Essay

Indicators for Monitoring Biodiversity: A Hierarchical Approach

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Abstract: *Biodiversity is presently a minor consideration in environmental policy. It has been regarded as too broad and vague a concept to be applied to real-world regulatory and management problems. This problem can be corrected if biodiversity is recognized as an end in itself, and if measurable indicators can be selected to assess the status of biodiversity over time. Biodiversity, as presently understood, encompasses multiple levels of biological organization. In this paper, I expand the three primary attributes of biodiversity recognized by Jerry Franklin — composition, structure, and function — into a nested hierarchy that incorporates elements of each attribute at four levels of organization: regional landscape, community-ecosystem, population-species, and genetic. Indicators of each attribute in terrestrial ecosystems, at the four levels of organization, are identified for environmental monitoring purposes. Projects to monitor biodiversity will benefit from a direct linkage to long-term ecological research and a commitment to test hypotheses relevant to biodiversity conservation. A general guideline is to proceed from the top down, beginning with a coarse-scale inventory of landscape pattern, vegetation, habitat structure, and species distributions, then overlaying data on stress levels to identify biologically significant areas at high risk of impoverishment. Intensive research and monitoring can be directed to high-risk ecosystems and elements of biodiversity, while less intensive monitoring is directed to the total landscape (or samples thereof). In any monitoring program, particular attention should be paid to specifying the questions that monitoring is intended to answer and validating the relationships between indicators and the components of biodiversity they represent.*

Resumen: *La biodiversidad es hasta ahora una consideración menor en la política ambiental. Se ha visto como un concepto demasiado amplio y vago para ser aplicado en las regulaciones y el manejo de los problemas del mundo real. Este problema se puede corregir si la biodiversidad es reconocida como un fin por si misma, y si se pueden seleccionar indicadores cuantificables para determinar el estado de la biodiversidad a través del tiempo. La biodiversidad, como se entiende actualmente comprende múltiples niveles de organización biológica. En esta disertación, extiendo los tres atributos primarios de la biodiversidad reconocidos por Jerry Franklin — composición, estructura y función — dentro de una jerarquia que encaja a incorpora los elementos de cada uno de los atributos en cuatro niveles de organización: paisaje regional, ecosistemas de las comunidades, población de especies y genética. Los indicadores de cada atributo en los ecosistemas terrestres, en los cuatro niveles de organización, son identificados para propósitos de monitoreo ambiental. Los proyectos para el monitoreo de la biodiversidad se beneficiarian de una unión directa con la investigación ecológica a largo plazo y de un compromiso para probar hipótesis relevantes a la conservación de la biodiversidad. Un lineamiento general es proceder de arriba para abajo, empezando con una escala-burda de inventario de los patrones del paisaje, de la vegetación, de la estructura del hábitat y de la distribución de ls especies, después superponer los datos sobre niveles de presión para identificar las areas da alto riezgo y de empobrecimiento. La investigación intensiva y el monitorio peude ser dirigido a los ecosistemas de alto riezgo y a los elementos de la biodiversidad, mientras que un monitoreo ménos intenso se puede dirigir al total del paisaje (o a muestras del mismo). En cualquier programa de monitoreo, se debe de poner atención especial al estar especificando las preguntas que el monitoreo pretende resolver y al estar validando las relaciones entre los indicadores y los componentes de la biodiversidad que representen.*

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Introduction

Biological diversity (biodiversity) means different things to different people. To a systematist, it might be the list of species in some taxon or group of taxa. A geneticist may consider allelic diversity and heterozygosity to be the most important expressions of biodiversity, whereas a community ecologist is more interested in the variety and distribution of species or vegetation types. To a wildlife manager, managing for biodiversity may mean interspersing habitats to maximize edge effects, thereby building populations of popular game species. Some nonbiologists have complained that biodiversity is just another "smokescreen" or environmentalist ploy to lock up land as wilderness. No wonder agencies are having difficulty defining and implementing this new buzzword in a way that satisfies policy-makers, scientists, and public user groups alike.

