*Humankind must choose science to understand how to care for Earth.*

# The Developing Role of Ecotoxicology in Industrial Ecology and Natural Capitalism

Achieving sustainable use of the planet will require a new paradigm regarding the relationship between human society and the environment and a concomitant paradigm on the responsibility of those now living to provide a quality life for their descendants for an indefinite period of time. Both industrial ecology and natural capitalism provide useful guidelines and case histories on how these two paradigm shifts might be achieved.

The seminal publication on natural capitalism is the book *Natural Capitalism: Creating the Next Industrial Revolution*, by Paul Hawken and Amory and Hunter Lovins (*1*). The authors believe that the traditional definition of capital as "accumulated wealth in the form of investments, factories, and equipment" is inadequate and that an economy should be based on four types of capital to function properly: *a*) human capital, in the form of labor, intelligence, culture, and organization; *b*) financial capital, consisting of cash, investments, and monetary instruments; *c*) manufactured capital, including infrastructure, machines, tools, and factories; and *d*) natural capital, consisting of resources, living systems, and ecosystem services.

Natural capitalism envisions the use of natural systems without abusing them, which is the essence of sustainable use of the planet. I do not use the term "sustainable development" because the word "development" implies growth to most people, and infinite growth on a finite planet is an oxymoron. Sustainable use of the planet requires that the relationship between human society and natural systems be sustainable and that the close relationship between ecosystem health and human health be recognized.

Tibbs (*2*) believes that the view of industrial systems and ecosystems as polar opposites is archaic and that a continuum must develop from the merging of the two systems. The focus in industrial ecology is narrower than in natural capitalism, but the essential idea of the coexistence of industrial and natural ecosystems would encourage the protection and accumulation of natural capital in areas where it is now in danger or unlikely to flourish.

McNeill (*3*) has shown that, in the course of the twentieth century, the human race has undertaken, without intending to do so, a giant and uncontrolled experiment on Earth. Unquestionably, environmental transformations have occurred during the twentieth century on a scale and at a rate that are unprecedented in human history. Ecotoxicologists are well aware that many of the effects of human society on natural systems are nonlinear and that a multiplicity of thresholds and break points exist, most of which only become apparent after they have been crossed. However, societal decisions are usually expressed through public and private institutions, most of which tend to resist change. As a caveat, institutional stability is essential to societal stability, but the rate of change must bear some resemblance to both the temporal and spatial rates of change on the planet. Moreover, the environmental literacy of the general public and of its representatives is totally inadequate to cope with the multidimensional problems that the economic/technologic system is creating. One of the major problems has been identified by Kahn (*4*) and Odum (*5*)—the tyranny of small decisions, which individually seem insignificant but, in the aggregate, can have tremendous consequences. Environmental literacy is an extremely important issue because it is not clear how far global societies (particularly those emphasizing individualism, such as the United States) will agree to modify their personal lifestyles and expectations to conform with the measures necessary to achieve sustainability, including preservation and accumulation of natural capital. In the United States and elsewhere in the world, the conservative opinion rejects any infringements on individual rights and various levels of political sovereignty. The question of individual rights and political sovereignty has been quite evident in the discussions of such issues as global warming at the Kyoto conference and other conferences. An extreme version of this view is that the custody and care of natural systems and a variety of other social issues can be best solved by the marketplace economy. Even when mainstream science accepts a hypothesis, as is the case for global warming, a tiny number of contrarians can stop change because both the media and some politicians believe that until there is unanimity on the subject, no action is justified. Ecotoxicologists can expect this view to continue.

