Money stones on one of the Yap islands.

The Biosphere and the Sustainability Coalition

by David F. Ludwig and Timothy J. Iannuzzi

Weapons were not the only products of the nuclear and thermonuclear bomb programs of World War II and the Cold War. Ironically, the entire field of systems ecology, which merged tool kits of biology and engineering, was an important, if serendipitous, outcome.

We owe the inheritors of our world our best and hardest work as we prepare to hand things over to them.

From a technical perspective, specific radioactive materials entered the environment during the development and deployment of atomic weapons. These compounds acted as *radiotracers*—they could be tracked from environmental media to organisms and back again. Known half-lives and biochemical behaviors allowed quantification of biological processes that were intractable until that time. This allowed biologists to step back from organisms, populations of organisms, and communities of populations and view the biological hierarchy as a coherent, functional system. The term *ecosystem*, coined in the 1930s, referred to the relationships of organisms and their physical and chemical environments.[1] By the 1950s, however, it was clear that there was a meaningful hierarchy of patterns and processes in the living world (subcellular organelles, cells, individual organisms, populations, communities, biomes) analogous to that in the physical/chemical world and that *ecosystems* had broader meaning and many more dimensions than initially thought. Brothers Eugene P. and Howard T. Odum published a most important book that illustrated the workings of ecological systems.[2]

Rachel Carson (1907-64) wrote *Silent Spring*, showing that human behavior, well-being, and economics were integral components of ecosystems.

The Roots of Systems Ecology

The realization that ecosystems had an underlying reality that could be applied to understanding the living world brought debate among ecologists. Until the Odum's book was published, *ecologists* were specialized in subfields—animal or plant ecologists, limnologists (fresh water) or marine biologists, herpetologists (reptiles and amphibians) or mammalogists. Ecologists were suddenly thrown into a world where deconstructing biology into its component parts was inadequate experimental design. Tools were needed to evaluate whole systems—ecosystems—as functional interactive systems. Those tools were fortuitously becoming available as an outcome of nuclear weapons programs.

A key was the understanding that the laws of physics applied not just generally to living systems, but they applied very specifically and could be used to quantify relationships among the components of living systems at any scale. Until this time, the science of ecology was conducted primarily by counting. How many organisms of what species are present in what spatial area of a certain habitat? As habitats change with time[3], how do the numbers of species change? Which species drop out of the counts; which ones appear? Through the 1940s, botanists and zoologists who *did* ecology did it by enumeration.[4]

In the new world of systems ecology, we added calorimetry—measurement of energy content—to our toolbox. By accounting for the thermodynamic laws, we could now track the flux of energy through the ecosystem, from the sun to plants to herbivores to carnivores. Now we could understand, as one author put it, "why big fierce animals are rare."[5] In large part it is because energy transfer is inefficient. To get from plants to large carnivores, roughly 50-to-90 percent of the energy present at each level in the food web is lost to the level above. Physics constrains biology in fundamental ways.

When ecologists turned their attention to whole systems, exploring the transformations of radioactive tracers, they realized that there was another aspect of biological patterns and processes *missing* from their interpretations. This was the human element. By the 1960s, it was becoming clear that human beings affected and were affected by ecosystem interactions. A most familiar example was published by Rachel Carson in 1961—*Silent Spring*. It built on the methodologies developed by systems ecologists, but it traced the pesticide DDT (and related molecules) through ecosystems and warned of potential effects of widescale and long-term applications. The book was important, not only because of its innovative application of ecosystems thinking. Carson's work (in this and other books[6]) showed that human behavior, well-being, and economics were integral components of ecosystems. This came as something of a shock to reductionist scientists just learning to deal with whole systems outcomes.

Interdisciplinary Origins

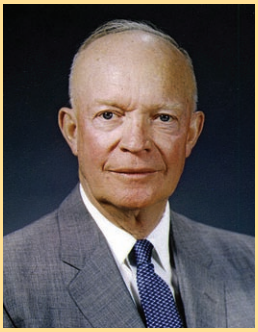
We should have seen it coming. The word *ecology* comes to us from the Greek *oikos*—meaning house, after the

Indo-European *weik*—with implications of clan, village, and vicinity. *Logia* is from the Greek via German—*study*. The word *economy* is from the same root *oikos*, with *nomos*—management, via Indo-European *nem*—to assign or allot.[7] In effect, ecology and economics are closely related concepts, the former the study of and the latter the management of, the *oikos*—the biosphere.

