Earth Systems Engineering and Management

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The impact of human activities on natural systems of all kinds has grown to the point that we need to engage consciously in earth systems engineering and management.

I address why this is the case, and what I mean by such a provocative term. In addition, I explore what we can learn from relevant experience, and how this daunting task should be approached.

FALSE DICHOTOMY

Technology is the means by which human cultures interact with the physical, chemical, and biological world. It is through technology that a human imprint has been made on the physics and chemistry of every cubic meter of air and of water. Critical dynamics of heavy metals flows and grand elemental cycles — nitrogen, carbon, sulfur, phosphorus, hydrologic — are increasingly dominated by the (usually unintended and sometimes unforeseen) byproducts of the technological activities of our species. The biosphere itself, at levels from the genetic to the landscape, is increasingly a human product. Few biological communities can be found that do not reflect human predation, management, or consumption. As Gallagher and Carpenter [1, p. 485] remark in introducing a special issue of *Science* on human-dominated ecosystems, the concept of a pristine ecosystem, 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." Even those considered "natural" almost inevitably contain invasive species, frequently in dominant roles: "The world's ecosystems will never revert to the pristine state they enjoyed before humans began to routinely crisscross the globe . . . ." [2, p. 1836]. While it may be true that we as individuals did not deliberately set out to dominate the carbon or nitrogen cycle, or to create a planet of mixmastered species, our economic, technology, energy, and transportation systems — the linked technological, economic, and population growth characteristic of the Industrial Revolution — have had precisely that effect [3]-[7]. In short, the earth has become a human artifact. Science fiction books have long spoken of terraforming Mars; ironically, we have all the while been terraforming earth.

The increasingly tight coupling between predominantly human systems and predominantly natural systems is not a sudden phenomenon. Greenland ice deposits reflect copper production during the Sung Dynasty in ancient China (ca. 1000 B.C.), as well as by the ancient Greeks and Romans; spikes in lead concentrations in the sediments of Swedish lakes reflect production of that metal in ancient Athens, Rome, and medieval Europe [8], [9]. Contrary to popular belief, anthropogenic carbon dioxide buildup in the atmosphere began not with the industrial revolution with its reliance on fossil fuel, but with the deforestation of Eurasia and Africa over the past millennia [10]. Human impacts on ecosystems have similarly been going on for centuries, from the probable role of humans in eliminating megafauna in Australia and North America, to the clear role of human transportation systems in supporting invasive species around the world [2], [11], [12]. In this sense, recent books lamenting the "end of nature" [13] — "nature" taken as pre-human and pristine wilderness — obviously miss the mark by centuries. It is not that nonhuman "nature" has ended; rather, what such often anguished commentary represents is that the gap between the reality of the world as human artifact and the cultural construct of "nature" has grown so large that the fiction of "nature as other" can no longer be maintained.[1]

Thus, in a real sense there are no "natural" systems anymore, and the distinction between "human" and "natural" systems is somewhat misleading in its superficial clarity. Clearly there are phenomena, primarily geologic — volcanoes and plate tectonics come to mind — that human activities do not affect. But against this must be balanced the reality that the dynamics of most fundamental systems — the nitrogen, carbon, phosphorous, sulfur, and hydrologic cycles; the biosphere at various scales from genetic to regional; and the climate and oceanic circulation systems — are increasingly dominated by anthropogenic activities. Of course, there are degrees of influence: there are obviously systems whose dominant dimensions are nonanthropogenic, such as perhaps an isolated tundra biological community, and those whose dominant dimensions are anthropogenic, such as industrial or economic systems (and it is in this sense that this paper will refer to "natural" and "human" systems throughout). But the reality of tight coupling between the two domains must always be borne in mind. This is of particular importance given the well-known difficulty that social scientists and physical scientists have in communicating with each other, and the institutional realities of differing languages, communi-

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[1] *Although it is a basic and well-established principle of modern sociology that many concepts that people regard as self-evidently "real" are in fact cultural constructs, many people have trouble accepting this [23]. This is particularly true in the environmental arena, where advocates, who frequently are personally committed to concepts such as "wilderness" and "nature," view them as purely objective and self-evidently worth protecting as such. That different cultures may construe these constructs differently, or that they may be transitory reflections of a particular stage of Western thought as opposed to transcendent verities, is accordingly not accepted by many Western, especially American, environmentalists [15].*

ties, and worldviews between the two groups which exacerbate the natural–human dichotomy, and make integrated study of such systems extremely challenging.

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KEY THEMES

There are three important themes that weave through the evolution of the terraformed earth. The first is the relationship of humans to the planet. Initially, humans, then in a hunter-gatherer culture, were like any other species embedded in the biosphere, and their activities were endogenous to it. With the evolution of agriculture, however, the species began to evolve to dominate local natural systems and, with the deforestation of Europe and North Africa during the 10th to 14th centuries, began the process of climatic change as well [14]. At this point, elements of human culture grew to be exogenous to the natural systems they worked with, and the mental model of stewardship evolved: humans as caretakers for the relevant aspects of nature (primarily, as the stewardship image implies, pastoral). This model is still prevalent today, but it has been rendered obsolete by the industrial revolution and concomitant growth in human population, technology, and economic systems. Humans are now once more endogenous to fundamental earth systems, but in a different relationship than originally: they now increasingly define the dynamics and behavior of those systems. The journey has been from "being natural" (e.g., hunter/gatherer society), to opposing and controlling nature (the Enlightenment, settlement of the American West [15]), to absorbing nature into the human experience. Perhaps it is best, if somewhat simplistically, summarized by saying that human experience was endogenous to nature; now much of nature is endogenous to human experience.