Conservation biologists now recognize the biodiversity issue as involving more than just species diversity or endangered species. The issue is grounded in a concern about biological impoverishment at multiple levels of organization. Increasingly, the American public sees biodiversity as an environmental end point with intrinsic value that ought to be protected (Nash 1989). The heightened interest in biodiversity presents an opportunity to address environmental problems holistically, rather than in the traditional and fragmentary species-by-species, stress-by-stress fashion. One way to escape the vagueness associated with the biodiversity issue is to identify measurable attributes or indicators of biodiversity for use in environmental inventory, monitoring, and assessment programs. The purpose of this paper is to provide a general characterization of biodiversity and to suggest a set of indicators and guidelines by which biodiversity can be inventoried and monitored over time. I emphasize terrestrial systems, but many of the guidelines apply to aquatic and marine realms.

Defining and Characterizing Biodiversity

What It Is and What It Is Not

A widely cited definition of biological diversity is "the variety and variability among living organisms and the ecological complexes in which they occur" (OTA 1987). The OTA document described diversity at three fundamental levels: ecosystem diversity, species diversity, and genetic diversity. These three kinds of biodiversity were noted earlier by Norse et al. (1986). Unfortunately, most definitions of biodiversity, including OTA's, fail to mention processes, such as interspecific interactions, natural disturbances, and nutrient cycles. Although ecological processes are as much abiotic as biotic, they are crucial to maintaining biodiversity.

Biodiversity is not simply the number of genes, species, ecosystems, or any other group of things in a defined area. Knowing that one community contains 500 species and another contains 50 species does not tell us much about their relative importance for conservation purposes. Ecologists usually define "diversity" in a way that takes into consideration the relative frequency or abundance of each species or other entity, in addition to the number of entities in the collection. Several different indices, initially derived from information theory, combine richness with a measure of evenness of relative abundances (e.g., Shannon & Weaver 1949; Simpson 1949). Unfortunately, the number of indices and interpretations proliferated to the point where species diversity was in danger of becoming a "nonconcept" (Hurlbert 1971). Diversity indices lose information (such as species identity), are heavily dependent on sample size, and generally have fallen out of favor in the scientific community. As Pielou (1975:165) noted, "a community's diversity index is merely a single descriptive statistic, only one of the many needed to summarize its characteristics, and by itself, not very informative." Despite such warnings, diversity indices still are used in misleading ways in some environmental assessments (Noss & Harris 1986).

Agencies prefer to promulgate and enforce regulations based on quantitative criteria, even though qualitative changes in community structure are often the best indicators of ecological disruption. When a natural landscape is fragmented, for example, overall community diversity may stay the same or even increase, yet the integrity of the community has been compromised with an invasion of weedy species and the loss of species unable to persist in small, isolated patches of habitat (Noss 1983). Qualitative changes at local and regional scales correspond to a homogenization of floras and faunas. As a biogeographical region progressively loses its character, global biodiversity is diminished (Mooney 1988).

A Hierarchical Characterization of Biodiversity

A definition of biodiversity that is altogether simple, comprehensive, and fully operational (i.e., responsive to real-life management and regulatory questions) is unlikely to be found. More useful than a definition, perhaps, would be a characterization of biodiversity that identifies the major components at several levels of organization. This would provide a conceptual framework for identifying specific, measurable indicators to monitor change and assess the overall status of biodiversity.

