Biomonitoring:
The Crucial Link Between Natural Systems and Society

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How ironic that, in humankind's quest for sustainability, so little attention is given to the biospheric life support system upon which the human species depends. Since natural systems cannot speak to human society, a continuously operating feedback loop is essential for providing information about a natural system's condition in time to take corrective action when necessary. Investigators must replicate the important cause/effects pathways of natural systems. *Biomonitoring* is surveillance undertaken to ensure that previously established quality control conditions are being met. *Surveillance* is the systematic and orderly gathering of data to determine what is happening, but without a prior commitment to initiate remedial action if quality control conditions do not remain within an acceptable range. In order to take remedial action before severe damage has occurred, sampling must be sufficiently frequent and the results quickly available to provide an early warning of deleterious conditions. Micro- and mesocosms are not miniature ecosystems, but rather systems of lesser complexity that provide useful information on selected ecosystem attributes. Their design, study, and extrapolation to larger, multivariate ecosystems require considerable professional judgment. Properly used, micro- and mesocosms provide evidence for decision making that can prevent or diminish damage to larger natural systems for which they act as surrogates.

Key Words: Ecosystems; Biomonitoring; Sustainability of life forms: Microcosms, Mesocosms.

Introduction

The biospheric life support system, which has produced conditions so favorable to the human species, is essential to sustainable use of the planet. Obviously, monitoring the condition of the 30+ million species that collectively comprise the biospheric life support system is impossible. Clearly, system-level attributes are essential, but, since the entire planet is being used for a global experiment, a problem arises with scale. Microbial communities provide a level of complexity essential to this undertaking with the additional advantage of smaller temporal and spatial scales. Microorganisms should be used in biomonitoring for several compelling reasons. (1) A cosmopolitan distribution facilitates comparisons of test results in geographically different regions. (2) Problems of scale are diminished. (3) Replicability is as good as, or better than, tests with larger organisms. (4) Environmental realism is higher than in tests using larger organisms. (5) The number of test species is dramatically increased when using microorganisms, thus displaying natural variability much better than tests with a limited array of larger organisms. (6) Testing with microorganisms is less likely to antagonize animal rights activists. (7) Validation of laboratory tests in field enclosures is facilitated and much less costly.

Terminology

The following definitions of three quite different activities have all been referred to as monitoring: *sampling* – gathering data at a particular place at a particular point in time; *surveillance* – a systematic and orderly sampling over a significant span of time (at least for one entire seasonal cycle and preferably many more); *monitoring* – surveillance undertaken to ensure that previously established quality control conditions are being met. Naturally, anyone wishing to avoid the responsibility of making a professional judgment will always use the word *monitoring* merely to refer to the activities of sampling or surveillance.

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Biomonitoring is the use of living material to confirm or validate that previously established quality control conditions important to living systems are being met. This idea is not new. Intensive care units in hospitals use heart

rate, blood pressure, respiratory function, and other parameters to assess whether a patient is having a recurrence of a problem. Deviation from pre-established quality control conditions sets off alarms that bring an emergency response team to take corrective action. The same procedure is true of monitoring in nuclear power plants, industrial production lines, airplanes, submarines, spacecraft, and a variety of other situations where quality control conditions are important. Biomonitoring is the environmental counterpart of such control systems that are so important to the quality of human life. Chemical/physical monitoring usually accompanies biomonitoring of the environment because determining the cause of a warning often requires chemical/physical information.

Technological vs Ecosystem Services

Earlier writings on biological monitoring (e.g., Cairns et al., 1970a,b; 1977; Cairns and Dickson, 1973) envisioned an environmental quality control system that would permit use of non-degrading environmental assimilative capacity of societal waste, thereby protecting the integrity of natural systems but simultaneously taking advantage of their services (e.g., Daily and Ellison, 2002). This concept would permit the coexistence of a technological society with natural systems and permit humans to enjoy the benefits of both worlds (Cairns, 1996a,b). In theory, this relationship of keeping technology sufficiently restrained so that it does not imperil natural systems is still possible. However, the outcome is more uncertain than it was when biological and environmental monitoring were in their infancies because of the rapid expansion of technology and the decline of natural systems.

