Interrelationships between the Precautionary Principle, Prediction Strategies, and Sustainable Use of the Planet

John Cairns, Jr.

Department of Biology, Virginia Polytechnic Institute and State University, Blacksburg, Virginia, USA

In this article, I examine the relationships between new concepts of human activity in the environment and several prevention strategies used to plot a course toward sustainable use. Natural capitalism and industrial ecology are relatively new concepts that provide a framework for environmental management. Although the precautionary principle puts into policy a determination to prevent environmental damage before it occurs, natural capitalism and industrial ecology go beyond the prevention of environmental damage to the optimization of environmental interactions. The risk assessment tools necessary for preventive management continue to be essential. However, additional tools are needed to go beyond prevention to optimization. A holistic, scientific approach to the human place within the environment is needed, including both interdisciplinary and large-scale research. ***Key words:*** **environmental management, natural capitalism, precautionary principle, prediction strategies, sustainability.** ***Environ Health Perspect*** **111:877–880 (2003). doi:10.1289/ehp.5871 available via** ***http://dx.doi.org/*** [Online 3 December 2002]

The increased rate and extent of change in both natural systems and human society increase vulnerability to serious environmental "surprises." However, the number of environmental surprises may be significantly reduced by developing a holistic strategy that focuses on aspects of human society's relationship with natural systems. In this commentary I present a series of concepts for sustainability that are almost certainly linked, based on both case history and experimental evidence. Interrelatedness is assumed because the entire planet appears to be functioning as a single system (e.g., National Academy of Engineering 1997; National Research Council 1996; Odum 1989; Youngquist 1997). Ideally, these concepts would be more closely linked, but there is a good explanation for this situation. "Top-down" research, that is, research that is based on the entire system, is not common. "Bottom-up" research, that is, research based on the system components, is very common. This is true for most scientific research, including toxicology. One can make a case for using ecosystem services as toxicologic end points (Cairns 1995). Ecosystem health concepts are useful as management tools (Cairns and Niederlehner 1995). Finally, it should be possible to develop a field of landscape ecotoxicology (Cairns and Niederlehner 1996). These "top-down" approaches should be combined with the "bottom-up" approaches for a holistic view of an entire system at various levels of organization.

A major problem in developing predictive models for complex, multivariate systems is the possibility of discontinuities (a lack of continuity or the appearance of irregularities). System-level monitoring can provide an early warning of a discontinuity if it is well designed. One must assume that the systems being studied are sustainable in order to apply the precautionary principle effectively. This change in focus will involve determining which human practices are unsustainable and requires reexamination of methods of prediction, detection, and tolerance of risk. In this article, I examine the relationships between the reworked concept of humans in the environment and prevention strategies. The precautionary principle puts into policy a determination to prevent environmental damage before it occurs. However, natural capitalism and industrial ecology advocate going beyond prevention of environmental damage to a goal of optimizing environmental systems. Tools to implement these new paradigms include a holistic, scientific approach to the place of humans within the ecosystem, including both interdisciplinary and large-scale research combined with the traditional tools in risk assessment, such as threshold determination and biomonitoring.

Sustainable Use or Sustainable Development

The general aim of sustainability is to optimize use without abuse of the planet's ecologic life support system. In doing so, human society is attempting to provide for the needs of the current and future generations. But it is far from clear that "sustainable use" or even "sustainable development" of the planet can be achieved. Both concepts are homocentric because each envisions perpetual occupation of the planet by one species over all others; the primary objective is perpetuating and improving the lot of humans and not the optimization of the integrity and health of the planet's ecologic life support system and natural capital. In contrast, sustainable use of the planet acknowledges human society's dependence on the planet's ecologic life support system in the form of natural capital and seeks to optimize a harmonious, mutualistic relationship between human society and natural systems (Cairns 1994).

It may be necessary to adopt new paradigms in which balancing the planet's technologic and ecologic life support systems is a primary goal (Cairns 1996). A promising new paradigm is natural capitalism (Hawken et al. 1999). Natural capitalism recognizes the critical interdependency between the production and use of human-made capital and the maintenance and supply of natural capital. The traditional definition of capital is accumulated wealth in the form of investments, factories, and equipment. In fact, human economy requires four types of capital to function properly:

- Human capital, in the form of labor and intelligence, culture, and organization
- Financial capital, consisting of cash, investments, and monetary instruments
- Manufactured capital, including infrastructure, machines, tools, and factories
- Natural capital, made up of natural resources, living systems, and ecosystem services.