Franklin et al. (1981) recognized three primary attributes of ecosystems: composition, structure, and function. The three attributes determine, and in fact constitute, the biodiversity of an area. Composition has to do with the identity and variety of elements in a collection, and includes species lists and measures of
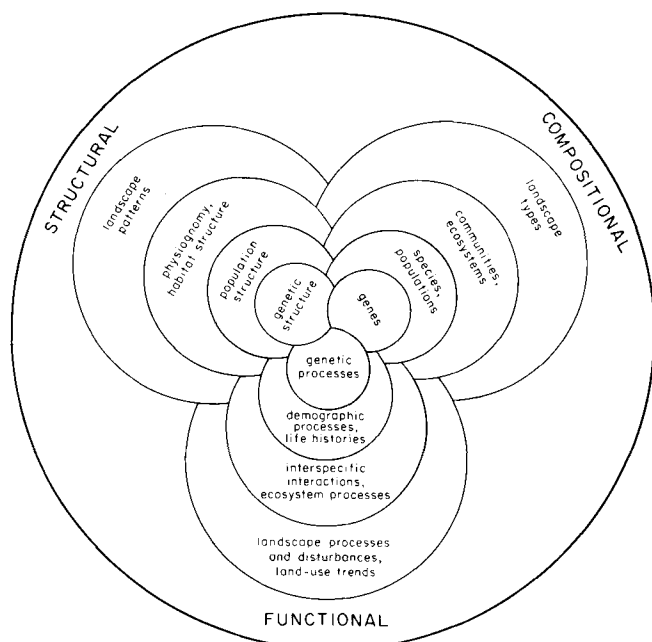
species diversity and genetic diversity. Structure is the physical organization or pattern of a system, from habitat complexity as measured within communities to the pattern of patches and other elements at a landscape scale. Function involves ecological and evolutionary processes, including gene flow, disturbances, and nutrient cycling. Franklin (1988) noted that the growing concern over compositional diversity has not been accompanied by an adequate awareness of structural and functional diversity. Hence, structural simplification of ecosystems and disruption of fundamental ecological processes may not be fully appreciated. Here, I elaborate Franklin's three attributes of biodiversity into a nested hierarchy (Fig. 1). Because the compositional, structural, and functional aspects of nature are interdependent, the three spheres are interconnected and bounded by a larger sphere of concern (i.e., Earth).

Hierarchy theory suggests that higher levels of organization incorporate and constrain the behavior of lower levels (Allen & Starr 1982; O'Neill et al. 1986). If a big ball (e.g., the biosphere) rolls downhill, the little balls inside it will roll downhill, also. Hence, global problems such as greenhouse warming and stratospheric ozone depletion impose fundamental constraints on efforts to preserve particular natural areas or endangered species. The importance of higher-order constraints should not suggest that monitoring and assessment be limited to higher levels (e.g., remote sensing of regional landscape structure). Lower levels in a hierarchy contain the details (e.g., species identities and abundances) of interest to conservationists, and the mechanistic basis for many higher-order patterns.

The hierarchy concept suggests that biodiversity be monitored at multiple levels of organization, and at multiple spatial and temporal scales. No single level of organization (e.g., gene, population, community) is fundamental, and different levels of resolution are appropriate for different questions. Big questions require answers from several scales. If we are interested in the effects of climate change on biodiversity, for instance, we may want to consider (1) the climatic factors controlling major vegetation ecotones and patterns of species richness across continents; (2) the availability of suitable habitats and landscape linkages for species migration; (3) the climatic controls on regional and local disturbance regimes; (4) the physiological tolerances, autecological requirements, and dispersal capacities of individual species; and (5) the genetically controlled variation within and between populations of a species in response to climatic variables. "Big picture" research on global phenomena is complemented by intensive studies of the life histories of organisms in local environments.

Another value of the hierarchy concept for assessing biodiversity is the recognition that effects of environmental stresses will be expressed in different ways at different levels of biological organization. Effects at one level can be expected to reverberate through other levels, often in unpredicatable ways. Tree species, for example, are known to be differentially susceptible to air pollution, with some (e.g., *Pinus ponderosa*) highly sensitive to photochemical oxidants such as ozone (Miller 1973). Different genotypes within tree species vary in their tolerance of air pollution. A decline in a tree population due to air pollution would alter the genetic composition of that population, and reduce genetic variation, as pollution-intolerant genotypes are selected out (Scholz 1981). If a declining tree species is replaced by species that are either more or less pyrogenic, or otherwise regulatory of disturbance dynamics, changes in biodiversity could be dramatic as the system shifts abruptly to a new stable state.

Selecting Biodiversity Indicators

Why Indicators?

Indicators are measurable surrogates for environmental end points such as biodiversity that are assumed to be of value to the public. Ideally, an indicator should be (1) sufficiently sensitive to provide an early warning of change; (2) distributed over a broad geographical area, or otherwise widely applicable; (3) capable of providing a continuous assessment over a wide range of stress; (4)

Figure 1. Compositional, structural, and functional biodiversity, shown as interconnected spheres, each encompassing multiple levels of organization. This conceptual framework may facilitate selection of indicators that represent the many aspects of biodiversity that warrant attention in environmental monitoring and assessment programs.

relatively independent of sample size; (5) easy and cost-effective to measure, collect, assay, and/or calculate; (6) able to differentiate between natural cycles or trends and those induced by anthropogenic stress; and (7) relevant to ecologically significant phenomena (Cook 1976; Sheehan 1984; Munn 1988). Because no single indicator will possess all of these desirable properties, a set of complementary indicators is required.