Once 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 (*6*). Arguably, future trends in ecotoxicology will depend on the degree to which the precautionary principle is adopted globally when dealing with toxic substances; at present, there has been more rhetoric than implementation. Nevertheless, this principle is one of the major keys to sustainable use of the planet and is the only viable alternative to the idea of taking no action until some crucial environmental threshold has been crossed with severe consequences to the environment—and often to human health as well. The precautionary principle is also the key to the orderly and systematic development of the field of ecotoxicology. If ecotoxicology is limited primarily to addressing emergencies because the precautionary principle was not implemented, then the field will be expending more time on difficult remedial actions, possibly hindered by long delays in courts of law, rather than on preventative action, which is far less costly in the long run and provides more opportunity for developing fundamental concepts and principles. However, implementing the precautionary principle requires a multidimensional accelerated process of social learning, which must include learning what is needed to cope with the human health and environmental hazards that rapid technologic and economic developments are producing.

Both natural capitalism and industrial ecology involve temporal and spatial scales far greater than those possible in laboratory tests, even with the most elegant microcosms or mesocosms. They also operate in a multidimensional framework far more complex than even the most elaborate microcosms or mesocosms. The best test systems for natural capitalism are probably the industrial/ecologic hybrid systems advocated by Tibbs (*2*). This endorsement does not mean that the test systems presently used by ecotoxicologists are outmoded, but merely that the range of testing must move beyond the laboratory

to the kinds of systems being discussed here. For the industrial/ecologic hybrid systems to provide the most information possible, some carefully planned risks must be taken, and regulatory agencies must be sufficiently flexible to permit this to be done. Further, the information generated by the hybrid system must be available generally and widely shared. Because some ecologic damage is inevitable under these circumstances, ecotoxicologists must be well acquainted with the field of ecologic restoration. Accidents can also be valuable sources of ecotoxicologic information if they are openly and immediately studied by qualified personnel and if a variety of experimental remedial measures are permitted to expand the information base. This concept espouses a new relationship between industry and governmental agencies that is likely to be viewed with distrust by many citizens who may already be suspicious of both groups.

End points characterizing ecosystem health and integrity are not those routinely used by ecotoxicologists, and yet they are central to sustainable use of the planet, delivery of ecosystem services, and all of the components of natural capitalism and industrial ecology. In human health, the absence of symptoms of disease is no longer regarded as evidence of a healthy condition; other measurements involving fitness are now used to assess the health of the body. Robust health and fitness are closely linked whether the ecosystem or the human condition is being assessed. However, a substantial difference exists between the two. Humans have homeostasis: a series of feedback loops and regulating mechanisms keep human attributes, such as respiratory rate, blood pressure, and temperature, within relatively narrow limits. Ecosystems, on the other hand, exhibit homeorhesis—variability within limits, but without the finely tuned feedback loops that are characteristic of individual humans. Furthermore, when humans exceed limits by a marked degree, death or serious impairment of function usually result. These responses are also true for ecosystems, but they may reach a new equilibrium state and not return to the previous state, as humans are capable of doing, up to a point. Thresholds and break points are important for both humans and ecosystems, but they must be interpreted differently.

In the exploratory stages of the development of these new responsibilities for ecotoxicologists, surprises will not be uncommon. Bright (*7*) discusses three types of environmental surprises:

- Discontinuities (abrupt shifts in a trend or previously stable state). The abruptness is not necessarily apparent on a human scale; what is important is the time frame of the processes involved
- Synergism (a change in which several phenomena combine to produce an effect that is greater than would have been expected from adding up individual or separate effects). Ecotoxicologists are quite familiar with this phenomenon at the single species level, but not at higher levels of biological organization, such as communities, ecosystems, or landscapes
- Unnoticed trends (an unnoticed trend, even if it produces no discontinuities or synergisms, may still do a surprising amount of damage before it is discovered).

As a consequence, there is a high probability, almost a certainty, that one or more crucial environmental thresholds will be crossed, even if the precautionary principle is implemented to a much greater degree than it is now. Therefore, ecotoxicologists should be prepared to take remedial ecologic restoration measures promptly when it is apparent that a threshold has been crossed, while simultaneously gathering evidence that will enable monitoring activities in the future to provide more effective early warning signals when this particular threshold is being approached. Ecosystems, like humans, have a certain amount of resilience or ability to recover from disequilibrium situations. The promptness of both the detection of the early warning signals and the remedial responses will reduce the severity of the consequences and the time of recovery as well.

