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MONITORING CHALLENGES AND INNOVATIVE IDEAS[1]

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INTRODUCTION

Monitoring programs are difficult to design even when they focus on specific problems, such as water quality in a particular body of water. Ecosystems are complex, and it is often impossible to predetermine what aspects of system structure or dynamics will respond to a specific insult. It is equally difficult to interpret whether a response is a stabilizing compensatory mechanism or a real loss of capacity to maintain the ecosystem.

The problems are compounded in a broad monitoring program designed to assess ecosystem "health" at regional and continental scales. It is challenging in the extreme to monitor ecosystem response, at any scale, to past insults as well as an unknown future array of impacts.

The challenge can be illustrated by problems in data interpretation. When indicators are remeasured after 5 to 10 years, some values will have changed. Does the change indicate a trend or normal fluctuations? Stochastic fluctuations in weather can account for many short-term changes. A number of ecological phenomena, such as predator-prey cycles, are known to fluctuate normally over 3 to 10 year cycles.

Reliable evidence of trends requires monitoring over a long period of time. Likens (1983) showed that 20 years of continuous records were needed at Hubbard Brook to determine statistically significant trends in watershed geochemistry. Goldman (1981) showed that 15 years of secchi disc readings were needed at Lake Tahoe to establish a statistically significant reduction in transparency. Only these extended data sets allow unambiguous association of a change in an indicator measurement to an ecosystem trend.

But in spite of the challenge, systematic monitoring is critically needed to balance anecdotal information. A single warm summer causes media speculation that global warming has started. But, it is clear that we have not been measuring weather long enough to be able to characterize all of the normal trends. Nevertheless, the newspapers and television jump on every short-term fluctuation as evidence of monotonic change. Systematic monitoring with statistically valid designs is needed to produce reliable indicators of trends.

The present paper will examine some of the fundamental issues and challenges raised by large-scale monitoring efforts. The challenges will serve as a framework and as an excuse to discuss several important topics in more detail. Following the discussion of challenges, we suggest some basic innovations that could be important across a range of monitoring programs. The innovations include integrative measures, innovative methodology, and creative interpretation.

FUNDAMENTAL MONITORING CHALLENGES

As a framework for this presentation, we will consider the basic challenges under three headings: multiple objectives, ecosystem complexity, and the ambiguity of ecosystem "health."

Dilemmas arising from multiple objectives:

The first challenge presented to a monitoring program results from its own objectives. Major programs are large and expensive. Selling the program, therefore, requires objectives that appeal to a variety of potential sponsors and users.

Multiple objectives may be a necessary part of program development. But it must also be realized that multiple objectives lead to multiple and varied expectations that may be very difficult to fulfill. The problem can be illustrated by drawing on the stated objectives of the U.S. Environmental Monitoring and Assessment Program (EMAP). The intent is not to be critical of EMAP. The use of multiple objectives is ubiquitous, and the comments apply to most general monitoring programs.

The overall objective of EMAP is to monitor ecological status and trends, developing estimates by region, state, and nation that are statistically valid, unbiased by sampling, and with known confidence intervals. This objective appears relatively innocent. The aim is ambitious but achievable. The problems begin when this general objective is subdivided into a series of ancillary objectives. For present purposes, we consider four categories.

The first category deals with the extent of ecological resources and their geographic distribution. This level of objective is addressed by remotely-sensed data, appropriately classified into ecological resources. The first important challenge is to choose a spatial resolution for the map and an appropriate classification scheme that permits assessment of important ecosystem or habitat types. These are not trivial challenges. For example, false indications of change can result from slight changes in interpretation of the classification scheme by later interpreters. But, with this proviso, the objective is eminently achievable within current scientific understanding and technological expertise. The second challenge is to translate the changing "map" of ecosystems into a meaningful assessment of environmental health. We return to this challenge in a later section of the paper.

The second category of objectives goes beyond the ecological "map" to questions about ecosystem structure and function. What proportion of the existing natural ecosystems are in good or acceptable condition? What proportion is degrading or improving and at what rates? Unlike the first category of objectives, this category significantly challenges state-of-the-art scientific understanding. This category raises the spectre of "ecosystem health." We return later to the matter of whether or not the concept of "health" can be unambiguously defined.

The third category of objectives seeks correlations between ecosystem conditions and anthropogenic impacts. The EMAP program seeks to associate ecological monitoring with pollutant exposure monitoring and so draw conclusions about the causes of ecosystem degradation. This class of objective relates directly to EPA's need to determine if corrective steps taken by the agency are working.