The use of indicator *species* to monitor or assess environmental conditions is a firmly established tradition in ecology, environmental toxicology, pollution control, agriculture, forestry, and wildlife and range management (Thomas 1972; Ott 1978; Cairns et al. 1979). But this tradition has encountered many conceptual and procedural problems. In toxicity testing, for example, the usual assumption that responses at higher levels of biological organization can be predicted by single-species toxicity tests is not supportable (Cairns 1983). Landres et al. (1988) pointed out a number of difficulties with using indicator species to assess population trends of other species and to evaluate overall wildlife habitat quality, and noted that the ecological criteria used to select indicators are often ambiguous and fallible.

Recent criticisms of the use and even the concept of indicator species are valid. Indicator species often have told us little about overall environmental trends, and may even have deluded us into thinking that all is well with an environment simply because an indicator is thriving. These criticisms apply, however, to a much more restricted application of the indicator concept than is suggested here. The final recommendation of Landres et al. (1988) is to use indicators as part of a comprehensive strategy of risk analysis that focuses on key habitats (including corridors, mosaics, and other landscape structures) as well as species. Such a strategy might include monitoring indicators of compositional, structural, and functional biodiversity at multiple levels of organization.

An Indicator Selection Matrix

Table 1 is a compilation of terrestrial biodiversity indicators and inventory and monitoring tools, arranged in a four-level hierarchy. As with most categorizations, some boxes in Table 1 overlap, and distinctions are somewhat arbitrary. The table may be useful as a framework for selecting indicators for a biodiversity monitoring project, or more immediately, as a checklist of biodiversity attributes to consider in preparing or reviewing environmental impact statements or other assessments.

Four points about choosing indicators deserve emphasis. (1) The question "What are we monitoring or assessing, and why?" is fundamental to selecting appropriate indicators. I assume that the purpose is to assess biodiversity comprehensively and as an end point in

itself, rather than as an index of air quality, water quality, or some other anthropocentric measure of environmental health. (2) Selection of indicators depends on formulating specific questions relevant to management or policy that are to be answered through the monitoring process. (3) Indicators for the level of organization one wishes to monitor can be selected from levels at, above, or below that level. Thus, if one is monitoring a population, indicators might be selected from the landscape level (e.g., habitat corridors that are necessary to allow dispersal), the population level (e.g., population size, fecundity, survivorship, age and sex ratios), the level of individuals (e.g., physiological parameters), and the genetic level (e.g., heterozygosity). (4) The indicators in Table 1 are general categories, most of which cut across ecosystem types. In application, many indicators will be specific to ecosystems. Coarse woody debris, for example, is a structural element critical to biodiversity in many old-growth forests, such as in the Pacific Northwest (Franklin et al. 1981), but may not be important in more open-structured habitats, including forest types subject to frequent fire.

Regional Landscape

The term "regional landscape" (Noss 1983) emphasizes the spatial complexity of regions. "Landscape" refers to "a mosaic of heterogeneous land forms, vegetation types, and land uses" (Urban et al. 1987). The spatial scale of a regional landscape might vary from the size of a national forest or park and its surroundings up to the size of a physiographic region or biogeographic province (say, from 10^2 to 10^7 km^2).

The relevance of landscape structure to biodiversity is now well accepted, thanks to the voluminous literature on habitat fragmentation (e.g., Burgess & Sharpe 1981; Harris 1984; Wilcove et al. 1986). Landscape features such as patch size, heterogeneity, perimeter-area ratio, and connectivity can be major controllers of species composition and abundance, and of population viability for sensitive species (Noss & Harris 1986). Related features of landscape composition (i.e., the identity and proportions of particular habitats) are also critical. The "functional combination" of habitats in the landscape mosaic is vital to animals that utilize multiple habitat types and includes ecotones and species assemblages that change gradually along environmental gradients; such gradient-associated assemblages are often rich in species but are not considered in conventional vegetation analysis and community-level conservation (Noss 1987)

The indicators listed for the regional landscape level in Table 1 are drawn mostly from the literature of landscape ecology and disturbance ecology. General references include Risser et al. (1984), Pickett and White (1985), and Forman and Godron (1986). O'Neill et al.

