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The emergence of global environmental awareness*

John Cairns, Jr.[1]

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Abstract—An effective plan for global ecosystem management must be developed in the next 10 or 20 years. Awareness of the need has recently emerged, but still no integrated resource management system is universally accepted. A fragmented management approach has not been effective. Any successful course of action must be based on three assumptions: (1) that science can determine how ecosystems function, (2) once this is known, the social/political system will be able to protect ecosystems to the extent needed for the survival of human society, and (3) reality will take precedence over political expediency because Mother Nature cannot be fooled. This discussion focuses on the transition from awareness to taking effective action.
Keywords: global environmental awareness; ecosystems function; human society.

"I am utterly convinced that most of the great environmental struggles will be either won or lost in the 1990s, and that by the next century it will be too late to act."

Thomas E. Lovejoy
Bioscience Vol. 38,
No. 10, 1988

"The universe does not make concessions to ignorance."

Robert Sheaffer
Resentment Against Achievement
Prometheus Books, Buffalo, New
York, 1988

Is there a problem?

The first Earth Day and the period following it persuaded a sizable segment of the general public in most developed countries that environmental problems required immediate attention. Although Rachel Carson's Silent Spring identified a widespread problem caused by the use of

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[1]University Center for Environmental and Hazardous Materials Studies and Department of Biology, Virginia Polytechnic and State University, Blacksburg, Virginia-24061-0415 U. S. A.

DDT and other pesticides, most of the icons of this period had a geographic location: Love Canal, Times Beach, Mimiyata/Japan. Most people not living near a problem area could take comfort in the fact that this was not in their backyard. Then came the era of acid rain, and somewhat later acid snow, and an uneasy feeling developed that environmental problems transcend even the largest political and geographic boundaries. The usual argument arose about whether any harm was in fact occurring to the environment—whether there was "scientific proof." Even those who accepted, sometimes reluctantly, the evidence of an association between combustion of fossil fuels and acid rain assumed that any problem with a technological origin had a technological solution. It was particularly comforting to identify the villain—the steam electric generating plants fueled by coal—as one of the "deep pockets" with the resources to correct the problem if only enough legislation and political pressure were brought to bear. Some also found comfort in the fact that acid precipitation (both dry and wet) appeared to affect some geographic areas more intensely than others. At the very least, the association between the origin of the environmental stressor and the environmental effects was not close. About the same time, awareness escalated of the increasing amounts of carbon dioxide entering the atmosphere and the possibility of the greenhouse effect (i. e., global warming). Concern heightened about the ozone layer and some global action was even taken to mitigate the deleterious effects. Initially, even these global threats were associated with technological advances. However, a number of books have appeared (Ehrlich, 1981) that call attention to the rather startling rate of extinction of species caused by the destruction of tropical rain forests and other similar actions elsewhere in the world, much of which could be done by relatively primitive technologies. Possibly a major focus on this problem was the conference on biodiversity co-sponsored by the U. S. National Academy of Sciences and the Smithsonian Institution, which documents this loss in a public way (Wilson, 1988a). Media coverage on this problem was much greater than ever before and, while the global loss of species is still not as much a matter of public concern as acid rain and the greenhouse effect, it is nevertheless receiving significant attention. Thomas Lovejoy(1988), in the Plenary Session address at the American Institute of Biological Sciences, indicated that 2000 km^2 of new growth forest would be required to remove each billion ton of carbon as dioxide from the atmosphere annually. The total amount in excess of "normal" was estimated to be between 2.5 and 3.5 billion tons per year. This provides an interesting link between the two global problems of the greenhouse effect and the extinction of species. If tropical rain forests were left in tact, or even restored in some areas where this might be possible, not only would carbon dioxide be stored for substantial periods of time as biomass, but some valuable habitat for endangered and threatened species would be preserved. Paul and Anne Ehrlich (1981) have noted that environmental disturbances of the kind just described are as great a threat to human society as is nuclear weaponry.