Relating ecosystem condition to anthropogenic impacts is, of course, extremely important. This is, in fact, one of the primary motivations for environmental monitoring. The objective does, however, imply an understanding of causal relationships that represents a state-of-the-art challenge to ecology.

The extent of the challenge depends largely on the individual case. Bluegreen algal blooms make one suspect phosphorus amendments. Unusual fish mortality makes one suspect alterations in water temperature and/or chemistry. Dysfunctional, yellowed foliage makes one suspect air pollutants. Similarly, increased water clarity may be reasonably attributed to successful efforts to control siltation. Increased raptor populations may be reasonably attributed to successful controls on pesticides. There are many similar cases in which causality has been independently established by research, and monitoring data can be related to anthropogenic causes.

On the other hand, how do you interpret tree mortality when accompanied by drought stress and insect pests? In the absence of controls, how can you determine the extent to which air pollutants contributed to the mortality. Similarly, how do you interpret reduced recruitment of fish? Have your efforts to increase water quality failed? Or is the recruitment failure due to any of dozens to hundreds of other causes? Ordinarily, no statistically valid statement can be made. Attributing causal linkages involves experimentation that goes beyond the scope of monitoring. Stated in the simplest terms, unambiguous attribution of causation demands experimental controls that do not exist in monitoring programs. Monitoring can suggest, but it can seldom demonstrate causality.

The fourth and final category of objectives goes beyond causality to prediction. The EMAP program wishes to develop innovative methods for anticipating emerging problems before they become crises. The problem with this objective can be simply stated. If scientists cannot tell you what caused the change you have just seen, they certainly are not able to tell you what happens next. We return in a later section to a more detailed analysis of why it is so difficult to predict ecological systems. For now, suffice it to say that an objective that says that a monitoring program will warn you beforehand of a critical change is going to raise expectations that cannot always be fulfilled. Saying that monitoring can predict change is not a challenge, it is an impossibility. Ecological systems will continue to surprise us. The one thing you can count on is that at some future time, some crisis will indeed occur that you did not and could not anticipate.

But it may be objected that anticipating future change does not really involve prediction. Rather it involves an "early warning system" that detects a significant change before it becomes a crisis. This interpretation evades the prediction problem but falls into its own unique trap by establishing an unreasonable expectation. If anything ever happens that you didn't detect, the objective is not achieved and the program is deemed a failure.

The question is whether or not it is really possible to devise a monitoring program that can beat the early warning system formed by the vast network of local naturalists? Can any feasible program beat several million observers? Can you establish a statistically valid trend before local newspapers have assured the public, beyond any shadow of a doubt, that the trend has been going on for years? Stated factitiously, the only feasible "early warning system" is an 800- telephone number posed in every bait and tackle shop in the country.

If you object that casual observers will see a change first but cannot say how significant the change is, you are still trapped on the horns of the dilemma. The systematic determination of a statistically significant trend may take years to establish. Because of the length of time involved, there is no guarantee that you can establish the trend before the situation becomes a crisis.

The real point is that multiple objectives, necessary for the initiation of large-scale monitoring programs, present a series of dilemmas or challenges. Stated negatively, multiple objectives tend to raise expectations that cannot ultimately be fulfilled. Stated positively, the objectives of

(1) detecting change in extent and distribution, (2) assessing ecosystem condition, (3) suggesting causality, and (4) assessing the risk of future crises present a noble, if quixotic, challenge to the science of ecology. Whether or not they are stated explicitly, this set of fundamental objectives underlies many monitoring programs and might well serve as a definition of Applied Ecology.

Dilemmas in dealing with a middle-number system:

Ecosystems are middle-number systems (O'Neill and Waide 1981, Allen and Starr 1982, O'Neill et al. 1986). There are too many components to consider each entity separately. Thus, we are denied the small-number approach that has been so successful in Physics. In a small-number system, each component can be considered in a separate equation dealing with all possible interactions. On the other hand, ecosystems do not contain Avogadro's number of nearly identical components. Thus, we are denied the physicist's approach to large-number systems, like gases, where only average properties, such as temperature, need be considered. In middle-number systems, there is no known procedure for ignoring complexity (Weinberg 1975).

The dilemma posed by middle-number systems is profound. It is certainly possible to set up an experiment, controlling almost all relevant interactions, and establish predictable relationships. Thus, we can measure a consistent relationship between net primary production (NPP) and temperature in a potted plant in an environmental chamber. But set everything loose at once and predictability goes to hell in a handbasket! We know a great deal about NPP but farming remains a high-risk venture.

