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Book review

A synopsis of the book Ecological Indicators for the Nation

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The U.S. Environmental Protection Agency requested the National Research Council (which is the operating arm of the U.S. National Academy of Sciences and the U.S. National Academy of Engineering) to carry out a critical scientific evaluation of indicators to monitor ecological changes from either natural or anthropogenic causes. More specifically, the National Research Council was asked to identify criteria for evaluating biological indicators, to evaluate methods of indicator development, to provide examples of indicators that have proven useful, and to identify areas where further research is likely to yield more useful and powerful indicators. In addition, the National Research Council was to examine what aspects of environmental conditions and trends should be monitored.

Indicators are designed to inform investigators quickly and easily about something of interest. They communicate information about conditions and, over time, about changes and trends. Like economic indicators, environmental indicators are needed because it is not possible to measure everything. Indicators can be useful at many levels——community, state, ecoregional, watershed, national, and international——and better indicators are needed at all of these scales. Additionally, better ways are needed of matching the scales at which indicators are useful to the scales of ecological processes.

Ecological Indicators for the Nation concentrates on indicators that can support national decision making, but also illustrates how the recommended methods can be used to develop indicators whose primary use would be at local and regional scales.

The report notes that ecological indicators that describe the state of the nation's ecosystems and command credibility and attention from the public and decision makers have been elusive. This situation is partly the result of the complexity of multivariate ecological systems. This report concludes that more attention should be given to the criteria for developing and using successful ecological indicators.

A brief summary of the criteria for evaluating indicators follows.

· General importance. Does the indicator provide information about changes in important ecological and biogeochemical processes? Does the indicator reveal something about major environmental changes that affect wide areas?

· Conceptual basis. Is the indicator based on a well understood and generally accepted conceptual model of the system to which it is applied? Is it based on well-established scientific principles? The conceptual model provides the rationale for the indicator, suggests how it should be computed, and enables the researcher to understand the features of the indicator and how it changes.

· Reliability. What experience or other evidence demonstrates the indicator's reliability? The best evidence for the reliability of an indicator is, of course, successful previous use. Nevertheless, all existing indicators should be analyzed retrospectively before assuming that their use should be continued. A newly proposed indicator inevitably lacks a historical record of reliability. Nonetheless, if it is based on a well-established scientific theory and if a retrospective analysis has indicated that it probably would give information on important changes in an environmental process or product of concern, its reliability is provisionally established. When indicators are new, development and experience will be needed to make them operational.

· Temporal and spatial scales. Does the indicator reveal national, regional, or local ecological conditions, processes, and products? Are the changes measured by the indicator likely to be short term or long term? Can the indicator detect changes at appropriate temporal and spatial scales without being overwhelmed by variability? To determine what an indicator indicates, the kinds of data needed to compute it, and how changes in it should be interpreted, the temporal and spatial scales of the processes measured by the indicator need to be clear.

· Statistical properties. In the areas of accuracy, sensitivity, precision, and robustness, has the indicator been shown to serve its intended purpose? Is the indicator sensitive enough to detect important changes but not so sensitive that signals are masked by natural variability? Are its statistical properties understood well enough that changes in its values will have clear and unambiguous meaning?

· Data requirements. How much and what kinds of information are necessary to permit reliable estimates of the indicator to be calculated? How many and what kinds of data are required for the indicator to detect a trend? Most ecological indicators depend on data gathered by means of long-term monitoring. The challenge is deciding which rates of change to watch and to determine which of the changes observed represent significant departures from expected natural variability. Once an indicator is selected, monitoring must be used to gain experience with the likely meaning of changes in the indicator's values. Experimental studies——themselves requiring monitoring——should be used to determine whether the stress/response relationships suggested by the monitoring program are indeed causal. The use of the indicator may change as additional insights are gained into its behavior and the underlying processes that cause it to change.