Before the Agricultural Revolution, during the hunter-gatherer period, the life support system for humans was essentially ecological. Since the Agricultural Revolution and, subsequently, the Industrial Revolution, increasing numbers of people have become dependent on technological services to deliver food and energy and to treat waste materials. Catastrophic disruptions, such as earthquakes, hurricanes, floods, and the like, have shown how much even temporary disruptions of technological services can affect the well-being of human society, especially locally. Disruptions in ecosystem services are less obvious when they are incremental or ameliorated by an overlay of technological services. For example, the loss in flood buffering capacity along the Mississippi River is a sorely lost ecosystem service, but is only evident every decade or so when major flooding occurs.

Significant numbers of people believe that technological solutions can be found for any and all environmental problems. However, current estimates of the cost to replace all ecological services by comparable technological services are sobering. Avise (1994) estimated that the cost of replacing ecosystem services by technology and/or managed ecosystems in Biosphere 2 (an experiment in which a large but contained system was inhabited by a few humans and a variety of other species) was a staggering $9US million per person per year. Achieving a balance between the provision of ecosystem and technological services will require both continual information about natural system condition and a willingness of human society to improve and, when necessary, restrain the delivery of technological services in order to prevent unacceptable levels of damage to the delivery of ecosystem services.

Environmental Monitoring for Sustainable Use of the Planet

Developing a monitoring system so that ecosystem services (Table 1) essential to the well-being of human society are maintained is quite a different activity than merely protecting natural systems for their own sake, although both activities are laudable. Acknowledging human society's dependence on ecosystem services and its vulnerability to their failure dramatically changes the perception of human society's relationship with natural systems from user and exploiter of these resources to one of mutual dependence. Unquestionably, human society has the capacity to destroy, within this century, the ecological integrity of most ecosystems as they now exist. Human society also has the capacity to preserve these global ecosystems if given appropriate monitoring information upon which to base decisions and the will to protect ecosystems out of enlightened self-interest. A few illustrative changes in monitoring practices based on this new relationship follow.

(1) Functional attributes will become much more important than they now are because they are more practical endpoints for larger spatial and temporal scales. Structural and functional measurements alternate as one moves up a hierarchical scale, with each function contributing to the structures at the next hierarchical level. Since the scales relevant to various environmental problems are increasing and are becoming farther removed from the intrinsic time

scale of individual human observation, functional measures may be more accessible and increasingly important as structural changes are modeled at a scale inaccessible to individual human observation. Traditional structural attributes commonly used in monitoring efforts (e.g., counting number of species) have been quite effective at the local level. However, ecosystem performance at larger temporal and spatial scales may be more important.

(2) As the scales relevant to environmental problems increase, endpoints characteristic of new levels of ecological organization become increasingly important (e.g., Cairns and Niederlehner, 1996). Populations and species are the customary level at which ecologists and biologists work (e.g., Harte et al., 1992), but landscapes require a new focus (Holl and Cairns, 2003). Considerable doubt exists about the robustness of extrapolations from one level of biological organization to another (e.g., Smith and Cairns, 1993).

(3) As temporal and spatial scales expand, more special interest groups will become involved and, inevitably, real or perceived conflicts of interest will emerge. Integrated environmental management (Cairns et al., 1994) will be essential for identifying such situations before polarization occurs and also for helping resolve the conflicts over the multiple use of finite resources before damage to the resources occurs.

Increasing awareness of human society's vulnerability to failure in either technological or biospheric life support systems is a crucial component of biomonitoring. Just as quality control is essential to the reliable provision of technological services, biomonitoring is the key to quality control for reliable provision of ecological services. Humans generally want the benefits of both ecological and technological systems for their descendants since they, as the current population does, depend on both. Individuals can catch another plane, buy another car, or change their brand of shampoo if they think quality control is lacking, but they cannot change planets, at least not yet.

The Risk-Uncertainty Paradox

Yet another consequence of the increasing scale of environmental problems is an increase in the uncertainty of the predictions of environmental outcome and consequences. Tolerance of scientific uncertainty and tolerance of risk are both proper subjects for debate before decisions are made. However, they are linked — acting with an intolerance of uncertainty often demands a high tolerance for risk. If the consequences are severe, one should be willing to act even in the face of high uncertainty. Impairment of ecosystem services certainly seems to fall in this category.