One of the most interesting features of middle-number systems is the uncompromising reaction of mankind in general and scientists in particular. "Give me a bit more time, a bigger computer, and a lot more money and I will crack the problem. I simply don't understand enough yet." There is no way to demonstrate definitively the error of this credo, but it remains a statement of blind faith. The statement is founded on an undying faith in the fundamental orderliness of the universe and the near-infinite capacities of the human mind to grasp that orderliness. Heisenberg's uncertainty principle, the stochastic nature of quantum mechanics, chaotic analysis, and the human experience of several centuries has done little or nothing to shake our confidence.

The dilemma of middle-number systems is an important point and some examples will drive the point home. Human economic systems are also middle-number systems. Incredible sums of money are spent monitoring the economic system. What simple set of indicators, measured across time and space, would permit you to detect a trend and predict crisis? Would any conceivable set of monitoring indicators, for example, have predicted that Iraq would invade Kuwait and throw the Stock Market into a tizzy?

Okay, but economics is a human system and we know they are complex. Surely things get better if we deal with a purely physical system. Surely physics, the mother science, has everything in hand and we children can learn at our mother's knee. So let's consider a simple physical system, the weather. Once again, incredible sums of money are spent in monitoring. But there is no "800" number you can call to find out if it will rain here week after next!

Well, alright, but weather involves the global system and we can't do much with that vast a scale. Let's get down to a nice deterministic, mechanical system that we know plumb EVERYTHING about, say the automobile. Can you predict when the car will break down on the day you purchase it? How do you monitor to prevent crises? You can monitor hundreds of factors and then a piece of metal fatigues or a hose breaks and your prediction goes out the window!

Whether or not middle-number systems ultimately turn out to be predictable is a matter for the future to decide. The profound dilemma for us to ponder is that we cannot predict their behavior now. If we converted the U.S. defense budget to the effort, we could not devise a medical monitoring program that could predict who will die of what cause and when. Therefore, any environmental monitoring program must face the inescapable reality that no simple set of indicators can capture the complexity of a middle-number system. We can make educated guesses, but we know of no way to proceed beyond guesses.

We certainly can choose indicators wisely. We can devise measurements that indicate undesirable trends. But we cannot predict and prevent crises. Oil tanker captains will continue to drink too much at the wrong time. Equally important, we cannot develop any simple set of measures that will detect all possible undesirable trends. We can design prudently. But we must be careful not to raise unreasonable expectations. Because ecosystems are middle-number systems, NO monitoring program can be perfect or foolproof.

Dilemmas in defining ecosystem "health":

Specific monitoring programs are always simpler to design and interpret than general programs. Production foresters monitor for wood production. The "healthy" ecosystem maximizes wood production. One can measure tree growth and even core the trees for rot to determine quality. But in a general program, designed to assess ecosystem "health" (Schaeffer et al. 1988, Hunsaker and Carpenter 1990), it is difficult to avoid conflicts arising from differences in value systems.

Monitoring programs are public programs. The EMAP program, in particular, is designed to provide decision-makers and the general public with assessments of the state of the environment. As a result, it is difficult to separate the question of ecosystem "health" from questions of human values.

The problem can be illustrated by contrasting the view of preservationists with those whose living depends on the utilization of natural resources. The preservationist considers any change of the ecosystem away from the natural, unmanaged state as "unhealthy." In contrast, those who utilize the resource may emphasize maximum utility. To the forest manager, an old growth forest is full of rotten, damaged trees. Leaving the system unmanaged leads to an "unhealthy" state. To the industrialist, a "healthy" environment is one that retains its capacity to process and detoxify wastes.

The problems posed by conflicting values can lead to amusing anecdotes. In the early 1970's a controversy arose over the Indian Point Power plant. The cooling system drew water from the shallow spawning areas of the striped bass and threatened the population (Van Winkle 1977). Early assessments indicated that there would be little impact on the "health" of the Hudson River ecosystem, since the striped bass would simply be replaced by other species. Nevertheless, the impact on the striped bass was considered important and the power plant built cooling towers. Fifteen years later there are problems in the Hudson River. The commercial fishermen harvesting shad for roe are complaining. There are so many striped bass that they are clogging nets and making the fishery unprofitable.

This example indicates how different value systems yield different definitions of health. To the sportsman, increasing bass populations are a sign of vigorous "health." To the shad fisherman, the bass are a sign of imbalance and ill health.

