Earth Systems Engineering: The Role of Industrial Ecology in an Engineered World

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Summary

A principal result of the Industrial Revolution and concomitant changes in human population levels, technology systems, and culture has been the evolution of a world in which the dynamics of major natural systems are increasingly dominated by human activity. Many resulting anthropogenic perturbations of fundamental natural systems—for example, the nitrogen and carbon cycles and heavy metal stocks and flows—have been both unanticipated and problematic. Reducing such unintended consequences of human activity will require development of the ability to rationally engineer and manage coupled human–natural systems in a highly integrated fashion. Such “earth systems engineering” activity will rely on industrial ecology studies and methodologies to provide critical elements of the required science and technology (S&T) base. Although the need to develop such an earth systems engineering/industrial ecology capability is clear, it is also apparent that the current S&T base, institutional structures, and ethical systems are inadequate to support such activity. Accordingly, it is desirable to begin to develop such support structures while recognizing that premature attempts to engineer fundamental natural systems should be discouraged.
Introduction

Roll on, thou deep and dark blue ocean, 
roll!
Ten thousand fleets sweep over thee in vain;
Man marks the earth with ruin, his control 
Stops with the shore; . . .
(Lord Byron, “Childe Harold’s Pilgrimage”)

Lord Byron lived from 1788 to 1824, when the population of the world was only some 900 million people and economic activity and the concomitant anthropogenic footprint on the globe was considerably lighter (e.g., world coal extraction in 1800 was approximately 15 million metric tons; in 1987 it was 3,334 million) (Cohen 1995). Romantic that he was, the relatively new, and painfully obvious, human and environmental toll of the Industrial Revolution, as well as the human futility of constant warfare in Europe, were more than sufficient to touch off a bitter and cynical poetic response. Still, as with most romantics of the period, he clutched at straws: There were parts of nature so overwhelming, so fundamental, that the contagion of humanity could not infect them. The oceans would endure, a pristine refuge from human rapaciousness. Indeed, this mental model and its psychological appeal—the need for a refuge from people, their things, their greed, and their impacts—remains powerfully attractive to many today.

But industrial ecology is an integrative scientific and technological field, “the objective multidisciplinary study of natural and economic systems and their linkages with fundamental natural systems” (IEEE 1995, 3). Although the allure of the romantic vision is strong, industrial ecologists in particular need to recognize that “natural” and human systems of all types and at all scales have in fact been increasingly tightly coupled—coevolving together—for millennia, and the process is accelerating. As regards the oceans of Byron, for example: “[many marine biologists] point out that Earth’s growing human population is putting unprecedented pressure on life in all parts of the sea” (Malakoff 1997, 486). More broadly, Gallagher and Carpenter (1997, 485) introduced a special issue of Science on human-dominated ecosystems by noting that the concept of pristine ecosystems, untouched by human activity, “is collapsing in the wake of scientists’ realization that there are no places left on Earth that don’t fall under humanity’s shadow.” As long ago as 1989, Scientific American titled a special issue “Managing Planet Earth”; in the lead article, Clark noted that “[i]t is as a global species that we are transforming the planet. . . . Self-conscious, intelligent management of the earth is one of the great challenges facing humanity as it approaches the 21st century” (1989, 47).

The codependence of natural and human systems is not new learning. Some 2200 years ago, the Elder Tai in China was moved to caution that “if a human ruler likes to destroy nests and eggs, the phoenix will not rise. . . . if he likes stopping the watercourses and filling up the valleys, the tortoise will not show itself” (quoted in Needham 1956, 272). And indeed, copper production during the Sung Dynasty (ca. 1000 years BP [Before Present; that is, before the current date]), as well as in Athens and the Roman Republic and Empire, is reflected in deposition levels in Greenland ice (Hong et al. 1996), and lead production in ancient Athens, Rome, and medieval Europe is reflected in increases in lead concentration in the sediments of Swedish lakes (Renberg et al. 1994). The buildup of carbon dioxide in the atmosphere began not with the post–World War II growth in consumption of fossil fuel but with the deforestation of Europe, Africa, and Asia over the past millennia (Jager and Barry 1990). Human influence on the natural cycles of water, nitrogen, sulfur, phosphorus, and many metals is equally striking (Ayers et al. 1994; Nriagu 1994; Smil 1997; Vitousek et al. 1997). The human role in redistributing radioactive material, principally a result of military and energy production applications, is well known and is generating cleanup costs of billions of dollars per year (Shcherbak 1996; Physics Today special issue on radioactive waste 1997). Humanity’s impacts on biota, through direct predation and indirectly through the introduction of nonnative species, has been going on for centuries as well (Jablonski 1991; Barlow 1997). What is different is the striking discontinuity between the relatively minor and localized impacts that predominated before the Industrial Revolution and the global systemic impacts of
human activity that now characterize the interrelationships between human and fundamental biological, physical, and chemical systems (Ehrlich and Wilson 1991; Turner et al. 1990; Science special report 1997).

In fact, the distinction between a human system and a natural one is itself somewhat artificial in many cases. Economic systems are generally considered human and estuarine systems natural, for example, although each is inevitably a complex mixture of both. To the extent the terms refer to the predominant dimension—anthropogenic or nonanthropogenic—they are useful, and it is in that sense they are used in this article. To the extent, however, they become exclusionary, they embed misleading simplicity into analysis and policy development—and, indeed, scientific understanding. Ironically, the well-known difficulty that social scientists, studying human systems, and physical scientists, studying chemical, biological, and physical systems, have in communicating with each other exacerbates the artificial division between the two classes of system and makes integrated study of such systems institutionally challenging as well.

It is difficult to avoid the conclusion that primarily as a result of the Industrial Revolution, the scale and scope of human impact on critical natural systems has grown so large that it amounts to an unprecedented discontinuity at the scale of the globe itself. The dynamics of many fundamental natural systems are now dominated not by life as a whole but only by one species. The earth is increasingly a largely unintended product of human engineering. Until very recently, however, this engineering process has occurred without conscious recognition. It consists of the sum of human activities, grown to scales unprecedented for any species in the history of the globe. A myriad of economic and engineering decisions, evaluated and taken as if independent, are in reality tightly coupled to each other and to underlying natural systems. Each action in this process may, indeed, be planned, but the comprehensive systemic impacts, which are just becoming apparent, are in large part neither planned nor foreseen. Anthropogenic climate change; loss of biodiversity and critical habitat; degradation of soil, water, and air resources; dispersion of toxic metals and organics—these are the fruits of human engineering just as surely as the computer, the automobile, the modern office building, and the highway infrastructure.