Soft/hard science and dealing with decisions based on uncertain evidence

Ask any mathematician, physicist, chemist, or molecular biologist what science is, and the answer will probably involve one or more stereotypes. The most common is that hard science involves numbers accurate to several decimal places. Except for mathematics, the answer will probably involve controlled, repeatable experiments in which all variables are controlled or fixed except the one being studied. The stereotypes favored by the news media, theater, and the like involve people in white laboratory coats holding test tubes or using obviously complicated equipment with dials or, more recently, a direct computer output. The soft sciences (and the spoken word is usually pejorative) customarily involve criteria difficult to quantify and variables that are usually uncontrollable. As a matter of fact, the investigator is often unsure just what constitutes an important variable. Diamond (1987) has an interesting article on the National Academy of Sciences conflict centering on the candidacy of a professor of government at the Harvard whose admission to this prestigious organization was quite publicly opposed by a professor of mathematics. Diamond suggests that the labels "soft science" and "hard science" might well be replaced by difficult science and easy science, respectively. Nobel laureate H. A. Simon (1983) states that "what chiefly distinguishes creative thinking from more mundane forms are the willingness to accept vaguely defined problem statements and gradually structure them, a continuing preoccupation with problems over a considerable period of time, and an extensive background knowledge in relevant and potentially relevant areas." He further suggests the following as relevant to the discovery process: tolerance of ambiguity, persistence, knowledge, problem formulation, communication, and chance. No meter will measure the destabilizing effects globally of atmospheric warming, acid rain, or depletion of the ozone layer. Nevertheless, these are all problems of enormous societal significance, and underestimating such effects might well destabilize present human social systems to the point that they are no longer workable. By overdoing the hard science aspects of these complex problems in order to gain credibility (by having measurements to a number of decimal places and so on), some key variables may be ignored or de-emphasized that will invalidate any attempts to estimate global trends.

Just as no "scientific" proof exists that cigarette smoking is harmful to human health, no "scientific" proof will be available that excess accumulation of carbon as carbon dioxide in the atmosphere is a globally important destabilizing ecological factor. Furthermore, the scale in which these effects occur preclude carrying out a controlled, or even an uncontrolled experiment except the one now occurring globally. Plants can be exposed to larger than normal amounts of carbon dioxide, slight warming effects and so on; that is, components of the problem can be studied, but all of the problems collectively on the scale at which they will occur cannot be. This leads to two interesting operational questions: (1) should investigation wait until "conclusive" proof is available that these effects are highly probable and their exact consequences can be documented or (2) should scientists act as if the effects are likely to occur without "conclusive" proof because, if they do, the situation may not be reversible? In short, decisions must be made with a high degree of uncertainty regarding the outcome, and the solutions to the global problems cannot be undertaken by a single country or even a sizable group of countries with guaranteed effectiveness. Even a modest chance of success will require a truly global effort.

Burden of proof

Ideally, evidence should be provided that a particular course of action, such as the introduction of a globally used pesticide or the destruction of Brazilian tropical rain forests, would have no significant adverse environmental effects. This was the intention of the U. S. Toxic Substances Control Act, which explicitly stated that evidence regarding the effect on human health and the environment be provided before a new chemical or an old chemical used for a new purpose was marketed. Unfortunately, this is simply too much to expect. For example, can the People's Republic of China legitimately be asked to scrap plans for doubling its energy base primarily through the use of fossil fuels in the next 10 years because this will probably increase the amount of carbon dioxide in the atmosphere and, thus, exacerbate the greenhouse effect? Possibly yes, if the heavy energy users in North America, Europe, and elsewhere markedly reduced their use. As Garrett Hardin (1968) so eloquently stated in "The Tragedy of the Commons," the benefits and the beneficiaries are quite easily identified, the detrimental effects are often controversial, and the sufferers are often unaware that they are in that category.

Scientific awareness of global problems

Lederberg and Zuckerman (1986), in articles published in Nature, address the individual and institutional factors that affect the discovery process in the life sciences. Using the circumstances that surrounded Lederberg's discovery of genetic recombination of bacteria as an example, they analyzed the process of scientific discovery from the prospective of the sociologist/observer and the scientist/participant. Zuckerman and Lederberg suggest that discoveries may be classified as premature or postmature. "Premature discoveries, ..., are either passively neglected or actively resisted at the time they are made. Discoveries are premature because they are conceptually misconnected, ..., made by an obscure discoverer, published in an obscure place or are incompatible with prevailing doctrine.

For a discovery to quality as postmature, ..., it must have three attributes: (1) in retrospect, it must be judged to be technically achieveable at an earlier time with methods then available; (2) it must be judged to be understandable, capable of being expressed in terms comprehensive to working scientists at the time; and (3) its simplications must have been capable of having been appreciated." My inclination is to believe that scientific awareness of environmental problems frequently falls into the premature discovery classification, often for all three of the reasons given. This is not to denigrate the professional stature of some of the very distinguished people making these discoveries, but rather to note that they might be giants in their own discipline but relatively unknown outside of it. A case can also be made, however, for postmature discoveries. Acid rain and other forms of acid precipitation could easily have been discovered with available technology had appropriate measurements been made of both liquid and nonliquid deposition many years before any awareness of this problem developed. In fact, it was biological monitoring of the crudest sort, namely serious detrimental effects upon ecosystems, that alerted scientists to the problem, and then a series of investigations were undertaken, finally leading to the cause. In a sense, then, the awareness of global environmental problems fits into both categories in that discoveries are simultaneously premature and postmature. After problems are identified, existing methodology can give insights if the right measurements are made in the right places at the right time.

