SCALE, AWARENESS, AND CONSCIENCE: THE MORAL TERRAIN OF ECOLOGICAL VULNERABILITY

Robert H. Socolow

PU/CEES Report No. 303

Updated January 1999

Center for Energy and Environmental Studies
Princeton University
Princeton, NJ 08544
socolow@princeton.edu

Based on a talk delivered in the series: "Bioethics and Public Policy"
Institute for Social and Policy Studies
Yale University, New Haven, CN
January 18, 1996

A chapter in *Perspectives in Bioethics*
Arthur Galston, editor
to be published by Yale University Press in 1999

Abstract

Prosperity is stressing the environment. This interaction can be illuminated by separating out aggregate size (*scale*), available science (*awareness*), and the obligation to respond (*conscience*). Solutions require an evolving vision of the good life, a sustained commitment to open science, and a style of management of the Earth that is both active and reverent.

The three-dimensionality of ecological vulnerability

Ecological vulnerability is a big new idea, far more prominent on the intellectual landscape now than thirty years ago. At the core of the idea is the observation that our exuberant species is transforming the Earth's natural systems. Examples are both regional and global. Regional impacts include depleted fisheries and unhealthy urban air. Global impacts include less ozone in the stratosphere, a more acidic surface ocean, and higher atmospheric concentrations of carbon dioxide, methane, and several other greenhouse gases.

Ecological vulnerability is a permanent, if not yet familiar feature of the human condition, a new element of the human tragedy. Why has it become a prominent concern late in the twentieth century? There are three contributing factors:

1. The magnitudes of our effects (scale)

2. Our capacity to understand these effects (awareness)

3. The obligation we feel to respond to these effects (conscience)

These three factors are the three dimensions of ecological vulnerability. The salience of ecological vulnerability in our time – its substantiality, its obtrusive presence – is the consequence of the maturing of contemporary reality along all three of these dimensions. We humans are confronting a new world, where our prosperity, our awareness of the consequences of our prosperity, and our determination to address these consequences have all risen above some threshold of significance at approximately the same time.

The three-dimensionality of ecological vulnerability provides helpful coordinates for exploring its moral terrain.

Two-dimensional variants

One can easily imagine worlds where only two of the three dimensions of ecological vulnerability have matured, and one is nearly absent. It is instructive to identify each of these worlds.

2&3, but not 1: Awareness and conscience have matured, but not scale. Such an imaginary planet is much larger than ours, with the result that, in all instances, the impacts on environmental systems resulting from the actions of its human population are dwarfed by the impacts of natural processes. The relationship between cumulative human impact and natural capacity resembles what was once found (say, in the eighteenth century) on Earth. On the imaginary planet, however, environmental science is as well developed as ours today, capable of measuring and modeling both natural systems in the absence of human activity and the impacts of human activity on natural systems. And the moral sensibilities of the citizens are finely honed.

Accordingly, people in this imaginary world struggle to find appropriate ways to express their concern for future generations, frustrated that their science is telling them their efforts will make hardly any difference. Wishing the message to be false, they spend their time carefully documenting the minutiae of human activity. They are punctilious in the observance of ecological correctness. Theirs is a world of fetishism and misplaced angst.

People in our world sometimes assert that this imaginary world properly describes life on Earth today. They insist that our human society is still too puny to overwhelm nature. For example, in spite of abundant evidence to the contrary, they are captivated by arguments that the depletion of the stratospheric ozone layer is the result of gases coming from volcanoes; in their model of reality, the causative agent cannot possibly be industrial chlorofluorocarbons.

1&3, but not 2: Scale and conscience have matured, but not awareness. In this second imaginary world, impacts are indeed substantial, and people are morally sensitive about imposing risks on others. But there is no science available to guide action, and, as a result, people in this imaginary world fly blind. Resembling this imaginary world, perhaps, was our planet in the years of the Black Death in the fourteenth century, when bubonic plague was spreading relentlessly, and there was little understanding of infectious disease.