Some ecologists (the Odum brothers, their students, and colleagues were among the leaders) understood the importance of humans, economic beings, in the living world where money and its flux and transformation were otherwise meaningless. Attempts were made, and are still being made, to understand outcomes of the *nomos* for the *logos* of the system.[8] But it has proven difficult to find tools that allow us to understand quantitatively what we can see plainly qualitatively—that money changes things.

Why might this be? After all, systems ecology can account for the quantitative effect on, say, energy flow, of the information content of an ecosystem. For example, systems with a lot of biological information—very diverse ecosystems—have energy-flux profiles that differ from those with less information—say, agronomic monocultures. But we have not had the same success in understanding money in this context.

Part of the problem is that it is difficult for non-economists to understand what money actually IS.[9] In our classes, we illustrate this conundrum via the *money stones* of the Yap Archipelago in the Pacific. On these tiny islands are a number of large, heavy stones, cut into various sizes of rock *donuts*. This stone is not available on Yap. The quarries are on other islands far to the west. Somehow, using ocean-going canoes, the Yapese cut these stones and transported them over hundreds of miles of open water (when I teach this, I can't help but muse over how many stones—and canoes and canoe crews—were lost in process) and placed them in prominent public spaces on the main island. These stones became a form of currency. A rather abstract form, for sure. On Yap, you might own a portion of a money stone. Say, you own a quarter radius of one of the stones. There are no marks on the stone to indicate who owns what, it is common knowledge. Now you need a dowry for a daughter's long-planned wedding. You can bargain a segment of your segment, or your entire segment, as payment for the food, drink, and other festivities and another portion for the dowry itself. If you serve chicken, the farmer who provides the chickens takes ownership of an appropriate-sized piece of your piece, of the stone—and can use that piece, in turn, to purchase more chicks to raise.



President Dwight D. Eisenhower, warned of the dangers of a military industrial complex.

But here's the thing. These stones are big and heavy. You don't move one just because you own some or all of it. It stays where it is, and knowing who owns how much of which stone or stones is part of the culture. Notice that no energy is transformed or transferred in money stone transactions. You simply own a piece of stone, and you can pay someone with your piece of stone, which they will now own.

Yet the transaction—the payment-for-purchase—has a large impact on the ecosystem. You've purchased a flock of chickens. These chickens are cooked and served, so the farmer needs more chicks, and he needs food and water for the new flock, plus a place to recycle or dispose of wastes. Compiling those things alters the environment in response to money changing hands. Except it never actually *changes hands*. It just sits there, same place, new owner.

This strikes us odd. In our transactions, *something* changes hands. Cash, a check, a credit card, or a credit card number. So there is some flux of matter and energy in non-money-stone transactions, although it has clearly been reduced in recent years with the advancement of electronic transfers over paper transactions.[10] But the energy content of a credit-card transaction, while non-zero, is nonetheless very low relative to the ecological outcome of the economic activity—and certainly not proportional. The amount of energy that goes into producing, circulating, and spending $1,000 to purchase, say, a case of very high-end Bordeaux red wine is a result and cause of massive environmental changes. The vine pruning, fertilizing, weed control, disease control, harvest, and production of the wine from pressing the fruit through bottling and sale take an enormous amount of energy in many forms: diesel-tractor fuel, basketry from harvested reeds, the calories people expend in harvest and production, and the metals and polymer parts of the pressing and fermentation infrastructure. That $1,000 generates big environmental changes.

Did we mention engineering? Much of what links economic processes to environmental outcomes is engineering. In our example, you will need engineers to design, build, and maintain the presses and vats, the conformation of the vineyard land, irrigation systems, and the vehicles that get the wines to market and that haul fertilizers and fungicides. In this model, engineering enables economics to be linked to ecology with direct affects on the ecosystem. And thus it is a crucial aspect, a focal point, of human interaction with the environment. So, for much of our interface with the rest of the world, it is a loose collaboration of engineers, economists, and ecologists who design, produce, operate, and manage things.