· Skills required. What technical and conceptual skills must the collectors of data for an indicator possess? Does the collection of input data require highly technical, specialized knowledge if the data are to be accurate, or is data collection a relatively straightforward process? An indicator capable of commanding broad attention must be based on data that are accurate and, equally important, perceived by all to be accurate. Because the collection of data for ecological indicators (i.e., monitoring) is sometimes perceived by scientists as boring or less interesting and prestigious than "scientific research" (i.e., hypothesis-driven investigation), it is important to provide incentives for consistent and accurate data collection. One design is developing monitoring programs so that the information also has scientific value (i.e., can be used to answer research questions). Most indicators embody hypotheses about the functioning of ecosystems. To the degree that such hypotheses can be made explicit in the design of indicators, their development and the subsequent monitoring of them should generate a great deal of valuable scientific information.

· Data quality. No indicator of environmental quality is reliable unless the underlying data that are used to construct or calculate it are accurate. Attention to data quality during archiving and computational phases cannot substitute for the quality of the input data. In this critical sense, the ultimate responsibility for data quality must lie with the investigators who collect it. Clear documentation of sampling and analytical methods is necessary if future investigators are to understand exactly how each indicator was calculated. This requirement is particularly important as methods and instrumentation change, so that data from early parts of the time series are quantifiably comparable to data from later parts of the same time series.

· Data archiving. A monitoring system to track ecological indicators requires archiving capabilities that provide interested parties access to the data. For indicators that are direct representations of environmental samples, the archive simply needs to save a record of the measurements. In general, the minimum number of physical samples saved should ensure the ability to recalibrate the entire data set, should this become necessary because of changes in sampling or analytical technologies. The costs of preserving physical samples in forms that do not decay or otherwise change must be weighed against the opportunity cost of not being able to recalibrate a data set with improved or modified measurement techniques. The complete description and availability of the models and the data used to calculate indicators are just as important as the availability of the underlying data themselves; otherwise, future comparisons might actually not compare the same things. The archive must be robust enough to ensure that the time series of the indicator can be reprocessed as models improve.

· Robustness. Robustness is defined here in a nonstatistical sense, as an indicator's ability to yield reliable and useful numbers in the face of external perturbations. In other words, is the indicator relatively insensitive to expected sources of interference? Are technological changes likely to render the indicator irrelevant or of limited value? Can time series of measurements be continued in compatible form when measurement technologies change? To continue to gather data by outdated methods is undesirable. Nevertheless, because long-term data sets are essential for detecting most environmental trends, technological changes must be incorporated into monitoring programs in ways that do not destroy the continuity of the data sets or render consistent interpretation of the changes impossible. Crosscalibration of measurements is especially important for remotely sensed data.

· International compatibility. Is the indicator compatible with indicators being developed by other nations and international groups? Not all indicators used in the United States, especially those relating to specific regions, ecosystems, or species, need to be compatible with indicators developed and used in other nations. However, national-level indicators signal changes that are likely to transcend national boundaries. Effective responses to these changes may require international action. If the signals that trigger actions are not meaningful to the affected nations, appropriate multinational responses are certain to be more difficult to mount.

· Costs, benefits, and cost effectiveness. Costs and benefits associated with implementing proposed ecological indicators are important because resources for monitoring are limited and should be used efficiently. The cost of developing and monitoring an indicator, which can continue to accrue as the indicator is used and refined and as new data and technologies develop, can be estimated objectively. The benefits——the value of the information obtained——are more difficult to estimate. The greater the benefits of an indicator, the higher the costs that can be justified in developing and implementing it. Cost effectiveness is also an important criterion. If one assumes that the information an indicator yields is essential, can it be obtained for less cost in another way? If so, the indicator is not cost effective. The value of the information was the National Research Council committee's first consideration in every indicator recommended.

The committee that produced the report used the above criteria, together with a conceptual model of the factors that most strongly influenced ecosystem functioning. The goods and services that ecosystems provide to humans depend directly or indirectly on the productivity of ecosystems, i.e., their ability to capture solar energy and store it as carbon-based molecules. Productivity, in turn, is strongly influenced by temperature, moisture, soil fertility, and the structure and composition of ecological communities——factors familiar to all ecologists but not necessarily to decision makers. Measures of the presence of native and exotic species are also important inputs to national ecological indicators, especially since invasive species are often greatly disruptive of the functioning of natural systems.