Getting from awareness to action

Ideally, the objective is to detect the practices that, if continued, will result in significant harm, but before appreciable harm to the environment occurs. This requires a robust predictive capability, but, as the distinguished Welsh ecologist Harper (1982) notes, ecology has not been renowned for its development of a predictive capability. There are, of course, some notable exceptions to this, such as the work of Robert McArthur and a number of other investigators. Nevertheless, single species toxicity tests are still used as the primary means of predicting biological response of complex communities and ecosystems, without validating the assumptions upon which these predictions are made with anything approaching persuasive scientific evidence (National Research Council, 1981; Cairns, 1980). In the newly developing field of restoration ecology, however, the inability of ecologists to make robust predictions about the outcome given a particular sequence of events is most notable. In fact, two distinguished ecologists, Bradshaw (1987) and Ewel (1987), feel that restoration ecology will be the acid test for the field of ecology in terms of predictive capability. Although some major funding organizations are aware of these deficiencies in the field of ecology that could affect the well being of global human society, such testing still does not seem to be high on the priority list for funding. Such investigations are not in one sense "pure science" because they are intimately related with the problems caused by the human race and are major determinants of its ultimate fate. In another sense, as Diamond (1987) notes, such testing is the hardest kind of science, namely dealing with multiple, uncontrollable variables, not all of which are even identified. These problems do, however, fit Nobel laurate H. A. Simon's (1983) definition of creative thinking as defined earlier in this discussion. Although Professor Simon's focus on human creativity was on those individual characteristics that influence a creative process in basic research in the physical sciences, his factors relate to the biological sciences as well (tolerance of ambiguity, persistence, knowledge, problem formulation, communication, and chance). In fact, they are important for both basic (theoretical) research and practical (applied) problem solving. Unfortunately, in my own institution (a land grant university with the motto "that we may serve"), a distressing number of younger colleagues are preoccupied with whether a subject is theoretical (i. e., of no practical value) or applied. Lest the reader think that I am being unduly critical of colleagues in my own institution, it is worth noting that Jared Diamond (1987), a member of the family of the National Academy of Sciences (NAS) for eight years at the time the article just cited was written, felt it necessary to note that the U. S. Congress established the Academy in 1863 to act as official advisor to the U. S. government on questions of science and technology. The National

Academy of Sciences in turn established the National Research Council (NRC), and NAS and NRC committees continue to provide reports about a wide range of practical and applied matters, from nutrition to future army contracts. I have served on 15 NRC/NAS committees and would not have invested such a huge amount of time if I did not think these activities were extremely worthwhile and intellectually stimulating. However, one cannot help noting that the fear of being tainted by the word " applied" affects both individuals and professional organizations. With global crises of a magnitude that might well threaten the stability and structure of human society and with problems that Lovejoy (1988), who is certainly no wild-eyed fanatic, feels must be resolved in the next 10 years or they will be out of control, young academicians addressing such problems should be given at least the same opportunities for tenure and promotion as those in the theoretical sciences. Further, if they are capable of working effectively with other disciplines, as most of these problems require, it should not be regarded as disloyalty to their home department or basic discipline. I have spent so much time on this subject because of the very definite implication that anyone who is not a "pure" or "theoretical" scientist must therefore be necessarily "impure" or "totally applied."

Once the major difficulty of categorizing persons as theoretic or applied is overcome and the basic question is whether they are effective or ineffective, the following matters need urgent attention in order to get from awareness to effective action.

1. The condition of the planet must be viewed as a quality control problem. This means: (a) establishing desirable, acceptable, and unacceptable conditions for an array of biological/chemical/physical conditions, (b) establishing a global monitoring system with rapid information feedback on these qualities to one or more central units (Cairns, 1989). With present computer and satellite transmission capabilities, the transmission should be no problem. Identifying the qualities to be measured, especially biological ones, will be. (c) organizing a group capable of taking immediate corrective action when some quality has gone outside acceptable conditions. Since these conditions are pre-established, it is not a matter for courts of law or interpretation, but rather a matter for immediate corrective action as it would be in an industrial quality control system.

2. A global concensus must be reached on these qualities (or at least a majority agreement) along with agreement on the methods used to make the measurements. These are standard methods in the sense of having gone through a review process in such organizations as the American Society for Testing and Materials, the American Public Health Association, and the like. These methods may be modified, but they must be endorsed by professionals in the field as the most effective means of making desired measurements. This does not mean they are free of faults, but rather that the faults are generally known. The methods must also be sufficiently well understood so that a wide variety of persons with differing professional capabilities can use them effectively. Ideally, of course, such measurements should be totally automated, which is possible for many chemical/physical assessments and even some biological ones.