People in our world sometimes assert that this second imaginary world properly describes life on Earth today. They focus on the deficiencies in our environmentally relevant science, rather than on our prowess. At every juncture, their preference is for delay. They emphasize that we are not yet in full command of the facts and that if we wait until we have more information, we will find better ways out of trouble.

1&2, but not 3: Scale and awareness have matured, but not conscience. In this third of our three imaginary worlds, effects of human action are large and understood to be large, but attention is elsewhere. Of concern is only the present day: *après nous le déluge*. Ethics are tribal. Crises arise, preventive action has not been taken, and damage is high. Many suffer, the weak especially.

People in our world usually do not assert that this imaginary world describes life on Earth. No one wants to concede that we are inadequately endowed with conscience. But many argue that our obligations to future generations are minimal, relative to our obligations to those closest to us today, including ourselves. Their priorities resemble the priorities in the third imaginary world.

We are not strangers in any of these worlds. Our behavior is often more appropriate for one of these worlds than for our own. Each is a convenient refuge from reality.

An example: Human impacts on the nitrogen cycle

One finds examples of ecological vulnerability almost everywhere today. Again and again, a productive line of inquiry is to ask how some particular natural system works and what effects human activity is having upon it. One finds, consistently, that at least some effects are large, that the significance of these effects is partially (but not fully) understood, and that actions designed to reduce these effects are ethically complex.

Such a pattern of answers is found today when one inquires about the natural cycles of many, if not most, of the elements in the periodic table. Consider the nitrogen cycle. In the overall global nitrogen cycle, there are two subcycles: a fixing-unfixing subcycle and a fixed-nitrogen cycle. In the fixing-unfixing subcycle, certain species of "nitrogen-fixing" bacteria change atmospheric nitrogen (N_2) into forms usable by plants (simple single-nitrogen molecules, called "nutrients"); simultaneously, other, "denitrifying" (in effect, unfixing) bacteria return the nitrogen to the atmosphere by rebuilding N_2 from nitrogen nutrients. In the fixed-nitrogen cycle, fixed nitrogen passes through many fixed chemical forms: nutrients are taken up by living plants and animals, while simultaneously the nitrogen in plants and animals, usually long after their death, is returned to nutrient forms through decomposition. Once within the fixed-nitrogen subcycle, a nitrogen atom cycles back and forth between nutrient and plant matter many times before it is recycled to the atmosphere through the fixing-unfixing subcycle [Ayres, Schlesinger, and Socolow 1994, Kinzig and Socolow 1994].

Inspecting the ancient air archived in ice cores in the glaciers in the Arctic and the Antarctic, scientists can infer that between two thousand years ago and as recently as fifty years ago the overall nitrogen cycle was in approximate equilibrium. In particular, through the fixing-unfixing cycle, nitrogen-fixing bacteria transformed atmospheric nitrogen into nitrogen nutrient at a rate of between 100 and 200 million metric tons of nitrogen per year (100-200 Mt(N)/yr), and denitrifying bacteria transformed nitrogen in nutrients back to atmosphere nitrogen at approximately the same rate.

Human activity is currently doubling the previous rate of nitrogen fixation. The largest contributor is nitrogen fertilizer production, which begins with the production of ammonia from atmospheric nitrogen. Driven by the Green Revolution, global nitrogen fertilizer production has grown more than six-fold in the past 35 years: from 13 Mt(N)/yr in 1961 to 87 Mt(N)/yr in 1996 [International Fertilizer Industry Association 1998]. The two other large contributors to anthropogenic nitrogen fixation are deliberate planting of nitrogen-fixing crops, such as soybean and alfalfa (roughly, 40 Mt(N)/yr), and high-temperature combustion in engines and boilers (roughly, 30 Mt(N)/yr) [Galloway 1998].