Table 1.   Indicator variables for inventorying, monitoring, and assessing terrestrial biodiversity at four levels of organization, including compositional, structural, and functional components; includes a sampling of inventory and monitoring tools and techniques.

| | *Indicators* | | | |
	Composition	*Structure*	*Function*	*Inventory and monitoring tools*
Regional Landscape	Identity, distribution, richness, and proportions of patch (habitat) types and multipatch landscape types; collective patterns of species distributions (richness, endemism)	Heterogeneity; connectivity; spatial linkage; patchiness; porosity; contrast; grain size; fragmentation; configuration; juxtaposition; patch size frequency distribution; perimeter-area ratio; pattern of habitat layer distribution	Disturbance processes (areal extent, frequency or return interval, rotation period, predictability, intensity, severity, seasonality); nutrient cycling rates; energy flow rates; patch persistence and turnover rates; rates of erosion and geomorphic and hydrologic processes; human land-use trends	Aerial photographs (satellite and conventional aircraft) and other remote sensing data; Geographic Information System (GIS) technology; time series analysis; spatial statistics; mathematical indices (of pattern, heterogeneity, connectivity, layering, diversity, edge, morphology, autocorrelation, fractal dimension)
Community-Ecosystem	Identity, relative abundance, frequency, richness, evenness, and diversity of species and guilds; proportions of endemic, exotic, threatened, and endangered species; dominance-diversity curves; life-form proportions; similarity coefficients; C4:C3 plant species ratios	Substrate and soil variables; slope and aspect; vegetation biomass and physiognomy; foliage density and layering; horizontal patchiness; canopy openness and gap proportions; abundance, density, and distribution of key physical features (e.g., cliffs, outcrops, sinks) and structural elements (snags, down logs); water and resource (e.g., mast) availability; snow cover	Biomass and resource productivity; herbivory, parasitism, and predation rates; colonization and local extinction rates; patch dynamics (fine-scale disturbance processes), nutrient cycling rates; human intrusion rates and intensities	Aerial photographs and other remote sensing data; ground-level photo stations; time series analysis; physical habitat measures and resource inventories; habitat suitability indices (HSI, multispecies); observations, censuses and inventories, captures, and other sampling methodologies; mathematical indices (e.g., of diversity, heterogeneity, layering dispersion, biotic integrity)
Population-Species	Absolute or relative abundance; frequency; importance or cover value; biomass; density	Dispersion (microdistribution); range (macrodistribution); population structure (sex ratio, age ratio); habitat variables (see community-ecosystem structure, above); within-individual morphological variability	Demographic processes (fertility, recruitment rate, survivorship, mortality); metapopulation dynamics; population genetics (see below); population fluctuations; physiology; life history; phenology; growth rate (of individuals); acclimation; adaptation	Censuses (observations, counts, captures, signs, radio-tracking); remote sensing; habitat suitability index (HSI); species-habitat modeling; population viability analysis
Genetic	Allelic diversity; presence of particular rare alleles, deleterious recessives, or karyotypic variants	Census and effective population size; heterozygosity; chromosomal or phenotypic polymorphism; generation overlap; heritability	Inbreeding depression; outbreeding rate; rate of genetic drift; gene flow; mutation rate; selection intensity	Electrophoresis; karyotypic analysis; DNA sequencing; offspring-parent regression; sib analysis; morphological analysis

(1988) developed and tested three indices of landscape pattern, derived from information theory and fractal geometry and found them to capture major features of landscapes. Landscape structure can be inventoried and monitored primarily through aerial photography and satellite imagery, and the data organized and displayed with a Geographical Information System (GIS). Time series analysis of remote sensing data and indices of landscape pattern is a powerful monitoring technique. Monitoring the positions of ecotones at various spatial scales may be particularly useful to track vegetation response to climate change and disruptions of disturbance

regimes. Statistical techniques applicable to landscape pattern analysis were summarized by Risser et al. (1984) and Forman and Godron (1986).