False Positives and Negatives

Traditional health and industrial monitoring systems produce both false positives and false negatives. In an environmental monitoring context, a false positive is a signal that some deterioration has occurred in the system when, in fact, it has not. A false negative is the absence of a signal when unacceptable changes in quality have occurred. The earlier use of sentinel species yielded false positives if the sentinel species was more sensitive to a particular toxicant than were the other resident species and false negatives for some other toxicant for which the relative sensitivities were reversed. Reductions of errors can be accomplished by a better understanding of the system being monitored and by multiple lines of evidence. Integration of environmental monitoring programs will provide both. In addition, some attempt is being made to re-address the balance between false positive and false negative errors in risk assessments. Traditional scientific approaches control false positives at the expense of additional false negatives; this design may be inappropriate in a risk assessment context (Shrader-Frechette, 1993).

Why Use Microorganisms?

If one were starting biomonitoring de nova, one might reasonably start with the dominant group of organisms on the planet, both in biomass and metabolic activity: the microorganisms. However, the status quo in biomonitoring must be contended with, and this faction has, in the past, been strongly adverse to using microorganisms for a wide variety of reasons, mostly based on inappropriate myths. These myths, which follow, block the extensive use of microorganisms in the field of ecotoxicology.

(1) **Myth: Biomonitoring data using microorganisms are difficult to replicate**. Niederlehner and Cairns (1994) studied microcosm toxicity tests with 12 chemical stresses and found that the relative sensitivity of certain end points was consistent over toxicant type. This research involved a sizable array of species, and changes in species composition did occur at very low levels of chronic stress. End points responding at increasing levels of stress may include declines in species numbers relative to expected numbers, decreased oxygen production, and decreased total production. Other end points were quite sensitive in response to some toxicants but insensitive to others (e.g., autotrophic biomass). In addition, other end points responded unpredictably to stress, showing stimulation under some

conditions and impairment under others. Although no empirical evidence exists, one theory is that a sizable array of species not selected for either tolerance or sensitivity to a particular chemical will exhibit a random distribution that ranges from very sensitive to very tolerant, with the majority of organisms in between. When the number of organisms is adequate to represent the variability of a much larger group of organisms, a consistent response period might well be expected if the majority of organisms were of intermediate sensitivity. Cairns et al. (1985) used artificial substrate microcosm (AS-M) tests to evaluate the effects of many chemical stresses on a variety of community-level end points. Because the biological receptor in the AS-M is a community rather than a single organism, many end points can be monitored beyond reproductive success and other attributes of individuals. These end points, such as loss in diversity, are more similar to those used to judge ecological health in natural systems. The microcosms are more comparable to the complex multivariate ecosystems found in nature than to the single species toxicity tests low in environmental realism, all too commonly used in toxicology. This closer correspondence between the end point measured in the test and the end points of concern in the real world, coupled with sensitivity and variability as good or better than conventional single species tests, results in superior decisiveness (i.e., the ability to make management decisions based on the information collected). If consistency is defined as the degree to which responses to dissimilar stresses will be similar (Cairns et al., 1995), then both structural and functional end points of microorganisms compare favorably with those of single species tests using larger species. For the majority of the world's people, the most important argument for the protection and restoration of natural systems is the protection of the functional services that ecosystems provide to human society (e.g., Wilson, 1988; Ehrlich and Ehrlich, 1991; Cairns, 1997a).

(2) **Myth: Due to their short life cycles and high reproductive rates, long-term biomonitoring using microorganisms is irrelevant**. Microorganisms existed without the larger forms of life for a substantial portion of Earth's history. While robust, empirical evidence indicates that they exist quite well without humans, no comparable database has indicated that humans can exist without microorganisms. In short, humans are dependent upon microorganisms, but the reverse is not true. Humans may consider themselves the dominant species, but this assumption is clearly not the case as determined by numbers, biomass, or even such processes as nutrient and energy processing (combustion of fossil fuels and use of nuclear energy are excluded in this comparison). Short life cycles are beneficial in biomonitoring because studies of even modest duration should cover at least one life cycle of the specimen. The detritus-processing capability of microorganisms and invertebrates alone justifies giving serious attention to their well being, regardless of life cycle length.