The *scale* of human impact on a natural phenomenon can be measured as a fraction, with an effect in the absence of human activity in the denominator and the incremental effect of human activity in the numerator. When the fraction captures an important environmental concern, and the value of the fraction is close to unity (1.0) or larger, it is reasonable to call the effect "large." Thus, human impact on the nitrogen cycle, measured by fixed-nitrogen production, meets the test of large scale.

What about *awareness*? Both medicine and environmental science contribute insights into the damage caused by the build-up of fixed nitrogen in water and air [Socolow 1999]. An excess of fixed nitrogen can contaminate drinking water and can contribute to unhealthy air; it can also intensify acid deposition, eutrophication, stratospheric ozone depletion, and the greenhouse effect. Cumulative impact, in most cases, will depend on whether denitrifying bacteria keep pace with incremental nitrogen fixation, thereby preventing a relentless build-up of regional and global stocks of fixed nitrogen. Assuming that a continuous build-up of fixed nitrogen does occur, perhaps the most troublesome long-term impact may be the disruption of ecological balance in unmanaged natural areas, as indiscriminate fertilization brings about differential responses across species, diminishing biodiversity and degrading ecosystem services [Tilman 1982, Schlesinger 1994, Vitousek 1994, Vitousek et al. 1997]. Because air and water can transport excess fixed nitrogen large distances, sites of inadvertent fertilization will often be far from the sites of deliberate fertilization for agriculture.

What about *conscience*? The environmental costs of excess fixed-nitrogen are a challenge to moral reasoning. The Green Revolution's high-yield agriculture has permitted global food production nearly to keep pace with global population growth over the past three decades. Because nitrogen fertilizer has made possible these high yields, it is sometimes regarded as a gift from the gods. Idolizing a technology or physical resource, however, is never wise. Nitrogen fertilizer is just a commodity, much of it used to meet the food preferences of the prosperous.

After absorbing the messages of scale, awareness, and conscience, people must act. One goal is "precision agriculture," which fine-tunes timing and quantity of fertilizer application. Other goals include improving the management of crop residues, reintegrating grain agriculture and animal husbandry, and reducing waste in food transport and storage. Targeted subsidies can address the needs of the poor, and market mechanisms such as trading in fixed-nitrogen emissions at various spatial scales can help identify high-payoff environmental investments (Socolow 1999).

The analysis above of the fixed-nitrogen issue is prototypical. Considerations of scale, awareness, and conscience triangulate every environmental issue. For the remainder of this essay we examine how scale, awareness, and conscience, separately, illuminate aspects of environmental ethics.

The ethical content of the dimension of scale

Consider, first, *the ethical content of scale*. It is here that we encounter judgments about consumption.

The scale of environmental impact is directly related to the level of consumption measured in physical (but often not economic) units. When consumption is viewed in physical terms, it is associated with flows of materials: their extraction from below ground, from water, or from the air; their chemical and physical transformation; and their return to the environment, generally in altered form.

A physical view of consumption does not penetrate to the core of the phenomenon. Working inward, the next layer of analysis probes why a particular desired human benefit involves particular resource impacts (why lighting is provided by certain lightbulbs, why visiting a friend is accomplished with a particular vehicle); the analysis probes choices among available technologies.

At a still deeper level one asks why particular benefits are desired. Here, one encounters territory that is surprisingly little explored. Identifying the consumption activities that are environmentally significant (travel by vehicle, for example) has been a far more active area of research than probing the determinants of consumption (why travel is desired) [United Nations Secretariat 1997, Stern et al. 1997].

The dominant model of the determinants of consumption is the ladder. The ladder has a sequence of rungs. Those on each rung have an income somewhat lower than the income on the rung above. With the passage of time, a household with rising income will climb the rungs, adopting the consumption patterns of each higher rung in turn. The driver of consumption, by this model, is emulation. Such a ladder model has been confirmed in studies of fuel choice for cooking, for example. With increasing income in many developing countries, cooking fuel changes, predictably, from firewood to charcoal to liquid petroleum gas to natural gas and electricity [Sathaye and Tyler 1991].