A similar example can be developed around management of Yellowstone National Park. Park policy is to leave things alone and the system will develop into a pre-Columbian balanced state. Other ecologists argue that the pre-Columbian system saw frequent Indian fires and extensive hunting of elk and bison. Man is a part of the system, not an intruder. The extensive fires in 1988 and ungulate pressure on some community types are seen by some as demonstration of the wisdom of the ecologists' view. But the fact remains that different views of the ecosystem led to significant differences of opinion as to whether or not undisturbed forest growth and expanding ungulate populations indicated improved ecosystem "health."

It is not clear that any indisputable definition of ecosystem "health" can be devised. In these circumstances, the fundamental challenge is to come up with a suite of measurement indicators that address multiple value systems and consider a variety of interpretations of ecosystem health. And, of course, all of this has to remain within budget!

INNOVATIVE APPROACHES TO MONITORING

Let us now turn from the dilemmas that make monitoring a challenge. If we focus too long on the challenges, we may decide that monitoring is too difficult to attempt. In fact, we have little choice but to begin. And in beginning, we need to exhaust our creative energies in seeking new ways to address the problems. I would like to suggest three areas that can generate significant innovations: integrative measures, remote telemetry, and creative data interpretation.

<u>Integrative measures of ecosystem health</u>:

One innovative approach to monitoring ecosystem health involves integrative measures. i.e., single indicators of overall health. We established in the preceding section that holistic measures probably cannot be used as the sole indicators. Nevertheless, integrative indicators can play an important role, and I would like to take a few moments to consider the possibilities.

Integrative measures focus on critical system functions. These functions are maintained by complex interactions, so that impacts on any process and/or population is likely to be detected. This is the logic involved in monitoring a child's health by taking its temperature.

At a fundamental level, humans are homiotherms. Body temperature is complexly regulated by a large number of vital processes. Therefore, a simple measure of body temperature is often an accurate indicator of whether something is wrong with any of the vital functions.

A similar approach to ecosystem health considers the basic nature of ecosystems. At a fundamental level, ecosystems are biogeochemical systems that dissipate energy to maintain organic structures in an inert geochemical matrix (O'Neill and Waide 1981). It seems logical, therefore, that meaningful integrative measures could be associated with energy processing and nutrient recycling. Both processes involve complex interactions among many components and confer a degree of homeostatic control (Reichle et al. 1975, O'Neill and Reichle 1980).

O'Neill and Giddings (1979) argue that integrative measures are important because they can be immediately interpreted in terms of ecosystem health. Similar interpretations are possible for a few "keystone" species. If there is a measured effect on the keystone population, there are immediate consequences for other components of the system. But, in general, it is difficult to go from an effect on one species to an impact on the total ecosystem. The health of an organism is not affected by the demise of individual blood cells. Populations remain healthy while individuals come and go. Similarly, ecosystem integrity may be little affected when species are lost and replaced. On the other hand, effects on critical ecosystem processes have an immediate impact on the ability of the system to maintain itself. This interpretation can be made without having to determine beforehand which of the myriad populations is most sensitive to a new disturbance (O'Neill et al. 1977, Van Voris et al. 1980). O'Neill (in press) has recently reviewed the potential candidates for integrative measures. Although the review does not consider the practicality of the methods for large-scale monitoring, it documents the type of indicators that can be measured at the ecosystem scale.

There are four candidate measures based on energy processing. The ratio of primary production to respiration (P/R) can be measured in aquatic ecosystems to determine if the energy balance is sufficient to maintain biotic integrity. The measure has been shown to be sensitive to temperature (Beyers 1962), light (Copeland 1965), grazing (Beyers 1963, McConnell 1962), and toxicants (Gidding and Eddlemon 1978, Whitworth and Lane 1969). A second potential measure is Power, defined as energy flow per unit biomass (Odum and Pinkerton 1955). O'Neill (1976) and DeAngelis (1980) show that power is related to the ability to recover from disturbance. The third measure considers the periodicities in a time series of ecosystem metabolism. Using spectral analysis, continuous measurements of metabolism are analyzed for periodicities. Van Voris et al. (1980) proposed that the number of periodicities was related to ecosystem stability and Dwyer and Perez (1983) confirmed the relationship experimentally. Finally, we can include the direct measurement of gas exchange considered by Gosz and colleagues elsewhere in this volume.

