of B_1 and B_2 such that

$$0.6v_1(b_1) + 0.3v_2(b_2) < 0.61$$

can be eliminated since even with B_3 at its optimum level, the overall score would not be equal to the cutoff level of 0.71. We can also exclude any combination of B_2 and B_3 such that

$$0.3v_2(b_2) + 0.10v_3(b_3) < 0.17$$

because in combination with the best level of B_1, the overall value would be less than 0.71. Finally, we can screen on the pair of attributes B_1 and B_3 such that

$$0.6v_1(b_1) + 0.1v_3(b_3) < 0.41$$

because even with the highest B_2 level, the overall value of the species would fall below the cutoff level.

Evaluation of Candidate Species

Once we have determined the single attribute values for the candidate species we are ready to aggregate the values into a model in order to score the alternatives. In using the additive model, we are assuming additive difference independence. This means that the strength of preference in a single attribute is unaffected by other constant attributes. The shape of a value function would be unaffected when constructed at different levels of other attributes. This is very complicated to prove, and for the sake of simplicity, we will assume that it holds true. These weights can then be entered into the equation

$$v(b) = \text{sum } w_i v_i(x_i)$$

where $v_i(x_i)$ is the value of site b on the attribute i, w_i is the importance weight of i, and v is the value of b. Once the values are determined for all of the indicator species, it is easy to compare the overall values of the different species to determine which is the best indicator species at a given site. At a site with low species diversity, the decision maker can examine the multiattribute value functions for the site to determine if there is one with a high enough value to be a useful indicator species.

Sensitivity Analysis

When using decision analysis, we develop a formal value structure that includes subjective concerns and quantifies the objectives. This quantification allows us to conduct a sensitivity analysis in order to see how the decision changes when the data in the decision analysis differs from the best value estimates. Sensitivity analysis allows us to determine the conditions under which the various alternative indicator species would be chosen and where the switch over points are.

Sensitivity analysis is performed when the decision maker has structured the problem, and has the numbers and the model relevant to it. Sensitivity analysis provides insights into what is important in the problem. In sensitivity analysis we vary the form and parameters of the single attribute value functions, and the multiattribute value function to see how the decision changes when values and weights are different.

Dominated Alternatives

The first step in using sensitivity analysis in a problem is to eliminate dominated alternatives. This is what our screening model does, by eliminating alternatives which could not be the best option. The options remaining after the screening process are unlikely to be dominated in terms of all of the attributes, but any that are dominated can be eliminated.

Changes in Attribute Values

We can vary the values of the attributes for the various candidate species to see how this effects the rankings of the alternatives. It is often useful to look at the best and worst alternatives and the range of an attribute for all of the attributes. We outline this in Table 2. Since B_3 has a fairly heavy weight and a large range, it is a clear choice for a sensitivity analysis. A sensitivity analysis could also be performed for the other attributes, but because the range is not that great, it is not likely to affect the ranking of the alternatives.

We can examine percent changes in the overall species scores due to percent changes of inputs for the attributes. For example, suppose the screening process has left the decision maker with five species, A - E. In Table 4 we examine how the percent input numbers for these species on attribute B_3 affect the overall scores of the five species. When using the original values the highest scoring species is A with a value of 0.80. Species A also dominates in overall score when the value of B_3 is decreased. However, when the input numbers for attribute B_3 are increased by 50%, Species B is the highest scoring species overall.

Changes in the Scaling Constants

We can vary the weights of the attributes to see how the ranking of the candidate species changes. We can perform this for the weights of the screening function and the multiattribute value function. We can change the value of one scaling constant while keeping the ratios of the other scaling constants the same.

Suppose species A - E have the values on attributes B_1 - B_5 as shown in Table 3. From looking at these values, we can observe that A will win for high weights of B_1 and option D will dominate at high weights of B_3. We can also see that species B is the most evenly balanced in terms of all the attributes.

Suppose also that the decision maker at the site is concerned about cost and thinks that he or she may want to weigh costs more heavily. We can vary the weight of attribute B_3 while keeping the ratios of the other weights constant. We can apply these weights to the single attribute values for the five species, and calculate the overall scores for the species at the various weights. We can compare these weights in a graph of the form of Figure 3. In the graph, Alternative A is the highest scoring at low weights of B_3. When the weight equals 0.25, there is a switch to B. There is a second switch to species D when the weight of B_3 reaches 0.35. Species C and E are dominated throughout. Alternative B is the most evenly balanced in terms of the attributes and is therefore subject to the least fluctuation when varying the weights. Since species B is near the top scoring species the decision maker may choose species B if he or she is uncertain about the weights.

Choosing Indicator Species: A Hypothetical Example

Introduction

In order to illustrate this framework for choosing indicator species, we will examine a case study site. Elements of this case study are real and elements are hypothetical. The site and site-specific and contaminant-specific information is real. Species-specific information for attributes was unvailable. Therefore information used in scoring species on attributes and weighting the attributes is hypothetical. The information in this case study is hypothetical and intended only to illustrate how the framework could be used. Background information on Polycyclic Aromatic Hydrocarbons is taken from Ron Eisler's review of PAH effects on fish, wildlife, and invertebrates (Eisler 1987).

The hypothetical site is a contaminated river that flows through two counties in Wisconsin. The river is 10.6 miles long and has a drainage area of 21 square miles. Land use in the watershed is quite diverse. Land use is 60% rural and 40% urban in the watershed. Grassy meadows, mesic hardwood forests, agricultural lands and emergent cattail marsh are the dominant vegetation covers of land along the stream in both counties. These cover types provide good wildlife habitat for a variety of species.

There are several pollutant sources in the watershed, both point and non-point. There are 7 industrial and 1 municipal state permitted discharges to the river. Water quality impacts from these impacts is thought to be minimal. Pollution from nonpoint sources is much more significant. Urban land uses generate more pollution per square mile than rural uses. There is a great deal of erosion in the watershed due to the hydrologic group C and D soils which dominate throughout the watershed. These soils are highly erosive due to poor infiltration rates. Stream channelization, sedimentation, increased turbidity, creosote toxicity, and pollution from non-point runoff may all contribute to the demise of various species at the site.