Even the most simplified ladder model does not presume that the per capita environmental impact of consumption simply increases as the ladder is climbed. Environmental damage from the consumption of the very poor often exceeds environmental damage from consumption a few rungs above. Accelerated slash-and-burn agriculture that does not give the land time to recover, cooking with wood on an open fire, discharging untreated wastes into rivers that become sewers – these are some well-known examples of poverty's resource-intensiveness, its disproportionate impact on the environment. Higher up the ladder, however, environmental impact increases with income.

Population size enters the ladder model only as a multiplicative factor, and thus tends to disappear from view. Yet population size is obviously critical to impacts due to scale. And population size has direct impacts on individual expenditures that a multiplicative model cannot capture. Strains produced by total number of people engender expenditures on pollution control, congestion-related expenditures, and expenditures to obtain privacy [Cohen 1995; Kates 1997, Bloom and Williamson 1997].

The ladder model, in its most elementary form, presumes that there is just one ladder and that the ladder has no branches. From the nomad to the sheik there is a single ascent. From the urban slum dweller to the denizen of a suburban estate there is also a single ascent. The model of an unbranched ladder is gaining support today, as an increasingly large fraction of the world's population assents to a single concept of the good life. For shorthand, call this concept "Western." The good life is equated with the maximization of experiences. It is marked by an emphasis on self-realization, a zest for activity, a search for comfort and autonomy, and an accumulation of goods. Travel prevails over sitting still, and cars over buses.

For much of history, civilizations, especially in Asia, defined the good life differently. Self-examination, inner peace, subordination of desire – all were advocated effectively. Serious people once questioned whether the "undeveloped" countries, including those in Asia, could develop along Western lines, or even wished to. In the recent past, however, "undeveloped" was replaced by "underdeveloped," or "less developed," or "developing." There are no separate categories for "conventionally developing" and "unconventionally developing." The issue is settled. Apart from a few special cases where traditional alternatives are still being explored, the western ideal of the good life is unchallenged globally today. Development is no longer a matter of "whether," nor of "how," but only of "when."

People wish to use the ladder model to discern the environmental consequences of future consumption. A ladder model with static preferences at every rung predicts that aggregate environmental damage from human consumption will increase, once the dominant ascent on the ladder is not from very poor to poor but from poor to what is loosely called "middle class." An amended ladder model that takes into account the effects on preferences of technological change provides a more ambiguous forecast, because, in many instances, the direction of technological change is toward reduced environmental damage per unit of consumption. As a result, greater environmental damage in not an inevitable accompaniment to increased global economic well-being. Nonetheless, there are ample grounds for concern that the planet's environment may be significantly degraded, even with technologies designed to reduce environmental impacts, if ten billion people reach today's higher rungs.

In addition to technological change, there will be changes in values. The ladder model at its most simplistic locates these changes only on the highest rung, where there is no one to emulate. What is judged desirable by the most privileged people is endowed with glamour a few rungs below and is copied in each successive generation by ever larger numbers of people. The long-term environmental consequences of the American heavy automobile are highlighted by such a model.

In fact, value change originates at every rung of income or social status. It is not decreed from the top. The decisions to spend substantial private and public resources to clean the air and water and to protect land from development have been broadly based consumption decisions. Even more broadly based has been the world-wide decision to have fewer children. Future regional and even global average fertility rates below replacement level begin to be credible. When such rates persist, total population does not stay on a plateau after reaching its peak (as embedded in all orthodox projections), but decreases indefinitely. In decisions about pollution, land, and child-bearing one can discern an adaptive feedback that may substantially transform the environmental prospect.

The ladder model has a tight grip on today's visions of the future. Accordingly, it needs careful testing. Especially worthwhile are explorations of its key assumption that consumer choice is dominated by emulation of the choices made on the rungs immediately above. It is also critical to gain insight into how consumption patterns evolve to reflect evolving values. From an environmental perspective, several trends are promising [Kempton, Boster, and Hartley 1995, Daly 1996].