3. Since the planet is either approaching or has already exceeded its carrying capacity for humans, certain "freedoms" will be lost in order to have the system function effectively. For example, a forest acting as a global carbon sink may not be freely destroyed for economic gain, or such a freedom may be severely limited. Presumably, some form of compensation for acting as the custodian of a global carbon sink would be forthcoming from those producing the carbon. As a rather simplified example, a steam electric power plant burning fossil fuel and loading the atmosphere with carbon dioxide should "rent" compensating carbon sink somewhere in the world. The oceans and other carbon sinks that are on common ground (owned by no individual or nation) might be regarded as sinks for emissions too small to tax (individuals), or for which a tax cannot be enforced (termites). Nations with high per capita energy consumption, such as the United States, might be limited so that other nations (e. g., the People's Republic of China or India) can expand energy production to a closer approximation of those nations with a high per capita energy consumption.

4. An awareness of a global economy has developed slowly. Since "economics" and "ecology" originate from the same Greek word, global interdependence with regard to ecosystems should be readily accepted. However, as recently as July 11, 1988, Newsweek indicated that protecting other species from extinction was a matter of ethics and morality rather than survival.

5. Three major occurrences indicate that global carrying capacity or tolerance of ecosystems for present practices have been exceeded: (a) atmospheric accumulation of carbon as carbon dioxide at the rate of 2.5 to 3.5 billion tons annually; (b) the dramatic rate of species extinction (e. g., Wilson, 1988a); and (c) such phenomena as the changes in the ozone layer and acid rain. A large number of the global problems could be mitigated if certain kinds of wastes were not generated. In addition, materials now regarded as wastes could be used as resources. For example, recycling paper, glass, and such metals as aluminum would reduce the pressing need for landfills, prevent these materials from intruding into ecosystems such as the ocean, and would have other benefits abundantly documented elsewhere as well. It is heartening that the USEPA, in a document Future Risk: Research Strategy for the 1990s (September, 1988), has given a high priority to the prevention of pollution generation at the individual, community, industrial, and federal and state governmental levels. Recycling and reuse is the second highest priority; treatment, once the highest priority, is now third; and reducing exposure is fourth. Nevertheless, these enlightened measures will not be easily implemented. In my own state of Virginia, a bottle bill introduced annually for many years by Senator Madison Marye has been shot down in flames in the 1988 meeting of the legislature. Segregation of household wastes (bottles, cans, paper, garbage) is fiercely resisted by some citizens, even in an enlightened university community. Closer interactions among the disciplines will definitely accelerate the process of resolving waste reduction and recycling, and the information justifying these must be presented in a form intelligible with sufficient documentation to the people who must be

persuaded.

Developing a global monitoring system

Types of monitoring to be carried out, frequency of monitoring, level of detail, and geographic area to be covered should all be highly correlated with the decision being made. Although it is a sine qua non that ecologists must play a strong role in making these decisions, their efforts will be less effective if the use of the information in decision making process is not carefully considered. Decision analysis is commonly used in a number of other professions (e. g., Behn and Vaupel, 1982; Keeney and Raffin, 1976) and even in the field of ecology (Maguire, 1988). However, many ecologists are not even aware of the literature on decision analysis, and an even smaller number have actually used the process. My discussion here assumes three major goals for global climate/ecosystem monitoring: (1) to maintain balanced biological communities, (2) to protect both structural and functional integrity of ecosystems, and (3) to protect biodiversity.

The term "balanced biological community" almost certainly would be difined differently by a randomly chosen assortment of ecologists. "Balance" could be defined in terms of the proportion of organisms at each trophic level, in terms of species dominance, or in terms of the successional process that would incorporate such things as the MacArthur/Wilson equilibrium model (MacArthur and Wilson, 1963). The second goal, protecting structural and functional integrity of ecosystems, could be defined in terms of bio/geochemical cycling (Bormann and Likens, 1979) or in a variety of other ways. Goal three, protecting biodiversity, has recently been given considerable scientific and public attention that has resulted in such meetings as the National Forum on BioDiversity (co-sponsored by the U. S. National Academy of Sciences and the Smithsonian Institution–Wilson, 1988a) or the Symposium on Biotic Impoverishment (sponsored by the Woods Hole Research Institution, Woodwell, in press). Extinction of species is occurring at a rate far in excess of previous centuries, and possibly at a rate unprecedented on earth. If too many species are lost (and no one knows how many constitutes too many in ecological terms), maintaining the other community qualities mentioned will be difficult.