The property of concern is an 88 acre abandoned industrial site located immediately south of Milwaukee. When in operation between 1921 and 1976, the facility included a creosote plant. Creosote is a brownish oily liquid composed chiefly of polycyclic aromatic hydrocarbons obtained through the distillation of coal tar and used as a wood preservative. Wastes from this facility were discharged to surface soils and to the river until 1970 when the Wisconsin Department of Natural Resources (WDNR) issued an order to pretreat wastes and discharge to the sanitary sewer system. In 1971, several youths received serious chemical burns while wading downstream.

Fate In the Aquatic Environment

The majority of PAHs entering aquatic environments remain close to the site of deposition. They are persistent and potent human carcinogens (Lee and Grant 1981). In aquatic environments, PAHs may evaporate, disperse in the water column, become trapped in sediments, or concentrate in aquatic organisms (Suess 1976). Most PAHs are associated with particulate matter, with only about one third present in dissolved form (Lee and Grant 1981). PAHs dissolved in the water column degrade rapidly though photooxidation (EPA 1980). The ultimate fate of PAHs in sediments is biotransformation and biodegradation. PAHs degrade very slowly in sediments.

Toxicity

Toxicity is most pronounced among crustaceans and least among teleosts (Neff 1979). In all but a few cases, PAH concentrations that are acutely toxic to aquatic organisms are several orders of magnitude higher than those found in even the most heavily polluted waters (Neff 1979). Polluted sediments however, may contain PAH concentrations that are acutely toxic. These sediments have limited bioavailability and indicator species must be carefully chosen.

Exposure

When assessing species' exposure to PAHs, the decision maker needs to consider whether the organism is a soil feeder, bottom feeder, or feeds in the water column.

Bioconcentration factors (BCFs) must also be considered. A bioconcentration factor is the ratio of the concentration of a contaminant in the organism to the concentration in the immediate environment. Most organisms rapidly accumulate (bioconcentrate) PAHs from the ambient medium, but these substances don't tend to biomagnify in the food chain. PAH uptake rates for different species of organisms are highly variable, being higher in algae, molluscs, and other species which are incapable of metabolizing PAHs (Neff 1982). Bioconcentration factors tend to increase with increasing molecular weight of the PAH, with increasing octanol/water partition coefficient values, with time until approaching an apparent equilibrium value, with increases in dissolved organic matter in the medium, and lipid concentration in the organism (Lee and Grant 1981).

A series of detailed studies have been performed to study the impacts of creosote contamination on soil, groundwater, and surface water resources of the river (EPA 1977A,B). These studies indicate that creosote contaminated stream banks, bottom sediments, groundwater, and surface runoff are a continuous source of creosote and associated polycyclic aromatic hydrocarbons (PAHs). Soil concentrations of PAHs at the site were found to be in excess of 279,000 mg/kg at depths of 15 feet (EPA 1977A). Groundwater at the site is also heavily contaminated. Groundwater flow from the site and into the river provide a continuous source of PAH contamination in the river.

Bottom sediments and river bank soils are heavily contaminated by PAHs. PAH concentrations in bottom sediments range from 0 to >20,000 mg/kg. USEPA sponsored two consultants to develop and test demonstration projects for removal and disposal of contaminated river sediments. Although these demonstration projects were somewhat successful in removing PAH contaminated river sediments, high levels remain in bottom sediments and along lower banks. EPA suspects that contaminated groundwater and runoff continue to be released from the site. EPA would like to monitor the success of these and any future remediation efforts.

Polycyclic Aromatic Hydrocarbons (PAHs) consist of hydrogen and carbon in the form of two or more fused benzene rings. There are thousands of PAH compounds, each differing in the number and positioning of aromatic rings, and the substituents on the rings. Unsubstituted lower molecular weight PAHs containing 2 or 3 rings exhibit acute toxicity and other adverse effects to organisms (Lee and GRant 1981). Higher molecular weight PAHs containing 4 to 7 rings are significantly less toxic, but many of these compounds are carcinogenic, mutagenic, or teratogenic to a variety of organisms, including fish and other aquatic life, amphibians, birds, and mammals (lEE AND Grant 1981). PAHs show little tendency to biomagnify in food chains, despite their high lipid solubility (Cook and Dennis 1984). This is probably because PAHs are rapidly metabolized.

Species' responses to PAHs are highly variable, and are influenced by a number of chemicals, including other PAHs. Until these interaction effects are understood, the results of single substance lab tests may be extremely difficult to apply to contamination at field sites (Eisler 1987).

Choosing Indicator Species

Our decision maker is an ecologist at the site who wants to select indicator species to monitor the remediation efforts in the river. It is much simpler to choose species when a single chemical is involved so that we can avoid interactive effects between different chemicals. However, most Superfund sites contain many different contaminants and we will examine a site with a number of contaminants. Since it is impossible to choose species that are sensitive to all of the chemicals at the site, the decision maker chooses several chemicals which he or she judges are representative of the chemicals at the site and for which there is a large amount of toxicological data. There is some uncertainty in how the interactive effects of many chemicals at the site will alter species' responses, but the measurement of this uncertainty is beyond the scope of this paper. These chemicals for which there is toxicological data should include a compound with 2 or 3 rings to monitor for acute toxicity and a compound of 4 to 7 rings to monitor for chronic toxicity effects. We will focus on choosing indicator species to monitor for an acute toxicity endpoint to illustrate the use of the framework for choosing indicator species. The chemical analyses of the river sediments indicated a large proportion of the two ring compound naphthalene. Since there is a large amount of toxicological data for this chemical, the decision maker decides to make it the focus of species sensitivity for the acute toxicity endpoint.

A comparison site was examined upstream and 37 potential indicator species were identified by an ecologist at the site. Only aquatic organisms are being considered since PAHs are rapidly metabolized and therefore do not biomagnify in terrestrial organisms further up the food chain which could potentially be exposed. The decision maker was only provided with information pertaining to fish and aquatic invertebrates, so these are the only organisms which will be considered in this problem.

The decision maker examines the objectives hierarchy in Figure 1 and judges that it corresponds to what is important in choosing indicator species at the site. The decision maker also believes that due to the large number of potential indicator species at the site, it is appropriate to quantify the objectives at the B level of the objectives hierarchy with 5 objectives rather than the C level with 17 objectives. The decision maker also decides that the attributes chosen in the hierarchy suit his or her needs.