The ethical content of the dimension of awareness

Consider, next, *the ethical content of awareness*. It is here that we encounter judgments about science and technology. There are two imperatives: 1) to enhance those portions of the scientific enterprise likely to illuminate critical environmental issues, and 2) to strengthen the norms of science in arenas of controversy.

Wherein is the moral imperative to enhance those portions of the scientific enterprise likely to illuminate critical environmental issues? It arises from our obligation to preserve the capacity of future generations to enjoy experiences that they value as much as we enjoy what we value. Such a formulation was made explicit in the report of a United Nations commission, *Our Common Future*, popularly known as the Brundtland Report, after Gro Harlem Brundtland, the commission's chairman: "Humanity has the ability to make development sustainable – to ensure that it meets the needs of the present without compromising the ability of future generations to meet their own needs." [World Commission on Environment and Development 1987, p.8].

To achieve such an objective, each generation must provide the next generation with new capabilities in order to compensate for bequeathing to the next generation a natural environment more degraded than the one it inherited. Such degradation will not be universal, but it is likely to be pervasive. The Earth's largest and purest or highest-grade (lowest entropy) oilfields, fresh-water aquifers, and mineral deposits are likely to disappear, for example, so that future generations will have to make do with only the Earth's next lowest entropy resources. Where geology threatens to impoverish, the intergenerational accounts can be balanced by scientific understanding, new instruments and devices, and more subtle and effective policies. An obligation to provide future generations with enhanced capabilities is easier to defend than an obligation to preserve every particular experience available today [Solow 1991]. To be sure, we retain specific responsibilities for unique features of our natural, aesthetic, and historical legacy. And we have obligations toward species other than ourselves.

Enhanced capabilities require the vigorous pursuit of what the late Donald Stokes, in *Pasteur's Quadrant*, calls "use-inspired basic research" [Stokes 1997], research that both addresses practical concerns (here, environmental compatibility) and searches for generalizable principles. Two subjects of contemporary use-inspired basic research are ecosystem services and industrial ecology. Ecosystem services are the benefits human beings gain from natural ecosystems, ranging from cleansing the air and water to enabling such finely tuned processes as pollination. Research on ecosystems is focusing, for example, on the relationship between alteration of the species composition of an ecosystem and degradation of its service functions [Daily 1997].

Industrial ecology focuses on how the industrial system is embedded in the natural environment [Socolow et al. 1994; Graedel and Allenby 1994, Ayres and Simonis 1994, Frosch 1997]. Firms and networks of firms are stage center. Flows of materials through the economy are visualized as rearrangements of the stuff we find on or close to the surface of the Earth [Socolow 1994]. Research in industrial ecology focuses, for example, on the recycling and scrap industries (which "close loops," extending the time materials spend within the industrial system), and on patterns of ownership involving lease rather than sale. Among the systems recently studied are lead [Socolow and Thomas 1997], wood products [Wernick, Waggoner, and Ausubel 1998], metals [Wernick and Themelis 1998], and nitrogen [Socolow 1999].

As important as deepening the pursuit of use-inspired basic research is strengthening the norms of science in arenas of controversy. Science gains its strength from 1) the methodology of trial and error, 2) the tradition of open access to results, and 3) the presumption of international collaboration.

The methodology of trial and error strengthens science by not condemning failure. Research is pursued along parallel tracks, with the expectation that many tracks will later be abandoned. It has been said that in order to know the truth, it is necessary to imagine a thousand falsehoods. Deciding which research areas to pursue more deeply and which approaches to replicate widely is an iterative process, informed by the evaluation of each completed experiment.

The tradition of open access to results strengthens science by providing a mechanism for peer review, replication, error detection, and the transfer of knowledge from one application to another. Further, open access is the engine of democratization. It encourages debate and the formation of consensus. Open access permits media involvement, at its best fostering a comprehending and properly skeptical public.