A second important question involves the level at which subjectivity — independent status as a free, rational, and moral agent — is posited. The reason this issue arises is because, especially when looking at the effects of fundamental technological systems over long time frames, the idea that people "engineered" the results seems somewhat of a stretch. Thus, for example, virtually all island ecologies have been significantly impacted by invasive species in the last few centuries [4]. These species arrived as a result of the expansion of Eurocentric civilization, a cultural phenomenon, which was made possible by a complex evolution of technological capabilities (especially in transportation and navigation systems) and economic interests. If the concept of "engineering" is limited to the individual engineer and a particular artifact (e.g., an accurate timepiece), it does not make sense to say that the global restructuring of biota as a result of this process was "engineered." On the other hand, it is apparent that, although each engineering advance, and each voyage, may be taken individually, taken as a whole the processes involved were so ubiquitous and pervasive that they resulted in an anthropogenic restructuring of island biota (as well as a lot of other effects). Thus, what was not engineered at the level of the individual was arguably engineered at the level of society (in this case, European). Thus, the appropriate level of subjectivity in this case may be cultural, rather than individual.[2]

The reason this matters is because ethical responsibility vests at the level of conscious choice. If the scope of engineering, invention and design is limited to individual artifacts and projects, then it enables refusal to take operational and ethical responsibility for the systems effects. Thus, for example, it is apparent that human activities over the past millenium have con-

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[2] *The attribution of subjectivity (independent status as a free, rational, and moral agent) to levels of society higher than the individual, although it is not common in today's individualistic culture, has a long history in Western thought. Plato in The Republic held the structure of the polity and the individual to be analogous; Kant declared that his Categorical Imperative imposed a moral standard not just on individuals, but on the nation-state as subject; Hegel believed history was the coming into consciousness of human culture as a whole (the Geist, translated as "Mind" or "Spirit"); and Marx saw class, not individuals, as the relevant subjectivity. This is not simply a metaphysical issue: if subjectivity exists at levels higher than the individual, one can wonder what its dynamics, operational ethics, and desired outcomes are — and, critically, whether they align with the desires and ethics of individuals. The Western tradition implicitly assumes that they do, but it is not clear that this alignment is necessary logically, structurally, or operationally.*

tributed significantly to climatic change, and that shifts in climate, especially if accompanied by changes in oceanic circulation patterns, will have dramatic effects on biodiversity and human society (including, quite probably, mortality rates). But limiting the concept of human engineering only to the individual, artifactual level means that, despite current activity, there is no sense in which human society, taken as a whole, is yet being tasked with the moral obligation to respond rationally and constructively to its clear impacts on the carbon cycle and climate system.

It is therefore necessary to expand the definition of engineering, design, and management to the scale of the technological and cultural systems that are, in fact, now beginning to dominate the dynamics of many natural systems. This is a principal rationale for earth systems engineering and management (ESEM), which can be seen as the acceptance of responsibility for the ethical and operational implications of what the human species has already been doing for centuries, and is continuing to do at a rapidly increasing rate. It is not traditional engineering and project management — but neither is it a new and completely foreign concept. It is, in a sense, the denouement of the evolution of applied science and technology *(techne)* that began in ancient Greece and Rome, and has been globalized by the industrial revolution [16].

Another important theme is complexity, but here also a certain caution is necessary to avoid superficiality. For example, there has been a considerable literature recently implicitly drawing on the analogy between natural and ecological systems, and human systems. This can be useful, as the development of the field of industrial ecology demonstrates [17]-[19]. Indeed, both human and natural systems are similar in that they are technically complex; the learnings from the latter can indeed inform our understanding of the former. But the relationship is one of analogy. Failure to also understand the profound differences can lead to superficial reasoning or even nonsense — the burgeoning literature that suggests restructuring global capitalism or transnational corporations to resemble gardens is ample evidence of that. In particular, it is important to understand that human systems are of a different, and higher, class of complexity than natural systems. Human systems and human history are strongly affected by unpredictable contingency, partially as a result of the exercise of (bounded) free will, and the nature of humans as relatively autonomous, moral agents [20]-[23]. Moreover, human systems are characterized by a powerful reflexivity: a natural system such as a salt marsh is not changed by what a scientist may learn about it, but human systems, which internalize knowledge as it is developed, and thus change continually in an accelerating process of reflexive growth, are [24]. Additionally, the evolutionary processes of culture, technology, and social knowledge are uniquely human projects, with their own dynamics and timeframes, which have no parallel in traditional natural systems [14], [16], [25].

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CONTEXT

Thus, the context of ESEM requires that one comprehend not just the scientific and technological domains, but the social science domains — culture, religion, politics, institutional dynamics — as well. The human systems implicated in ESEM are extraordinarily powerful, with huge inertia and resistance to change built into them, and ESEM will fail as a response to the conditions of our modern world unless these are respected and understood. The evolution of eurocentric Judeo-Christian capitalist and technology systems has swept the globe [20], [21], [25], [26]. Relevant implications of this historical process include commoditization of the world, including nature, which in developed countries is increasingly purchased at stores in upscale malls, in theme parks (reflecting not "natural" ecological dynamics but late 20th century ideology, including, of course, corporate sponsorship), and as eco-tour packaged "experiences" [15]. The process of commoditization, the globalization of culture through movements such as, e.g., postmodernism,[3] and urbanization have had several fundamental effects. First, the concepts of "nature," "wilderness," and related terms are fundamentally changing for many people. Second — and contrary to the oversimplistic and mistaken idea that the world is, in globalizing, becoming more homogeneous and simple — the complexity of society, and of the couplings between human and natural systems, is increasing radically. A superficial homogeneity (e.g., proliferation of U.S. fast food options around the world) is more than overcome by the increased access to global cultures and artifacts of all places, kinds, and times enabled by world transportation and information networks (indeed, this cultural heterogeneity — pastiche — is the very foundation of postmodernism). Finally, this increased complexity is reflexively affecting the governance structures within which environmental and technological issues have traditionally been addressed: the absolute primacy of the nationstate is being replaced by a far more fluid, and complex, dynamic structure involving a number of stakeholders, including private firms, NGOs, and communities of all kinds.

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The implications of this evolution are not just of academic interest, but are absolutely pivotal to understanding the challenges faced by ESEM. Because of the increasingly tight coupling between human and natural systems, we are now reaching a point where the dynamics of natural systems are no longer governed simply by their internal structures and dynamics, but can only be understood in relationship to the human systems with which they are coupled. The systems implications of this are profound in two ways. First, it means that, from a systems perspective, the contingency and reflexivity inherent in human systems is imported into natural systems. Think, for example, of the carbon cycle and the way it is now being affected by the Kyoto process, and its associated scientific, institutional and cultural elements. Trying to understand this cycle without understanding its human elements would be foolish. Or consider the ecology of the Hawaiian Islands: it simply cannot be studied without dealing with invasive species of all kinds — and they, in turn, reflect the expansion of the eurocentric Judeo-Christian civilization, and associated technologies, especially transportation modes. The natural history of the Hawaiian Islands is a human history, written into its ecology.