(3) **Myth: Using a mixture of species of different sizes and abundance with rapid reproductive rates and short life cycles makes the determination of thresholds extremely difficult**. A tension exists at present in the field of biomonitoring that results from the desire for both replicability and environmental realism. Replicability is almost always achieved by standardization (which means simplification) and controlling all the variables (which masks the dynamic nature of natural systems). As Cairns (1992a) notes, the most commonly used threshold in environmental toxicology is the LC50 (or modifications thereof), where 50% of the organisms die or are otherwise affected at a certain concentration of a chemical for a particular period of exposure under specified environmental conditions. Most commonly, this particular threshold is derived from single species laboratory tests low in environmental realism. If the field of biomonitoring truly examines the effects of chemicals on complex, multivariate ecosystems, serious consideration must be given to thresholds other than those now commonly used in the field of environmental toxicology. Attributes at the community and ecosystem level of organization (e.g., energy flow and nutrient spiraling) are not demonstrated al lower levels of biological organization. Key issues are whether extrapolation is possible from one threshold to another within the same level of biological organization and from one level of biological organization to another for thresholds that do not exist at many levels. Thresholds may, in some instances, be artifacts of testing procedures and may not exist in natural systems. Nevertheless, society must make management decisions about risks with available methods, including those designed to identify some point or threshold below which no deleterious effects are observed. Therefore, the multiplicity of thresholds in multispecies toxicity testing, rather than being a weakness, is an advantage in making management decisions. The field of biomonitoring is in the early stages of a major paradigm shift, driven by three interrelated forces: (a) the consideration of sustainable use of the planet, (b) the protection of ecosystem services (i.e., those ecological functions deemed useful by human society), and (c) the shift from emphasis on producing no deleterious effects to organisms and natural systems to maintaining them in robust health. Clearly, no single threshold, or even a small number of thresholds, is suitable for meeting these three needs.

(4) **Myth: Small organisms are more likely to alter the chemical, even physical, nature of the material being tested, which further impairs replicability**. All organisms, by their presence, alter the environment in which

they live. Persuasive evidence exists that species of fish can alter the composition of the macroinvertebrates lower than they are in the food web and these, in turn, will lower the composition of the microbial community. The illusion of stability resulting from the use of organisms with comparatively long life cycles does increase replicability as a consequence of eliminating most of the dynamics of natural systems. Taken in geological time, everything is in turmoil; the illusion of stability results only from the time perspective of humans. Even then, a moderately careful researcher cannot fail to observe the dynamics of natural systems. What is really at issue here is that the ecological and environmental realism, resulting from the fact that small organisms may quickly alter the chemical/physical nature of the test system, make interpretation difficult for the research investigator. Environmental realism resulting from chemical transformations and other similar activities of microorganisms causes analytical problems for investigators because they resemble natural systems more closely than the highly artificial, single species test systems using vertebrates and macroinvertebrates. The question is: Which most closely resembles natural systems and results in the most reliable decisions?

(5) **Myth: The degree of professional training necessary to use microorganisms exceeds that required to work with large invertebrates and vertebrates**. This idea is really a spurious argument! The basic question is: Are the simple tests carried out by persons with less skill likely to lead to appropriate decisions or is there a strong possibility of making serious errors of judgment? Decisions based on inadequate or inappropriate information can lead to serious deleterious effects on human health and/or the environment, as has happened many times in the past. The type of tests selected should be based on the type of information that is necessary to make a particular decision (e.g., Cairns et al., 1993). Selecting simple, direct, inexpensive "solutions" to problems is a poor way of saving money when the costs of faulty decisions are high!

(6) **Myth: Humans need not be as involved with microorganisms as they are with vertebrates and, even to a considerably lesser degree, with macroinvertebrates**. The issue here is quite simple — if one can get more robust scientific information from microorganism testing than one can get from an organism one would keep as a pet or at least associate with recreationally (e.g., fish), which is the rational choice? In addition, selecting test organisms to which people feel emotional attachments has a distinct disadvantage. Animal rights activists are more likely to picket laboratories using charismatic creatures than those using microorganisms. However, the basic decision should always be based upon the type of testing that will provide the most useful information for making decisions.