Monitoring landscape composition requires more intensive ground-truthing than monitoring structure, as the dominant species composition of patch types (and, perhaps, several vertical layers) must be identified. Landscape function can be monitored through attention to disturbance-recovery processes and to rates of biogeochemical, hydrologic, and energy flows. For certain ecosystems, such as longleaf pine–wiregrass communities in the southeastern United States, a disturbance

measure as simple as fire frequency and seasonality may be one of the best indicators of biodiversity. If fires occur too infrequently, or outside of the growing season, hardwood trees and shrubs invade, floristic diversity may decline, and key species may be eliminated (Noss 1988). In many landscapes, human land-use indicators (both structural and functional: e.g., deforestation rate, road density, fragmentation or edge index, grazing and agricultural intensity, rate of housing development) and the protection status of managed lands may be the most critical variables for tracking the status of biodiversity.

In addition to strictly landscape-level variables, collective properties of species distributions can be inventoried at the regional landscape scale. Terborgh and Winter (1983), for example, mapped the distribution of endemic land birds in Columbia and Ecuador and identified areas of maximum geographic overlap where protection efforts should be directed. Scott et al. (1990) developed a methodology to identify centers of species richness and endemism, and vegetative diversity, at a scale of 1:100,000 to 1:500,000, and to identify gaps in the distribution of protected areas. In most cases, repeating extensive inventories of species distributions would be impractical for monitoring purposes. Periodic inventories of vegetation from remove sensing, however, can effectively monitor the availability of habitats over broad geographic areas. Inferences about species distributions can be drawn from such inventories.

Community-Ecosystem

A community comprises the populations of some or all species coexisting at a site. The term "ecosystem" includes abiotic aspects of the environment with which the biotic community is interdependent. In contrast to the higher level of regional landscape, the community-ecosystem level is relatively homogenous when viewed, say, at the scale of a conventional aerial photograph. Thus, monitoring at this level or organization must rely more upon ground-level surveys and measurements than on remote sensing (although the latter is still useful for some habitat components).

Indicator variables for the community-ecosystem level (Table 1) include many from community ecology, such as species richness and diversity, dominance-diversity curves, life-form and guild proportions, and other compositional measures. Structural indicators include many of the habitat variables measured in ecology and wildlife biology. Ideally, both biotic and habitat indicators should be measured at the community-ecosystem and population-species levels of organization (Schamberger 1988). The functional indicators in Table 1 include biotic variables from community ecology (e.g., predation rates) and biotic-abiotic variables from ecosystem ecology (e.g., disturbance and nutrient cy-

cling rates) that may be appropriate to monitor for specialized purposes.

Tools and techniques for monitoring biodiversity at the community-ecosystem level of organization are nearly as diverse as the taxa and systems of concern. Plant ecology texts (e.g., Greig-Smith 1964; Mueller-Dombois & Ellenberg 1974) contain much information on community-level sampling methodology. A tremendous literature exists on bird census techniques, the most complete single reference being Ralph and Scott (1981). Bird community data can be readily applied to environmental evaluations (e.g., Graber & Graber 1976). Long-term bird surveys across the United States, such as the U.S. Fish and Wildlife Service's Breeding Bird Survey (BBS) program (Robbins et al. 1986), are used to monitor temporal trends in species populations, but could be interpreted to monitor guilds or the entire avian community of a defined area. Small mammal, reptile, and amphibian monitoring are discussed in several papers in Szaro et al. (1988). Useful summaries of wildlife habitat inventory and monitoring are in Thomas (1979), Verner et al. (1986), and Cooperrider et al. (1986). Karr's index of biotic integrity (IBI; Karr et al. 1986), which collapses data on community composition into a quantitative measure, has been applied with success to aquatic communities, and terrestrial applications are possible (J. R. Karr, personal communication).

Population-Species

Monitoring at the species level might target all populations of a species across its range, a metapopulation (populations of a species connected by dispersal), or a single, disjunct population. The population-species level is where most biodiversity monitoring has been focused. Although the indicator species approach has been criticized for its questionable assumptions, methodological deficiencies, and sometimes biased application, single species will continue to be important foci of inventory, monitoring, and assessment efforts, for two basic reasons: (1) species are often more tangible and easy to study than communities, landscapes, or genes; (2) laws such as the U.S. Endangered Species Act (ESA) mandate attention to species but not to other levels of organization (except that the ESA is supposed to "provide a means whereby the ecosystems upon which endangered species and threatened species depend may be conserved").