The "humanization" of natural systems raises another absolutely critical point: the pivotal role of values in determining the structure of the external world. Because virtually all natural systems of any consequence have already been inescapably altered by human activity, there can be no question of returning to "pristine" nature (if such a state ever existed). Whether it is the Western U. S. or Hawaii with invasive species; Australia with the ancient extinction of magafauna; the Great Lakes, Baltic Sea, or Everglades; or just rebuilding a river ecology severely impacted by industrial activity — there is no "natural" state to return to. First, of course, all these systems have been evolving to respond to different conditions over geologic time; there is no particular "base state." With human intervention, they have been further modified — and any attempt to "restore" them is, in effect, a further modification to suit human cultural and ideological norms. Difficult as it is to accept — there is no natural history anymore: there is only human history. What these systems will be in the future

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[3] *Terms such as "high modernism" and "postmodernism" are not well defined, even in the relevant literature. "High modernism" approaches have tended to be elitist and technocratic. Think, for example, of Robert Moses and the way he drove his expressways and constructions through existing neighborhoods in New York City, destroying them in the process; or the way the old Soviet Union diverted the flows of two major rivers feeding the Aral Sea, the Amu Dar'ya and the Syr Dar'ya, resulting in changes in climate across Asia, extinction of some 85% of the fish species in the Sea; and a loss of 75% of the Sea's volume in a few short years. Postmodernism is generally atemporal and ageograpical, characterized by pastiches of cultures, times, places, and ideas; it also tends towards consumerism. Think of Disney's Epcot Center, with (primarily plastic) reproductions of bits and buildings from various times and cultures, from all around the world. A second principle characteristic of postmodernity is its insistence on moral and cultural relativism: if taken as supportive of multiculturalism and tolerance, this arguably informs an appropriate governance structure for ESEM. If taken at its extreme, of course, it is patently ridiculous. Harvey [20] and Anderson [47] are useful sources for exploring the nuances of modernism and post-modernism.*

is a human decision, a human choice. Having realized this, we cannot escape the ethical responsibility for that choice. But whose values will determine that choice — what religion, what culture, what subgroup? The centrality of values and ethical choice to environmental decisionmaking around the world is apparent.[4]

DEFINITION AND CASE STUDIES

Given this context, a more precise definition of ESEM can now be presented: ESEM is the capability to rationally engineer and manage human technology systems and related elements of natural systems in such a way as to provide the requisite functionality while facilitating the active management of strongly coupled natural systems. ESEM also aims to minimize the risk and scale of unplanned or undesirable perturbations in coupled human or natural systems. “Technology systems” in this sense is to be read broadly, as the means by which human beings interact with their environment; it thus includes not just artifacts, but the economic, cultural, and ideological context within which they are used.[5] As the examples below illustrate, ESEM in many cases will deal with large, complex, evolving projects and technologies, with complicated governance, ethical, scientific, cultural, and religious dimensions and uncertainties. It does not replace traditional disciplines such as political science, economics, sociology, engineering, or physical and biological sciences: rather, it draws upon and integrates them in the context of ESEM applications, and thus expands them as well. ESEM augments, but does not replace, existing fields.

In most cases, the social and physical scientific and technical knowledge necessary to support ESEM approaches is weak or nonexistent, and the evolution of the institutional and ethical capacity necessary to complement ESEM is, if anything, in an even more primitive state. Accordingly, ESEM is best thought of as a capability that must be developed over a period of decades, rather than something to be implemented in the short term. It is also important to note that ESEM is not “new” in that it argues that humans as a species should now begin to engineer the world. That is already happening. What is new about ESEM is the assumption of responsibility for what we as a species are already doing, and the determination to develop the capability to do so more rationally and ethically.

> The biosphere itself, at levels from the genetic to the landscape, is increasingly a human product.

ESEM is a new field of study and practice, but it does not spring from nothingness. Rather, it builds on practices and activities that are already being explored, some newer and less developed than others. In this, it is like industrial ecology, which is an umbrella area of study including both applied methodologies (such as life cycle assessment, or LCA, and design for environment, or DFE), and research methods (such as materials flow analysis, or MFA). Thus, the first case study explores an ESEM methodology, “adaptive management,” which has been developed in the context of resource management. The second looks at urban areas as ESEM projects. There is obviously a huge body of knowledge and several disciplines that deal with this subject matter — much of which is informative for the development of ESEM principles. What the ESEM approach adds in this instance is a new envisioning of urban centers (particularly megacities, defined as over ten million population) as nodes in energy, material, ecological and knowledge systems scaled from the local to the global, across many time scales, and involving many different kinds of human systems. The third case study looks at carbon cycle and climate system management efforts, an area where the ESEM approach is already latent (in geoengineering proposals, for example), but where the rational, comprehensive, systems-based ESEM approach has yet to be adopted. Finally, the last case study involves scenarios drawn

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[4] *It is also extensively ignored, for many reasons. First, many of the stakeholders — environmentalists, technologists, scientists, industrialists - are naïve positivists, and don’t recognize the value-laden mental models with which they approach these issues and conflicts. Second, most people of any stripe are much more comfortable speaking the “language of science” rather than the “language of values,” even when it is clearly values that are at issue. Thus, discussions around the Kyoto Accord are often framed in technical terms, when in fact what is at issue are very different concepts of the world [35], [48].*

[5] *As Grubler [14, p. 21] comments, “...technology cannot be separated from the economic and social context out of which it evolves, and which is responsible for its production and its use. In turn, the social and economic context is shaped by the technologies that are produced and used.” Heidegger [16, p. 35] in his essay “The Question Concerning Technology” takes the more extreme position that “the essence of technology is nothing technological,” in that technology reflects the essence of being human, and cannot be separated out from the project of human evolution.*

from the infomation revolution: these illustrate both the complexity of the issues with which ESEM must deal, and the almost complete ignorance which characterizes current understanding.

> The cultural construct of "nature" has grown so large that the fiction of "nature as other" can no longer be maintained.

Adaptive Management and the Everglades

An excellent example of an ESEM methodology where considerable work has already been done is "adaptive management," defined in one of the leading texts as providing "ways for active adaptation and learning in dealing with uncertainty in the management of complex regional ecosystems" [27, p. ix]. Adaptive management techniques have been developed in part in response such challenges as reengineering the Everglades, restoring the vitality of the Baltic Sea, managing toxics in the North American Great Lakes region, or establishing longterm forestry management programs in New Brunswick and elsewhere. Although still nascent, adaptive management even at this initial stage provides a number of important principles for the broader umbrella concept of ESEM [27], [28].