For the most part, the emergence of an anthropogenic world has been sufficiently subtle and complex, and human practices so relatively unsophisticated, that humans and human institutions either have not consciously recognized what is occurring or, alternatively, have minimized the importance of the implications. The latter course is easier in cases where scientific uncertainty can be used to justify a lack of concern; this state, of course, characterizes many earth systems engineering situations. Conveniently, then, the ignorance of decision makers in such situations has allowed them to avoid taking responsibility for this result, but such easy denial is no longer either objectively supportable or, arguably, ethical.

It is one thing, however, to recognize the need to explicitly and completely assume responsibility for global systems; it is another to do so responsibly. The intellectual tools that such a task implies are not yet in place. The multidisciplinary field of industrial ecology, although it cannot substitute for the evolution of appropriate ethical and institutional systems yet to occur, has a significant role to play in supporting their development. The magnitude and complexity of the research and development effort this will require is daunting, however, for our ignorance in this area is far more complete than most people realize (Allenby 1998). Moreover, development of these industrial ecology tools must proceed in parallel with the evolution of appropriate institutional, ethical, and policy systems; to a large degree, it is in these latter areas, heavily imbued with religious and cultural values, where awareness of the challenge is lowest and the barriers to change are most substantial (Allenby 1997, 1999; Rejeski 1997).

Conceptually, earth systems engineering may be defined as the study and practice of engineering human technology systems and related elements of natural systems in such a way as to provide the required functionality while facilitating the active management of the dynamics of, and minimizing the risk and scale of unplanned or undesirable perturbations in, strongly
coupled fundamental natural systems (e.g., the grand elemental cycles, hydrological cycle, critical habitats, and atmospheric or oceanic systems). Several elements of this definition require emphasis. First, the focus is on technology systems, not artifacts. Thus, for example, elements of engineered earth systems may range from design of a carbon sequestering fossil fuel power plant, to an agricultural system that modulates the pertinent dynamics of the nitrogen cycle, to the Internet as an environmental technology that (partially) dematerializes information generation and transfer. Although artifacts are obviously part of such systems, and they are at one level engineered qua artifacts, in earth systems engineering projects they are treated as elements of systems, in their economic and cultural contexts and as they are coupled to natural systems. Second, the goal is to actively manage the dynamics of affected natural systems rather than only trying to minimize impact (although, of course, this is one possible tactic). In this way, technology system designers and managers are required to explicitly assume responsibility for such impacts and, more importantly, for the integrated dynamics of the underlying natural systems. This attempts to get at the “tyranny of small decisions,” where a series of small decisions taken independently and rationally in context add up to a result that is suboptimal because of their cumulative impacts on the systems within which they are embedded (for a discussion of such dynamics in the economic regulatory context, see Kahn [1971, 239]).

Third, only engineering projects or systems that affect “fundamental” natural systems rise to the level of earth systems engineering. This is obviously a somewhat subjective criterion that will vary depending on circumstances; it is perhaps best left vague at this early stage and defined with increasing specificity through actual practice. Moreover, there is a “proximity” test that must be imposed, because virtually any significant technology system impacts fundamental natural systems in some way. Thus, one must ask how tightly coupled (how proximate) the technology system is to the concomitant perturbation of the natural system in question.

This article argues that given the already profound human impacts on natural systems, it is no longer a question of whether we must learn how to do earth systems engineering. Population growth, urbanization, increasing levels of production and consumption, and accelerating environmental damage—irreversible in the short term (e.g., global climate change) or even forever (e.g., species extinction, human mortality)—leave little choice. This should not be construed as naive technological optimism, however, but unhappy reality, for it is equally apparent that current knowledge, institutional capability, and ethical frameworks are inadequate to meet this challenge. Hubris, and concomitant premature manipulation of critical natural systems, are a real potential danger. If we were not already doing such damage unintentionally, we should not dare to try to engineer such complex systems intentionally. But existing impacts and extinctions are real, and the domination of critical systems' dynamics by humans is real, if unintended. Under these circumstances, it would be irresponsible, verging on unethical, not to begin the development of the capability for sophisticated earth systems engineering.

Identifying and understanding issues surrounding earth systems engineering situations in the abstract, however, is difficult. Accordingly, the first section of the article briefly presents some illustrative examples of existing and proposed earth systems engineering projects. These include a current example, the shrinking of the Aral Sea; a proposed “single construction” project, damming the Mediterranean to control shifts in ocean circulation driven by anthropogenic global climate change; fertilization of the ocean with iron to increase biological activity and thus diminish anthropogenic effects on the carbon cycle; and sequestration of carbon from fossil fuels. Such carbon sequestration, combined with a shift to hydrogen rather than hydrocarbon fuels for transportation and small energy generation requirements (the so-called hydrogen economy), is another mechanism for reducing human impacts on the carbon cycle. In each case, of course, the tools and systematic approach of industrial ecology are the means by which these earth systems engineering proposals can be explored and evaluated. Subsequent sections address some of the more abstract issues raised by the examples.
Examples of Earth Systems Engineering

Once it is recognized that human and natural systems have been coupled in a meaningful way for centuries, it is relatively easy to see examples of earth systems engineering in the past and potential examples for the future. Indeed, earth systems engineering concepts have been particularly of interest in the context of global climate change. Keith and Dowlatabadi (1992), for example, list a series of mitigation options for what they term “geoengineering” responses to global climate change: direct ocean disposal of carbon dioxide, ocean fertilization with phosphate, ocean fertilization with iron, reforestation, solar shields increasing the planet’s albedo, stratospheric sulfur dioxide creation, injection of inert dust into the stratosphere, and injection of sulfur dioxide into the troposphere. In this article, I have chosen to use the term “earth systems engineering” rather than “geoengineering” because it encompasses the possibility of engineering a broader array of systems, including, perhaps, complex human ones (e.g., designing the physical, biological, and cultural dimensions of agricultural systems for optimal productivity and resiliency on a national state basis). The focus is on engineering because at a general level, technology systems are the means by which humans impact natural systems, and such systems are created by engineering activities. Increasingly, the engineering function is performed by multidisciplinary teams; individual engineers seldom have the breadth of scope and experience required by systems engineering, concurrent engineering, or earth systems engineering projects.

