Earth stewardship

Peter M. Eisenberger

The idea of Earth Stewardship has many origins but it was perhaps most dramatically imprinted on our consciousness as we witnessed the images of our planet as it was viewed from the Moon in 1969. Starting with Earth Day in 1970 in the United States and similar activities in other developed countries, increasing attention both politically and scholarly, has been paid to the nature of human impact on our planet. Politically, a new broad consensus—one that declares we need to be concerned about human impact on the environment—appears to have emerged in the developed countries. While there is consensus on the need to moderate our impact, significant disagreements exist about how much wealth-generation activities and other human endeavors need to be reoriented to protect the environment. Furthermore, tensions have emerged between the developed and underdeveloped countries as to who should pay and who should operate under the greatest constraints. These can be viewed as the first of many difficult choices we will need to make to achieve wise stewardship of our planet. Failure to make those choices wisely will create various threats to U.S. and global security.

Scientific studies have revealed distinctive signs that human activities are having impacts on a global scale. The ozone hole, signs of global warming, species extinctions, and pollution of our water, land, and air have been connected to human actions. Furthermore, the earth sciences have continued to enhance our understanding of the large natural changes in environment and species that occur even without human impacts. We now clearly recognize that the Earth's interior, surface, and atmosphere are a dynamic web of interconnected systems that have been and will continue to be subject to changes that produce significant consequences for humans. Examples include major glacial periods, smaller regional climatic changes, large scale volcanic eruptions, earthquakes, and even possibly the impact of comets or meteors from space. Our ecological studies have revealed that the net impact of these natural variations on species that occupied our planet before us has been dramatic, to the point of causing periodic mass extinction (Raup 1988).

In spite of the broad consensus on the need to moderate human impact on the environment, there exists a polarization as to how we should proceed. The polarization is at all levels: internationally, between developed and underdeveloped countries; between corporations seeking to create wealth by providing products and services for our use and governments concerned about the environment; between the recreational interests of individuals and the environmental concerns of other individuals.

The stakes in choosing the right path and then providing wise stewardship for our planet are great. In purely economic terms, natural systems that provide the energy, water, air, and other resources we need would cost an enormous amount to provide, even if it were possible, through human technologies. (A recent workshop at the National Center for Ecological Analysis and Synthesis concluded that the value of natal services is comparable to the gross world product [Costanza et al., submitted to *Science* November 1996].) The dislocation effects of massive climate change on a short time scale are hard to estimate but are in all likelihood large. However, any reduction in worldwide wealth generation will cause increased poverty and human misery promoting social instability. It will also weaken our ability to invest in the future and thus obtain the knowledge and tools to become wise stewards. Deeper spiritual and ethical issues are also of concern, striking at the core of our identity and our relationship to the natural world. This has moved E.O. Wilson to suggest a policy of zero species extinctions as an ethical requirement for our policies.

In the course of debating how we should proceed, extreme views have dominated the discussion. Global warming possibilities have been translated into massive global changes, species extinctions have led to speculation of destabilizing the global ecosystem, and population growth has been viewed as a threat to the planet. On the other hand some contend that the Earth is much more robust and that human ingenuity will be powerful enough to cope with natural and anthropogenically induced changes. Proponents of this view point to the enormous progress made since the first Earth Day in 1970 (Ausebel 1996). Furthermore they argue that without a robust economy we will not have the wealth needed to provide for human needs and to protect the environment, not to mention potential social upheaval.

What is particularly noteworthy about this intense debate, in spite of the fact that considerable progress has been made, is that while most people ultimately invoke global arguments, nobody really knows how the Earth system will respond either to future natural or human disturbances at any other scale than the very local (e.g. the river will be polluted if you dump toxic substances into it). We are beginning to understand some regional issues (e.g. identification of key components of ecosystems), but at the global scale there is almost no understanding of the impact of human and nonhuman changes. Those that are predicting doom or those that are confident of our ability to cope are simply guessing because of our incomplete understanding of the complex linkages that exist between all the components of the Earth's system and the resulting response that those linkages will provide at a global level. It is much like arguing about the impact of a particular action on human health in the absence of an understanding of some important parts of the immune system and its response to a particular treatment.