The decision maker can then move on to screening potential indicator species. The decision maker determines that when considering relative importance and the number of species that can be eliminated with each criterion, the order of the criteria is sensitivity (B_1), exposure (B_2), and ease and economy of monitoring (B_3). The decision maker then determines endpoints for the scales for the three screening attributes and assesses the value curves using the bisection method discussed in the framework section (see Figures (4,5 and 6).

The decision maker determines that he or she wants to weigh the attributes according to the formula

$$v(b_1, b_2, b_3) = 0.6v_1(b_1) + 0.3v_2(b_2) + 0.1v_3(b_3)$$

by using the weighting method discussed in the framework section.

The first screening criterion for which we collect information is B_1. The decision maker determines that the LC50 values for a 24 hour period all range from 920 - 150,000 ug/L. The highest scoring organism is species 29 (see Table 5) with a value of B_1 equal to 0.95. For this species, the minimum possible overall score would be

$$0.6(0.95) +.3(0) + .1(0) = 0.57.$$

A species with a value of B_1 less than 0.28 will not have an overall score higher than this species even if it has the optimum values for B_2 and B_3 since

$$0.6(0.28) + 0.3(1.0) + 0.1(1.0) = 0.57.$$

Therefore we can eliminate all species with a value of B_1 below 0.28. This corresponds to a sensitivity of 11,000 ug/L. When looking at sensitivity data for the potential indicator species, this eliminates species 1 - 13. Only the organisms not eliminated on B_1 will be screened on B_2.

The decision maker next collects exposure data on the indicator species not yet eliminated and determines the how these data correspond to values by comparing them on the value curve. The most highly exposed organism is species 28 with a value of B_2 equal to 0.90. This species also has a value of B_1 equal to 0.60. Species 29, the highest scoring species on B_1 ($b_1(v_1)$ = 0.95) has a B_2 value equal to 0.30. The minimum overall values for these two species would be:

species 28 = 0.6(0.95) + 0.3(0.3) + 0.1(0) = 0.66

species 29 = 0.6(0.60) + 0.3(0.9) + 0.1(0) = 0.63

Next the decision maker checks to see if there is a species which scores higher on the two criteria combined. Species 30 has a value of B_1 equal to 0.85 and a value of B_2 equal to 0.63. This gives species 30 a minimum possible score of

$$0.6(0.85) + 0.3(0.63) + 0.1(0) = 0.70$$

This new value of 0.70 allows the decision maker to raise the cutoff level to B_1 to 0.55 because even with B_2 and B_3 at their optimum levels, a species would fail to score higher than 0.70:

$$0.6(0.55) + 0.3(0.9) + 0.1(1) = 0.70$$

This eliminates species 14 - 24 from consideration.

The decision maker now checks to see if species can be screened on B_2 alone. Any species with a value of B_2 less than 0.10 can be eliminated because even when assuming the maximum values for B_1 and B_3, the species will not score higher than 0.70:

$$0.6(0.95) + 0.3(0.1) + 0.1(1) = 0.70$$

This eliminates species 25, 26, and 27.

After examining the overall scores of the remaining species, the highest overall score turns out to be $v(b_1, b_2, b_3) = 0.78$. On the last screening criteria, the decision maker does not want to use the highest possible value, because this may eliminate all but one species. The decision maker wants to be left with a reasonable number of candidate species to evaluate fully. The decision maker decides on a lower cutoff value of 0.73. The decision maker then checks to see if the species can be screened on the basis of B_3 alone. Taking the highest levels of B_1 and B_2, we get $0.6(0.95) + 0.3(0.90) = 0.84$. Since this is higher than the cutoff value of 0.73, we can't screen by B_3 alone.

The decision maker can now raises the cutoff level of B_1 to 0.60, because with B_2 and B_3 at their optimum levels, we get:

$$0.6(0.60) + 0.3(0.95) + 0.1(1) = 0.73$$

Therefore any species with a level of B_1 below 0.60 can be eliminated. This eliminates species 31 and 32. The decision maker could continue on and screen using pairs of attributes, but instead decides that the X species remaining is a good number to evaluate.

The original 37 species have been pared down to 6 candidate species. The decision maker then assesses the values for the attributes in terms of B_4 and B_5. This is done using the direct rating technique discussed in the framework section of the paper. After the values have been assessed, the decision maker determines the weighting function for the aggregation of the single attribute value function. Again, as in the framework section, the decision maker believes that additive independence holds and uses the additive model. Using cross attribute strength of preference, the decision maker determines an aggregate value function of:

$$v(b_1, b_2, b_3, b_4, b_5) =$$
$$0.3b_1(v_1) + 0.25b_2(v_2) + 0.2b_3(v_3) + 0.15b_4(v_4) + 0.1b_5(v_5)$$

By evaluating this formula for all of the candidate species, the decision maker determined the overall scores listed in Table 6.

We can perform a sensitivity analysis of the candidate species as was described in the framework section. The decision maker examines the range of attributes in Table 7. Because of its relative weight and range of values, the decision maker judges that objective B_1 is a clear choice for a sensitivity analysis.

The decision maker examines the changes in overall species scores due to changes in the input numbers for attribute B_1 in Table 9. At the original input values, species 35 is the highest scoring species. Species 35 also dominates at higher input values for attribute B_1. However, when the input numbers for B_1 are decreased by 50%, species 37 dominates (see Figure 7).

When examining changes in species scores due to changes in the attribute weights, the decision maker varies the weight of B_1 while keeping the ratio of the weights of the other attributes constant. From Table 8 we can see that depending on the weight of B_1, three different candidates could potentially be the best indicator species. When the weight of B_1 is 0.2 or less, species 35 achieves the highest overall score. When the weight of B_1 is greater then 0.2 but less than 0.8, the species 37 is the best indicator (see Figure 8). When the weight of B_1 is 0.8 or greater, then species 28 is the best indicator. However, species 37 remains consistently near the top throughout the variation of B_1 and is therefore the best choice.

Implications Of Using Decision Analysis In A Regulatory Setting

[illegible] a site to choose indicator species [illegible] consideration [illegible] the decision.