The principle differences between the historical and the proposed are two: one of scale and one of intent. In the past, earth systems engineering projects were in general more local and had less global impact, at least taken individually. This, of course, reflects the more local scale of human population levels and activity, only loosely coupled over regional areas and un-coupled at the global scale, that tended to dominate at the time (Turner et al. 1990). Second, to the extent a set of independently initiated human activities gave rise to “emergent characteristics” at regional or global levels, they tended to be unanticipated and unintended, at least in seriousness. It is the scale and intent that differentiate earth systems engineering from existing engineering disciplines, particularly environmental engineering (table 1 and figure 1). Naturally, there is some ambiguity in practice: Some environmental cleanups will last for many decades (although, at least in the case of most site cleanups under laws such as the U.S. Superfund statute, the risks tend to be localized).

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>“Environmental engineering”</th>
<th>“Earth systems engineering”</th>
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<tbody>
<tr>
<td>Scientific model</td>
<td>Reductionist (e.g., based on toxicology)</td>
<td>Integrative (e.g., based on industrial ecology)</td>
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<td>Scale</td>
<td>Short term/local</td>
<td>Long term/regional or global</td>
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<td>Culture/ethical content</td>
<td>Low</td>
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<td>Technology</td>
<td>Minor adaptations</td>
<td>Major evolution of technology systems</td>
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<td>Nature of engineered system</td>
<td>Primarily technical and economic</td>
<td>Coupled human–natural systems</td>
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<td>Engineering psychology</td>
<td>Control and complete systems definition</td>
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<td>Focus</td>
<td>Artifact design, construction, and performance</td>
<td>Systems dynamics: links, feedback loops, nonlinearities, and discontinuities</td>
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<td>Goal</td>
<td>“Home run”—fix problem for good</td>
<td>Continuous process maintaining dynamic systems in desired states</td>
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This raises an important point for the industrial ecologist, however. Just as industrial ecology does not replace but builds on previous reductionist approaches, earth systems engineering as an activity is firmly linked to past practices, although, given the differences in scale and complexity of the systems involved, the science, technology, institutional, and ethical issues involved are quite different. Learning from past experience with large projects and from current efforts to understand similar systems is accordingly both possible and highly desirable. Thus, for example, individual large construction projects such as the Aswan High Dam in Egypt, nuclear power systems in many countries, the Three Gorges dam project in China, or the Boston Central Artery and Tunnel project in the United States offer lessons in managing complex technologies, frequently tightly coupled with wider economic, ecological, technological, and hydrological systems. For example, bioengineering and the basic science behind it, such as the Human Genome project, can be considered an important effort in earth systems engineering and clearly raise a number of ethical issues. In this instance, however, particularly because of the obvious implications of application of bioengineering to humans, considerable substantive progress is being made in exploring the ethical implications (see, e.g., Kevles and Hood 1992; Reichenbach and Anderson 1995; Barlow 1997; Noble 1998). In some sense this dialog is a model for broader application across earth systems engineering in general.

**The Aral Sea Case**

Consider, for example, the case study of the Aral Sea, a classic example of unintended impacts (although easily predictable in hindsight [Postel 1996]) emerging at a regional level as a result of efforts to support higher levels of agricultural activity. Actually a lake, the Sea, which only decades ago was the fourth largest lake in
the world, has in a few short years lost about half its area and some three-fourths of its volume because of the diversion of 94% of the flow of two feeder rivers, the Amu Dar’ya and the Syr Dar’ya, primarily to grow cotton. The inefficiency of the resulting irrigation system is not uncommon; some estimates are that only 30% of the diverted water, carried in unlined canals through sandy desert soils, reaches its destination (Feshbach 1998). The results are staggering: desertification of the region (the resulting Ak-kum desert, expected to reach 3 million hectares in the year 2000, did not even exist 35 years ago); generation of some 40 to 150 million tons of toxic dust per year with substantial detrimental impacts on regional agriculture and human health; potential impacts on the climate regimes of China, India, and Southeastern Europe; increased salinization of the Sea with resulting loss of 20 of 24 fish species in the Sea; and a drop in the fish catch from 44,000 tons in the 1950s to zero today, with a concomitant loss of 60,000 jobs, a reduction in nesting bird species in the area from 173 to 38, and possibly even the release of biological warfare agents previously contained because they were quarantined on an island in the Sea (Voskreseniye Island) which is now becoming a peninsula (Postel 1996; Feshbach 1998).

The most obvious initial observation is that this case study is archetypal; such water management activities have been going on for centuries, frequently with unanticipated or undesirable impacts and often with significant political implications. Indeed, in the case of ancient China, massive irrigation projects were a signature of, and a major coevolved institution supporting, the development of highly organized feudal power as long ago as the Chhin state in the Wei valley, some 2300 years BP (Needham 1954). Over historical time, a number of societies are believed to have been weakened, if not collapsed, because of their failure to manage water resources, primarily for agricultural uses. Even today, by far the largest use of water resources is for agricultural irrigation (L’vovich and White 1990).

This case study thus poses a somewhat extreme example of the unintended impacts that can result when earth systems engineering is undertaken without sufficient study and with too much hubris driven by inadequate understanding of the full system. In this instance, as in most cases, problems arise not because such projects do not have benefits but from the failure to understand the full range of associated costs. It should be noted, however, that although the physical system impacts in this example may be unusually severe, such biological impacts are common, at least locally, to many large water management and general development projects. For example, Nature Conservancy data indicate that apart from extinctions that have already occurred, 36% of fresh-water fish species, 38% of amphibians, 50% of crayfish, and 56% of mussel species are in jeopardy in the United States, not usually considered a center of extinction activity (Doyle 1997). The three main forcing functions for this impact on aquatic biodiversity are agriculture, dams, and exotic species, all anthropogenic causes, raising the broader question: If we as a species are already heavily engaged in engineering the biosphere, what kind of end state do we have in mind?