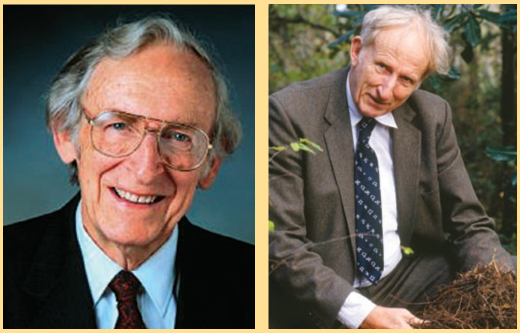
Ike's Insight

But things have not been and are not so loosely linked in some contexts. In January 1961, Dwight D. Eisenhower used his last presidential address to warn of the consequences of a *Military-Industrial Complex* that he believed had risen in the U.S. in the wake of World War II.[11] From the perspective of holistic systems analysis, the MIC itself is an example of a self-organizing hierarchical open system. Inputs to the MIC include needs specifications and purchase orders (technical engineering information), money (economic information), and labor and materials (human and natural resources). The MIC infrastructure churns money, materials, and information into product outputs. By having components of the

MIC system itself flow both to and from the larger matrix of society in the form of personnel, strategic policy, tactical developments, the MIC helps assure that its environment is favorable for its own stability and growth.

Self-Organization is a Key

Self-organization and environmental modification are key properties of successful biological systems. True ecosystems exist at many temporal and spatial scales. There is a tendency to think of *ecosystem* as landscape-level phenomena, but any organized system with a *skin* or *membrane* recognizably constraining internal vs. external processes can be thought of as an ecosystem. In the heyday of systems ecology, roughly the 1960s through 1980s, endless beer-and-pizza debates were devoted to ecosystem definitions and scale, similar to (and as productive as) Renaissance theological debates about angels fitting on heads of pins. What emerged from graduate-school indigestion, though, was a useful and practical definition. An ecosystem was self-organized inside a recognizable membrane such that processes occurring inside and outside the membrane were more active than processes operating through the membrane. And the most successful ecosystems monitored their own immediate environs and modified it when necessary and when possible by sending signals of matter, energy, and information across the membrane into the larger world.[12]



Brothers **Eugene,** left, and **Howard Odum** published a book that illustrated the workings of ecological systems.

Careful parsing of the previous paragraph suggests that the ability of a system to modify its own environment is a real key to persistence. Bacteria, both pathogens and free-living forms, are masters at this. Microbial films are formed by cellular exudates, which link the cells to the substrate, and which develop over time, becoming more functionally active and complex. The self-organized bacterial cells in turn organize their environment in favorable ways, maximizing the stability and persistence of the whole system.[13]

At this point, it is obvious that organisms possessing technology and engineering, and with matter and energy surpluses that can be converted to environmental investment (that is, economics), should be most able to modify their matrix and persist. A few animals act as environmental engineers—beavers build dams and winter housing, and mole-rats create spectacular specialized tunnel systems and harvest their food sustainably.[14] Some ants and termites create massive infrastructure, and harvester or leaf-cutter ants operate complex and persistent agricultural systems.[15]

Technology Rules

But nobody does it like we humans do. Our awesome technological abilities, highly-developed economies, and ability to anticipate and plan for the future have taken us well over the threshold of environmental modification —a process that began very early in our history. The entire biosphere is now under our control, whether we like it or not.[16] To date, beginning in the Pleistocene Epoch, we have managed the biosphere by default[17]—which has led us, in general, to trouble. "Awesome technological abilities" applied without careful, comprehensive, and adaptive planning are not a recipe for success. Nor, however, are they a recipe for disaster.

Some definitions may be helpful now. In one sense, we can simply define successful environmental management as the persistence of human beings in the biosphere. But this is not a very satisfying or useful definition. After all, humans can survive in very difficult environments. If we say that persistence is one element we need to consider, but that quality-of-life or habitat quality is similarly important, we start to see where we need to go. The goal is not survival alone. It is survival at a reasonable standard of quality. We can call this broader standard of success *sustainability*. A sustainable biosphere allows humans not only to survive, but to prosper. This is indeed a more difficult objective for our species. But it is imperative if we are to leave our children and their children and generations to come with a world worth inhabiting.