Natural capital is the aggregate of all the systems in the biosphere. Natural capital is not only the basis for other forms of capital but also the source of the ecosystem services that constitute the planet's ecologic life support system. At present, humankind's continuing progress is restricted by the decreasing fisheries brood stock, reduced by overfishing. Underground aquifers are being depleted more rapidly than the recharge rate because of the increasing efficiency of pumping technology. All the chainsaws in the world cannot compensate for the disappearance of primary forests, including topical rainforests. These are just a few examples of natural capital. Although natural systems are the source of desired materials, such as wood, water, and fish, they are also important because of the services they provide (e.g., Costanza et al. 1997). A forest provides services such as water storage and flood management. Healthy natural systems automatically supply services such as breathable air, quality water, rainfall, oceanic productivity, topsoil, and waste processing

Address correspondence to J. Cairns, Jr., Department of Biology, 1020 Derring Hall, Perry St.,Virginia Polytechnic Institute and State University, Blacksburg, VA 24061 USA. Telephone: (540) 231-8010. Fax: (540) 231-9307. E-mail: jcairns@vt.edu

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(both natural and anthropogenic). Natural capitalism advocates both protection and accumulation of natural capital; if natural capital is accumulating, less concern about protecting it may be appropriate. Enhancing natural capital forces human society to focus on practices that enhance the integrity of natural systems. One of the expectations of natural capitalism is that cumulative ecologic damage from harvesting natural resources would be markedly reduced.

A concomitant component of natural capitalism is industrial ecology (Tibbs 1992). Industrial ecology recognizes hybrid industrial–ecologic systems. Industrial systems are designed as interlocking artificial ecosystems that interface with natural systems. The human-made and natural systems are managed rather than artificially viewed as separate and minimally related. This change in view encourages changes in industrial processes so that they are more congruent with ecologic processes. All waste products from industrial production are designed to be reintroduced into natural systems as a useful resource to those natural systems, not merely as nontoxic waste. Because this approach requires attention to cycling, it can also serve as an early warning signal when industrial components are not congruent with ecologic processes.

Inherent in both natural capitalism and industrial ecology is the premise that human society will benefit from preventing damage to environmental systems before it occurs. Thus, the tools used in environmental management to predict and prevent damage come into play.

The Precautionary Principle

The precautionary principle focuses on preventing environmental damage before it occurs. The precautionary principle (Raffensperger and Tickner 1999) states,

> When an activity raises threats of harm to human health or the environment, precautionary measures should be taken even if some cause-and-effect relationships are not fully established scientifically.

The principle itself has support from the Third Ministerial Declaration on the North Sea that was signed by various North Sea states (NAVF 1990) and by the United Kingdom (Her Majesty's Government 1990), as well as from the United Nations Rio Declaration (Cameron 1994).

The precautionary principle is a policy statement that the uncertainty inherent in a scientifically based assessment of risk should not negate management action. The precautionary principle becomes particularly important when dealing with problems of large temporal or spatial scales, such as global warming or human population growth, where uncertainties involved in prediction of risk are necessarily high and will remain so even with continuing research. Generally, there is less uncertainty and, consequently, less reliance on the precautionary principle for local, well-characterized risks and the intermediate levels in between.

Although science is viewed as the incontrovertible foundation for making policy decisions, sustainable use of the planet requires a dynamic interaction between science, social ethos, and policy. Environmental science can establish a baseline of the nominative state of natural systems and estimates of the stress caused by toxic chemicals, habitat alterations, climate change, and so forth. From this information, predictive models can be developed. Precautionary measures will clearly depend on accurate information about ecologic thresholds and break points that would cause disequilibrium. This will require effective communication among these three components. However, the societal ethos (or set of values) has not been clearly articulated, and policy making has been confused by claims that the health and ecosystem risks have been exaggerated and that precautions to prevent harm have been exaggerated. Sustainable use of the planet requires that these essential interactions be improved.