**The Dam Across the Strait of Gibraltar**

The possibility that global climate change could result in abrupt shifts in global ocean circulation patterns is generally recognized (Broecker 1997). More specifically, Johnson (1997a) has hypothesized that as a result of human reduction of fresh-water flow into the Mediterranean Sea, increased salinity in that water body could lead to a higher volume of outflow from the Mediterranean basin at Gibraltar. This in turn could modify high-latitude oceanic–atmospheric circulation patterns in such a way as to cause extensive glaciation in Canada and cooling in northern Europe. As mitigation, he proposes a partial dam across the Strait of Gibraltar, which would limit the outflow and reverse the climate deterioration, "thus holding off the next ice age." The dam would be a huge construction project designed to limit the Mediterranean flow through the Strait to some 20% of what it is now; Johnson estimates that it would most likely take decades to construct and would require some 1.27 km³ of material. The proposal has been strongly criticized and defended (Marotzke and Adcroft 1997; Johnson 1997b).
Several points about this proposal are of interest. The first is that the shift in salinity in the Mediterranean is primarily a result of human diversion of water from the Nile; some 90% of the Nile's 2,700 m^3/sec flow is now diverted for agriculture or lost through evaporation. Significantly, much of this is due to the Aswan High Dam, so the (potential and unanticipated) effects of shifts in the salinity of the Mediterranean—such as increased Canadian glaciation—are attributable, at least in part, to a single hydrologic construction project. Nor, although I do not focus on it here, are the impacts of the Aswan High Dam limited to ocean circulation effects; of 47 commercial species that were harvested in the Nile before construction, only 17 were still harvested a decade after it was built, and the annual sardine harvest in the Eastern Mediterranean has dropped by some 83%, possibly as a result of the Dam's capture of nutrient flows previously available downstream (Postel 1996). If the projected climate perturbations do come to pass, then they will thus be a prime example of how humans are, in fact, engineering earth systems today, albeit in ignorance. The case also illustrates that earth systems engineering is not something new; rather, in its augmented form it is a response, both environmentally and, arguably, morally necessary, to the current scale of human activity and the resulting impacts on coevolving natural systems.

The second is the scale and nature of the perturbation and impacts, which clearly speak to the complexity of these systems. The potential causal connections run from an historical pattern of increasing human water use around a large basin, with a single large construction project as a possible triggering event, leading by a series of perturbations of natural oceanic and atmospheric circulation patterns to severe and disruptive climate changes in far removed highly populated areas with concomitant economic and social costs. As is frequently the case with environmental perturbations, the economic and environmental costs and benefits are differentially realized across classes of people, countries, economic sectors, and geographic regions (Allenby 1999). Egypt benefits from the Aswan High Dam, and Europe and Canada may face adjustment costs. How can institutional, scientific, ethical, and technological systems evolve to manage such situations, especially given the inherent time lags and uncertainties? And, when the system is considered as a whole, where is (are) the best place(s) to intervene to mitigate human activities causally linked to the perturbations in question (i.e., anthropogenic forcing functions), system response, and/or costs?

Iron-enriched Phytoplankton Blooms

The idea is simple: Growth of oceanic phytoplankton populations is, at least in some cases, limited by iron, so artificially introducing iron into oceanic systems would result in phytoplankton blooms that would absorb carbon and then die. At least some percent of the resulting carbonaceous material would sink to the bottom of the ocean, thereby depositing the carbon in a long-term sedimentary sink. Bench experiments by Martin demonstrated increases in phytoplankton biomass when fertilized by iron (Monastersky 1995), a result that was later tested and verified in situ in oceanic systems (Behrenfeld et al. 1996; Coale et al. 1996; Cooper et al. 1996). The latter experiments, however, demonstrated that although bloom and absorption of carbon dioxide occurred, iron tended to precipitate out of solution rapidly, reducing the possibility that this mechanism could prove a viable tool for mitigating global climate change by capturing carbon in sinks (Kerr 1994). Moreover, changes in community structure in the fertilized regions occurred; in particular, diatom biomass increased substantially (85 times baseline), whereas other groups, particularly microzooplankton and the smaller autotrophs, showed far less response (doubling of biomass over baseline) (Coale et al. 1996). Other results included an increase in dimethyl sulphide production by phytoplankton that, when and to the degree exchanged with the atmosphere, would be converted into sulphate aerosols, which could exert a cooling effect on the climate (Turner et al. 1996).

Although obviously at a preliminary state, this set of experiments and hypotheses begins to develop the necessary scientific understanding to design a tool that, like that discussed below, could become part of a human-engineered carbon cycle. The gaps in the necessary knowledge
and the difficulty of intervening in complex systems without generating unanticipated changes in systems that may appear far removed (e.g., the concentration of sulphate aerosols) are apparent even from this brief description. Note, however, that unlike the proposal for a dam across the Mediterranean, this option can be explored at small scales and, if justified, could be implemented incrementally. This important consideration in earth engineering is discussed in the last section of this article.

**Fossil Fuel Systems as Basis for Carbon Cycle Management**

The last case study is conceptually simple: Carbon dioxide resulting from fossil fuel combustion in power plants is captured and sequestered for centuries in the ocean, deep aquifers, geologic formations, or other reasonably long-term sinks. Many technologies to capture the carbon dioxide emissions and inject them into various sinks currently exist, and especially if carbon capture is implemented at the initial design stage rather than retrofitted, such systems appear to be technologically and economically feasible (Adams and Herzog 1996; Herzog and Drake 1996; Socolow 1997). For example, in the first instance of carbon sequestration for environmental reasons, Norway's state-owned petroleum company, Statoil, is currently sequestering the carbon dioxide content of the gas it is extracting from the Sleipner gas field off the coast of Norway (the carbon dioxide content of the gas is about 9%) back into an aquifer about 1,000 m below the seabed. Statoil finds this economically preferable to paying the $55/ton carbon dioxide tax that would apply if the gas were simply vented (Hileman 1997). Thus, there is a proof of concept even though a number of issues, from environmental impacts, to technological and economic feasibility, to liability, remain to be resolved as regards each potential technological option.

When combined with the possibility of a hydrogen economy, such carbon sequestration raises the possibility of being able to exploit fossil fuel reserves without a substantial increase in carbon dioxide emissions and thus global climate change—essentially, to decarbonize fossil fuel consumption (Socolow 1997). So far, so good; this is an example of mitigating human impacts, of stewardship. But considering the anthropogenic domination of important aspects of carbon cycle dynamics, one might be inclined to push further and ask whether carbon sequestration/hydrogen technologies could become an important control mechanism in a deliberately engineered human carbon cycle governance system (figure 2). Here, the global set of fossil fuel plants is tuned to produce over time the desired atmospheric concentration of carbon dioxide, given other variables (e.g., impacts on vegetation, desired degree of global climate change, lag times of various components of the systems involved, changes in solar insulation, other carbon dioxide emissions, concentrations of other greenhouse gases, use of other mitigation technologies such as energy efficiency and biomass sequestration). The control functions of such a system are twofold: the ratio of biomass and municipal waste to fossil fuel input into the system and the amount of carbon dioxide emitted to that sequestered. By manipulating these ratios and in conjunction with the entire suite of carbon control methods (figure 3), the system is moved toward the target atmospheric concentration of carbon dioxide.