Noss (1990) lists five categories of species that may warrant special conservation effort, including intensive monitoring (1) ecological indicators: species that signal the effects of perturbations on a number of other species with similar habitat requirements; (2) keystones: pivotal species upon which the diversity of a large part of a community depends; (3) umbrellas: species with large area requirements, which if given sufficient pro-

tected habitat area, will bring many other species under protection; (4) flagships: popular, charismatic species that serve as symbols and rallying points for major conservation initiatives; and (5) vulnerables: species that are rare, genetically impoverished, of low fecundity, dependent on patchy or unpredictable resources, extremely variable in population density, persecuted, or otherwise prone to extinction in human-dominated landscapes (see Terborgh & Winter 1980; Karr 1982; Soulé 1983, 1987; Pimm et al. 1988; Simberloff 1988). Not all of these categories need to be monitored in any given case. It may be that adequate attention to categories 2–5 would obviate the need to identify and monitor putative ecological indicator species (D. S. Wilcove, personal communication).

For species at risk, intensive monitoring may be directed at multiple population-level indicators, as well as appropriate indicators at other levels — the genetic level, for example (Table 1). Measurements of morphological characters are often useful. The regression of weight on size for amphibians and reptiles, for instance, provides an index of the general health of a population (Davis 1989). Within-individual morphological variability (e.g., fluctuating asymmetry in structures of bilaterally symmetrical organisms) can be a sensitive indicator or environmental and genetic stress; composite indices that include information from several morphological characters are particularly useful (Leary & Allendorf 1989). Growth indicators (e.g., tree dbh) and reproductive output (e.g., number of fruits, germination rates) are common monitoring targets for plants.

Often, monitoring at the population-species level is directed not at the population itself, but at habitat variables determined or assumed to be important to the species. Habitat suitability indicators can be monitored by a variety of techniques, including remote sensing of cover types required by a species (Cooperrider et al. 1986). It has sometimes been assumed that monitoring habitat variables obviates the need to monitor populations; however the presence of suitable habitat is no guarantee that the species of interest is present. Populations may vary tremendously in density due to biotic factors, while habitat carrying capacity remains roughly constant (Schamberger 1988). Conversely, inferences based solely on biotic variables such as population density can be misleading. Among vertebrates, for example, concentrations of socially surbordinate individuals may occur in areas of marginal habitat (Van Horne 1983). Monitoring both habitat and population variables seems to be essential in most cases.

Genetic

In wild populations, demography is usually of more immediate significance to population viability than is population genetics (Lande 1988). Due to cost, monitoring

at the genetic level usually is restricted to zoo populations of rare species, or species of commercial importance such as certain trees. Lande and Barrowclough (1987) discussed techniques available to directly measure and monitor genetic variation, and much of the genetic portion of Table 1 is adapted from their paper. Although some indices of morphological variability may be good indicators of genetic stress (Leary & Allendorf 1989), variation in morphology can be confounded by phenotypic effects. Electrophoresis of tissue samples is the preferred technique for monitoring heterozygosity and enzyme variability (allozymes), probably the most common measures of genetic variation. Heritability studies (e.g., offspring-parent regression, sib analysis) can be used to determine the level of genetic variation for quantitative traits. Chromosomal polymorphisms can be monitored by karyotypic analysis, and the use of restriction endonucleases to cut DNA allows direct assessment of genetic variation (Mlot 1989). The severity of inbreeding depression can be evaluated from pedigrees (which, however, are seldom available for wild populations).

Implementation

Monitoring has not been a glamorous activity in science, in part because it has been perceived as blind data-gathering (which, in some cases, it has been). The kinds of questions that a scientist asks when initiating a research project — about causes and effects, probabilities, interactions, and alternative hypotheses — are not commonly asked by workers initiating a monitoring project. In most agencies, monitoring and research projects are uncoordinated and are carried out by separate branches. Explicit hypothesis-testing only rarely has been a part of monitoring studies, hence the insufficient concern for experimental design and statistical analysis (Hinds 1984). Perhaps monitoring will be most successful when it is perceived (and actually qualifies) as scientific research and is designed to test specific hypotheses that are relevant to policy and management questions. In this context, monitoring is a necessary link in the "adaptive management" cycle that continuously refines regulations or management practices on the basis of data derived from monitoring and analyzed with an emphasis on predicting impacts (Holling 1978).