(7) **Myth: Human society should not acknowledge its dependence upon microorganisms in natural systems**. Abundant evidence demonstrates the many ways in which human society depends on microorganisms. Nevertheless, acknowledging dependence on such simple creatures is viewed as humiliating to many humans. Humans fear them when they cause diseases, are annoyed by them when they cause food to spoil, and are irritated when they kill other creatures and cause allergic reactions in humans (e.g., the red tide off the US Florida coast), but, somehow, acknowledging dependence on them is repugnant to many members of human society. Until humans do so, however, the choices, even in science, are not likely to be as appropriate as they otherwise would be.

Compelling Reasons for Using Microorganisms in Biomonitoring

(1) **A cosmopolitan distribution facilitates comparisons of test results in geographically different regions**. Although acquiring empirical evidence of cosmopolitan distribution is virtually impossible, circumstantial evidence indicates that this concept is probably correct (e.g., Cairns, 1991, 1993). One of the most compelling bits of circumstantial evidence is that taxonomic keys developed in Europe (e.g., Kahl, 1930) have been used with excellent results in Asia, North and South America, Australia, and Africa. When Professor Shen Yun-Fen of Academia Sciencia, China, visited my laboratory some years ago and examined microorganisms from this region, she had no difficulty recognizing them as morphologically similar, arguably identical, to those found in China, Korea, and Russia. Prygiel et al. (1999) provide much evidence for this correspondence from European rivers. When I participated as a protozoologist on a study of the upper Amazon River in Peru (Patrick et al., 1966), the species found there were morphologically similar to those seen in rivers throughout the United States. The possibility exists that quite different physiological races of these morphological species exist, but, if one uses a community of microorganisms rather than a few species, then problems caused by physiological races would disappear for reasons stated earlier. The disadvantage of using a natural accrual system to obtain protozoans for toxicity testing (mentioned earlier) is that one will almost certainly get a different array of species each time, although the more common species will continue to reappear. However, the particular species present are less important than getting an array of differential responses to toxicants or, more important, a random distribution of such responses, which diminishes very substantially the theoretical problems

involved in using a somewhat different species each time. Evidence cited earlier shows that the consistency is quite high. However, the greatest advantage of the cosmopolitan distribution, namely the facilitation of exchange of research information, is a very strong asset.

(2) **Problems of scale are diminished**. Most microorganisms individually inhabit a relatively small space in natural systems and, although the ones associated with substrates may be swept away and carried long distances by water currents, their home range on a particular substrate is undoubtedly very small. Fish, on the other hand, move over comparatively enormous ranges, and the geographic scale of their home range is generally beyond the capabilities of a laboratory toxicity testing system. Therefore, while spatial scale problems always exist in laboratory systems, they are diminished as a consequence of using microorganisms. Also, because of the comparatively short life cycles of microorganisms, the temporal scale problems are diminished.

(3) **Replicability using microorganisms is a good as or better than for tests with larger organisms**. Replicability was discussed earlier concerning the myth that replicability for toxicity testing involving microorganisms is difficult.

(4) **Environmental realism is higher than is the case for tests using larger organisms**. Clearly, the use of small organisms increases the probability of including a wide variety of ecological niches in a single test container. In some cases where extremely persistent toxic chemicals are used, disposal of the material from a toxicity test must go through hazardous chemical disposal procedures, which are generally quite costly. Use of microorganisms in small-scale tests dramatically decreases the volume of hazardous materials for disposal at the conclusion of the test. Thus, environmental realism increases and, because of the small size of the test systems, physical requirements in the laboratory and costs of disposing of hazardous components of test systems are decreased when the tests have been completed.

(5) **Using microorganisms increases dramatically the number of test species, thus displaying natural variability much better than tests with a limited array of larger organisms**. The advantages of using communities rather than single species have already been discussed. Generally, the range of natural sensitivity or variability in response to a particular toxicant or mixture of toxicants is better displayed than is possible with a single species. Also possible are interactions that are generally excluded from toxicity test systems using larger organisms, such as predator-prey relationships.