Four integrative measures can be derived from nutrient processing. The decomposition of complex organics involves complex population interactions and is sensitive to toxicants (Coughtrey et al. 1979, Jackson and Watson 1977, Ruhling and Tyler 1973, Tyler 1976). Second, Schindler et al. (1980) proposed a combination of pH and dissolved oxygen as a measure of the organizational state of an aquatic ecosystem. Waide et al. (1980) showed that the measure is sensitive to perturbation. Third, recycling in streams is measured by the spiralling length (distance traveled by a nutrient as it recycles through the system, Newbold et al. 1981). Changes in spiralling length indicate disturbance to nutrient processing and are measurable in the field (Newbold et al. 1983). Finally, any unusual change in the nutrients leaking out of a terrestrial ecosystem clearly indicate that something is wrong with the recycling process (Likens et al. 1977, O'Neill et al. 1977, Van Voris et al. 1980, Swank 1987).

This brief review suggests the important properties required of a useful integrative measure. First the measure should involve a basic function such as energy processing or nutrient recycling. Therefore, a change in the measure immediately indicates an alteration in the ability of the ecosystem to maintain itself. Second, the measured process should be the resultant of many interacting components so that an effect on any of the components will be reflected in the measurement.

There will probably always be some debate among ecologists as to the merits of holistic indicators. In particular, ecologists seldom agree on the relative merits of monitoring sensitive species versus holistic measures of ecosystem function. The holist argues that a measure of overall ecosystem function detects changes anywhere in the system. The population ecologist argues that locating the most sensitive species is always a better strategy. Impacts can be seen earlier in the sensitive species and monitoring can be better focused and probably less expensive.

Both sides of the argument have merit. It is clear, for example, that some holistic measures, such as primary production, may be relatively insensitive to disturbance. O'Neill and Giddings (1979) showed that considerable shifts in phytoplankton communities can occur without a detectable change in total production. Others have argued that gross system function changes slowly while species responses may be immediate and unequivocal. Furthermore, because we know a great deal more about individual species requirements, population effects may be more meaningful in suggesting causation.

The counterargument points out that holistic measures based on nutrient cycling have been shown to be very sensitive (O'Neill et al. 1977, Van Voris et al. 1980). In addition, effects on critical ecosystem processes have immediate implications in terms of the ability of the ecosystem to maintain itself. And although some specific sensitive species may show the earliest impact, there is no way to guess which species will be sensitive to the next impact. Furthermore, loss of a single species may be interpreted as an ecological change but may not indicate a degradation of ecosystem "health." Replacement by a competing species may be a normal compensatory mechanism at the ecosystem level.

Holistic measures, therefore, have much to recommend them. Such measures may be the first indicators of a problem. In monitoring the health of a child, one first takes an holistic measure, such as body temperature, and only then seeks specific symptoms. But by the very fact that they are responsive to a great variety of insults, they will be poor indicators of any specific cause. The better an holistic indicator is for early warning, the less useful it will be for specifying causes.

Remote sensing revisited: Monitoring by telemetry

One of the most innovative suggestions for ecological monitoring involves telemetric measurement of ecosystem functions (Committee on Planetary Biology 1986). By this approach, a satellite is used to read a signal from an instrument. In essence, any low maintenance instrument can be placed in the field and supplied with a radio and an antenna. Thereafter, the instrument can be activated and queried periodically.

Ordinarily, a grid of the instruments would be placed in the field and would remain for the period of measurement, perhaps for several months during each remeasurement period. It is certainly not beyond possibility to place the instruments in more permanent installations and take remeasurement data more frequently.

The possibilities of this approach are truly mind-boggling and only limited by the ingenuity of engineers in developing reliable, compact instruments. Clearly, the approach could be used for soil moisture, tree diameter change, stream stage height, water stress in trees, etc.

The availability of compact chromatographs makes this approach particularly exciting. One could remotely monitor CO_2 and other gases in plant canopies. One could monitor nutrient concentrations in soil water or aquatic ecosystems. By burying the sensor, it should be possible to follow stages of decomposition by analyzing byproducts in soil gases (D. C. White, personal communication).

While the approach holds great promise, there are two important drawbacks. First, the approach requires high initial capital cost in instruments. Eventually the initial expense would result in substantial savings in labor costs. Once placed, the instruments can remain in place for extended periods of time at no additional cost. Nevertheless, the high initial cost may make the approach difficult to sell. The second drawback involves the design of no-maintenance instruments. Labor costs for repair and calibrating the instruments at remote locations might make the approach infeasible.