As an example, consider the Everglades. This unique ecosystem has been altered by an 1800 mile network of canals built over the last half century to support agricultural and settlement activity, which has diverted some 1.7 billion gallons a day of water flow. Invasive species, especially the melaleuca and Australian pine, are outcompeting native species, aided by human disturbance (e.g., draining marshes, increasing fire frequency). The nesting success of birds, a predominant animal form in the Everglades, has declined at least 95% since the mid-1930s. The natural cycles that once defined and supported the Everglades in a stable condition, including rainfall and water distribution patterns, and nutrient cycles, have been profoundly affected by human settlement patterns, agriculture, tourism, industry and transportation systems and, importantly, the various management regimes which have been attempted over the past 100 years. And nothing more clearly illustrates the coupling between "natural" and "human" systems than the Everglades, for perhaps the most important single factor in the biological structure of the Everglades is the sugar subsidy which supports the predominant form of agriculture in the area [29].

In response to the imminent danger of collapse of the Everglades as a functioning ecosystem, a $7.8 billion Everglades restoration project has been proposed. Its intent is to restore waterflow to previous levels, while continuing to support industrial, agricultural, settlement, and other human activity. The process by which this evolution will be guided I take to be "adaptive management." Especially given the political and policy divisions, not to mention differing values with which people approach this issue, it is not clear whether this extraordinary challenge can yet be successfully accomplished.

An ESEM approach, while including the adaptive management process, might be said to subtly change the problem definition as well. Rather than primarily reacting to a perceived set of perturbations with the goal of "restoring" a previous state or "setting things right," ESEM begins by considering the Everglades — and most similarly situated earth systems — as products of human design. Whether intended at the level of the individual engineer or manager, or not, human modification of the fundamental dynamics of the Everglades has already occurred. There is no "pristine" system to return to, and Florida will not be depopulated. Even if it were, the species distributions and natural cycles have been altered by humans, and will evolve in different ways as a result. The Everglades are now, and always will be, a system defined by humans: it will never be "natural" again. The challenge thus becomes not one of restoration to a hypothetical past state, but one of ethical and rational choice based on projections of systems evolution over time. In other words, where adaptive management has a certain flavor of responding to immediate pressures (reactive), ESEM seeks to understand, engineer, and manage over time, accepting that the evolution of the Everglades has become a human design responsibility (proactive). Note that this does not negate the need for adaptive management, especially in the short term; rather, it suggests that adaptive management is an important part, but only a part, of an integrated ESEM approach.

Urban Areas

Another instructive ESEM case study is provided by major urban areas. Great cities are, after all, highly complex; combine human and natural systems at all scales; have enormous implications as centers of material and energy flows; are nodes of significant consumption; and are where a large and growing human population increasingly centers. The difficulties of megacity governance, especially in developing countries, are well documented. The complexities of major projects within megacities, such as the Boston Central Artery/Tunnel construction project, are also well known. The challenges posed by megacities to the environment and future human wellbeing are also substantial: estimates are that about 80 million people a year are moving into cities, mostly in the developing world — that's the equivalent of establishing 8 new megacities a year for the foreseeable future.

Urban areas have been studied and discussed for a long time, so this class of examples of ESEM is a particularly rich source of insights. The most obvious one, perhaps, is an appreciation of the depth of our ignorance: no one has yet mapped a large city in terms of its impacts across both geographic and temporal scales. What impacts does a megacity actually have on fundamental natural systems, and at what scales? We just don't know; this is obviously a major research target for ESEM.

Beyond that, the relevant literature offers hundreds of years of discussion about the interplay between culture and technology systems in the urban context. Thus, for example, the rise and fall of high modernism in urban planning and development is instructive. High modernism generally is characterized by an imperial, elitist, and technocratic approach with a deep contempt for the "barbarism" of the past; it ignores local context and culture in the interest of implementing "universal, scientific" principles, often at great human cost (think of Faust). In urban development and engineering, the high modernist approach is perhaps best personified by the work of Le Corbusier and Robert Moses. The former attempted to impose geometric perfection on the urban landscape, demanding that cities be planned with reference only to science and geometry [30]. Critics such as Jane Jacobs have pointed out that this effort to impose Platonic idealism on a complex, dynamic, human system was ill-conceived, hubristic, and doomed to failure, a critique that has generally been accepted [31], [32]. Moses brooked no interference from the unwashed masses, and his grandiose constructions across New York City, while they have inspired some, have been held by others to be responsible for destroying the human vitality of significant city spaces such as the Bronx [31], [33]. By way of comparison, consider the approach taken by the engineers managing the Boston Central Artery/Tunnel (CA/T) project. The initial phase of their activities consisted of seeking public input and working with local neighborhoods and stakeholders, as they recognized that an infrastructure project of the scale proposed, which would change the structure of downtown Boston significantly, would fail unless it met the needs of local communities and cultures, as well as broader regional infrastructure demands [34]. Jencks discusses similar examples in Great Britain [32, pp. 104-106]. The lesson is not that major engineering projects cannot be done in urban settings, but that they must be understood not just as technocratic undertakings, but as contributions to an evolving cultural system that must be environmentally sensitive, to boot.

But there are limits to the ability to simply apply systems engineering, no matter how culturally and environmentally sensitive, to complex human/natural systems. In this regard, it is instructive that efforts to apply systems engineering approaches and principles to urban redevelopment, which were especially popular in the 1960s, universally failed [34, pp. 165-185]. Thus, systems engineering and management approaches can be applied *in the context of* complex megacity environments *to specific projects*, but are not sophisticated enough in themselves to engineer and manage megacities as a system.

Given our analysis above, this should be no surprise. Individual projects that can treat cultural dimensions as important but bounded by project definition are of a different dimension of complexity than managing the city system as a whole. The latter necessarily includes human systems of many different kinds and at many different scales, with their inherent contingency and unpredictability, as endogenous.

Thus, several important conclusions regarding ESEM can be drawn from the urban case studies. For one, even in such well-studied areas, there are large gaps in knowledge that become apparent when one takes an ESEM perspective (e.g., how do urban centers function in material and energy networks?). The urban example also makes clear the danger of hubris (particularly technological hubris) and oversimplification: high modernism has proven to be a dysfunctional approach to urban issues, and even systems engineering, a less ideological and more sophisticated discourse, has not been effective. And this is perhaps the most profound lesson to be drawn from these case studies: cities are, to a large extent, self-organizing systems, and any decision-maker's ability to manipulate them directly is quite limited. So it is with much of ESEM; a proper knowledge of our limits when working with such complex systems is critical.