(6) **Testing with microorganisms is less likely to antagonize animal rights activists**. Cairns (1998) has noted that compassion for other organisms is often highly targeted, sometimes as a consequence of films such as "Bambi." In the article just cited, the removal of wild horses from the US Bureau of Land Management land, because the horses had exceeded carrying capacity, was used to illustrate this point. Compassion was registered for the fate of the horses, which were sometimes eventually eaten by humans in other countries. Arguably, no compassion was exhibited for the rare and endangered plants and habitat being destroyed because the wild horses had no natural predators and exceeded the carrying capacity of their environment. Targeted compassion generally focuses on charismatic species, such as baby seals, cranes, tigers, pandas, and the like. Even scientists who hold microorganisms in high esteem would not describe them as charismatic in the view of the general public. Therefore, since information is needed about the probable effects of chemicals in the environment before they are actually released and since laboratory tests with microorganisms provide scientifically sound evidence, it seems sensible to use them more extensively than is now done.

(7) **Validation of laboratory tests in a field enclosure is facilitated and much less costly**. Arnegard et al. (1998) developed a small chamber that could be placed in a stream and was capable of holding a microbial community. This design isolated the toxicant from the stream environment in which the unit was placed, but enabled replication of such natural variables as light and temperature. The device was so small that, unlike a large field enclosure, it had no observable effects upon adjacent habitats. Since validation of laboratory tests in field situations is becoming increasingly important and since one hopes to diminish or eliminate any deleterious effects on natural systems while doing this, the size of the field enclosure is obviously of crucial importance. In this regard, microorganisms have a dramatic advantage.

Future Needs

Sustainable Use of the Planet

Earth's human population (e.g., Stanton, 2003) and its artifacts continue to grow while natural systems continue to shrink. Mainstream organizations are now proclaiming that many of human society's present practices are unsustainable (e.g., World Commission on Environment and Development, 1987). Increased recognition continues of the need to monitor global change (e.g., Cairns, 1992b) and to establish goals and conditions for sustainable use of the planet (e.g., Cairns, 1997b). Finally, monitoring is needed to ensure that new practices, thought to be sustainable, actually are (e.g., Cairns, 1997a). Reports occur in the literature on how businesses that are environmentally sensitive can also be the most profitable in the 21st century (e.g., Hawken et al., 1999). If, as some believe (e.g., Collins, 1999), corporations will shape future values, they must become more environmentally sensitive than they now are. Much progress toward this more enlightened state can be achieved merely by eliminating perverse subsidies (e.g., Myers and Kent, 1998). Collectively, these changes constitute a major paradigm shift comparable to the Agricultural and Industrial Revolutions. In order to be relevant, biomonitoring must be consilient with sustainable use of the planet.

Qualified Personnel

All biomonitoring systems require knowledge of the organisms involved. Even at the single species level, a researcher must have knowledge of a considerable array of species to make an appropriate choice. At the community, ecosystem, and landscape levels of biological organization, qualified personnel must be able to identify a substantial array of organisms and be knowledgeable of the ecological niche they occupy. Without such people, even the most robust biomonitoring methods will not function as they should. The primary, arguably only, source of qualified personnel is educational institutions, particularly colleges and universities. Yet, the number of students being taught the fundamentals of systematics and taxonomy has declined dramatically in the last half century, and the number of faculty has declined as well. The number of faculty capable of teaching such courses has reached a dangerously low level, especially in view of the extended time needed to instruct a graduate student in these areas. Biomonitoring methodology has developed at an amazing rate in the last 50 years, but it cannot be used at the necessary global scale with an inadequate number of qualified personnel.

Some biomonitoring systems can be automated, but qualified personnel are still essential to determine what should be measured and how often, as well as to interpret the results. I remain very optimistic about the role of biomonitoring in preserving the integrity of the biospheric life support system, but I am pessimistic (sometimes verging on barely controlled panic) about the paucity of qualified personnel to operate the system effectively.

Biomonitoring Publications

For those using biomonitoring methods that involve kinds of species and number of individuals per species, an adequate number of publications are available, but many are in languages unfamiliar to many potential users. This failing is often an obstacle for research investigators who might reasonably be expected to use taxonomic keys in a foreign language, but cannot. If biomonitoring is to be used on a large scale in all regions of the planet, language is a major obstacle to be overcome. Translations by competent professionals or, better still, books produced by skilled taxonomists in the primary language are badly needed. Professor Shen Yunfen's (1990) book *Modern Biomonitoring Techniques Using Freshwater Microbiota* is a superb example of filling this need for China. It includes 749 species of protozoa with descriptions, figures, and keys. Best of all, the book shows how to use the taxonomic information in a biomonitoring context. However, Professor Shen Yunfen's book is not being used on the scale it should be because of inadequate numbers of competent professionals. This need is not her fault, but rather a worldwide failure to recognize the need for continual monitoring of the health and integrity of the planet's biospheric life support system without which human society could not exist.