The presumption of international collaboration strengthens science by permitting any scientist or engineer to address any problem, irrespective of where the individual works and where the problem is particularly pressing. Problems judged to have the greatest prestige or market interest gain broad-based international attention. Unfortunately, these are usually not the most pressing environmental problems.

The ethical content of the dimension of conscience

Consider, finally, *the ethical content of conscience*. It is here that we encounter judgments about deliberate action.

Two kinds of deliberate action are often distinguished: mitigation and adaptation. Mitigation is preventative; it is designed to reduce the magnitudes of expected effects or their rate of onset. Mitigation includes both "first-generation" end-of-pipe pollution control and, increasingly, "next generation" clean processes that embed ecological concerns [Chertow and Esty 1997]. Adaptation is designed to reduce the consequences of the expected effects after they arrive. Adopting energy efficient technology is mitigation, building dikes is adaptation. Some actions are part one and part the other: planting a forest may both sequester atmospheric carbon (mitigation) and reduce the hydrological and ecological impacts of future climate change (adaptation).

The ethicist may ask whom mitigation or adaptation is intended to benefit. Investments addressing ecological vulnerability can be compared with other self-interested investments on behalf of the next one or two generations, such as investments in education. It is not easy to assess whether, within and across nations, a particular package of mitigation and adaptation investments is progressive or regressive. The beneficiaries are likely to include both those whose basic needs are at risk and those who have a large financial stake. A mitigation program to slow the rise in sea level helps both the millions of poor people who live in the floodplain of the Ganges in Bangladesh and those with million-dollar homes at a beach.

Investments on behalf even of the poorest members of a future generation can be regressive, relative to investments on behalf of today's poor [Schelling 1992]. Targeted investments on behalf of today's poor are morally compelling. A world is within reach where the entire population is adequately fed, has access to safe drinking water, and is free of many infectious diseases. The greater the success in providing basic human needs for today's people, the more compelling the case for addressing the ecological vulnerability of future generations.

A mitigation program can be judged by whether it can proceed in small steps that permit incremental learning, and by whether there is room for turning back. Such judgments are particularly germane to "Earth systems engineering" proposals, which are global in scope [Keith and Dowlatabadi 1992, Allenby 1998]. An example is the proposal to continue the use of fossil fuels while "sequestering" the resultant carbon dioxide so that it does not enter the atmosphere, thereby slowing the rate of climate change. Fossil fuel is chemically processed into hydrogen fuel and byproduct carbon dioxide, and the carbon dioxide is piped into deep aquifers or the deep ocean. The merits of this proposal are being widely discussed [Herzog 1997, Hileman 1997, Socolow 1997, Parson and Keith 1998].

The processes by which Earth systems engineering proposals are evaluated require legitimation. Some cures are worse than the disease. And some cures will work. There are many parallels with the engineering of the genome. Who will guard the guardians? And who will protect us from guardians of the guardians who see their task as avoiding every potentially slippery slope, thereby annulling the spirit of experimentation, so critical to our future?

Finally, how can the spirit of experimentation be reconciled with reverence? We are changing the Earth too much and too quickly to be able to defend doing nothing [Dyson 1975]. But the Earth is sacred. It needs not only our stewardship, but our love.

Toward more persuasive prophesy

The prophets of ecological vulnerability would like to be as persuasive as their contemporaries (often the same people) who preach the need to prevent nuclear war. Nuclear prophets articulate the terrible costs of wrong action, and they are believed. Ecological prophets use a similar vocabulary. But their foresight is doubted. Their message is resisted.

The difference is not only that ecological prophets have arrived more recently on the scene. (After all, the message of the nuclear prophets was resisted too, for several decades.) The difference is also the consequence of the greater incompleteness of ecological prophesy.