Global Climate Change Mitigation

A third example of nascent ESEM is provided by the effort to mitigate global climate change. There are many aspects of this process which are highly desirable; in general, for example, the scientific effort and organization (e.g., establishment of the Intergovernmental Panel on Climate Change) are exemplary. Moreover, there are an encouraging number of independent initiatives intended to identify technological opportunities to either reduce climatic change (e.g., engineering the Earth's albedo) or adjust to global climate change once it occurs.

The negotiations process is less encouraging. To begin with, it essentially treats the earth as just one big factory, attempting to impose what amounts to a command-and-control, end-of-pipe solution on the global economy as a whole. Moreover, the global climate system, with dynamics extending over a period of centuries, is tightly coupled to major human technology systems — energy, transportation, material transformation, agriculture — yet the technological discourse has not been a major component of the climate change negotiations, which are dominated by an environmental (and to some extent an economic) discourse. Equally problematic, fundamental cultural and ethical issues may be the most important part of the climate change debate, yet they remain a peripheral element of the negotiations, and are frequently disguised in technological or scientific jargon. Implicit in these negotiations is perhaps the most important ethical question we as a species will have to answer over the next decades — what kind of world do we want to design? — yet it is not being raised, and certainly not being addressed, in the negotiating process.[6] The lack of a comprehensive, systematic approach is apparent in this case study. The process is far from recognizing, much less addressing, the real challenge: to accept responsibility for engineering and managing the carbon cycle, and the climate system, as a whole [35].

An ESEM approach begins by including all relevant considerations, including the technological — in essence, drawing the right boundaries around the problem. Applied to this case study, it immediately calls into question the fundamental lynchpin of the current approach: limit use of fossil fuels. Rather, one begins by recognizing that many major developing countries will be under strong pressure to use fossil fuels, especially coal, as the basis for their energy systems: not to do so, which could well consign them to permanent underdeveloped status, is not likely in the real world. This, in turn, focuses attention on a critical technological question: Is it possible to burn fossil fuels in central power plants and not contribute to climatic change?

It now appears that the answer may be yes, that carbon dioxide resulting from fossil fuel combustion in power plants can be captured and sequestered for centuries to millenia in the ocean, deep aquifers, geologic formations, or other long term sinks. Although there are some economic and energy penalties, the technologies for accomplishing this are available and feasible [36]. With appropriate engineering and feedstock selection, the power plant can be designed not as an emitter or as a non-emitter, but as a variable-release control node in a managed carbon cycle system. Moreover, the plant can produce a mixture of secondary energy sources, especially hydrogen and electricity, which can support most energy use throughout the economy. In short, looking at social and cultural constraints — the inevitability of attempts by developing countries to grow their economies, which will require significantly more energy generation capability than they have now — combined with technological sophistication, immediately begins to offer a whole set of options that to date have not even been part of the political process.

Although the carbon sequestration technology is critical given highly probable energy generation scenarios, at least over the next half-century, many other ways to manage the carbon cycle and, thereby, to stabilize the climate system, exist. Biomass plantations, ocean fertilization, energy efficiency, evolving technology mixes, different patterns of living and built infrastructure — all will have some impact: the question is really not whether they will, but whether they can be blended into a system that is rationally understood, designed, and managed (remembering the humbling lesson from urban management all the while). Accordingly, the ESEM fossil fuel plant system must be taken as just one component of the ESEM project to engineer the carbon cycle. But, of course, the carbon cycle especially is not independent of other natural and human cycles. It is tightly coupled to the nitrogen cycle, for example (as we are liable to find to our dismay when a massive shift to biomass as a carbon sink and source results in yet further perturbations to that little understood cycle). And the carbon

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[6] *A critical point implicit in many of the global environmental discourses is whether it is ethical to privilege the present. Thus, for example, global climate change negotiations seek to stabilize current climatic conditions, which removes an important source of variability that has affected the evolution of life on this planet. It thus seeks to remove an important driver of biological evolution. Opposition to biotechnology implicitly privileges current genetic structures over what may be evolved in the future. This privileging of present systems, human and biological, is a powerful ideological and ethical statement that is surprisingly unconscious for most participants in these dialogs. More generally, of course, there is no generally accepted answer to the question of what kind of world humans do (or should; the two are not the same) want, but a dialog that explores the options, including their distributive costs, benefits, and risks, is highly to be desired. Not addressing such a fundamental issue does not make it go away, but simply turns it into a social pathology as it is expressed dysfunctionally in other ways.*