We have, in fact, made considerable headway in not only preserving the future of human life, but maintaining a reasonable level of environmental quality. In the developed world, environmental regulations analogous to the U.S. Clean Air Act, Clean Water Act, Comprehensive Environmental Responsibility, Cleanup, and Liability Act, and Resource Conservation and Recovery Act have substantively improved the quality of our collective habitat. International regulations such as the United Nations Compensation Commission and the Migratory Bird Treaty have helped us advance further. Even in the developing world, where the standard of success is of necessity weighted to survival and persistence as the first priority, environmental quality is generally improving. We have made enormous strides in sustainability since the 1950s.[18]

To some extent, we've hit a wall in our ongoing efforts to improve and maintain a sustainable biosphere. We focused enormous effort and infrastructure on reducing and controlling environmental releases of toxic industrial chemicals. This made considerable sense, as Rachel Carson told us in 1961. However, in the process of controlling such chemicals, the environmental management system that we built, incorporating regulators, policymakers, planners, scientists, environmental and civil engineers, and enforcement specialists, has taken on its own life and forward momentum. We continue to pursue and *manage* industrial chemicals in the biosphere despite having largely solved that particular problem. The *team* of regulators *et al.* has largely done its

job. This is not to say there are not still chemical threats to the environment. There are many, and they are more intense in the developing world. However, on a relative scale, as a society, we have generally succeeded in managing industrial chemicals.

And, while we were accomplishing that worthy objective, we found ourselves as a society more interested, in recent decades, in other levels in the biological hierarchy than the ecosystem. Biotechnology and nanotechnology have largely taken pride-of-place at the interface of humankind and the biosphere. To a degree, the field of *systems ecology* doesn't exist any longer as a free-standing discipline. Funding, both commercial and public research money, flows to biotech and nanotech investigators. The interdisciplinary nature of systems ecology, one of its strengths, has lost its reason-for-being as we've found it more profitable and interesting to merge chemistry, physics, engineering, and biology at the molecular scale rather than the landscape. But the fact that we've taken our eyes off the ecosystem ball doesn't mean the game is won.

The Legacy: Our Kid's World

The environmental problems that we are handing to our children and theirs are no longer primarily those of uncontrolled chemical releases. Our successes in that arena have let other issues emerge and gain importance. Potable water, nutrient (fertilizer) pollutants, biodiversity, habitat quantity and quality, safe and sufficient food, soil quality and quantity, and an array of potential impacts associated with climate change (including the spread of disease organisms for humans and domesticated animals and plants) are the real issues now. But the teams we built to manage chemical pollution are having a tough time coming to grips with these shifting priorities. The process of managing toxic chemicals is basically (in an abstract *best case*) one of science-driven regulation and subsequent enforcement. That model may be insufficient for the immediate future of the biosphere.

For example, consider the city of Calcutta (or Kolkata), India. In the 1800s, municipal waste was deposited on the eastern boundary of the urban area. Over time, people learned to sort the garbage to recover recyclables, compost organic materials, and farm vegetables on what was (and is) essentially a landfill. In the first half of the 20th century, sewage and surface water (stormflow) were combined and outfalls run to the east of the city. Vegetable farmers took advantage of the water supply to supplement field fertility, and a proportion of the water was run into a sequence of aquaculture ponds. Pond effluent is used for downgradient paddy farming and also taken back to the upgradient vegetable gardens. This tightly integrated and highly effective recycling system has been producing substantive quantities of fish and vegetables for decades. The produce is sold in wholesale markets within the 12,000 hectare area serving the operation, and also in the city itself. All is sold fresh, within hours of harvest.

The Calcutta Waste Wetlands ecosystem was formed, developed, and maintained by combined cultures of the people-in-place. It is not a legislated, protected, or subsidized special operations zone (although it was recently protected as a United Nations RAMSAR site). Land ownership has varied with time, and for a period absentee speculators purchased and combined much of the area, but apparently it has more recently been returned to largely smallholders. The local cooperation among farmers, aquaculturists, economists, engineers, entrepreneurs, scientists, and technologists is maintained only informally. In other words, the *team* that solved the coupled problems of solid and liquid waste management for the enormous city of Calcutta came together of its own will and successfully addressed many issues where more formal interdisciplinary management efforts have failed.[19]

This is not to say there aren't ongoing problems and issues of safety, public health, economic fairness, efficiency, and others arising daily. Such issues are constant, and among them is the ever-present pressure on the land from urban expansion, along with the fact that only a portion of the total wastewater flow from the city is used in the waste-wetlands system, the remainder being released as raw combined sewer flow to the estuary. The important lessons of the Calcutta system are in the collective nature of the problem-solving effort and the on-the-ground accomplishments of flexible and adaptable interdisciplinary webs of relationships.