Help can come from all three of the dimensions of ecological vulnerability. If the scale of human impact can grow less quickly, as a result of first-round interventions like a global climate agreement, valuable time will become available. That time can be used to improve awareness: targeted experiments in science, technology and policy can clarify the more and less serious environmental threats and the more and less promising responses. And, in that same time, our consciences can be more fully engaged in understanding what is required to manage the Earth actively, yet with reverence.

ACKNOWLEDGEMENT

The invitations of Arthur Galston, the editor of this volume, to speak in his lecture series and to write for this volume build upon a relationship that began almost thirty years ago. At that time I was searching for ways to bring my disciplinary background in pure physics to bear on the relatively unstructured problems in environmental studies. He was one of the few senior professors at Yale (where I was an Assistant Professor) who said it could be done. He was one of an even smaller number who said it *should* be done. I gave it a try, and I am still at it. I am hugely in Arthur's debt for his encouragement and vision.

REFERENCES

Allenby, Braden, 1998. "The role of industrial ecology in an engineered world." To be published in *Journal of Industrial Ecology*, MIT Press.

Ayres, Robert, William Schlesinger, and Robert Socolow, 1994. "Human impacts on the carbon and nitrogen cycles." In *Industrial Ecology and Global Change*, R. Socolow, C. Andrews, F. Berkhout, and V. Thomas, eds. Cambridge, UK: Cambridge University Press. pp. 121-155.

Ayres, Robert, and Udo Simonis, eds., 1994. *Industrial Metabolism: Restructuring for Sustainable Development.* Tokyo: United Nations University Press.

Bloom, David, and Jeffrey Williamson, 1997. "Demographic transitions and economic miracles in emerging Asia." *National Bureau of Economic Research Working Paper 6268.* Cambridge, MA: National Bureau of Economic Research.

Chertow, Marian, and Daniel Esty, eds., 1997. *Thinking Ecologically: The Next Generation of Environmental Policy.* New Haven, CT: Yale University Press.

Cohen, Joel, 1995. *How Many People Can the Earth Support?* New York: Norton & Co.

Daily, Gretchen, ed., 1997. *Nature's Services: Societal Dependence on Natural Ecosystems.* Washington, D.C.: Island Press.

Daly, Herman, 1996. *Beyond Growth.* Boston, MA: Beacon Press.

Dyson, Freeman, 197. "The hidden cost of saying, No!" *Bulletin of the Atomic Scientists*, June 1975, 23-27.

Frosch, Robert, 1997. "Toward the end of waste: Reflections on a new ecology of industry." In *Technological Trajectories and the Human Environment*, Jesse Ausubel and Dale Langford, eds. Washington, D.C.: National Academy Press, pp.157-167.

Galloway, James, 1998. "The global nitrogen cycle: changes and consequences." *Environmental Pollution*, in press.

Graedel, Thomas, and Braden Allenby, 1994. *Industrial Ecology.* Upper Saddle River, NJ: Prentice Hall.

Herzog, H.J., ed., 1997. Proceedings of the Third International Conference on Carbon Dioxide Removal, Cambridge, MA, 9-11 September 1996, *Energy Conversion and Management*, Vol. 38, Suppl., 689 pp.

Hileman, Bette, 1997. "Fossil Fuels in a Greenhouse World." *Chemical and Engineering News*, 75:34-37, August 18, 1997.

International Fertilizer Industry Association, 1998. Webpage at http://www.fertilizer.org.

Kates, Robert, 1997. "Population, technology, and the human environment: A thread through time." In *Technological Trajectories and the Human Environment*, Jesse Ausubel and Dale Langford, eds. Washington, D.C.: National Academy Press, pp. 33-55.

Keith, David W., and Hadi Dowlatabadi, 1992. "A serious look at geoengineering." *Eos* 73(27), 289-296.

Kempton, Willett, James Boster, and Jennifer Hartley, 1995. *Environmental Values in American Culture.*

Cambridge, MA: MIT Press.

Kinzig, Ann, and Robert Socolow, 1994. "Human impacts on the nitrogen cycle." *Physics Today* 24(11):24-31.