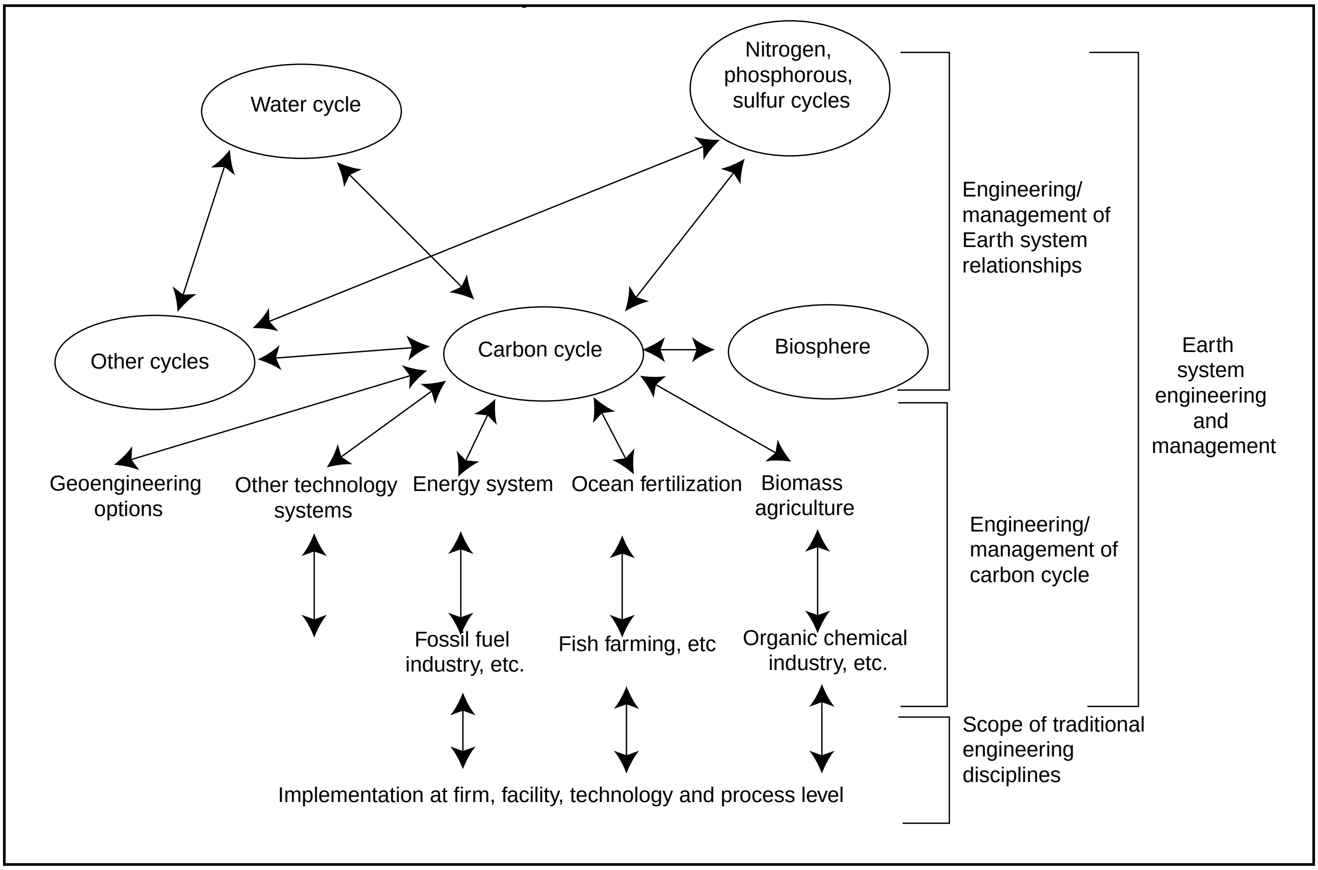

Figure 1. Earth Systems Engineering and Management: Carbon Cycle Schematic

cycle cannot be considered without thinking of the biosphere, which in turn raises questions about genetically modified organisms (GMOs), and the role of genetic engineering in managing the carbon cycle [3].

Throughout history, humans have continually designed and engineered the carbon cycle. That is, of course, what agriculture is all about. In this instance, however, engineering and managing the carbon cycle itself is not the critical goal; it is stabilizing the climate system (and, concomitantly, the oceanic systems as well). There are additional technological means by which this can be accomplished, which come under the general idea of geoengineering. For example, Johnson [37] has proposed building a dam across the Strait of Gibralter in an effort to avoid climate-change-induced shifts in high-latitude oceanic circulation systems. Similarly, a number of proposals that would change the reflectivity of the planet have also been made (for example, injecting a fleet of thin aluminum balloons in space between the earth and the sun, which would reduce the amount of energy striking the earth's surface) [38], [39]. By and large, these appear to be regarded by the primarily environmentalist community negotiating global climate change issues as more science fiction than possible alternatives — if they are considered at all. This begs the real question, of course, which is the risks, costs, and benefits of geoengineering alternatives compared to other options. This, in turn, may in large part depend on how well each proposal meets the ESEM principles discussed at the end of this article: the Gibralter Dam, for example, is neither incremental nor easily reversible, while a test of a small amount of aluminum balloons might be feasible, and is reversible since the balloons could be designed initially to fail quickly, thus providing test data at (possibly) low risk.

The current climate change negotiation process illustrates a particular inflexion in human history. ESEM is clearly implicit in the project — manage all human activities so as to change existing anthropogenic contributions to certain fluxes in the carbon cycle, with the goal of stabilizing climatic and oceanic systems. Indeed, this case study provides a useful illustration of ESEM and its implications. Thus, Fig. 1 provides an overview schematic (one of many possible given the complexity of the system) that illustrates three conceptual levels. At the highest level, the effort is to maintain desired functionality of fundamental cycles (natural ones are illustrated; obviously, human systems such as agriculture, forestry, and fisheries are also integral to this project, but they are not listed for simplicity's sake). At the next level, systems and technologies pertaining primarily to carbon cycle management are designed and managed, but, in sharp contrast to existing practices, they are treated as a portfolio of options: the effort is to achieve desired performance of the carbon cycle as a whole, not just any single alternative. Finally, it is important to remember that underlying many of these options are "traditional" engineered systems: ESEM supplements, but does not replace, these activities.

As Fig. 1 makes clear, the mental models, knowledge base, and institutional capacity have yet to catch up to the reality. With the carbon cycle in particular, one must engineer and manage on a global scale. But this does not mean centralized control, or legislated universal mandates — the globalization of command-and-control. Rather, it means that whatever mechanisms are used to move towards the desired state (which has yet to be defined in any coherent, explicit manner) must rely on decentralized governance mechanisms, disparate cultures, and complex, ever-shifting constellations of technical, economic, and social alliances. The importance of information, and information embedded in market function, could not be more apparent. And that introduces the last case study: looking at the information industry, and information infrastructure, from the ESEM perspective.

ESEM and the Internet

One way to define a complex system conceptually is by the amount of information required to uniquely define it: the more information required, the more complex the system. Similarly, it is apparent that an essential basis of human existence, and the *sin qua non* of cultural and technical evolution, is information of all kinds — embedded, implicit, explicit, scientific, technological, mythological, religious. I posit that we must learn to engineer and manage a world that is rapidly evolving towards greater complexity, and where human systems are an increasingly important component of most fundamental systems. I obviously imply a central role for information and information systems (an agglomeration some people call the infosphere). This case study, then, raises the question of how the Internet might be regarded as an ESEM case study.