The latter is a particularly important point if we think back to where we started this essay. The Manhattan Project was an unprecedented and rigorously formal collaboration among physicists, chemists, and engineers involving government, academic institutions, and commercial corporations. The importance of the private sector grew between the World Wars, and it was natural at the start of WW II in the U.S. to include companies as integral to the weapons design and production efforts. Academia provided much of the intellect, and government provided the impetus and the muscle to get the job done, partly in the form of investment and partly via military necessity.

The far-less-formal collaborations that developed and operate the Calcutta Wastewater Wetlands system are similarly multidisciplinary. One reason that success has not repeated itself may well be that it is unique. The informality of the process means it was truly spontaneous, so that *managing* to produce such a cooperative enterprise is a major challenge.

Perhaps we need to leverage the best aspects of the formal—Manhattan Project—and informal—Calcutta—models of interdisciplinary collaboration. The emerging environmental problems, those that we are leaving for our kids to deal with, are inherently complex. Solving those

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problems will require innovation and action across scales of hierarchy and among many technical disciplines. Our experience as investigators of complex urbanized ecosystems demonstrates that scientists, engineers, and economists can cooperate successfully.[20] It shows that stakeholders across a spectrum of interests—the private sector, government, academia, and consulting enterprises—can join to get things done that would be impossible for any one or two sectors to handle alone. If we are going to manage our environment by design and not by default, and at the large scale and small reflecting the range of our impact, it is important that we innovate and collaborate. Effective interdisciplinary collaboration, as demonstrated by both the Manhattan Project and the Calcutta Wastewater Wetlands, can yield even more effective innovation. There is no *code* needed.

We are talking about the Sustainable Biosphere Project, in a matrix where scientists bring the data, engineers bring the actions, and economists bring investments, and the table that all this is heaped on is occupied by regulators, industrial experts, academics, and consultants. We owe the inheritors of our world our best and hardest work as we prepare to hand things over to them.

Notes

1. Arthur Tansley is generally credited with the concept and the word, in Tansley, 1935, "The Use and Abuse of Vegetational Concepts and Terms," *Ecology* 16:284-307.

2. E.P. and H.T. Odum, 1953, *Fundamentals of Ecology*. The Odum's concept of holistic ecology was greatly supported by Lindemann, R.L., 1942, "The Trophic-Dynamic Aspect of Ecology," *Ecology* 23:399-418.

3. The process of change-over-time is known as ecological succession, where one recognizable habitat replaces another in sequential, orderly fashion unless the system trajectory is upset or re-set by outside influences (such as human development). The processes of succession continue after such impacts, but the pathway is changed.

4. This is a gross over-simplification of the then state-of-the-science of ecology, but, in concept, is not far off. E.g., some evolutionary ecologists studied changes in organisms with habitat changes. Even that exercise involved enumeration; as in "how many fin spines does fish species A have in habitat B vs. habitat C"?

5. Colinveaux, P. 1979. *Why Big Fierce Animals are Rare*. Princeton University Press.

6. Among other works, Carson published *The Sea Around Us* and *The Edge of the Sea*, both emphasizing her perspectives on human interactions with the biosphere. See *www.rachelcarson.org*.

7. The etymology is from *The American Heritage Dictionary of the English Language*, third edition, 1992, Houghton Mifflin Company.

8. An excellent and innovative introduction to this and other ideas is Vermeij, G.J. 2004. *Nature: An Economic History*. Princeton University Press.

9. Economists are also far down the learning curve, but their field has terminology and grammar allowing it to sound like it knows what's going on. Whether that understanding is reflected in the understanding of functions in the *real world* remains an open question.

10. The money stones are now more of tourist thing, but some retain ceremonial transfer of wealth via money-stone apportioning.

11. There are many sources providing video, text, and analyses of Eisenhower's speech. An interesting perspective is available at *www.sourcewatch.org/index.php?title=military-industrial_complex*, which cites the film *Why We Fight* as a source.

12. Much theoretical ecology literature is devoted to this subject. Most interesting are Conrad, M. 1983, *Adaptability: the Significance of Variability from Molecule to Ecosystem*, Plenum Press, NY; and Higashi, M. and T.P. Burns (eds) 1991, *Theoretical Studies of Ecosystems: the Network Perspective*, Cambridge University Press, Cambridge.