Potentially responsible parties (PRPs) at a site are going to be concerned with which species is chosen as an indicator species at a site. The choice of species will affect the level of cleanup necessary at a site. A species that is going to need a parts per billion level of cleanup is going to cost a PRP more in cleanup costs than [illegible] needs a cleanup to the parts per million level. Therefore the PRP may push to use the species that would require a less extensive cleanup. On the other hand, a public interest group may want EPA to use the indicator species that requires a more extensive cleanup, in order to ensure that the ecology of an area is protected as much as possible. Therefore the choice of indicator species is likely to be called into question by different groups with different priorities and agendas.

A useful technique for choosing indicator species should [illegible] all experts to discuss their differences of opinion on how the species should be ranked in terms of their usefulness as indicator species. For example, an ecologist working for EPA may judge that a particular indicator species should be used [illegible] a biologist [illegible] other species [illegible] they rank [illegible] indicator species. Experts can compare [illegible] species, the attributes they [illegible] species, and how their judgments differ in terms of [illegible] for particular species.

[illegible] the values or weights of attributes, experts can conduct sensitivity analyses [illegible] changes in these numbers actually affect the relative ranking of species. Sensitivity analysis can also show the [illegible] where one species becomes better than another when different values are put into the model.

When conducting a sensitivity analysis, it may [illegible] apparent that the highest scoring species may not be the best choice. For example, one species may score [illegible] near the top despite variations in attribute weights and values while the other high scoring species may drop in rank significantly for changes in certain attribute weights and values. Experts may then agree that the most consistently scoring species is the best choice.

The use of a panel of experts for choosing indicator species would greatly strengthen the process. A panel of experts could use the decision analysis framework to debate the ranking of species, and a decision by a panel of experts would be more likely to stand up in court.

An ecological [illegible] indicator species [illegible] In this [illegible] which [illegible] That [illegible] a matter of [illegible] and [illegible] [illegible] this paper [illegible] expert [illegible] and clarify his or her judgments, and [illegible] judgments are sometimes [illegible] for political, [illegible] or other reasons. The framework in this paper is [illegible] setting. However, the choice [illegible] may be framed in a larger way [illegible] requires a political resolution.

[illegible] ecological assessment, the point [illegible] the ecology of a site can be crucial. [illegible] be compared to a control site, or to historical [illegible] the site. Alternatively, expert judgment [illegible] be used to determine what the ecology of a site should [illegible] like.

The use of indicator species involves focusing on single species or groups of species. Often it may be more useful [illegible] measures such as species richness or diversity. The particular method that is most useful for an ecological assessment at a site will be based on site-specific and contaminant-specific considerations and will have to be judged by an expert or group of experts at the site.

Appendix

Table 1
Sensitivity of Selected Organisms to Napthalene

Organism	Concentration in medium (ug/l)	Effect	Reference
Dungeness crab, <u>Cancer magister</u>	2,000	LC50 (96 hr)	Neff 1979
Grass shrimp	2,400	LC50 (96 hr)	Neff 1979
Amphipod, <u>Elasmopus pectenicrus</u>	2,680	LC50 (96 hr)	Neff 1979
Sandworm	3,800	LC50 (96 hr)	Neff 1985
Mosquitofish, <u>Gambusia affinis</u>	150,000	LC50 (96 hr)	Neff 1979

Table2
Range of Attributes

Attribute	Best Option Species, Score	Worst Option Species, Score	Range
B1	0.94 (A)	0.68 (E)	0.26
B2	0.90 (E)	0.65 (D)	0.25
B3	0.97 (D)	0.50 (A)	0.47
B4	0.85 (B)	0.60 (D)	0.25
B5	0.92 (E)	0.73 (D)	0.19

Table3
Values of Species on the Attributes

Species	B1	B2	B3	B4	B5	Overall
A	0.94	0.85	0.50	0.82	0.87	0.80
B	0.80	0.70	0.80	0.85	0.80	0.78
C	0.75	0.80	0.62	0.71	0.74	0.73
D	0.70	0.65	0.97	0.60	0.73	0.73
E	0.68	0.90	0.72	0.70	0.92	0.77

Table 4
Sensitivity of Overall Species Scores to
Changes in Input Numbers for Attribute B3

Species	-75%	-50%	-25%	Original	+25%	+50%	+75%
A	0.73	0.75	0.77	0.80	0.83	0.85	0.88
B	0.66	0.70	0.74	0.78	0.82	0.86	0.90
C	0.64	0.67	0.70	0.73	0.76	0.79	0.82
D	0.59	0.63	0.68	0.73	0.78	0.83	0.88
E	0.66	0.70	0.73	0.77	0.81	0.84	0.88

Table5
SpeciesSingleAttributeValues

	Sensitivity	Value	Exposure	Value	Economy	Value
1	13,000	0.23	--	--	--	--
2	25,000	0.15	--	--	--	--
3	52,000	0.07	--	--	--	--
4	25,000	0.16	--	--	--	--
5	11,000	0.27	--	--	--	--
6	52,000	0.07	--	--	--	--
7	150,000	0	--	--	--	--
8	31,000	0.12	--	--	--	--
9	43,000	0.09	--	--	--	--
10	16,000	0.21	--	--	--	--
11	26,000	0.14	--	--	--	--
12	60,000	0.06	--	--	--	--
13	34,000	0.11	--	--	--	--
14	6,500	0.35	--	--	--	--
15	4,500	0.42	--	--	--	--
16	6,000	0.37	--	--	--	--
17	4,000	0.45	--	--	--	--
18	3,100	0.52	--	--	--	--
19	3,000	0.54	--	--	--	--
20	5,000	0.40	--	--	--	--
21	5,500	0.39	--	--	--	--
22	4,500	0.42	--	--	--	--
23	3,000	0.54	--	--	--	--
24	3,400	0.50	--	--	--	--
25	1,800	0.70	15,000	0.07	--	--
26	1,600	0.73	4,500	0.05	--	--
27	1,300	0.82	25,000	0.08	--	--
28	2,500	0.60	750,000	0.90	450,000	0.52
29	1,000	0.95	250,000	0.30	210,000	0.67
30	1,200	0.85	500,000	0.63	6,000,000	0.10
31	3,100	0.52	240,000	0.29	175,000	0.71
32	2,600	0.57	400,000	0.47	1,560,000	0.30
33	1,300	0.84	120,000	0.17	800,000	0.42
34	2,000	0.67	50,000	0.12	260,000	0.63
35	1,600	0.73	500,000	0.61	300,000	0.60
36	1,200	0.85	470,000	0.57	50,000	1.0
37	2,400	0.61	600,000	0.82	600,000	0.48