Arguably, one of the strongest components of the precautionary principle is the emphasis on a comparative analysis of alternative courses of action. The goal is to determine whether each course of action is technologically and scientifically feasible and, if it is, what benefits and what effects on natural systems and human health and safety are expected. It is not clear where the responsibility for this evaluation should lie. Many believe it is the responsibility of the national governments. For example, in the United States after the 11 September 2001 terrorist attacks, citizens were stunned to learn that the U.S. Federal Aeronautics Administration had never considered the possibility of terrorists using hijacked commercial airplanes in this way. Should the government be held responsible for not anticipating (or preventing) this attack?

There is a strong belief in some quarters that the precautionary principle is hostile to science. However, a large number of these statements appear in publications that are not peer-reviewed. In fact, the precautionary principle requires scientists to develop and improve the methods and procedures for studying complex natural systems, interactions of system components, cumulative effects, and the like. But the effort requires that both integrative and reductionist science (by specialists) ultimately be analyzed by a transdisciplinary group or team. One problem is the willingness of some specialists, government agencies, and industries to declare some chemical or course of action "safe" because the public demands a simple guideline. On the other hand, sustainability requires an understanding of very complex systems and the recognition that science does not fully understand the complexity of the natural world; consequently, there will always be some degree of uncertainty. The precautionary principle was developed as a concept to defragment both science and policy. Jane Lubchenco (1998) (former president of the American Association for the Advancement of Science) stated the problem eloquently:

> The future is quite likely to involve increasing rates of change; greater variance in system parameters; greater uncertainty about responses of complex biological, ecological, social, and political systems; and more surprises.

In contradiction to the precautionary principle, many people believe in a potential technologic solution to every environmental problem. Under this assumption, damage to the environment is acceptable because any resulting scarcity, discomfort, or death will motivate the technologic achievements that will relieve the problem (Myers and Simon 1994). Doubtless, the precautionary principle will not be implemented until there is a general recognition that there is not a technologic solution to every environmental problem caused by technology. In addition, although environmental goals may be multifaceted, it is not mathematically possible to maximize for more than one variable at the same time (von Newmann and Morgenstern 1947). Yet, there is no global agreement on what should be optimized.

The precautionary principle leads to precautionary measures. When the goal is to prevent damage before the fact, active management of the environment is undertaken. These measures can include discharge limitations, restrictions on land use, protection of key ecologic components, or harvesting restrictions. Before any of these management actions take place, a scientific phase must be undertaken in which a risk is assessed. This assessment of risk often involves tools such as the determination of thresholds, application factors, and biomonitoring.

However, prevention of damage is a less ambitious goal than those expressed in natural capitalism and industrial ecology. The goal of optimizing both human-made and natural systems and their myriad interactions goes beyond that of preventing damage.

Prediction Strategies

Interdisciplinary. Tools to implement a management strategy that not only prevents environmental damage before the fact but also optimizes the place of humans in the environment must include a holistic, scientific approach. Such an approach must include both interdisciplinary and large-scale research that is combined with the traditional tools of risk assessment. This will be most effective if prevention opportunities were analyzed at the same time.

The age of specialization and reductionist science has solved many problems but has left society poorly equipped for estimating the outcomes of anthropogenic and natural stress upon both natural and socially complex multivariate systems. Human society places primary responsibility for the generation of knowledge upon its major research universities. However, these institutions may not be ideally structured for this pursuit. An emphasis on disciplines, rather than on issues, isolates individual professionals in a university spatially (housing by discipline), intellectually (different rites of passage for each discipline), and economically (some disciplines are "haves" and others are "have-nots"). One of the primary justifications for these isolating mechanisms is that each discipline has so much information to assimilate, and in many instances requires so much technical skill, that a high degree of specialization is essential to professional survival. Moreover, the best way to achieve professional status is to publish in a limited array of similar, specialized journals using a unique disciplinary language, often described by uncharitable outsiders as jargon. Communicating in a form understandable to the general public is regarded as "soft" science of low quality (Cairns 1993). Arguably, many of the difficulties that interdisciplinary teams experience in achieving a synthesis result less from ignorance of the components of the problem and more from viewing problems too narrowly in order not to lose status in their discipline. The situation is exacerbated when the problem involves both natural and social sciences or any two or more groups with little common ground.