Note that as with systems engineering projects (such as, e.g., the Boston Central Artery and Tunnel, the development of the ARPANET, or the Atlas missile program), management and organizational skills are just as critical as traditional engineering disciplines, if not more so (Hughes 1998). Indeed, it is likely that in many cases engineering and management of earth systems will rely heavily on decentralized mechanisms such as markets and loosely networked institutions rather than centralized control mechanisms to distribute information and encourage evolution of the system(s) as a whole toward the desired dynamic state(s). This must be done carefully and within prudent bounds defined by current science and technology (S&T), institutional, and ethical capabilities, however. For example, a firm called Ocean Farming, Inc. has proposed privatization of approximately 800,000 square miles of oceanic areas off the Marshall Islands for purposes of iron fertilization and associated fish farming activities, in part touting the carbon sequestration benefits of the
activity. Concerned scientists have noted, among other things, the potential for irreversible destruction of coral reefs or generation of toxic algal blooms (Nardis 1998). From an earth systems management and engineering perspective, therefore, one would take the position that any such activity—particularly at production rather than experimental or pilot scale—given the current relatively primitive state of knowledge about costs, benefits, S&T implications, and alternative options for carbon system engineering, is premature and irresponsible and should not be permitted. Equally, however, the possibility that such market-based activity could eventually be a part of a robust carbon system engineering and management system should be recognized and the appropriate efforts to generate information that would support (or discourage) such a set of activities made part of the research and development (R&D) agenda.

As this example suggests, the S&T base, institutional capacity, and ethical infrastructure to support such an assumption of human responsibility for the functioning of a fundamental earth system do not yet exist. To urge immediate implementation of an earth systems engineering program in its totality in the immediate future would be irresponsible. Arguably, however, it is equally irresponsible not to be supporting the R&D, public dialog, and institutional development that could lead to the development of such a capacity. Indeed, individual pieces of it, like the activities at Sleipner, already exist, and R&D projects testing components of such a system—building experimental coal-fired plants that in fact capture and sequester their carbon dioxide, for example—should begin immediately to facilitate learning and data acquisition. It bears repeating that the question is not whether humanity is manipulating the carbon cycle. The science clearly demonstrates that that question has already been resolved de facto. The only question remaining is how responsibly the species will perform that function, and industrial ecology, with its systems approach and integrative perspective, will be an important part of the answer.
Ethical and Institutional Infrastructure

Note that there is, at least in some sense, a significant difference between the concept of stewardship and that underlying earth systems engineering, which requires active management of complex human-natural systems. Stewardship tends toward a passive approach: Live on the earth and manage human activity in such a way that impacts on natural systems are minimized. The concept has connotations derived from a preindustrial pastoral mental model. Earth systems engineering, however, requires that human institutions accept not just moral responsibility for human–natural systems but move beyond to assume an active management role for most global systems (how such a role could, or should, be exercised would vary, of course, depending on the nature of the system and the importance of anthropogenic perturbations to it). For example, a stewardship approach to global climate change might rely on reducing global emissions of anthropogenic carbon dioxide and other greenhouse gas emissions to “safe” levels; indeed, this was the approach adopted in the Kyoto negotiations. An earth systems engineering approach, however, would imply developing an institutional ability to deliberately modulate the carbon cycle to maintain specified atmospheric concentrations of carbon dioxide and other greenhouse gases to achieve and maintain a desired global state. In the first instance, the goal is to reduce human impact; the latter approach presupposes that the linkages among systems is such that explicit human management of relevant global systems, including both natural and human components, is required.

Even a brief consideration of the religious and ethical issues raised by these two approaches shows how different they really are. It is one thing to say “I will take care of the world by limiting my role and treading lightly,” another to recognize that “I am actively responsible for the world and everything in it, and I will decide what lives and dies through active intervention and management of fundamental natural systems.” The first approach is at the core of much existing environmental legislation and regulation. It is, in turn, supported by a number of increasingly accepted principles, such as that the polluter should pay for cleaning up its pollution

Figure 3 Carbon cycle: earth systems engineering schematic.
(the “polluter pays” principle, which simply re-states in ethical terms the economic principle that welfare is generally increased by the internalization of externalities). The ethics of stewardship, which inherently assumes that the natural and human spheres are different (i.e., there has to be a “natural” sphere for the “human” sphere to be a steward of), are not radical. To a great extent, they at least do not appear to be incompatible with many existing theological systems, in principle if not in practice. Moreover, because the duality of the natural and human is assumed, stewardship concepts do not displace the role of deities, in particular over nature.1

But this changes profoundly as soon as any human institution asserts the right—indeed, the obligation—to manage global systems and, concomitantly, to make trade-offs that heretofore have widely been regarded as transcendent. Consider just briefly the question “How many people are you willing to kill to save a species?” or, conversely, “How many species are you willing to drive to extinction to save one human life?” Few people are willing to answer such questions; in fact, most would view them as profoundly offensive. The reason, of course, is that what many people regard as two moral absolutes have been posed against each other (and thus, implicitly, denied as absolutes): the unique value of a human life and the unique value of a species. Choosing either answer reduces the other to a conditional status. To make the transcendent—which for many people would include the deliberate killing of innocent human beings and extinction of species—subject to explicit human choice within a relativistic ethical framework is unacceptable to many people.

And yet such questions would merely be impolite and offensive were it not true that these precise trade-offs are occurring in many places around the world today. Science may not be good enough to precisely establish causality (“that coral species is dying because you bought leather sandals today”), nor are those who bear the costs, be they human or nonhuman, known in many cases to those who benefit. Moreover, the trade-offs are almost never transparent and in practice are buried in debates about endangered species versus property rights or environment versus lifestyle, consumption, and infrastructure development. Nonetheless, that this trade-off is occurring and that it is a result of human population and economic growth is clear (Turner, et al. 1990; Science special report 1997). That human institutions can plead ignorance is less and less a tenable excuse. As a species, humans are now making, and continue to make, such choices every day. It is simply done in ways that are invisible both to individuals and to social and cultural institutions (Luhmann 1989).