Table6
Values of Candidate Species

Species #	B1	B2	B3	B4	B5	Overall
28	0.60	0.90	0.52	0.25	0	0.55
29	0.95	0.30	0.67	0.50	0.50	0.62
30	0.85	0.63	0.10	0.60	0.70	0.59
35	0.73	0.61	0.60	0.80	1.0	0.71
36	0.85	0.57	1.0	0	0.20	0.62
37	0.61	0.82	0.48	1.0	0.70	0.70

Table7
Range of Attributes

Attribute	Best Option Score, Species	Worst Option Score, Species	Range
B1	0.95(#29)	0.60(#28)	0.35
B2	0.90(#28)	0.30(#29)	0.60
B3	1.0(#35)	0(#36)	1.0

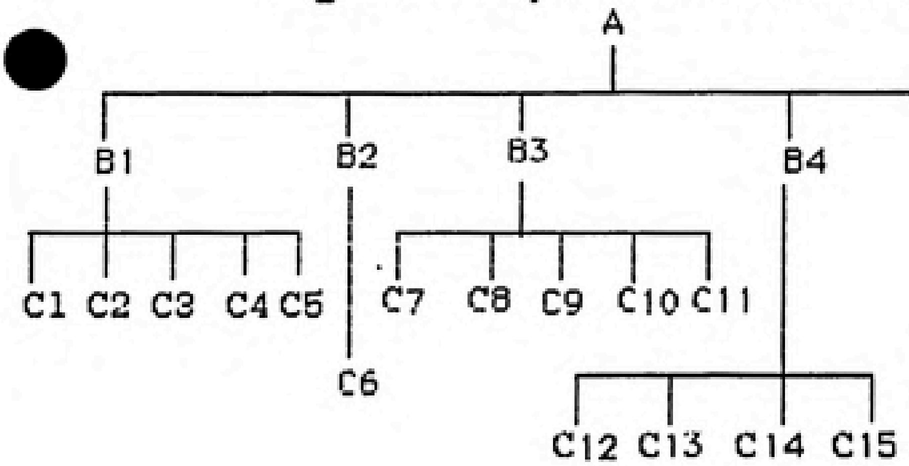
Table8
Variations in Species Scores with Variations in the Weight of B1

Weight of B1	#28	#29	#30	#35	#36	#37
0.8	0.80	0.38	0.62	0.64	0.58	0.79
0.5	0.66	0.51	0.61	0.67	0.60	0.74
0.4	0.62	0.56	0.60	0.69	0.61	0.73
0.3	0.57	0.60	0.59	0.70	0.61	0.71
0.2	0.52	0.64	0.59	0.72	0.62	0.70
0.1	0.48	0.68	0.59	0.73	0.62	0.68

Table 9
Sensitivity of Overall Species Scores to
Changes in Input Numbers for Attribute B1

Species#	-75%	-50%	-25%	Original	+25%	+50%	+75%
28	0.42	0.46	0.51	0.55	0.59	0.64	0.68
29	0.41	0.48	0.55	0.62	0.69	0.76	0.83
30	0.40	0.46	0.53	0.59	0.65	0.72	0.78
35	0.55	0.60	0.65	0.71	0.77	0.82	0.87
36	0.43	0.49	0.56	0.62	0.68	0.75	0.81
37	0.56	0.61	0.65	0.70	0.75	0.79	0.84