The basic assumption of the holistic, interdisciplinary approach is that, by examining large systems, one assesses attributes not observable in the fragments or components of the system and also gains important insights into which components are "key" and most worthy of detailed study. This method is sometimes referred to as the "top-down" approach. Its counterpart, the "bottom-up" approach, or reductionist strategy, assumes that the more restricted the field of study, the more fundamental it is, and that, by robust understanding of the fundamentals or components, the nature of the system will become evident. The effectiveness of the "bottom-up" strategy is always markedly diminished by variables observable only at the systems level. The "top-down" strategy is often made less effective by reductionist bias and institutional barriers resulting from a disciplinary organization.

The quest for sustainable use of the planet involves enormous spatial and temporal scales; the spatial scale is global, and the temporal scale involves an infinite number of human generations. Although assessing the relationship between human and natural systems is the primary challenge, risk assessment tools are also challenged by such a large scale. An implicit assumption is that whole systems have attributes not held by species or other levels of biologic organization. For example, at the single species level, one cannot study predator/prey relationships, energy flow, or nutrient cycling.

Thresholds. The determination of thresholds is the most basic of risk assessment tools. Thresholds seek to define the degree of stress that biologic systems can tolerate without displaying observable symptoms of harm. In reality, both individuals and ecosystems have numerous thresholds that correspond to their many component structures and functions. It is also true that, in seeking significant thresholds for risk assessment for every potentially important response that is monitored, many more are not examined. Errors of omission and errors of extrapolation occur.

Most known thresholds were established by crossing them in designed experiments, including small-scale laboratory experiments, microcosms, mesocosms, and field enclosures. However, as the spatial and temporal scales increase, the system of interest may be too large for the testing methods available. If the goal is to preserve the integrity or health of a large system (e.g., a landscape or even the biosphere), present methodology is helpful but often indirect.

The hierarchical biologic scale from submolecular to molecular to cell to ecosystem to planet requires that the diagnostic attributes change with each level of biologic organization. Concerns may range from mortality in a population to nutrient export in an ecosystem or disturbance propagation in a region. However, information is often extrapolated from one hierarchical level to another with only the most primitive of models. For example, in a toxicity test with fish exposed to a chemical substance, one often determines the point at which half the organisms expired and half did not. One then multiplies the concentration thus derived by some fraction known as the "application factor" or some similar term to derive a presumably "safe" concentration. A major danger is that single disciplines will focus intently on their area of specialization and "keep the blinders on" to other aspects of environmental issues.

In small-scale, designed experiments, considerable replicability is possible. The same test will yield the same threshold again and again. However, any resulting assessment of risk has considerable uncertainty because of untested assumptions inherent in the extrapolation from the test result to a prediction of harm in the real world. Even a modest extrapolation from a fish lethality test to a prediction of community effects in a river receiving waste would be compromised by the necessarily small number of test specimens used, the inability to include even a small fraction of all conditions under which exposure might occur, and the small number of species tested compared with the large number of species exposed. Each extrapolation from the effect observed to the effect of interest in the larger world engenders errors and uncertainty (Mayer et al. 1987; Mayer and Ellersieck 1986).

The dose response has been a major component of toxicology and was once the crux of predictive strategy in many environmental areas. Most dose–response strategies are developed from single species laboratory toxicity tests with low environmental realism. Replication of single species toxicity tests is common, and usually there is a close correspondence. This is even true for multispecies tests using microcosms, mesocosms, and field enclosures. But these are not miniature ecosystems, but rather one or a few of the multitude of interlocking cause-and-effect pathways that characterize an ecosystem. Because of the complex, dynamic, multivariate systems involved (ecosystems), validation of predictions of effects in natural systems from any laboratory test is problematic. As a consequence, thresholds are to ecosystem studies what the dose response is to laboratory toxicity tests. When a threshold is crossed, disequilibrium conditions usually develop in ecosystems. Thresholds are difficult to determine both in laboratory tests and in ecosystems (Cairns 1992). The dose response is important in estimating where the thresholds are, but not in estimating the ecologic consequences if the threshold is crossed. Holistic science requires the use of both in predictive strategies.