This is not surprising. Just as scientific, technological, and policy institutions have not yet adjusted to an environmentally constrained earth increasingly engineered by humans, neither have ethical or religious institutions. In a world of plentiful resources, which the Industrial Revolution essentially created for the human species, it was virtually possible by definition to have adequate resources for both “humans” and “nature” (Allenby 1999, 163–164). Moral systems that were evolved under such conditions would have no need to develop the ability to answer difficult questions about trade-offs between, for example, human lives and species extinctions. In a world of plenty, both could be absolutes—and both, of course, subject to the exigencies of fate and deity. In a world defined by human activity, however, such absolutes no longer pertain.

The question, then, is not whether humans at the species level have abrogated to themselves the powers formerly attributed to gods—the power to determine, through their collective action, life, and death not just of innocent people but of species and not just as a result of conflict but as a result of routine human activity. That is already done. The question rather is whether ethical and religious institutions have evolved the capability to think about and guide such truly fearful decisions, and here the answer must be no. Moreover, it is reasonable to anticipate substantial opposition to any attempt to exercise such power consciously; it is, in more than a metaphorical sense, “playing god.”

There is another ethical dimension to any consideration of earth systems engineering: the desired endpoint. In simple terms, the question “To what end are humans engineering—or should humans engineer—the earth?” is a moral, not a technical, question. Moreover, as suggested
above, human institutions are implicitly answering that question every day, thus positing an answer. To date, however, failure to recognize the strong coupling between human activity and the state of environmental systems has permitted the engineering process to proceed without explicit consideration of the ethical content of the results. At some point this veil of ignorance will be pierced, perhaps in addressing the complex issues raised by global climate change and possible mitigation strategies. After all, to “buy insurance” against poorly understood but potentially serious global climate change impacts by reducing carbon emissions, probably at some economic and social cost, requires the kind of balancing of risks, costs, and benefits (including risk of human death and species extinction) that cannot be resolved technically. Such decisions can be informed by science and technology, but their resolution embodies prioritizations that can only be made on the basis of (at least somewhat) internally consistent ethical systems. In fact, many areas of contention in the negotiations regarding global climate change reflect not so much disagreements about the science, where broad consensus exists (Mahlman 1997), but different views regarding what constitutes an equitable distribution of current and future costs and benefits—in other words, on the lack of an ethical structure that can support agreement on such a broad-reaching human response to a perturbed fundamental natural system—in this case, the carbon cycle.

This ethical gap is not the only difficulty, of course; in particular, it is reinforced by a lack of appropriate institutional structures. Ethical, institutional, and industrial ecology (science and technology) components must all evolve in parallel to provide the capacity for rational response to regional and global anthropogenic environmental perturbations.

More broadly, the very concept of sustainability requires choices, which, in turn, implies an ethical basis upon which such decisions can be made. The original definition of “sustainable development” by the Brundtland Commission—“development that meets the needs of the present without compromising the ability of future generations to meet their own needs” (WCED 1987, 8)—embodies implicit ethical, institutional, and science and technology dimensions and has perhaps had the effect of lulling people into a false complacency. There are, in fact, a myriad of potential “sustainable” worlds, depending on the choices that are made regarding a number of dimensions of global civilization: how many individuals, at what level of material well-being, with what level of equity, with what institutional systems, with what variability or stability, for how long, embodying what values (Cohen 1995; Allenby 1999, 34–38). In fact, a cynic might argue that a more likely “sustainable world” given human history is one characterized by economic and political elites protected from environmental and aesthetic insult by wealth and military power, while sustainability is maintained by highly variable mortality rates among the poor and concomitant low biodiversity.

One way of mapping the decision space involved is by use of a “psychocultural compass,” which illustrates two of the most critical dimensions (figure 4). On one scale is the range from humility in the face of the enormous complexity of such systems to the hubris that marks more than a few current proposals for earth systems engineering. On the other scale is the Cartesian duality, ranging from those who view the physical world and that which resides on it as the ultimate reality to those who view it as a distraction or even an illusion, a stage preparatory to eternal paradise, or at least physically migrating from the earth. Given this space, one can begin to map mental models, which may translate into very different definitions of sustainability and, thus, differing approaches to earth systems engineering. For example, millenarian theology (belief that the end of the world is near and a paradise, usually limited to the appropriate believers, is about to be established in its place) tends to lie in the upper right quadrant (see Noble 1998). On the other hand, those who find the concept of “the living earth,” Gaia, attractive tend to lie in the opposite quadrant (see Barlow 1997). The difficulty, of course, arises from trying to develop approaches to earth systems engineering that embody values lying roughly in the center space of the map; such values might completely satisfy no one, yet still serve as robust support for the decisions required.

The need for serious theological, ethical, and moral dialog in this area is emphasized by the
problem that choice at the level of the individual may or may not be relevant. In fact, the choice of path might be made by institutions at a relatively high hierarchical level in the system or determined by systems dynamics arising from the interactions of science and technology; natural, institutional, and cultural systems; and national states in ways that we are not yet capable of modeling or understanding (Allenby 1999, 34–38).

This, then, is a significant barrier to any substantial implementation of earth systems engineering. The moral structure that is required if such activities are to become widespread is at a very primitive stage of development. The social acceptance of the assumption of such power by any institution—academic, political, industrial, or religious—is likely to be minimal for a long time (and justifiably so, until the necessary competencies are developed). Moreover, it is not apparent where leadership in this dimension will come from, because there are currently no institutions that society has empowered to respond to this difficult challenge. This does not mean that individual projects cannot go forward, particularly where they can be done in line with the guiding principles discussed at the end of this article, and the perturbation to be addressed is immediate, difficult to reverse, and extensive in time and space. It does mean that the evolution of appropriate ethical and institutional structures is desirable and should be supported by those who become interested in earth systems engineering. It also is cautionary; technologists sometimes assume technical solutions to problems that have substantial ethical and cultural dimensions, and such solutions often fail (consider the example of nuclear power; see Pool 1997). Particularly where the "ethical infrastructure" is weak, special attention to the nontechnical aspects of such projects is critical. Not to do so is, quite simply, bad engineering.

**Implications for Engineering**

Conceptually, engineering lies somewhere between social and physical science. Engineered
artifacts and technological systems are basically the means by which science and culture are made manifest and therefore impact natural and human systems. As such, engineering at many different scales is integral to industrial ecology, and industrial ecology and engineering are both critical dimensions of earth systems engineering. Earth systems engineering, however, does not require that all engineers develop such a capability; rather, it is analogous to industrial ecology in that it augments, rather than replaces, the reductionist approaches and disciplinary fields that it integrates within itself.