Figure 1 Objectives Hierarchy



A = Choose the Best Indicator Species

B1 = High Signal to Noise Ratio

B2 = High Exposure to the Environmental Contaminant

B3 = High Ease and Economy of Monitoring

B4 = High Ecological Importance

B5 = High Social Value

Figure 2

Single Attribute Value Curve
Using the Bisection Method

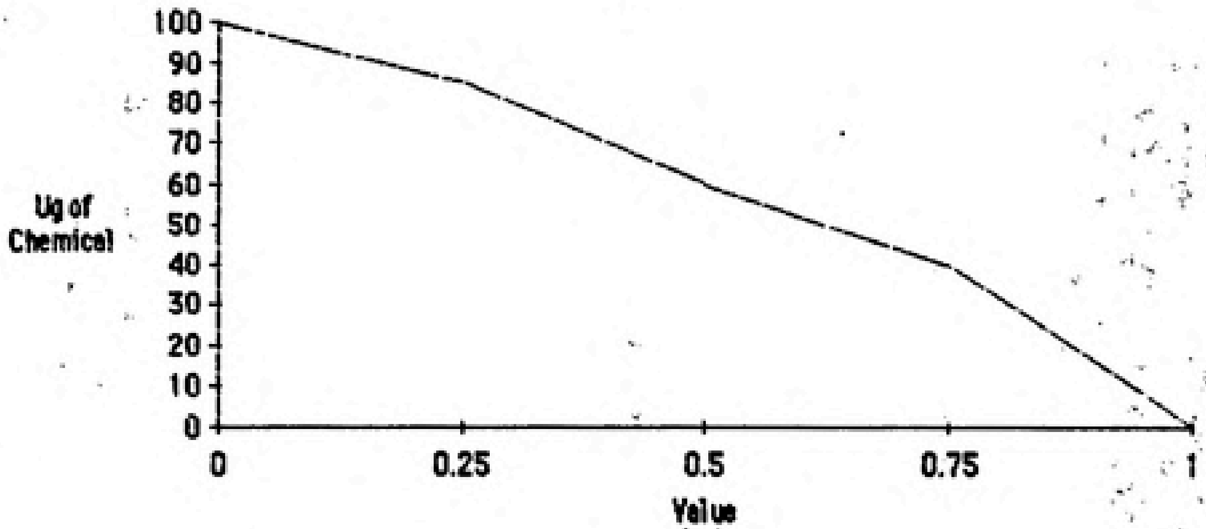


Figure 3

Sensitivity Analysis of
Ease and Economy of Monitoring Weight

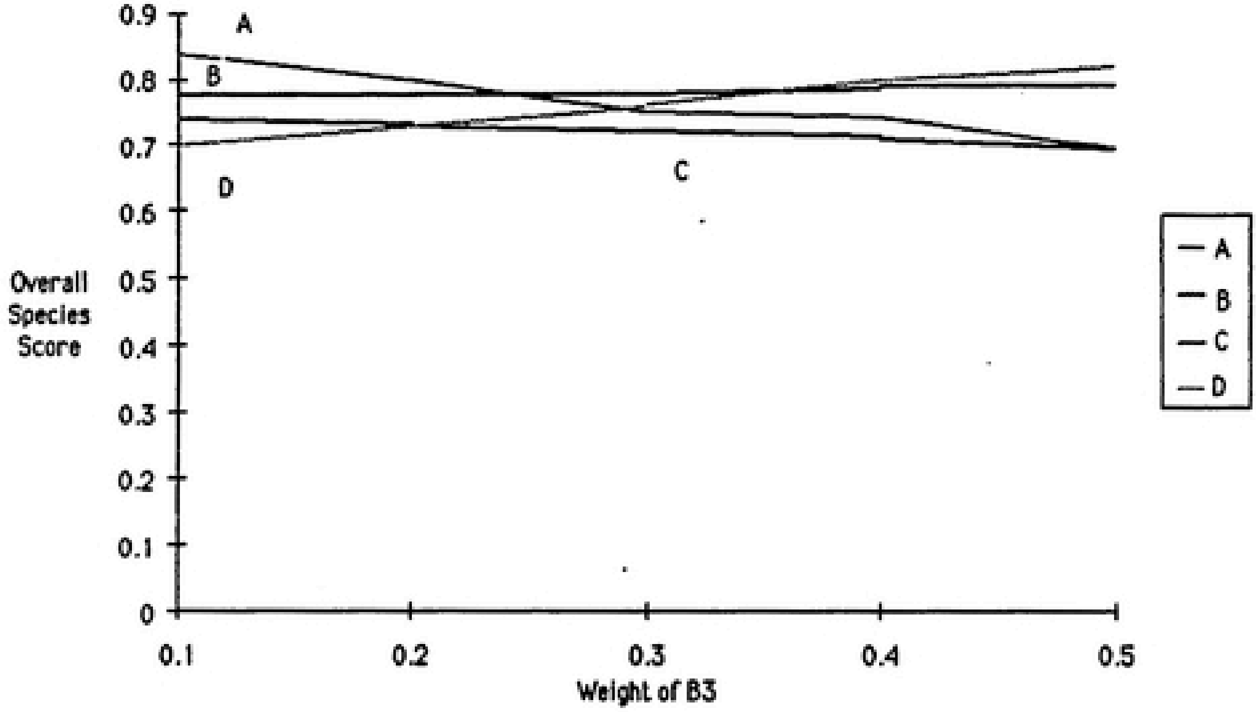


Figure 4

Sensitivity vs Value

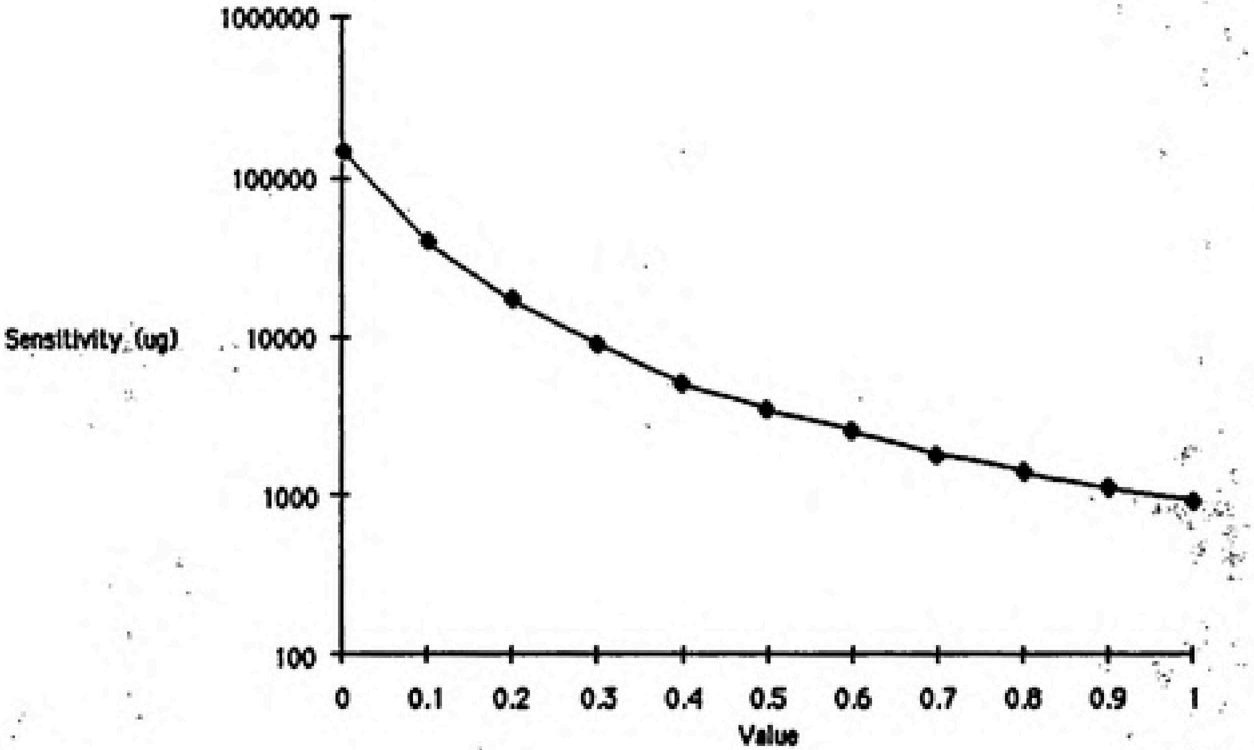


Figure 5

Exposure vs Value

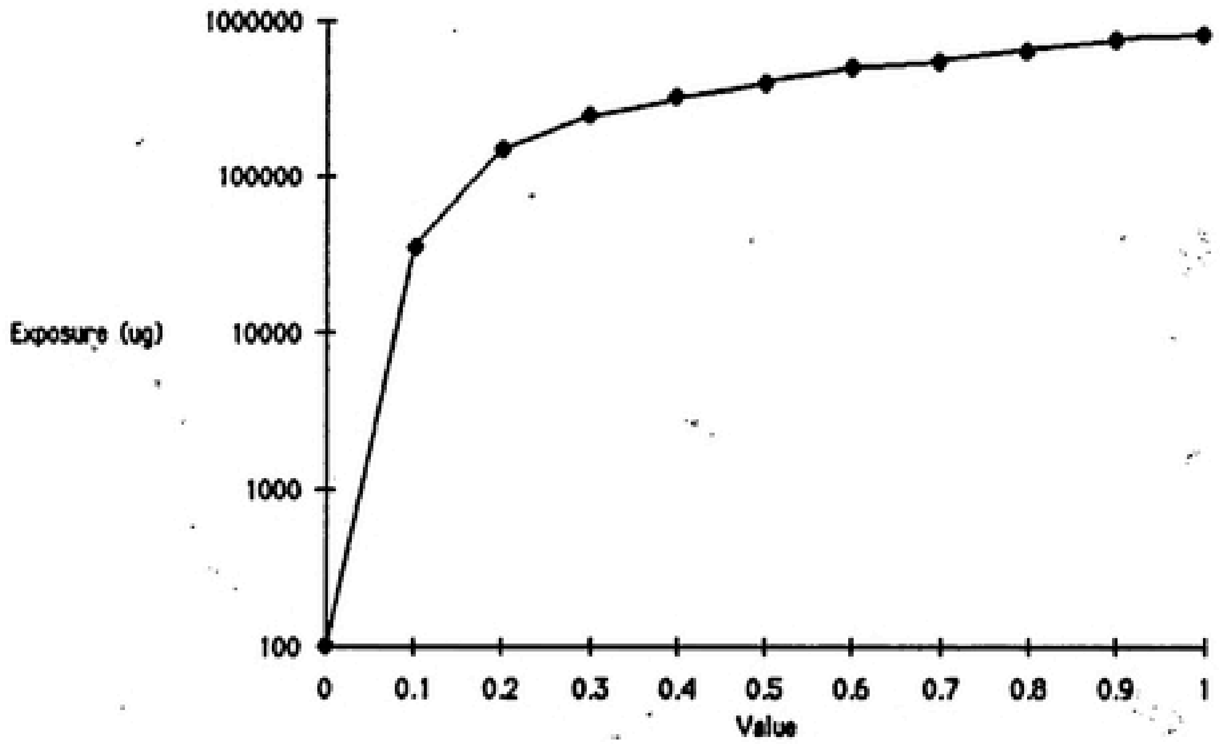


Figure 6