These objectives and goals are given for illustrative purposes only and demonstrate that ecosystem monitoring should be viewed as a component of a quality control system with the intent to define and maintain desirable ecological characteristics within pre-selected or predetermined limits. Biological monitoring serves as a feedback loop from natural systems to show whether or not quality control conditions are meeting preestablished goals. If they are not, the monitoring system should not only show that something is wrong but give some evidence upon which appropriate corrective action can be taken. In short, I reject monitoring as a data gathering exercise and embrace it only as an essential component of a quality control system. Data gathering alone might more properly be difined as "surveillance" (Hellawell, 1978).

Periodicity of data collections will depend on the statistical need to distinguish normal cyclic variation (or even ordinary variation within natural limits) from a trend. Unfortunately, trend analysis has not been investigated in depth for most ecological systems. This is particularly true for freshwater aquatic systems. In fact, despite abundant chemical/physical data, Smith *et al.* (1987) have indicated that it is impossible, based on present evidence, to establish reliable trends for chemical/physical water quality.

Although the indicator species concept might be useful if sufficient data were available on the precise detailed ecological requirements of indigenous species (Kingston, 1983), this information base is not available for most species. In fact, Wilson (1986b) makes a persuasive case that most of the species on earth have not yet even been named. This idea of unlimited, unnamed species indicates that their ecological requirements are probably unknown, and consideration of them as indicator species would be ineffective. John Harte (personal communication) speculates that neotinic salamanders in the Mexican Cut Preserve of the Nature Conservancy on the western slopes of the Rocky Mountains just on the western side of Schofield Pass in Colorado have suffered a decline in reproductive success. Preliminary experiments indicate that this decline is due to a pulse of acidic water from snowmelt that occurs approximately at the same time the species spawns. Nevertheless, although six years of tests have been carried out and the salamanders have been under surveillance for a far longer period than that, scientifically justifying a statement that the acid rain is inhibiting the spawning of the salamanders is still not possible. Circumstantial evidence indicates that this is quite probable, at least in some years, but making this statement in a professional peer-reviewed journal is not warranted. In consequence of the enormous information base necessary to prove that a deleterious effect has occurred or is occurring, species must be selected carfully. Not many species can be monitored in sufficient depth to establish normal variability and an ecologically significant deviation from the normal state. In addition, such studies must be carried out over substantial periods of time to be scientifically persuasive.

Selection of monitoring/sampling sites

Criteria for selecting sites, frequency of sampling, and level of detail required (together with a number of other factors) should all be determined by considering the ways in which the information will be used to make management decisions. Management is used in this connection with regard to environmental quality control in the sense that corrective or preventive action will be taken when necessary to ensure that natural systems stay within pre-determined quality control parameters. The most important decision likely to result from extensive surveys is that some information is redundant and that having information of one type will allow prediction of the outcome in other areas. Extensive surveys will also show which information is unique. Determination of information redundancy is exceedingly important since society simply will not pay to make every measurement that professionals know how to make. Additionally, even if this were to happen, over-sampling, particu- larly in fragile ecosystems, might result in more damage than the other anthropogenic activities from which the ecosystem is being protected.

The second major criterion for site selection is determining the extent of variability of natural systems so that normal cyclic variation is not confused with a trend. This means that the sites would have to be sampled not only extensively but over a long period of time. Presumably, if the information redundancy investigations are carried out carefully, a significant reduction in the amount of effort necessary will result.

A third major criterion for carrying out extensive surveys is to enable decision makers to make a distinction between regional, pollutional, and other ecological stresses and global stresses. This distinction will not be an easy one because the effects will most likely be a series of gradients extending from local and easily identifiable effects to long-range effects where multiple sources are contributing to degradation.

An array of ecosystems representing a broad spectrum of ecosystem types should be chosen for these exercises. Each ecosystem should be chosen for its capability of providing evidence or information to the decision makers that cannot be obtained from other ecosystems. Since most ecologists are not accustomed to thinking in these terms (i. e., selecting information on the basis of its decision making value), initial stages of the development should be carefully designed through a standard decision analysis process.