Although the need for biomonitoring of changes in community structure requires more qualified personnel and literature in a variety of languages, quite a number of methods have been used successfully for decades. Biomonitoring methods using functional end points are far less numerous as are qualified personnel and literature suitable for routine use by technicians (as opposed to research investigators). Yet, biomonitoring of ecosystem function is essential in the determination of the delivery of ecosystem services, which have tremendous monetary value (e.g., Costanza et al., 1997) and upon which the well-being of human society depends. Ironically, research funding for biomonitoring, which was never robust, now faces the threat of reduction in many parts of the world. Legislators do not appear to understand that research programs cannot be turned on as rapidly as one turns on an electric light — but they can be turned off this rapidly.

Biomonitoring data over large temporal and spatial spans can be used to distinguish normal variability from trends. This knowledge is important as human society approaches crucial thresholds or breakpoints as, for example, in the case for irrigation systems that provide much of the world's food supply (Postel, 1999).

Monitoring Earth's Carrying Capacity for Humans

Cohen (1995) discusses in considerable detail the difficulties of estimating Earth's carrying capacity for humans. Naturally, many uncertainties exist: scientific, cultural, religious, political, demographic, and economic. However, as Cairns (1999) notes, absence of certainty is not synonymous with absence of risk, although people often act as if it were. The best way to confirm the existence of a threshold is to cross it. On a small scale (for example, the effect of a toxicant on individuals), thresholds can be estimated fairly reliably in laboratory tests, especially when the calculations are validated in the field. However, on a global scale, one can only study the components and then model the probable aggregate effects. This design has not proven effective in producing precautionary action thus far for estimates of large-scale problems such as global warming. Vast financial interests are threatened, so one should not be surprised at a large, well-funded, negative publicity campaign. Such publicity is usually quite effective, since the general public is generally too busy with the problems of daily life to reach the level of environmental literacy necessary to evaluate complex, multivariate problems.

As a consequence, it seems likely that the carrying capacity of the planet will be exceeded (e.g., Ehrlich and Ehrlich, 2004; Diamond, 2005), and even then the consequences will not be immediately apparent because the biomonitoring system now in place is inadequate at the global and most regional levels. Robust evidence is not even available on how many species have been driven to extinction in the last century. Many of those nearing extinction have populations too small to be of major ecological significance, although they would be if their population sizes increased. Microbial biomonitoring should be linked to both extinction and recovery of larger species because they are interrelated in many ways. However, to accomplish all this, qualified personnel are essential; the educational system had better respond to this societal need before it is too late!

Table 1
A List of Some Ecosystem Services

Capture of solar energy and conversion into biomass that is used for food, building materials, and fuel
Breakdown of organic wastes, such as sewage, and storage of wastes that cannot be broken down, such as heavy metals
Maintenance of a gas balance in the atmosphere that supports human life; absorption and storage of carbon dioxide and release of oxygen for breathable air
Regeneration of nutrients in forms essential to plant growth (e.g., nitrogen fixation) and movement of those nutrients
Purification of water through decomposition of wastes, regeneration of nutrients, and removal of sediments
Storage of freshwater, retention and slow release of water after rains that provides flood peak reduction, and ground water recharge
Distribution of freshwater through rivers
Generation, maintenance, and binding of agricultural soils
Control of pests by insectivorous birds, bats, insects, and others
Pollination of agricultural crops by birds, insects, bats, and others
Development and archiving a genetic library for development of new foods, drugs, building materials, and waste treatment processes through both Mendelian genetics and bioengineering
Development and archiving a variety of "replacement" species, preventing expected disturbances such as fire, flood, hurricanes, and droughts from disrupting the provision of other ecosystem services
Storm protection through physical dispersal of wind and waves by plants
Control of both microclimate and macroclimate
Recreation and aesthetic satisfaction

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