Thresholds may sometimes even be an artifact of the experimental practice (Cairns 1992). Still, the determination of a threshold, despite all the weaknesses and difficulties involved in determining how to use it, does provide a rough index of relative risk that can be used early in planning to include environmental concerns in initial design decisions for any activity related to sustainability. In contrast, the absence of any evidence regarding the location of critical thresholds and break points is analogous to walking blindfolded in the dark near the edge of a cliff.

The analogy has some strengths but is weak in several respects. Most important, because of various lag times or insensitivity of measuring methods and procedures, a critical environmental threshold can be crossed without our being aware of it, at least not immediately. Like the coyote in the roadrunner cartoons, we may run off the cliff and hang in midair long enough to contemplate our fate before plummeting. Second, ecologic thresholds are rarely static because they are altered by a wide variety of cyclic and episodic phenomena. Although ecosystems do not have the homeostatic mechanisms present in humans and many other creatures, which assist in keeping such attributes as temperature or oxygen content of the blood within the nominative state, ecosystems may establish a new threshold rather than returning to the predisturbance condition. Ecosystems are dynamic, and consequently, management goals must be adaptive to be congruent with both normal variability and long-term trends.

Biologic monitoring. Biologic monitoring is intended to provide a feedback loop of information about the integrity and condition of natural systems so that remedial action can be taken when necessary. Biologic monitoring is surveillance undertaken to ensure that previously established quality control conditions are being met. Ideally, biologic monitoring is accompanied by chemical/physical monitoring. When properly designed, biologic monitoring can deliver useful information about the integrity and health of ecosystems (Cairns 2000, 2002; Cairns et al. 1982). Basically, in ecosystem biomonitoring, one is determining that crucial ecologic thresholds have not been crossed. The precautionary principle is intended to prevent a significant ecologic threshold from being crossed. In short, monitoring is both an early warning system for early detection of potential harm to ecosystems and validation (or invalidation) of prediction models. But early warning information has little or no effect without a management system capable of taking immediate corrective action. However, this management group must be literate in both toxicology and ecosystem structure and function. Biomonitoring, properly carried out, protects both natural capital and ecosystem services. Ecosystems provide economically valuable services at no direct cost. Biologic monitoring costs are justified to protect these economically valuable services.

Conclusions

The concept of the "commons" is rooted in the practices of the inhabitants of a group of privately owned houses surrounding an area for common use, but for which no individual is responsible. A simple example is a grazing area capable of supporting 100 head of cattle, so each of 100 families could have one cow without damaging the commons. However, if one family puts a second cow on the commons, they double their own benefits but at the loss (damage to the commons) of all 100 families. The classic paper on this subject is Hardin (1968). For the purpose of this discussion, damage to the global commons will occur if anthropogenic stress (e.g., pollution) reduces both natural capital and ecosystem services. Freedom to use the commons (e.g., the water, air, and land of Earth) must be accompanied by a responsibility to protect them. Thresholds and biologic monitoring are useful, especially when used in conjunction with the precautionary principle. Their effective use requires a clear statement of what human society is attempting to optimize. If sustainable development is the goal, a redefinition of the word "development" is in order. If sustainable use is the goal, it is essential to determine what present uses are unsustainable. Both terms may be too homocentric, that is, give inadequate attention to ethical obligations to life forms other than our own. If the goal is optimization of a mutualistic relationship between human society and natural systems, it is essential to begin discussions on just how this coevolutionary relationship will work. Some of the requirements that would be placed on human society will be unwelcome. As Hardin (2001) noted, tragedy is the price of freedom in the commons. Unless freedom is coupled with responsibility, the tragedy of the commons will continue. However, one of the consequences of acting irresponsibly may be loss of individual freedom, if continuing environmental damage erodes quality of life.

Because most theories are eventually proven to be incorrect, limited to special situations, irrelevant, or inadequate, the quest for sustainability is probably just another transitional stage. Still, emphasis on a harmonious relationship between human society and natural systems appears more useful than merely preventing harm to natural systems. This premise is not intended to denigrate preventative strategies but merely to assert that what worked in the past may not be entirely adequate for the future.

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Appendix

Additional Reading

For those not well acquainted with the literature on sustainable use of the planet (also called sustainability and sustainable development), the following reading list should be helpful.

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