As an illustration of how a biodiversity monitoring project might be implemented, imagine that a hypothetical agency wants to assess status and trends in biological diversity in the Pacific Northwest. This grandiose project might be carried out in ten steps:

1. *What and why?* It is first necessary to establish goals and objectives, and the "sub–end points" of biodiversity that the agency wishes to assess (and maintain). This is more a matter of policy-making than of

science. Goals for the Pacific Northwest might include: no net loss of forest cover or wetlands; recovery of old-growth coniferous forests to twice the present acreage; recovery of native grasslands and shrub-steppe from overgrazed condition; maintaining viable populations of all native species; and eradicating troublesome exotic species from federal lands. Sub–end points would correspond to these goals and encompass the health and viability of all elements of biodiversity identified to be of concern.

2. *Gather and integrate existing data.* Existing biodiversity-related data bases in state natural heritage programs, agency files, and from other sources would be collected, digitized, and overlayed in a GIS. These data would be mapped for the region as a whole at a scale of 1:100,000 to 1:500,000 (see Scott et al. 1990).

3. *Establish "baseline" conditions.* From current data, determine the extent, distribution, and condition of existing ecosystem (vegetation) types and the probable distribution of species of concern. Also, map the distribution and intensity of identified stressors (e.g., tropospheric ozone, habitat fragmentation, road density, grazing intensity).

4. *Identify "hot spots" and ecosystems at high risk.* Proceeding from the previous two steps, delineate areas of concentrated biodiversity (e.g., centers of species richness and endemism) and ecosystems and geographical areas at high risk of impoverishment due to anthropogenic stresses. Such areas warrant more intensive monitoring. In the Pacific Northwest, one prominent center of endemism is the Klamath-Siskiyou bioregion; an ecosystem type at high risk is old-growth forest (of all species associations).

5. *Formulate specific questions to be answered by monitoring.* These questions will be guided by the sub–end points, goals, and objectives identified in Step 1. Questions might include: Is the ratio of native to exotic range grasses increasing or decreasing? Is the average patch size of managed forests increasing or decreasing? Are populations of neotropical migrant birds stable? Are listed endangered species recovering? It will help if policy-makers can specify thresholds at which changes in management practices or regulations will be implemented.

6. *Select indicators.* Identify indicators of structural, functional, and compositional biodiversity at several levels of organization that correspond to identified sub–end points (Step 1) and questions (Step 5). Indicators can be chosen from the "laundry list" in Table 1, based on the criteria for ideal indicators reviewed above (under "Why Indicators?").

7. *Identify control areas and treatments.* For each major ecosystem type, identify control areas (e.g., designated Wilderness and Research Natural Areas) and areas subjected to different kinds and intensities of stress and management practices. Public and private forest

lands, for example, encompass a wide variety of silvicultural treatments.

8. *Design and implement a sampling scheme.* Applying principles of experimental design, select monitoring sites for identified questions and objectives. A design might include intensive sampling of high-risk ecosystems and species (identified in Step 4) and less intensive sampling of general control and treatment areas identified in Step 7 (but with sampling points and plots selected randomly within treatments). All treatments and controls should be replicated. Randomized systematic sampling of the total regional landscape (stratified by ecosystem type, if desired) would provide background monitoring and may serve to identify unforeseen stresses. Biology should drive the statistical design, however, rather than letting the design assume a life of its own.

9. *Validate relationships between indicators and sub–end points.* Detailed, ongoing research is needed to verify how well the selected indicators correspond to the biodiversity sub–end points of concern. For example, does a particular fragmentation or edge index (such as perimeter-area ratio or patch size frequency distribution) really correspond to the intensity of abiotic and biotic edge effects or the disruption of dispersal between patches in the landscape? Does the relationship between indicator and sub–end point hold for the entire range of conditions encountered?

10. *Analyze trends and recommend management actions.* Temporal series of measurements must be analyzed in a statistically rigorous way and the results synthesized into an assessment that is relevant to policy-makers. If the assessment can be translated into positive changes in planning assumptions, management direction and practices, laws and regulations, or environmental policy, the monitoring project will have proved itself a powerful tool for conservation.

Acknowledgments

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