13. See Page, W.J. and W.G. Martin, 1978. "Survival of microbial films in the microwave oven." *Can. J. Microbiol.* 24:141-143.

14. Many sources available. Nowak, R.M. and J.L. Paradiso 1983, *Walker's Mammals of the World*, Johns Hopkins University Press (4th edition] is complete and accessible to nonspecialists.

15. Referring to Gordon, D. 1999, *Ants at Work: How an Insect Society is Organized*, The Free Press, NY; and Helldobler, B. and E.O. Wilson 2009 *The Superorganism: The Beauty, Elegance, and Strangeness of Insect Societies*, W.W. Norton & Company, NY.

16. Environmental groups, some academics, and policy shops believe that "you can't fool with Mother Nature" and "Nature is in charge"; e.g., *www.greenpeace.org/international*. But we have fooled with nature, which is no longer solely in charge, even if she retains some of the threads of power. The fact of climate change alone should be sufficient to quell this argument, although it has yet to do so.

17. While there remain holdouts for a more *politically correct* view that human beings were not primarily responsible for the Pleistocene extinction of numerous species of mammals and birds in the Americas, Australia, and New Zealand, the evidence is in fact overwhelming, see *Twilight of the Mammoths: Ice Age Extinctions and the Rewilding of America* by Paul S. Martin, University of California Press 2005.

18. Our belief in improving environmental quality is not shared universally. Many non-governmental organizations, policy shops, and individuals have a deep stake in environmental pessimism or optimism and make little allowance for evidence from the alternative perspective. Reliable sources summarizing the state of the environment with a little more objectivity are McNeill, J.R. 2000, *Something New Under the Sun*, W.W. Norton & Company, NY; and Goudie, A. 2000, *The Human Impact on the Natural Environment*, MIT Press, Cambridge, MA. Expositions of the state-of-the-environment can be found in Lomborg, B. 2010, *Cool It: The Skeptical Environmentalist's Guide to Global Warming*, Vintage Books, NY; and Friel 2010, *The Lomborg Deception: Setting the Record Straight About Global Warming*, Yale University Press, New Haven. Our work reconstructing the environmental history of the urbanized Passaic River, NJ, provides detailed documentation of the environmental degradation, improvement, and still-to-do of a specific ecosystem and has been expanded to include other urban rivers. Entry to these can be gained via recent articles and books: Ludwig, D.F. and T.J. Iannuzzi, 2005, "Incremental ecological exposure risks from contaminated sediments in an urban estuarine river," *Integrated Environmental Assessment and Management* 1:374-390; Iannuzzi, T.J. and D.F. Ludwig, "An interdisciplinary investigation of ecological history and environmental restoration objectives in an urban landscape," *Ecol. Restoration* 23:157-165; Iannuzzi, T.J., D.F. Ludwig, J.C. Kinnell, J.M. Wallin, W.H. Desvousges, and R.W. Dunford 2002, *A Common Tragedy: History of an Urban Waterway*. Amherst Scientific Publishers, Amherst, MA.

19. The Calcutta Wastewater Wetlands is evolving and adapting, but is not well documented in formal technical literature. The best approach to learning about this is to conduct your own web searches. Portals worth seeing include: *www.ecotippingpoints.org/our-stories/indepth/india-calcutta-wetland-wastewater-agriculture-fishpond.html* and *www.indiawaterportal.org/node/442*. An economic model of the system is: Bunting, S.W. 2007, "Confronting the realities of wastewater aquaculture in urban Kolkata with bioeconomic modeling," *Water Research* 41:499-505. A widely cited general review is: Ghosh, D. 1988. "Wastewater-Fed Aquaculture in the Wetlands of Calcutta–an Overview. Tomado de: Wastewater-Fed Aquaculture," *Proceedings of the International Seminar on Wastewater Reclamation and Reuse for Aquaculture*, Calcutta, India, 6-9 December 1988.

20. An economist who has a radical and innovative vision for environmental management is Jack M. Hollander. His 2004 book *The Real Environmental Crisis: Why Poverty, not Affluence, is the Environment's Number One Enemy*, University of California Press, should be read by everyone interested in a sustainable future.