Again, I am making the assumption that the purpose of monitoring is to provide and early warning system to signal when the system has gone beyond certain pre-determined quality conditions or that the ecosystem is staying within these conditions as predicted. Intensive monitoring could serve as an error control feedback loop to show that predictions of safety were unfounded or that some unexpected event has caused excursion beyond pre-determined values. In this case, the speed of information generation should be the major determinant. Therefore, the parameters selected for measurement, whether chemical, physical, or biological, should ideally be amenable to direct computer interfacing. For example, the respiratory rhythm of fishes has been amenable to such direct interfacing. The ORSANCO system (1987) has a number of chemical/physical parameters already being measured with the utilization of a direct computer interfacing network. The parameters being monitored should be key characteristics (similar to body temperature, heart rate, and blood pressure for human condition monitoring). If these parameters are outside normal boundaries, they have a high probability for indicating serious consequences in other parts of the system. Once a computer interfaced system is set up, the frequency of sampling is almost irrelevent because the cost incurred is negligible for additional information. The system is running all the time, and the important consideration is to avoid an information overload. This can be done with a microprocessor that ensures that information is gathered at appropriate intervals. A number of statistical techniques are available that analyze such information, even if it is in cycles on a diurnal or some other basis (Sydor, 1982; Thompson, 1982). The location of these early warning system probes is exceedingly important, and no risk-free procedure is available to ensure that no major informational gaps occur. Freshwater systems should always have information gathering units above and below the confluence of major tributaries with a river system, in addition to above and below major industrial sites and so on. In some cases, extensive sampling of a river or lake can be carried out on a one time only basis to determine which portions provide information similar to other portions; a reduced number of sites can be selected on this basis. There is also the possibility of establishing some sites with continual or nearly continual monitoring with computer interfaced systems. Other sites may have extensive sampling on a periodic basis. The ORSANCO system uses both approaches in combination, resulting in considerable effectiveness for chemical/physical parameters only. Useful material on statistical considerations associated with determining sites for intensive surveys and intensive monitoring can be found in Green (1979) and Pielou (1977).

Selection of monitoring/sampling parameters

Biological, physical, and chemical parameters should be selected for their predictive value. This predictive value might be divided in two categories. The most important category is the instant recognition of striking changes in key parameters that indicate major deleterious ecological effects. Unfortunately, little direct scientifically justifiable evidence is available to indicate the predictive value of the most commonly used parameters. However, in aquatic systems, changes in dissolved oxygen concentration, pH, and suspended solids (other than short-term excursions) have been regularly associated with deleterious ecological effects (if outside normal limits). Unfortunately, minimal limits must be set on a site-specific basis. All-purpose global limits will almost certainly prove unsuitable. Also, determining the presence of persistent toxic chemicals with a high octanol/water partition coefficient and the environmental compartment in which they are most likely to be stored is worthwhile. In aquatic systems, these may appear only infrequently in substantial amounts in the water column but may be found in relatively high concentrations in both the biota and sediments. Biological parameters are even more difficult to select since, as Harper (1982) points out, ecology has not yet developed a significant predictive capability. Therefore, an assortment of both structural and functional parameters should be selected to determine which have the highest predictive value. The second characteristic also associated with predictive value is a high information redundancy, that is, information about one component of an ecosystem provides useful information about the probable condition of other components. Information redundancy has been given relatively little attention. However, an illustration of how this might work may be found in Kaesler *et al.* (1974).

Even if the average temperature changes only a few degrees, this altered average temperature in Canada and parts of the United States may also alter the growing season sufficiently to adversely affect many important grain food crops. The factors affecting the growing season of fish and macroinvertebrates in aquatic systems can furnish valuable information. Lakes changes in the time of the year at which stratification begins and lake turnover occurs should be extremely important in predicting effects of climate change.

Selection of monitoring/sampling methods

Since long-term studies have shown a balanced biological community maintains both structural and functional integrity, methods should be used to minimize the effects of the successional process (i. e., species replacement), which for some ecosystems is often quite rapid. The studies should not be markedly affected by seasonal variability. Although diversity indices were at one time denounced by theoretical ecologists, methods for determining both species richness and evenness are now coming into favor again. The reason for this is not that practicing ecologists are unaware of their deficiences but rather that theoretical ecologists have not offered a superior alternative. A variety of these diversity indices, as well as rarefaction indices (Smith, 1985) are available for this purpose. Chemical/physical indices most suitable for monitoring are those amenable to direct computer interfacing (e. g., Morgan, 1988) if only to minimize the amout of personnel time necessary. Instrumentation for this type of monitoring is now available and can be used for a variety of chemical/physical parameters. Additionally, they can be placed in remote locations inaccessible for assessing certain types of episodic events (i. e., severe forms such as acid rainfall and so on). Such inaccessible sites in relatively pristine systems might be the most desirable for global monitoring. Therefore, chemical/physical parameters suitable for computer interfacing and automated transmission will be particularly appropriate. For short-term evidence, respiratory signals from invertebrates and vertebrates have been shown by Morgan *et al.* (1988) to be effective and can be supplemented by diversity and rarefaction indices.