Consider, for example, the carbon cycle governance mechanism sketched out above in figures 2 and 3. The need for electrical, mechanical, and civil engineers to design the components of each fossil fuel plant, each element of the hydrogen and electrical infrastructure, is not negated by the proposed coupling of individual components into a network facilitating engineering of the carbon cycle itself. Rather, the need is for a new type of engineer, one who can work with systems that are inherently different from those usually taught in engineering schools and designed or operated by most currently practicing engineers. Earth system engineers must begin with a far broader and more flexible background so that, working with the appropriate teams, they can understand and work with the many different dimensions—scientific, technological, cultural, ethical—that earth systems engineering projects will typically display and the broad variety of stakeholders that these complex and broad-scale projects tend to impact. Figure 5 illustrates another example based on a nested set of models, and implying the need for a wide variety of engineered responses, which could involve biological, hydrological, logistical, and/or other subsystems.

Obviously, the implications for engineering education are substantial, especially given the already full curriculum that an undergraduate engineering student must carry today simply to graduate. This, along with the advisability that any engineering student today have a recognized specialty (mechanical, electrical, civil, etc.), argues that earth systems engineering is perhaps best begun as a graduate program, and at least some schools appear to be exploring this direction.\(^2\)
Principles of Earth Systems Engineering

As the previous discussion indicated, existing ethical/theological systems, institutions, and levels of science and technology are not yet adequate to support the ability to responsibly engineer earth systems in toto, at least those of any complexity. Nonetheless, previous experience with large engineering projects (especially hydrologic and civil) and complex technological systems, such as the space shuttle program in the United States, global air transport control and safety programs, and nuclear power systems in many countries, provides at least some initial principles that should apply to earth systems engineering activities. These should be regarded as preliminary—indeed, only illustrative—at this point, but they at least warn that developing this critical capability in an environmentally constrained world will not be trivial (indeed, some would say impossible, but that appears unduly defeatist at this preliminary juncture). The following principles are suggested as illustrative, rather than definitive, at this point:

1. Only intervene when required and to the extent required. The traditional medical axiom, “first, do no harm,” is a reflection of humility in the face of complexity, which is equally appropriate for earth systems engineering. This principle, of course, should be interpreted in light of the fact that substantial human intervention in many fundamental natural systems—the carbon cycle, the nitrogen cycle, the hydrologic cycle, heavy metal and radionuclide cycles, DNA—has already occurred or, after all, one would not need to consider earth systems engineering. In such cases, the task is not to avoid unnecessary intervention but to reduce the undesirable effects of that intervention through more active and rational management of the human and natural systems.

2. Know what the objectives of any intervention are from the beginning and establish metrics to track progress toward satisfying the objectives and provide early warning of unanticipated or problematic system response. Requiring such preparation for earth systems engineering activities is useful not just in itself but because it implicitly requires that the boundaries of the system(s) involved are defined and at least a hypothesized model of systems behavior is developed.

3. Engineering such systems must not be based on implicit or explicit models of centralized control in the traditional rigid sense; such an approach is appropriate for a simple well-known system but not for the complex unpredictable (and quite possibly chaotic) systems involved in these cases. In many cases, these projects will require integrated management of coupled biological, physical, and traditional engineered systems, with high levels of uncertainty, and control and feedback mechanisms will be widely distributed along many temporal and spatial scales (NASA has faced some of these issues in its attempts to build space colonies; see NASA 1979). Rather than attempting to dominate a system—as is, for example, the case when a building or a chemical manufacturing complex is constructed—the earth systems engineer will have to see herself or himself as an integral component of the system, closely coupled with its evolution and subject to many of its dynamics on an immediate feedback basis, with all the self-referential implications. This will require an entirely different psychology of engineering.

4. It follows that, whenever possible, engineered changes should be incremental and reversible rather than fundamental and irreversible. Thus, for example, fertilizing oceanic planktonic populations with iron should begin (if at all) with small target plots, heavily monitored to determine whether the effects are as predicted and what the unanticipated effects are, a stage that should last at least as long as the temporal scales of the responding system require. The Ocean Farming, Inc. commercial-scale ocean iron fertilization proposal, for example, contravenes this principle. Similarly, a major problem with
projects such as the proposed dam across the mouth of the Mediterranean is that it is a large, single, relatively irreversible engineered intervention in a complex physical system (ocean circulation). There is no room for the continuous learning and feedback that incremental engineering interventions support. In all cases, scale-up should allow for the fact that, especially in complex systems, discontinuities and emergent characteristics are the rule, not the exception, as scales change.

5. In a similar vein, experience with existing systems engineering projects demonstrates that the focus of the earth systems engineer will be on the characteristics and dynamics of the system qua system—the interfaces, links, and feedback loops among systems components—rather than just on the constituent artifacts (Hughes 1998). The focus is on system state rather than on artifact construction. This systems focus, of course, aligns with the industrial ecology approach.

6. Continual learning at the personal and institutional level must be built into the process, as is the case now in “high reliability organizations,” such as aircraft carrier operations or well-run nuclear power plants (Pool 1997). This learning process is messy and highly multidisciplinary and, accordingly, difficult to maintain even in the best of circumstances. For the current generation of engineers and scientists (indeed, virtually all professionals), heavily influenced by their reductionist training, it will be particularly difficult. It is also problematic because the learning will probably have to occur at an institutional rather than personal level because of the complexity of the systems involved and the inability of any single person, no matter how qualified, to understand them in their entirety (Allenby 1999, 34–38 and 133–147). Yet, given the need for earth systems engineering management structures to be highly adaptive and sensitive to feedback from the system(s) at issue, and particularly sensitive to unanticipated responses, this is a critical principle.

7. Principles 1 through 6 lead to the important principle that earth systems engineering should explicitly accept high levels of uncertainty as endogenous to the engineering function rather than thinking of engineering as an effort to create a system certain. The mental model must be one of working within complex systems where uncertainty and variability are endemic, not simple systems where it is possible to define system outputs from known inputs unambiguously (Allenby 1999, 133–147). For example, as Morgan and Dowlatiabadi (1997, 574A) point out, “nonlinear processes that determine climate span roughly 12 orders of magnitude, from microscopic to planetary scales, and it is doubtful whether even future supercomputers will be able to model processes across as much as half that range.” These are the types of systems with which earth systems engineering will have to deal.

8. Similarly, because of the complexity of earth systems engineering projects, management and organizational skills will be as important to success as traditional engineering skills. Stakeholder management, transparent processes for defining and implementing projects, and managing to meet social and cultural, scientific, and technological objectives will be necessary. The need for flexible, intelligent management is heightened because appropriate reliance on decentralized mechanisms, such as markets, will undoubtedly be necessary in many cases.