As in the case of the the carbon cycle/climate system, it is useful to begin by defining different relevant levels of the system. Depending on the purpose of the analysis, there are a number of ways that this could be done. In looking at the Internet and its potential environmental and social implications, we can identify four levels relating to infrastructure impacts. The first level is compliance of existing infrastructure operations with current law and regulation (infrastructure meaning not just the platforms supporting service, such as switches, routers, and fiber, but also the manufacturing facilities that make them). The second is reduction of environmental impacts associated with infrastructure operation; in the case of artifacts, this is increasingly captured by practices such as Design for Environment and product takeback. Network energy consumption and other important suppliers to network operations would also be included. The third is the direct impacts of the services based on the Internet and supporting platforms: telework, for example. The fourth is the indirect effects of services and the Internet itself — or what happens when cultural evolution accelerates dramatically as a result of the explosive growth in knowledge and information made possible by the Internet.

The compliance level is conceptually trivial: it is being done currently, both in the manufacture of infrastructure and technology platforms, and in their operation by service providers. It is a fairly well-understood activity, with relatively little uncertainty and cultural content. While not unimportant, for purposes of ESEM, it may be disregarded. The second level, direct infrastructure impact, is more problematic than compliance, but is at least conceptually fairly clear. It is at the third and fourth levels, then, that complexity and lack of knowledge become dominant — and, conversely, ESEM issues are most engaged. Two scenarios, one of a direct impact (telework) and one of an indirect impact, can help illustrate this point.

One familiar scenario is provided by telework, a generic term for any situation where an employee works away from a central office location (telecommuting, or working from home, for example). At many companies, telework is increasingly recognized as an important "triple bottom line" technology. It benefits firms economically, because they save on rent and can retain valuable employees, and because teleworking employees are generally more productive. It provides social benefits because employees and their families enjoy a higher quality of life. Moreover, traffic congestion, a major problem in many urban and suburban areas, is reduced, which benefits everyone who uses the roads. It provides environmental benefits because emissions are reduced if unnecessary commuting is limited; moreover, to the extent congestion is eased, emissions from all vehicles are reduced marginally as well [40], [41]. In all these cases, however, the data are incomplete to some degree, and the extent to which economic and cultural patterns will change over time in unpredictable ways must be considered in any comprehensive cost/benefit assessment. For example, is it likely that, in the longer term, the availability of Internet infrastructure, combined with the delinking of place with work, might [not] lead to completely different patterns of built environment with concomitant implications for demand for products (enhanced e-commerce); transportation systems (more dispersed populations requiring greater private transport); impacts on the vitality of urban centers; or increased gaps in quality of life between the "haves" (knowledge workers that could choose where and how to live, and pull entertainment, information, and personal connectivity from the Internet) and "have nots?"

Another instructive service scenario involves the rapidly growing phenomenon of e-commerce [42], [43]. In some applications, implementation of e-commerce sysems can cut waste significantly, leading to dematerialization of existing industrial operations. For example, it enables companies to shift from offering products, to offering services, with concomitant dematerialization of economic activity. Consider Home Depot, which has shifted from simply selling stuff to small contractors — its most important customer segment — to offering a web site service. Contractors log in, enter details of their job, and the Home Depot software calculates what they will need and arranges for just-in-time delivery to the job site, eliminating the usual industry practice of overestimating materials, which then get wasted. What is ordered gets used. Or consider the new practice of printing books on demand: each book has a customer waiting, eliminating huge amounts of paper and energy which would otherwise be used to print and distribute books which never get sold, and end up being returned to, and discarded by, the publisher. Or consider the case of Dell Computers. The usual practice in the computer industry is to maintain a 60 to 80 day average inventory. Especially given the rapid pace of technological evolution in that industry, that translates into a lot of inventory that never gets sold, thus becoming waste (and the warehouse space and transportation systems that are used, as well as the manufacturing impacts embedded in the product, are also wasted). Dell, on the other hand, uses its e-commerce systems, both upstream and downstream, to operate on about 6 days of inventory.

Well, so what? Are these dematerializing and energy efficiency effects important or not? No one honestly knows — and, in truth, no one knows how to go about thinking about these issues yet. For example, economic history asserts that advances in productivity have led to more, not less material consumption — and, as e-commerce is potentially a revolutionary jump in economic and material productivity, it might have just that effect. Dematerializing the specific, by shifting supply and demand functions throughout the economy, might just end up enabling discontinuously higher levels of consumption. Which dynamic will be the more important — and how policy can affect those dynamics to achieve greater economic, environmental and social efficiency — cannot be determined at this point and, indeed, is one of the reasons why ESEM research in this area is important.

In looking at the indirect effects of Internet services, consider also the possibility that the growth of information infrastructure may result in a profound shift in the technological grounding of perceived personal freedom. Currently, the technology that most people associate implicitly with their sense of personal freedom is the automobile; indeed, it is the predominant icon of individual freedom in the world (a major reason why certain regimes seeking to oppress women restrict their ability to drive).[7] This is one reason why regulating things like SUVs in the U.S. or speed limits on the autobahns in Germany is so difficult. However, it is foreseeable that personal freedom will increasingly be associated with access to the Internet and information services, a trend that broadband access to information systems, and the aging of populations in many countries, would significantly reinforce. Were this to occur, could it facilitate management of environmental impacts arising from transportation? Would it make, for example, speed limits on the autobahn more politically feasible? Do e-commerce and teleworking, which empower individuals, mark important stages on this route?

This case study in particular raises questions that might seem overly daunting at this point, and the temptation might be to just quietly let them lie. But, as in the other case studies, that ignores the important point that the dynamics inherent in information infrastructure and the Internet are not going to go away just because we think they are too complex for analysis. Whether we want to think about them or not, the interactions between these human technology systems and natural systems are both real and, potentially, extraordinarily powerful. As we continue to introduce these technologies, and they interact with each other, with our cultures, and with natural

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[7] *See, e.g., [18]. It is interesting, but not surprising, that the most powerful technological systems are those that provide significantly enhanced individual freedom. Energy technologies, automotive and transportation technologies, and now information technologies — all have a unifying characteristic of providing a greatly enhanced sense of individual freedom, whether from drudgery (energy technologies) or from place, or from social domination. Conversely, those societies that seek to reduce human freedom limit access to such technologies, whether it is by forbidding women to drive, or limiting access to the Internet.*

systems at various temporal and geographic scales, we also create the obligation to engineer and manage them as best we can. And that is a start.