Parson, E.A., and D.W. Keith, 1998. "Fossil fuels without CO_2 emissions" *Science*, Vol 282, No 5391, 6 November 1998, pp. 1053-1054.

Sathaye, Jayant, and Stephen Tyler, 1991. "Transitions in household energy use in urban China, India, the Philippines, Thailand, and Hong Kong." *Annual Review of Energy and the Environment, 1991*, 16:295-335.

Schelling, Thomas, 1992, "Some economics of global warming." *American Economic Review*, May 1992. Reprinted in *Economics of the Environment: Selected Readings.*, 3rd edition, Robert Dorfman and Nancy S. Dorfman, eds. New York: Norton & Co.,1993, pp. 464-483.

Schlesinger, W.H., 1994. "The vulnerability of biotic diversity." In *Industrial Ecology and Global Change*, R. Socolow, C. Andrews, F. Berkhout, and V. Thomas, eds. Cambridge, UK: Cambridge University Press, pp. 245-260.

Socolow, Robert, Clinton Andrews, Frans Berkhout, and Valerie Thomas, eds., 1994. *Industrial Ecology and Global Change*. Cambridge, UK: Cambridge University Press.

Socolow, Robert, 1994. "Six perspectives from industrial ecology." In *Industrial Ecology and Global Change*, R. Socolow, C. Andrews, F. Berkhout, and V. Thomas, eds. Cambridge, UK: Cambridge University Press. pp. 3-16.

Socolow, Robert, and Valerie Thomas, 1997. "The industrial ecology of lead and electric vehicles." *Journal of Industrial Ecology* 1(1):13-36.

Socolow, Robert , ed. 1997. *Fuels Decarbonization and Carbon Sequestration: Report of a Workshop*. Princeton, NJ: Princeton University, PU-CEES Report 302, September 1997.

Socolow, Robert, 1999. "Nitrogen management and the future of food: Lessons from the management of energy and carbon." *Proceedings of the National Academy of Sciences* (to be published).

Solow, Robert M. 1991. "Sustainability: An Economist's Perspective." Eighteenth J. Seward Johnson Lecture to the Marine Policy Center, Woods Hole Oceanographic Institution, Woods Hole MA June 14, 1991. Reprinted in *Economics of the Environment: Selected Readings*, 3rd edition. Robert Dorfman and Nancy S. Dorfman, eds. New York: Norton & Co.,1993, pp. 179-187.

Stern, Paul, Thomas Dietz, Vernon Ruttan, Robert Socolow, James Sweeney, eds, 1997. *Environmentally Significant Consumption: Research Directions*. Washington, D.C.: National Academy Press.

Stokes, Donald E., 1997. *Pasteur's Quadrant: Basic Science and Technological Innovation.* Washington, D.C., Brookings Institution Press

Tilman, D. 1982. *Resource Competition and Community Structure.* Princeton University Press, Princeton, New Jersey.

United Nations Secretariat, 1997. *Critical Trends: Global Change and Sustainable Development.* New York: United Nations Department for Policy Coordination and Sustainable Development.

Vitousek, P. M. 1994. "Beyond global warming: ecology and global change." *Ecology* 75:1861-1876.

Vitousek, P. M., J. D. Aber, R. W. Howarth, G. E. Likens, P. A. Matson, D. W. Schindler, W. H. Schlesinger and D.

Tilman. 1997. "Human alteration of the global nitrogen cycle: sources and consequences." *Ecological Applications* 7(3):737-750.

Wernick, Iddo, Paul Waggoner, and Jesse Ausubel, 1998. "Searching for leverage to conserve forests: The industrial ecology of wood products in the United States." *Journal of Industrial Ecology*, 1(3):125-145.

Wernick, Iddo, and Nickolas Themelis, 1998. "Recycling metals for the environment." *Annual Review of Energy and the Environment, 1998* 23:465-497.

World Commission on Environment and Development, 1987. *Our Common Future*. New York: Oxford University Press.