9. An important goal in earth systems engineering projects should be to support the evolution of resiliency, not just redundancy, in the system. The two are different; a redundant system may have a backup mechanism for a particular subsystem but may still be subject to difficult-to-predict catastrophic failure and a resilient system will resist degradation and, when it must, will degrade gracefully, even under unanticipated assaults. A salt marsh, for example, will resist degradation as urbanization occurs in surrounding areas in part because many established bio-
logical communities, taken as an overall system, are resilient.

Thus, for example, a resilient strategy for global climate change management would include not just carbon cycle management using a variety of mechanisms (e.g., iron fertilization, carbon sequestration, reforestation) but a broader range of mitigation options as well (Rubin et al. 1992). If any single option fails or proves to be too expensive, the overall global climate change management program could adjust gracefully elsewhere using other mechanisms (e.g., energy efficiency and demand side management). Which is to say, each engineered option might be subject to failure but the system itself would be engineered and managed to be resilient.

Analogously, it is preferable to design (or encourage the evolution of) inherently safe systems rather than engineered safe systems. An inherently safe system fails in a noncatastrophic way; an engineered safe system is designed to reduce the risk of catastrophic failure, but there is still a finite probability that such a failure may occur. This is an issue of at least public perception given that the more complex a system, the less all possible failure modes can be identified and addressed. Light water nuclear power plants, for example, are engineered to be safe but, as Three Mile Island demonstrated, are not inherently safe technologies. Thus, for example, if one were concerned about underground carbon dioxide sinks potentially releasing substantial amounts of the gas in a lethal manner, one would preferentially use deep geologic aquifers under the ocean rather than under populated areas. If the former failed, the carbon dioxide would (most probably) be contained in the deep ocean; if the latter failed, the escaping gas might impact human (and other biological) populations.

There must be adequate resources available to support both the project, and the science and technology research and development, necessary to ensure that the responses of the relevant systems are understood. Financial pressures can be particularly insidious with complex engineering technologies even today; Pool (1997) cites the Bhopal Union Carbide chemical plant and the Challenger incident as examples where pressures generated in part as a result of chronic underfunding resulted in catastrophic failure of such systems. Earth system engineering projects are likely to be at least as complex as existing technological systems and last over longer time periods than the usual budgetary cycles, meaning that they may be particularly prone to financial fluctuations. A corollary is that financial pressures to perform or meet deadlines should not be permitted to jeopardize the intelligent conduct of the project.

If any earth engineering project is to achieve public acceptance and social legitimacy, it must at all stages be characterized by an inclusive dialog among all stakeholders. Not all will agree, for a number of reasons, but to be successful, a project requires broad public support. Thus, for example, genetic engineering continues because the benefits are broadly appreciated by most of society, even as the technology itself is still vociferously opposed by an active minority. Government regulation of such activity by environmental, and food and drug, agencies in most countries helps legitimate the activity, as does rigorous scientific peer review. Government regulation and scientific acceptance are not, however, sufficient in all cases, particularly where the public fears that they are being exposed to risk to benefit private interests. The most obvious example of a complex technology system where these mechanisms have proven inadequate is, of course, civilian nuclear power. In the United States, for example, the secrecy and technological hubris that grew out of the nuclear weapons program and the nuclear navy meant that both the regulators and the experts were culturally adverse to open communication and dialog, with eventual results for the industry that were both predictable and disastrous (Pool 1997).
13. It is not enough to evolve the scientific and technological base for earth systems engineering activities that, broadly speaking, falls under the field of industrial ecology. As the discussion above indicates, there must be parallel evolution along two other fundamental paths: ethical/religious and institutional. Keith and Dowlatabadi (1992), for example, in their discussion of potential elements of climate change mitigation technologies note such institutional issues as sovereignty (who has authority over such comprehensive projects?), equity (how are costs and benefits distributed?), liability (who is responsible for unanticipated effects or failure of the engineered system to perform?), and security (can elements of such projects be used as weapons?). Of course, the more fundamental questions—What kind of world does the human species want? And what kind will it choose? And who should, or will, choose for it?—must await an evolution of theology and ethics and institutions capable of implementing the eventual choices.

Conclusion

Earth systems engineering may be defined as the study and practice of engineering human technology systems and related elements of natural systems in such a way as to provide the required functionality while facilitating the active management of the dynamics of, and minimizing the risk and scale of unplanned or undesirable perturbations in, strongly coupled fundamental natural systems. It involves developing technologies and strategies for managing complex coupled human–natural systems at very different scales, from highly granular to broadly integrated, in a comprehensive manner. This new area of engineering can draw on significant experience from past practices and results, particularly derived from projects involving complex technology systems and large natural systems (e.g., irrigation), and can draw much support from the evolving field of industrial ecology. Even so, it is apparent that the science and technology, institutional, and ethical infrastructures to support such approaches do not yet exist, although progress in relevant disciplines and technologies has been made on a piecemeal basis. This, and the fact that unanticipated consequences of such major programs could be quite significant, argues for a cautious and balanced effort to begin such a program.

I close on a personal note. No one would wish to suggest earth systems engineering if it were not necessary: The possibility of irreversible and fundamental damage from irresponsible misguided projects that, by definition, are both critical to the stability of global systems as we now know them and require intervention in highly complex and little understood systems, is too great. Our hubris, and often politically convenient underestimation of costs, especially where they cannot be immediately quantified or are borne by someone else, have often led to problematic activities in the past. Such hubris would find a rich field were we to prematurely implement earth systems engineering projects. But we are faced with the stark reality of a human world; we are, already, unintentionally engineering the world with impacts, such as loss of biodiversity, that are irreversible. Fundamentally, then, the question is not whether humans are engineering earth systems but whether humans will do so rationally, intelligently, and ethically. And to do so means that we must begin building the capacity for earth systems engineering now.

Notes

The author is the Environment, Health and Safety Vice President at AT&T and Adjunct Professor at Columbia University's School of International and Public Affairs. The opinions expressed in this article are those of the author only and do not necessarily represent those of AT&T, Columbia University, or any other entity with which the author has been or is now affiliated.

1. I am using the generic term "deities" because the discussion at this point is intended to be quite general, cutting across many religions and cultures, both spatially and temporally. Many of these were or are not monotheistic, a point that this term recognizes.
References