In balance, however, such an approach might turn out to be a good investment. One great advantage is that the control over the density of the data. In normal monitoring, the instruments might be queried over some standard measurement interval. However, if initial readings indicated a significant change, the density of information could be easily increased. Therefore, the approach holds promise of collecting sufficiently detailed temporal data to indicate the exact nature of the problem and its causes.

The creative interpretation of monitoring data

A third class of innovations focuses on interpreting monitoring data. As I pointed out earlier, simply measuring a change is quite different from assessing the implications of that change. I would like to propose that the creative analysis of EMAP data requires significant innovation. To illustrate the point I would like to explore how one might use landscape data to assess ecosystem health.

Landscape analysis, of course, represents an innovative approach to monitoring in its own right. Landscape indicators take a new approach by relating spatial patterns in landcover data, usually remotely sensed, to ecological processes operating on the landscape (O'Neill et al. 1988a, Hunsaker et al. 1990, Graham et al. in press). Consideration of these indicators is presented elsewhere in this volume. The challenge here is to explore how one might interpret landscape data to assess human impact or increased risk of environmental degradation (Hunsaker et al. 1990).

To begin with, significant assessments can be based on very simple measures of landuse changes. The simplest measure is the number of pixels, i.e., smallest units of spatial resolution, that change landuse between remeasurements. Loss of specific landscape features, such as windbreaks or riparian zones, can be immediately interpreted. Specific patterns would also be important, such as contiguous, uninterrupted agriculture adjacent to streams or lakes.

Reduction in percent occupancy by specific categories, e.g., forest or wetland, indicates habitat loss. This can be translated into increased risk to wildlife and, more importantly, increased risk to endangered species.

In many regions, endangered species are associated with very specific habitats. In eastern United States, for example, the Gray Bat (Myotis grisescons) requires a unique combination of streams near large roads, such as interstate highways. Table 1 reviews endangered species and their habitat requirements in the Southeast. In Florida, many species are associated with the sandy scrub and hardwood hammock habitats. Other species in the Southeast are restricted to granite outcrops. The importance of the species-habitat associations is that it is possible to go directly from an observation of landuse changes to an interpretation of increased risk to organisms protected by law.

Another simple measure of change would be increased miles of roads. Roads are a major contributor to wildlife mortality and often have an immediate impact on hydrologic pathways and water quality. It is well established in economic theory that the miles of new roads (and their quality) is predictive of future development and economic activity (Katzman 1974, Jones 1983). For example, in forested regions, logging roads provide access to new areas and can be associated with an increased risk of forest loss. In agricultural regions, the distance of a plot to the nearest paved road and the nearest market is a good indicator of intensity of agricultural activity (Dunn

1954). Thus, changes in the quantity and quality of roads can be interpreted in terms of increased economic activity (a societal good) and environmental impact (an ecological evil). The assessment is mixed, but the interpretation is clear.

Another simple measure would be the spatial extent and pattern of disturbances, such as, fire, pest, hurricane, tornado (Graham et al. in press). Similarly, the remeasurement data could be used to evaluate the rate of recovery from past disturbances. This simple monitoring of disturbance and recovery would be another direct method for assessing ecosystem health.

Simple calculations based on landcover can enhance interpretation. The index, U (the ratio of pixels in natural landcover to pixels in agriculture and urban, O'Neill et al. 1988a), is a simple measure of overall human impact. An observed change might be weighted by the tendency of the change to break up a single large patch into isolated smaller patches. Similarly, a pixel change could be weighted by the probability of the change forming a barrier to animal movement (Gardner et al. in press) or breaking up corridors along which wildlife move (Forman and Godron 1986). Such changes can be directly interpreted in terms of increased risk of losing wildlife and/or endangered species. One might also consider weighting pixel changes by the abundance of a specific landuse. In a region with very little wetland (or riparian or critical habitat), loss of such a pixel is much more important that in a region where the habitat is abundant.

One could also weight changes by spatial pattern. If 100 pixels changed from natural vegetation to human use over a time interval, to what degree are the changed pixels contiguous? It would be important to distinguish between 100 pixels scattered over the scene (little impact) and 100 pixels in a group (potential erosion or barrier to animal movement) and 100 pixels in a line (a road forming a new barrier).

Going beyond simple combinations of pixel changes, there are a number of measures, recently developed in Landscape Ecology, that relate changes in landscape pattern to changes in ecological processes. For example, empirical studies indicate that the fractal dimension of landscape patches (Milne 1988) indicates the extent of human manipulation of landscape structure (Krummel et al. 1987). Humans go for simple shapes, nature likes complex configurations.