The recommended indicators: Based on consideration of the desirable characteristics of indicators, the sources of data that underlie them, the models that support them, the criteria summarized above, and the conceptual model used, the committee recommended the following national ecological indicators in three categories.

· As indicators of the extent and status of the nation's ecosystems, the committee recommends land cover and land use.

· As indicators of the nation's ecological capital, the committee recommends total species diversity, native species diversity, nutrient runoff, and soil organic matter.

· As indicator of ecosystem functioning or performance, the committee recommends carbon storage, production capacity, net primary production, lake trophic status, stream oxygen, and for agricultural ecosystems, nutrient-use efficiency and nutrient balance.

For each indicator recommended in this report, information is provided on the following points insofar as possible.

- Why the indicator is useful.
- The ecological model that underlies the indicator.
- The range of values the indicator can take and what the values mean.
- The temporal and spatial scales over which the indicator is likely to change.
- Whether the needed input data are already being gathered and, if so, by whom.
- If the needed data are not being gathered, what new data are needed and who should collect them.
- The probable effects of new technologies on the ability to make the required measurements and how soon significant technological changes are likely.

In some cases, some experience will need to be gained in details of the behavior of the indicator, but all the indicators are based on soundly established scientific principles and experience. The proposed indicators are, in general, applicable to both managed (e.g., agricultural and silvicultural) and unmanaged ecosystems; the indicators of nutrient - use efficiency and overall nutrient balance are specific to agricultural ecosystems.

Illustrative Indicators

1 Indicators of ecosystem extent and status

(a) Land cover: This indicator includes both water and land ecosystems and records the percentage of land in each of the many land cover categories. Each time land cover is computed, the proportions in each category should be compared with those at the previous recording time. Data must be entered and stored separately for many categories of land cover types. Because the proportion of land in each category changes relatively slowly, land cover needs to be recorded only every 5 years, but its value should be computed annually so it can be used as inputs to other indicators.

(b) Land use: The largest ecological changes caused by humans result from land use. The changes include replacing major biological communities with agricultural systems, changing hydrologic and biogeochemical cycles, changing Earth's surface by creating buildings, transportation corridors, and so on. These changes affect the ability of ecosystems to provide the goods and services upon which human society depends.

2 Indicators of ecological capital

(a) Total species diversity: Total species diversity measures the ecological capital actually present and is the first recommended indicator.

(b) Native species diversity: Native species diversity reflects human impact on the land. Land that has been so transformed by people that it cannot support native species that would otherwise be there carries a heavy burden caused by human activities.

(c) Nutrient runoff: Nutrient runoff measures the loss of essential nutrients from the soil and is related to soil erosion——excess nutrients, especially nitrogen and phosphorus, reduce water clarity, increase nuisance algal blooms, and increase the incidence of hypoxia (low oxygen) in waters. The indicators can take values from zero (no discharge or runoff) to thousands of kilograms per square kilometer per year, with lower values being more desirable for most purposes. Because nitrogen and phosphorus runoff is largely a result of human activities, it can also be an indicator of the need for and effectiveness of environmental management.

(d) Soil organic matter: This indicator is the best one for soil condition.

3 Indicators of ecosystem functioning

(a) Carbon storage: Carbon storage is a direct measure of the amount of carbon sequestered or released by ecosystems. It is the difference between the sum of all non-plant respiration in an ecosystem——all of the CO_2 produced by detritivores and animals——and net primarg production. It measures the change in the total amount of carbon in an ecosystem, and hence indicates the ecosystem's carbon balance.

(b) Production capacity: Production capacity is measured by total chlorophyll per unit area. It provides a direct measure of the energy-capturing capacity of terrestrial ecosystems. An equivalent measure for lakes would be total chlorophyll per unit volume. Total chlorophyll is an excellent indicator because it is strongly correlated with an ecosystem's actual capacity to capture energy.

(c) Net primary production (NPP): Net primary production is a direct measure of the amount of energy and carbon that has been brought into an ecosystem; it also is a measure of productivity as understood in forestry and agriculture, i.e., the amount of plant material produced in an area per year.