If the information is to influence a decision and the decision is to maintain environmental quality within certain parameters, the time required for information generation is crucial. It is simply not possible to collect samples, preserve them, and analyze them months later and provide rapid feedback of information for management action. Therefore, all methods should be selected to optimize information generation time, and, ideally, all information should be fed directly into a computer with little or no personnel intervention (except for maintenance). Appropriate statistical methods for this kind of analysis should be utilized. Some examples of this type of analysis with computer interfaced systems are available in Thompson *et al.* (1982) and Sydor *et al.* (1982).

Two colleagues (one in biology and one in statistics) and I have been commissioned to find a "gold plated" data set that is an accurate predictor of major ecosystem changes such as recovery or degradation. It is, of course, impossible for three individuals over a six-month period to examine all possible suitable data sets, even superficially. However, we did examine a significant number in depth. The first thing we found was that in the United States the word "monitoring" is not used with precision despite the fact that Hellawell (1978) provided excellent definitions of the terms "survey," "surveillance," and "monitoring." These are frequently used as if they were synonymous. Hellawell (1978) defines them as:

> Survey: an exercise in which a set of standardised observations (or replicate samples) is taken from a station (or stations) within a short period of time to furnish qualitative or quantitative descriptive data.

Surveillance: a continued programme of surveys systematically undertaken to provide a series of observations in time.

Monitoring: surveillance undertaken to ensure that previously formulated standards are being met.

Most of the data sets we examined fit under the category of studies. A few fit well within the term "surveillance" in that they were carried out in a systematic and orderly fashion according to a pre-determined schedule but without determining the parameters or end points precisely that would initiate or trigger corrective action. We found no case that fits well Hellawell's definition of "monitoring." As a consequence, the efficacy of these investigations for the purpose of monitoring is speculative and unproven. That is , the selection of parameters that would trigger corrective action is determined by hindsight rather than foresight. The most one can make of these studies is that they might prove useful for the particular ecosystem in which they were carried out but not necessarily for other ecosystems. In fact, there is considerable doubt about their efficacy even in the ecosystem in which they were carried out since all the decision making processes were retrofitted, and this diminished confidence in their effectiveness for prediction substantially.

One notable exception to these comments are the investigations of Robert J. Livingston of Florida State University. He was able to identify several long-term cycles in the Appalachicola River/Estuary System and predict when these cycles would occur. The fact that the cycles occurred at least once in the predicted time and also in sequence validates their monitoring effectiveness.

I know of no study where anthropogenic effects on the environment were explicitly predicted, identified following the prediction with pre-selected ecological parameters, and corrective action taken (on the basis of the monitoring signals) that reversed the deleterious effects. In order for a monitoring system to be effective, it should provide a sufficiently early warning to enable effective correction action to be taken. There is simply insufficient evidence to conclude we know how to do this effectively. Additional monitoring data could be found, but, unless they fulfill all three criteria just discussed, their utility is questionable.

Some basic questions might help determine if a particular data base fits the requirements for effective environmental monitoring. An illustrative example follows.

Structural attributes

1. Are the numbers and kinds of species of all major groups of organisms typical of a balanced biological community present?

2. Is the data base on diversity, rarefaction, and other indices sufficient to distinguish normal variability from long-term trends?

3. Are all age classes of organisms with long life cycles present, and are all species reproducing at a rate sufficient to maintain viable populations?

4. Are normal food webs or food chains present and functioning?

Functional attributes

1. Is primary production being carried out at a normal rate (that of a balanced biological community) by the indigenous species?

2. Are the biogeochemical processes characteristic of this specific type of ecosystem proceeding at characteristic rates?

3. Are the nutrient spiralling and energy transfer processes occurring in ways characteristic of this particular ecosystem?