Reduction in habitat edges, e.g., pixels of forest adjacent to other landuses, can be related to wildlife suitability (Ranney et al. 1981, Gardner et al. 1989). Edges can also be related to biodiversity since edges normally have higher species diversity (Quinn and Hastings 1987, Quinn and Harrison 1988, Robinson and Quinn 1988).

In certain cases we can relate edges to size of patch. Cowbirds at the forest edge are nest predators on warblers. Patches have to be large enough so there are adequate warbler nest sites, far enough from edges that cowbirds cannot find them. If patches get too small, the warbler populations start to decline. Large patch size is also a habitat requirement for large carnivores, such as the red wolf.

Percolation theory (Gardner et al. 1987) provides a framework for relating specific aspects of landscape pattern to the probability that a randomly placed organism can move across the landscape and utilize the available resources Using the theory, changes in landscape pattern can be directly related to the percentage of a landscape that becomes isolated and unavailable as resource for wildlife (Gardner et al. 1989). Diffusion rates, developed from percolation theory, indicate how difficult it is to move across the landscape. The diffusion rate can then be interpreted in terms of either wildlife utilization or fire spread (Turner et al. in press).

Additional measures from landscape ecology are also applicable. Resource Utilization Scale (RUS) is a specific measure of the scale at which an organism must disperse to utilize all of the resources on the landscape (O'Neill et al. 1988b). As the landscape becomes fragmented, RUS increases and there is increased risk that organisms with poor dispersal ability will become extinct on the landscape. Contagion, the probability that a landuse is more "clumped" than the random expectation, has shown itself to be a valuable measure that influences many (probably all) of the other landscape level interpretations (e.g., O'Neill et al. submitted).

Much of what we understand about the influence of landscape pattern on ecological processes is based on the patch configuration of natural vegetation. The frequency distribution of patch sizes can be related to wildlife. Some species need a minimal patch size (Pickett and Thompson 1978). Fragmentation of a landscape from a few large patches to many isolated patches can be related to increased risk of losing many species of plants/animals (Pickett and White 1985). A similar measure would be the frequency distribution of distances between natural patches, e.g., nearest neighbor distances. These distances can be related to the difficulty of wildlife moving across the landscape and utilizing resources. It is also possible to interpret changes in the extent and pattern of clearing. For example, relative to erosion risk, one might weight clearings by slope and proximity to other clearings.

A number of other interpretations suggest themselves when we add ancillary data, such as the agricultural census, population numbers, or forest surveys. As a single example, loss of a pixel of forest (with recreational value) may be far more important in regions with large urban populations.

Another approach to assessment would compare current land cover to its potential. For example, it might be useful to express actual forest cover as a percent of potential forest cover. Similarly, one might compare current agricultural cover with a suitability index based on soils. These measures assess the degree to which the ecological resources are being used in appropriate ways.

The Forest Service has developed a number of models that relate habitat to suitability for wildlife. Using these models, changes in habitat extent could be directly related to risk of change in a wide array of animal species.

Landcover data can often be used to assess the risk of water quality degradation and hydrologic change (Omernik 1977, Osborne and Wiley 1988). Increase in agriculture/urban or decreases in natural vegetation indicates risk of future water quality problems. A more powerful indicator would weight the landcover change by distance from water, soil type, tendency to form continuous agricultural cover, and associated slope (calculated from Digital Elevation Models).

Another approach might focus on the risks of erosion, flooding, and other undesirable hydrologic events. A simple erosion assessment would include slope and vegetation while a more complicated indicator would also include soil characteristics (e.g., Universal Soil Loss Equation). A flood control indicator could include information such as vegetation cover (wetlands to modify peak flows) and surficial geology (Bedford and Preston 1988).

A third approach would focus on riparian ones and wetlands as buffers for maintaining the water quality of streams. Changes in width of buffers, weighted by slope and landcover, would be an important indicator. The actual index might be average width, or miles of riparian zone that are narrower than desirable. It would be possible to use the Canadian Timber Management Guide (Ontario Ministry of Natural Resources 1988) to set buffer zones around each water body and count pixels that encroached into this buffer. It might also be useful to find a way to include some indicator of contiguous vs. broken stream corridors.

A fourth method would use landuse data to estimate pollutant loadings to water bodies and assist in evaluating the risk of eutrophication and toxic effects. One approach would be the unit area load method which pairs known loading from a watershed with monitoring data to an unmonitored watershed that has similar characteristics.