Ecotoxicology has always been a multidimensional field. One of the major advances was combining the fields of environmental toxicology and environmental chemistry (*8*). A number of protocols have been recommended for determining at which level of detail the information base is adequate for both environmental toxicology and environmental chemistry in order to reduce uncertainty to a point where a persuasive decision can be made. The level of detail needed is an extremely important issue for ecotoxicologists, especially in the transitional stages of becoming effective participants in both natural capitalism and industrial ecology. With limited numbers and resources and a multitude of toxicants to deal with, it is necessary that the level of detail be appropriate for the particular problem being addressed, that is, ecotoxicologists must be prepared to reduce uncertainty to the point where a rational decision with minimal, but not zero, risk can be made. Ecotoxicologists must avoid the temptation to demonstrate their professional skills by measuring everything they know how to measure in the finest detail possible. If ecotoxicologists misjudge the level of measurement needed, then some problems, including some very crucial ones, will be neglected while a high level of detail is produced that may be unnecessary for the decision being made. Arriving at the appropriate level of detail is a particularly difficult decision in the United States, where attorneys abound in a very litigious society. Opposition attorneys make every attempt to characterize any level but the finest level of detail possible as professional incompetence, negligence, or laziness. Some law suits have required environmental scientists to make every possible measurement, even though the measurements were unnecessary in the professional judgment of the scientist for reasons described above.

For ecotoxicologists and other environmental professionals to function properly in the areas of natural capitalism and industrial ecology, it is probable that science courts will be developed where highly trained professionals can pass judgments on the adequacy and suitability of the evidence base and the rationale for decisions and judgments being made. These judgments are now handled inadequately in courts of law where the knowledge of legal matters is high, but there is little knowledge about matters of science and probabilistic determinations requiring scientific evidence. Almost every country has the equivalent of the United States National Academies of Science and Engineering and the National Research Council, which is the operating arm of these two academies in the United States. Such organizations could determine how science and engineering courts would be structured and staffed. They would also serve, for science and engineering, as the equivalent of the Supreme Court in the United States, which is the ultimate arbitrator of legal decisions. In short, they would be the ultimate final court of appeal for determining the adequacy of probabilistic evidence in science and engineering.

Such endeavors require much time and resources, and divert both scientists and engineers from what they regard as their primary responsibilities. However, if this new responsibility is not accepted, complex multidimensional scientific and engineering problems will be judged by those with inadequate literacy in these highly scientific and technical fields.

Given the urgency and the dimensions of these problems, it is not excessive to ask professional scientists and engineers to donate 10% of their professional time to help resolve these issues, which otherwise will not be resolved in ways satisfactory to them. There will undoubtedly be a widespread, deeply felt protest from people already working at what they judge to be the limits of their capacity. However, many scientific professionals are already spending huge amounts of time in courts of law, reaching solutions that are not satisfactory from a scientific or engineering point of view. Because natural capitalism and industrial ecology are social contracts, just as legislation is a social contract, there is no reason why courts of science and engineering should not be financially supported in the

same fashion as courts of law. This financial support is going to be difficult to obtain in an era of increased distrust of science as well as an increased distrust of the ways in which courts of justice work. Respect for both areas will require a vastly increased level of literacy in the general public regarding these problems. An increased level of literacy is the responsibility not only of the educational system but of television, radio, newspapers, magazines, and other media. The Internet provides a splendid opportunity for increasing literacy and for disseminating information on case histories of the implementation of both natural capitalism and industrial ecology in various areas of the world. Ecotoxicologists must, therefore, become much more accustomed to functioning adequately in this multimedia situation and in communicating as effectively with the general public as they do with their colleagues who already have a higher literacy in ecotoxicology. These changes require major paradigm shifts for which ecotoxicologists and their colleagues in other branches of science and engineering are not fully prepared. Yet, if natural capitalism and industrial ecology are to function, science courts are inevitable, although the exact form that the courts of science and engineering will take and the precise role of ecotoxicologists in these courts will doubtless develop over time. However, the necessity for these paradigm shifts is abundantly clear, and the time to make a decision to do them is almost certain to occur early in the twenty-first century. Those who are prepared for these shifts will, as usual, benefit most when they occur.