4. Are the colonization rates adequate to support normal successional processes?

Determination of monitoring priorities

To monitor global climatic changes effectively, the data sources must almost certainly be institutionally generated rather than being generated by an individual investigator. This is important because the highest quality data will undoubtedly come from research investigations of competent professionals. However, in order to acquire research funding, these professionals must modify hypotheses, methodology, and even areas of study. Consequently, systematic and orderly acquisition of data over long periods of time using the same methodology, sampling areas, analytical methods and so on are unlikely to be carried out by individuals but may often be carried out under institutional sponsorship over appropriate periods of time. For example, the environmental monitoring efforts at the Savannah River Plant in the United States cover terrestrial systems, wetlands, and aquatic systems for a period in excess of 35 years. This continuing effort covers a span of taxonomic organisms ranging from microorganisms to vertebrates. In some cases, data gathering has been under the supervision of a single individual. For example, Ruth Patrick was recently honored for 35 years of continual investigations of the aquatic systems and wetlands associated with the Savannah River Plant. Such situations are uncommon but do exist. Even so, changes in methodology inevitably occur as new sampling methods, such as electrofishing, are added to or replace existing collecting procedures. Ideally, both old and new sampling methods should be carried out concurrently through at least four seasonal cycles so that the extent to which each reflects the species distributions in the natural system can be accurately determined and differences in results can be accounted for. The studies of Robert J. Livingston of Florida State University already mentioned cover a period of approximately 20 years. Studies of the well-known Hubbard Brook ecosystem under the direction of Bormann and Likens (1979) provide evidence for both terrestrial and aquatic systems. The studies of the Coweeta ecosystem carried out by J. Bruce Wallace of the University of Georgia and his colleagues represent another source of baseline data that should be exceedingly useful. Except for the studies by Robert J. Livingston, all of the other studies have, in a sense, been institutionalized in that they will continue even if the principal investigator(s) ceases to coordinate sampling activities. This type of institutional commitment to an on-going sampling program will produce the most useful evidence for detecting ecological effects of global climatic changes.

One hopes that the gaps in data will be identified in a way related to the decision making process rather than from a "shopping list" of everyone's favorite group of organisms or favorite method. A long-term monitoring effort to determine the effects of global environmental changes cannot include every group of organisms for every parameter measurable. In order for a "gap" to be significant, demonstration of precisely how the additional information will affect the decision making process should be required. Hellawell's definition of monitoring (surveillance undertaken to ensure that previously formulated standards are being met) requires demonstration that changes in parameters being measured are related to global environmental changes and that they can provide an early warning system that will be suitable for initiating corrective action for permanent ecological damage that has occurred. If these criteria cannot be met, an information gap may indeed exist.

Initially, selection of too many sites for environmental monitoring than too few is advantageous so that a careful analysis of information redundancy can be made. An important factor not discussed elsewhere in this discussion is the consequences of either a false positive or a false negative in monitoring the adverse ecological effects of anthropogenic activities. A false positive is a signal that something is wrong and would presumably, if monitoring is used in the sense of Hellawell (1978), initiate corrective action even though, since the positive is false, corrective action is not required. This is likely to discredit the monitoring system and result in an unnecessary expenditure of funds. When funding is developed for this monitoring program, the unfortunate consequences of a false positive should not be minimized, especially if the funding is inadequate. The opposite side of the coin is the possibility of a false negative, namely that no adverse effects are occurring when in fact they are. A false negative could result if inappropriate or insensitive monitoring parameters were used. It might also result from the selection of sites that have a higher degree of integrity or are less subject to forces leading to disequilibrium than other sites. In order to avoid both false negatives and false positives, a larger number and a greater variety of sites should be chosen than will ultimately be needed for long-range programs. After a year or two of operations, information redundancy analyses can be made to determine for each specific site which kinds of evidence are good predictors of other kinds of evidence. This reduces the number of parameters examined. Concurrently, the same information redundancy analysis can be carried out among the sites used for monitoring. If there is little or no information redundancy, a careful examination should be made of the parameters chosen and the methodology used. Low information redundancy indicates that each and every site and each and every parameter is furnishing unique information for global environmental monitoring. Additionally, effectiveness of various types of data in decision making should be examined. Those types of evidence not affecting the decision should be eliminated.

Selection of sites should be based on the following criteria: (1) representative types of all major ecosystems, (2) replication of at least a few of the more critical sites (one can determine the site-to-site variability as well as similarities), (3) level of detail necessary with regard to the decision making process. For example, if organisms are being identified to species for diveristy, rarefaction, or other indices, one can carry out analyses to determine whether this level or a higher level of organization (e. g., genus) will make a difference in the decision making process, (4) validation of predictions made on evidence being gathered, for example, a list of changes leading to irreversible damage if no corrective action is taken. Parameters and methodology associated with these changes should be incorporated into the predictive model. If and when these changes occur and corrective action is taken, the effectiveness should be validated by determining if the system returned to a balanced biological community. In all cases, the use of decision analysis should be central to the selection of sites.

Concluding statement

The emergence of global environmental awareness will place a considerable burden on both scientists and engineers to produce a monitoring strategy to provide an early warning of large scale deleterious environmental effects. Reductionist science has produced many appropriate methods for making specific useful measurements, but much more integrative science and engineering will be required in order for the global quality control decision making process to be effective. In addition, scientists and engineers must learn to communicate complex technical information to political/social decision makers so that their decisions will be sound. This is an enormous undertaking unprecedented in the history of science and engineering. Unfortunately, only a decade may remain in which effective global action can be taken. Much more of the energy and resouces of the world's scientific and engineering community must be devoted to this crucial task if global society as we know it is to survive.

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