CONCLUSIONS

To the general public, environmental monitoring seems a simple task. After all, when the water smokes, turns purple, and the fish are all belly-up, one should be able to measure a change. Unfortunately, the real world is more complex and the changes we must detect are far more subtle. As a result, large-scale monitoring programs face significant challenges and will require large infusions of creativity.

The challenges are complex and we have only scratched the surface in the present paper. The most important innovations will be, of course, the ones we have not thought of yet and we cannot limit our imagination to the discussions above. Nevertheless, we can initially offer some take-home lessons:

1. Monitoring for resource extent and location is a reasonable goal. Assessing changes in this ecological map will require innovative approaches, but recent developments in landscape ecology foster optimism. However, considerable patience will be required to develop the essential baseline dataset.

2. Monitoring programs, and even ecologists, often mistake measurements for science. If the program contains no controls, the measurements cannot reach causality. Monitoring can only hope to show correlations. Without controlled experiments, you cannot demonstrate that toxicants caused cancer at Love Canal, you cannot prove that regulations are improving ecosystem health, you cannot even prove that aspirin cures headaches! Monitoring suggests, but does not demonstrate.

3. Ecosystems are complex, and complex in an insidious way that disarms all known approaches to unraveling complexity. Don't assume a monitoring program can predict or anticipate change. Assume rather that the ecosystem will continue to surprise you.

4. Include integrative measures of ecosystem function among your indicators. If you limit your program to population measures, you may pick the wrong populations. Include at least some holistic indicators as safeguards and to broaden the scope of value systems that are considered. Be particularly open to those measures that permit remote telemetry.

5. The substantive challenges involved in large-scale monitoring should not be used as excuses for not beginning the effort. Ecologists and other environmental scientists should roll up their sleeves and jump in feet first. Simply stated, we will never be able to effectively manage our natural resources or design future research without large-scale, long-term monitoring.

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Table 1. Endangered and threatened species associated with specific habitats in Southeastern United States (taken from Fish and Wildlife 1989).

Sandy Pine/Oak Scrub in Central Florida:

Florida Scrub Jay (Aphelocoma coerulescens coerulescens)
Eastern indigo snake (Drymarchon corais couperi)
Blue-tailed Mole Skink (Eumeces egregius lividus)
Sand Skink (Neoseps reynoldsi)
Wide-leaf Warea (Warea amplexifolia)
Four-petalled Pawpaw (Asimina tetramera)
Florida Bonamia (Bonamia grandiflora)
Pygmy Fringe Tree (Chionanthus pygmaeus)
Florida Golden Aster (Chrysopsis floridana)
Scrub Lupine (Lupinus aridorum)
Scrub Plum (Prunus geniculata)
Scrub Mint (Dicenandra fruteaceus)
Snakeroot (Erygium cuneifolum)
Lakelas Mint (Dicerandra immaculata)
Highland Scrub Hypernicum (Hypernicum cumulicola)
Papery whitlow-wort (Paronychia charctacea)
Wireweed (Polygonella basiramia)
Carter's Mustard (Warea carteri)

Granite Outcrops:

Granite Snapdragon (Amphianthus pusillus)
Quillwort (Isoetes melanospora)
Quillwort (Isoetes tegetiformans)

Wetlands:

Cape Sable Seaside Sparrow (Ammospiza maitima mirabilis)
Pondberry (Lindera melissifolia)

Beaches/Dune:

Piping Plover (Charadrius melodus)
Choctawhatchee Beach Mouse (Peromyscus polionotus allophrys)
Alabama Beach Mouse (Peromyscus polionotus ammobates)
Perdido Key Beach Mouse (Peromyscus polionotus trissyllepsis)

Table 1. (continued)

Hardwood Hammocks in Florida Keys:
Key Largo Woodrat (Neotoma floridana smalli)
Key Deer (Odocoileus virginianus clavium)
Key Largo Cotton Mouse (Peromyscus gossypinus allapatricola)
Ecotone: Pine/grassy
Gopher Tortoise (Gopherus polyphemus)
Rough-leaved Loosestrife (Lysimachia asperulaefolia)
Ecotone: Conifer/Hardwood:
Carolina Northern Flying Squirrel (Glaucomys sabrinus coloratus)
Ecotone: Scrub/agriculture:
Florida Grasshopper Sparrow (Ammodramus savannarum floridanus)

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