If sustainable use of the planet is to be achieved, both natural capitalism and industrial ecology or some variants of these two interrelated concepts must be adopted. However glorious the achievements in these two areas, human society will not know for many generations whether sustainable use of the planet has been achieved or exactly how natural capitalism and industrial ecology should be implemented. In fact, I have developed a series of speculative scenarios about sustainable use of the planet (*9*), only one of which is pleasant to contemplate. Numerous books describe why human society ignores serious environmental problems (*10*). Basically, the problems are the result of enormous numbers of personal decisions that individually seem small, but collectively are creating seemingly intractable problems. Ironically, perceptions of how to improve the personal lives of humans mask the fact that their collective well-being requires coordination of efforts and a societal ethos or guiding system of values different from the present. Technology has so benefitted individual lives that humans now believe (or act as if they believe) that there is a technologic solution to every problem or that economics combined with technology will provide the solution. Seidel (*10*) believes that failure to react to planet-imperiling circumstances does not lie in not knowing what is wrong or not knowing what to do about it, but rather in the failure to take this knowledge seriously enough to act on it. This belief is supported by the well-documented recounting of the ecologic collapse of ancient civilizations (*11,12*). It will seem strange to ecotoxicologists that their efforts, data, and predictions will be used in a societal context that is embedded in an environmental ethos or set of guiding beliefs because many are uncomfortable with the mixture of science and values (*13*). Thus, it is a view of balancing the perceived needs of human society with the needs of the biosphere and recognizing that the biospheric life support system is essential to humanity—humankind must choose science to understand how to care for Earth and establish a set of guiding values to apply the knowledge. I have spent over a half century in the field now known as ecotoxicology, and I am delighted to have lived long enough to see, if only dimly, the probable future path for the field and the wonderful opportunities for those who will carry on its exciting research.

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## References and Notes

1. Hawken P, Lovins A, Lovins H. Natural Capitalism: Creating the Next Industrial Revolution. New York:Little, Brown, & Co., 1999.
2. Tibbs HBC. Industrial ecology: an environmental agenda for industry. Whole Earth Rev 77:4–19 (1992).
3. McNeill JR. Something New Under the Sun: An Environmental History of the Twentieth-Century World. New York:WW Norton and Co, 2000.
4. Kahn AE. The tyranny of small decisions: market failures, imperfections, and the limits of economics. Kylos 19:23–47 (1966).
5. Odum WE. Environmental degradation and the tyranny of small decisions. BioScience 32(9):728–729 (1982).
6. Raffensperger C, Tickner JA. Protecting Public Health and the Environment: Implementing the Precautionary Principle. Washington, DC:Island Press, 1999.
7. Bright C. Anticipating environmental "surprise." In: State of the World 2000 (Brown LR, Flavin C, French H, eds). New York:WW Norton and Co, 2000;22–38.
8. Cairns J Jr, Dickson KL, Maki AW, eds. Estimating the Hazard of Chemical Substances to Aquatic Life. STP657. Philadelphia, PA:American Society for Testing and Materials, 1978.
9. Cairns J Jr. Unpublished data.
10. Seidel P. Invisible Walls: Why We Ignore the Damage We Inflict on the Planet – and Ourselves. New York:Prometheus Books, 1998.
11. Diamond J. The ecological collapse of ancient civilization: the golden age that never was. Bull Am Acad Arts Sci XLVII(5):37–59 (1994).
12. Diamond J. Paradises lost. Discover 18(11):68–78 (1997).
13. Suzuki D, McConnell D. The Sacred Balance: Rediscovering Our Place in Nature. New York:Prometheus Books, 1998.