(d) Lake trophic status: Indication of the trophic status of lakes can be developed from a few key characteristics that determine the functional properties of lakes and their ability to provide the many goods and services valued by human society. The key characteristics——nutrient status, net biological production, and water clarity——are closely interrelated and they are influenced by management of fertilizers, sewage, and other nutrient sources. Net biological production and water clarity can be measured by satellite imagery as well as by ground-based methods.

(e) Stream oxygen: Indication of stream oxygen is recommended as an indicator of the ecological functioning of flowing water ecosystems. It captures the balance between in-stream primary production and respiration. High stream oxygen indicates much photosynthetic activity and the likelihood of high nutrient concentrations, algal blooms, and rapid growth of leafy aquatic plants. Low stream oxygen indicates higher respiration than photosynthesis and the likelihood of organic enrichment from waste water or high plant production upstream. Low stream oxygen usually indicates that the water is not suitable for many species of aquatic animals, including fish.

In addition to the above five indicators (a through e) that are directly related to productivity, soil condition and land use are also related to ecosystem functioning.

4 Local and regional indicators

Indicators are needed reveal ecological status and trends at all spatial and temporal scales. Many indicators are useful at several scales. In addition, most policy and management decisions are made at scales defined by laws and regulations that have been established by political entities, such as local municipalities, counties, states, and the federal government. Despite the National Research Council Committee's focus on national-level ecological indicators, the committee was well aware of the need for such indicators at lower levels of political organizations.

(a) Productivity indicators: The committee recommended that the following forest indicators be given high priority: (1) productivity and tree species diversity, (2) soils, (3) light penetration, (4) foliage-height profiles, (5) crown condition, and (6) physical damage to trees. These indicators can be assessed using data that can be collected easily in the field.

(b) Indicators of species diversity: In addition to the national indicators of the status of species diversity, the committee noted that a nation needs indicators to evaluate the diversity status of a local area, such as a national park, or even an area exploited for human use. For evaluating the diversity status of such areas, the committee recommended three indicators: independence of the area, species density, and deficiency of natural diversity.

An indicator of independence. This indicator assesses the degree to which the species richness (i.e., number of species) of an area depends on immigration of individuals from surrounding areas. Two types of species contribute to local diversity. The first consists of source species, whose births exceed their deaths in the area and, thus, they can provide individuals to populate surrounding areas. The other type, sink species, is present only because immigrants compensate for their excess of deaths over births in the area. Isolating an area reduces immigration and, therefore, sink species will eventually disappear.

An indicator of species density. This indicator assesses whether an area supports more or fewer species than a reasonably defined reference area does. Managers typically wish to optimize the value of their reserves. It might appear that the more species housed in a reserve the better its condition, but this is not necessarily true. The reason is the changing patterns of land use can squeeze more species into a small area that cannot support so many species. As a result, species will be lost from the area. The indicator signals whether diversity in the area is likely to increase, decrease, or remain the same, and it estimates the probable final diversity of the area.

An indicator of deficiency in natural diversity. This indicator assesses the degree to which a site preserves exotic species of little or no conservation value rather than valued native species. When human uses dominate a landscape, natural assemblages of species disappear, but they are in part replaced by exotic species. Three factors contribute to the extraordinary abundance of a few species in anthropogenic environments: exotics may have had more time to adjust to humans; exotics may have escaped many of their natural predators; only a subset of native species (the tolerant ones) is pre-adapted to "degraded" environments.

Concluding statement

Ecological indicators are in the early stages of development, and most have been used primarily by research investigators rather than less well-trained individuals who usually make routine measurements. Even though the report deals with a complex subject, it is concise and well written and will repay the reader abundantly for going through it in its entirety. Further details may be obtained from the National Academy Press website at www.nap.edu. It was produced by the Committee to Evaluate Indicators for Monitoring Aquatic and Terrestrial Environments, Board on Environmental Studies and Toxicology, Water Science and Technology Board, Commission on Geosciences, Environment and Resources, National Research Council, 2101 Constitution Ave, NW, Lockbox 285, Washington DC 20055, USA.