APPLICATION PRINCIPLES

The discussion above illustrates several points. First, the difficulty and complexity of the systems with which ESEM must deal is obviously daunting: indeed, existing ethical and moral systems, economic and political institutions, and levels of scientific and technical knowledge are utterly inadequate to the task. But that does not mean that we can't begin to characterize ESEM by relying on lessons from adaptive management concepts, systems engineering, urban planning, and the evolution and management of complex technological systems such as the Internet, global air transport control and safety programs, and the like. Based on such experience, some preliminary ESEM principles can in fact be identified. These can be roughly sorted into three categories: theory, governance, and design and engineering.

> In short, the earth has become a human artifact.

Theory

The theoretical underpinnings of ESEM reflect several important realities, particularly the scope and scale of the systems involved, and our current levels of (often under-appreciated) ignorance. Accordingly, perhaps the most important principle of all is, appropriately, precautionary:

1) Only intervene when necessary, and then only to the extent required. This principle, similar to the medical admonition, "first, do no harm," is based on the same rationale: when faced with a complex, uncertain, inherently unpredictable, system, minimal interventions reduce the probability and potential scale of unanticipated undesirable system responses. Humility, not hubris, is called for.

2) At the ESEM level, projects and programs are not just scientific and technical in nature, but unavoidably have powerful economic, political, and cultural dimensions; in many cases, ethical and even religious considerations will be important as well. An ESEM approach should integrate all these factors.

3) Unnecessary conflict surrounding ESEM projects and programs can be reduced by recognizing the difference between social engineering — efforts to change cultures, values, or existing behavior — and technical engineering. Both need to be part of ESEM projects, but they are different disciplines and discourses, involving different issues and worldviews, and cannot be substituted for each other.

4) It follows from the above principles that ESEM requires a focus on the characteristics and dynamics of the relevant systems as systems, rather than just as the constituent artifacts. The artifacts will, of course, have to be designed in themselves as well; in this way, ESEM augments, rather than replaces, traditional engineering activities.

5) Boundaries around ESEM initiatives should reflect real world couplings and linkages through time, rather than disciplinary or ideological simplicity. It cannot be overemphasized that ideology, whether explicit or implicit, inevitably is a (frequently inappropriate and dysfunctional) oversimplification of the systems at issue and their dynamics, and such approaches should be avoided to the extent possible.

6) Major shifts in technologies and technological systems should be evaluated before, rather than after, implementation of policies and initiatives designed to encourage them. Thus, for example, encouraging reliance on biomass plantations as a global climate change mitigation effort should not become national or international policy until predictable implications — further disruption of nitrogen, phosphorus, and hydrologic cycles, for example — are explored.

Governance

Many authors have commented on obvious changes in the global governance system, which is migrating away from a model where the nation-state is sovereign, to one characterized by complex interactions among private firms, NGOs, communities, nation-states, and other interest groups [44], [45]. These changes, combined with the complexity of human and natural systems, give rise to a second category of principles involving ESEM governance.

1) ESEM initiatives by definition raise important scientific, technical, economic, political, ethical, theological, and cultural issues in the context of an increasingly complex global polity. Given the need for consensus and long-term commitment, the only workable governance model is one which is democratic, transparent, and accountable.

2) If any ESEM 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. The approach must be that of Salvucci, the leading systems builder on the Boston CA/T project, not that of Moses in New York City.

3) ESEM governance models, which deal with complex, unpredictable systems, must accept high levels of uncertainty as endogenous to the discourse, and view ESEM policy development and deployment as a dialog with the relevant systems, rather than a definitive endpoint. ESEM governance structures should accordingly place a premium on flexibility, and the ability to evolve in response to changes in system state and dynamics, and recognize the policymaker as part of an evolving ESEM system, rather than an agent outside the system guiding or defining it.

4) 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 [46]. This learning process is messy and highly multidisciplinary, but it is particularly critical with ESEM projects, which in many cases will involve significant experimentation and a highly interactive relationship with the systems at issue. 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. Current institutional and policy structures have generally been incapable of this degree of openness and learning [27], [28], so this must be regarded as a significant initial challenge for ESEM.

5) There must be adequate resources available to support both the project, and the science and technology research and development which will be 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 [44] 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; the rash of recent failures of the NASA Mars missions offer a reinforcing example.

Design and Engineering

Finally, there are a set of principles that inform the design and engineering of ESEM systems. These may operate at different design and implementation levels for a given ESEM project — for example, they may apply to projects involving ocean fertilization with iron to encourage phytoplankton growth and carbon dioxide uptake as a global climate change mitigation option, but not to global climate mitigation as a whole. They may also not be possible to satisfy in each instance, particularly if rapid action is needed to avoid irreversible and highly undesirable consequences. Nonetheless, taken together they do form the basis for desirable engineering practice in an ESEM environment.

1) Know from the beginning what the desired (and reasonably anticipated) outcomes of any intervention are, and establish quantitative metrics by which progress may be tracked. Additionally, predict potential problematic system responses to the extent possible, and identify markers or metrics by which shifts in probability of their occurrence may be tracked.

2) Unlike simple, well-known systems, the complex, information dense and unpredictable systems that are the subject of ESEM cannot be centrally or explicitly controlled. Rather than being exogenous to a system, the earth systems engineer will have to see herself or himself as an integral component of the system itself, closely coupled with its evolution and subject to many of its dynamics. This will require an entirely different psychology of engineering.

3) Whenever possible, engineered changes should be incremental and reversible, rather than fundamental and irreversible. 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. Lock-in of inappropriate or untested design choices as systems evolve over time should be avoided.

4) 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 still be subject to difficult-to-predict catastrophic failure; a resilient system will resist degradation, and, when it must, will degrade gracefully, even under unanticipated assaults. Accordingly, inherently safe systems are to be preferred to engineered safe systems. An inherently safe system, when it fails, 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.

ESEM AND EARTH AS ARTIFACT

Earth systems engineering and management may be defined as the capability to rationally engineer and manage human technology systems and related elements of natural systems in such a way as to provide the requisite functionality while facilitating the active management of strongly coupled natural systems. The need for ESEM arises because, as a result of the industrial revolution and concomitant changes in agriculture, population levels, culture, and human systems, the world has become a human artifact. Partially because this process has occurred over time frames that are longer than individual time horizons, and has involved institutions and technology systems rather than conscious individual decisions, recognition of this phenomenon, and appropriate responses, have yet to occur. Indeed, it is apparent that the science and technology, institutional, and ethical infrastructures necessary to support such a response have not yet been developed. The issue is not, however, whether the earth will be engineered by the human species: that has been and is already occurring. The issue is whether humans will do so rationally, intelligently, and ethically.

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