Ease and Economy of Monitoring vs Value

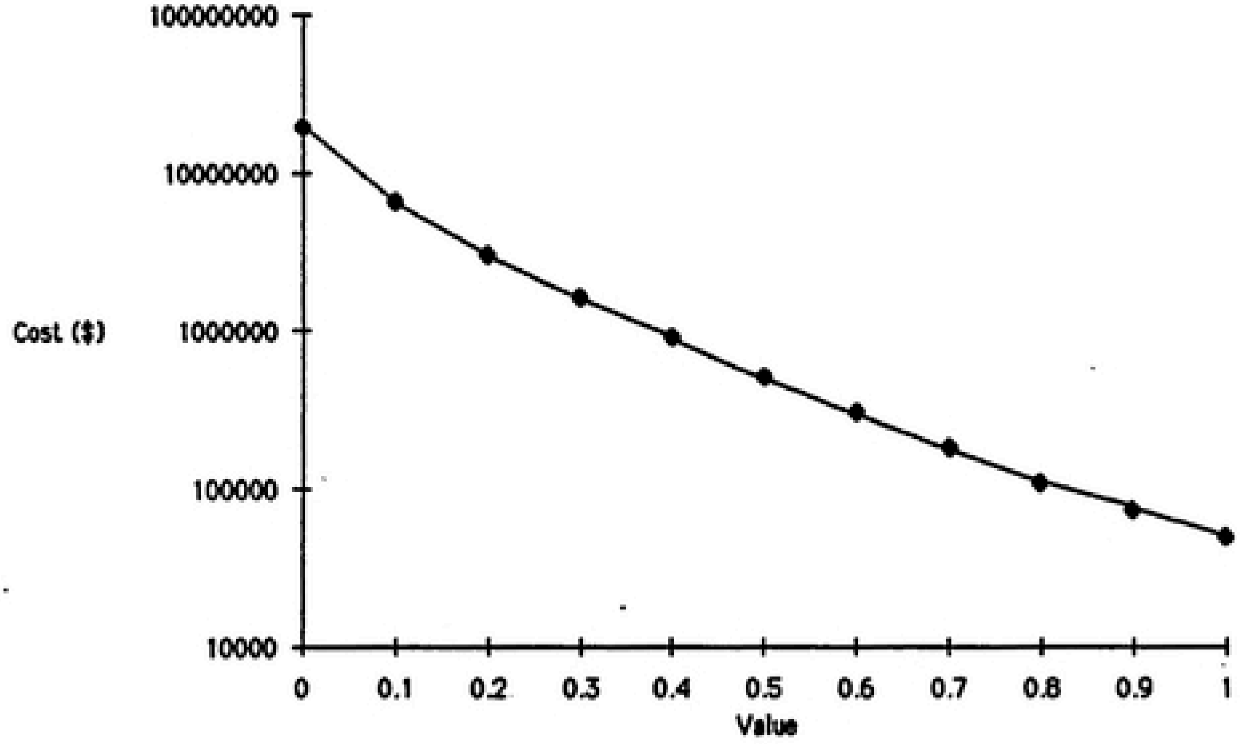


Figure 7

Sensitivity Analysis of Inputs for Attribute B1

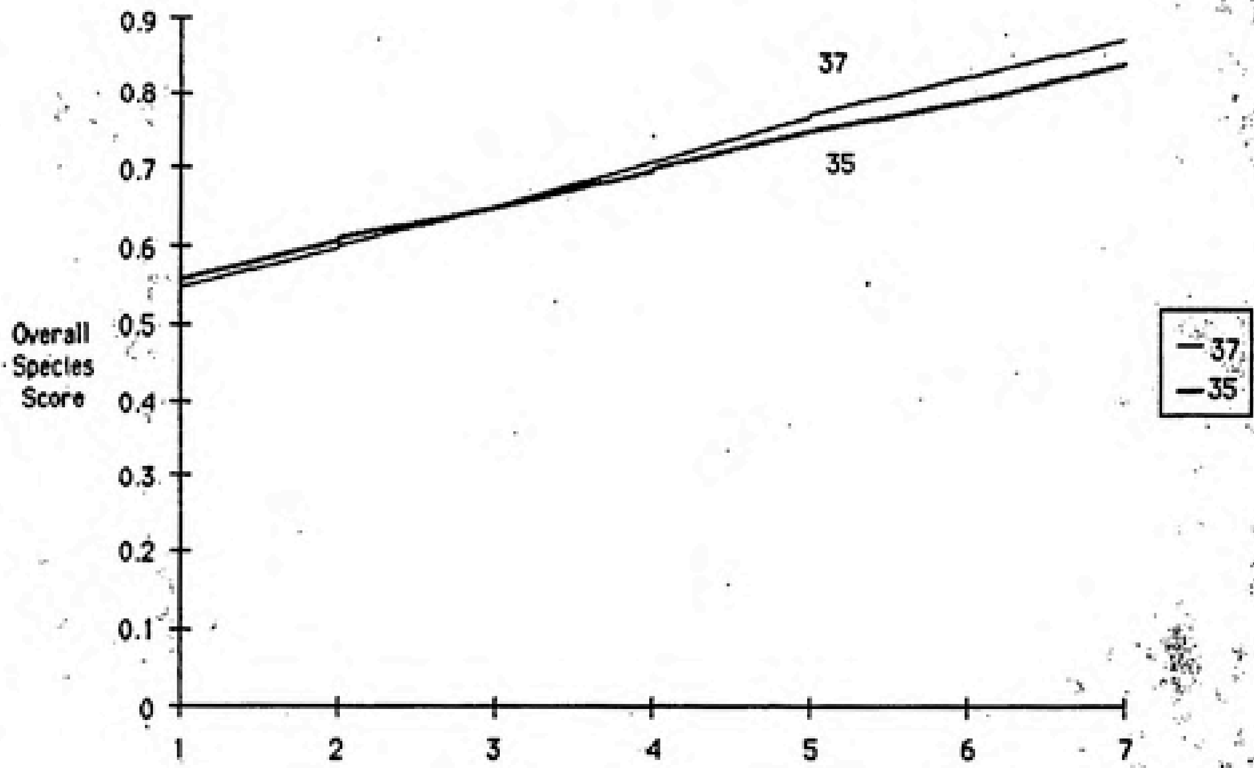
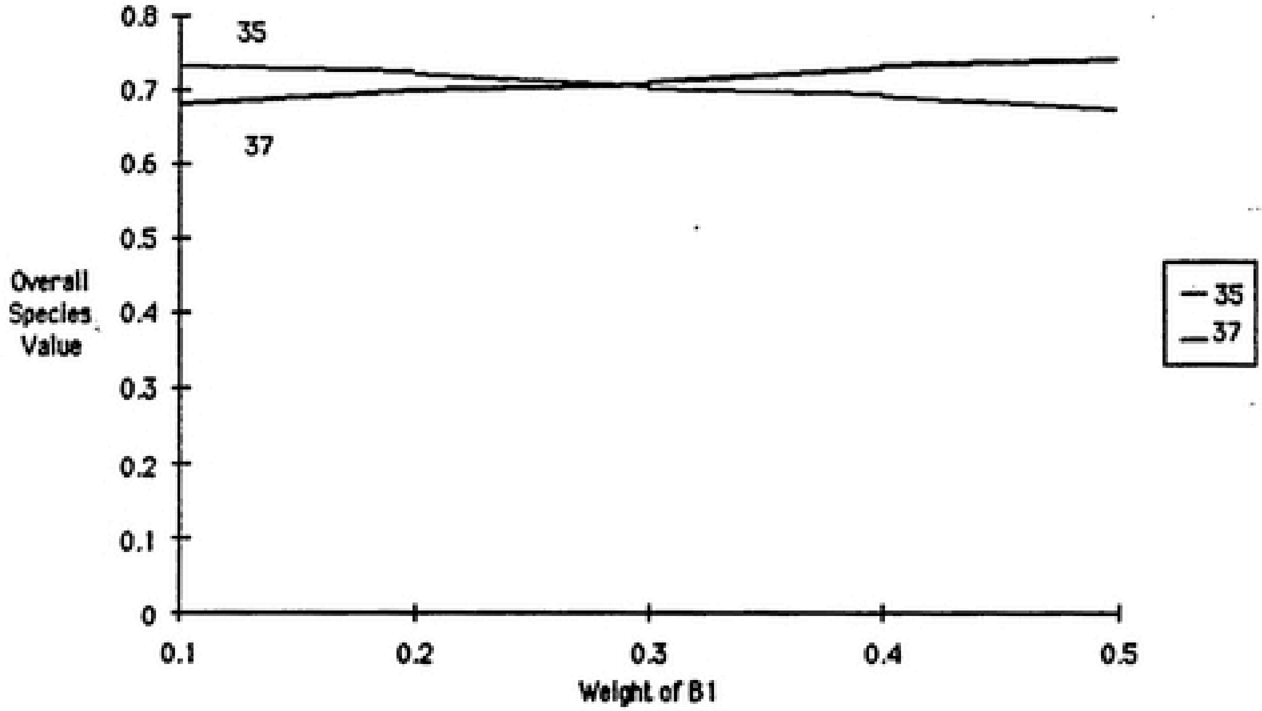


Figure 8
Sensitivity Analysis of
Species Sensitivity Weight



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