One way to quantify our current lack of understanding and simultaneously define the need for enhanced research efforts is to list a set of questions whose answers we need to know in order to make wise decisions on how to proceed.

Carrying capacity

- How many people can our planet support and at what cost to the environment as a function of consumption patterns and technological capability (e.g., pollution reduction systems, technology)?

Risk assessment

- How can we make meaningful risk assessments in cases of low probability outcomes with great impact?

- How can we identify beforehand the possible health consequences to humans and the biosphere of particular wealth generation (technology) or lifestyle options?

- How can we determine the robustness of the Earth/human systems to both natural and human perturbations?

- How can we best monitor the health of the Earth and its inhabitants to get an early warning on possible adverse effects?

Predictability

- How can we maximize the societal and environmental benefit of our increasing ability to predict climate (e.g., agriculture, flood control, human and ecological health)? How can we more generally transform knowledge of how physical, ecological, and social systems function into effective outcomes?

Preparing for change

- How and where can we best develop human habitats to minimize damage from natural phenomena (e.g., floods, earthquakes, etc.) as well as minimize its negative impact on the environment?

- How can we design the structure and infrastructure of our economy and business world to promote the greatest wealth generated at the lowest cost to the environment?

- How can we best protect other species and ecosystems (especially those that perform no "useful" function)?

Education/learning

- How can we provide the education/learning needed for humankind to make informed decisions with respect to the many tradeoffs we will continue to face (e.g., wealth generated versus environmental health)?

These questions and many others cannot be answered by studying an individual part of the Earth or human subsystem. Therefore, we need to extend our current studies by pursuing a more integrated approach that involves consideration of many parts of the Earth/human system. In turn these studies can help provide the knowledge base for wise global planning, global mitigation and global engineering. Taken together they can provide the basis for wise stewardship of our planet.

In describing a research program to provide the needed knowledge base, it is clear that both natural and human actions taken in one region of the Earth can impact those in other regions and countries, even places very distant from the sources. A clear example is our growing understanding of the connection between what happens in the seas off South America and the climate in North America, the eastern rim countries of the Pacific, as well as sub-Saharan Africa. This means that new global mechanisms for deciding upon and implementing Earth Stewardship will be required. Due to a lack of expertise, these very important issues will not be addressed here in any detail. In general terms, there is the critical need to include the social and political sciences as part of the research agenda in order to help develop the new policies and infrastructure needed to support wise stewardship.

In addition, as our understanding of Earth systems evolves there will clearly be a need to incorporate that understanding into our educational system at all levels. We need citizens to participate in the process of making the difficult tradeoffs that will almost certainly be required. Professionals in all kinds of endeavors will need to be informed so that they can also make the appropriate tradeoffs. The required educational reform and efforts will not be described though they clearly are a challenge to which our schools, universities, and informal learning institutions must respond.

Finally the description of the proposed research agenda will be quite general. This is not only required because of the limited expertise of the author, but more importantly, because deciding exactly how to proceed will require a planning effort involving leaders from a broad spectrum of disciplines and perspectives. The main point of this paper is to emphasize the need for a total systems approach for wise stewardship. This paper will end by describing a possible process for determining the priorities for a national research agenda.

Proposed research agenda

The proposed research agenda has three related components and bears some loose analogy to what has evolved in the health sciences. The proposed program for a "healthy" Earth/human system has one component that can be regarded as the search for the DNA equivalent for understanding the basic mechanisms that organize the Earth/human systems. The second is equivalent to the human genome project through which one will try to understand the relationship of the various Earth system component (e.g. air, water, soil, species) or human systems (policy, economics, law, health, technology) to one another and their impact on the overall system performance. Finally, the third component will be the equivalent of disease specific and public health studies and will involve increasing our detailed understanding of the individual components of the Earth/human system and the processes and approaches that can mitigate our adverse impacts. These disciplinary based studies must continue to be strongly supported even as we begin our efforts to focus on understanding the systems aspects because they will serve as the testing ground for our understanding of the overall system.

Global system

What kind of system describes the way the Earth responds to perturbations and how will (can) our human system respond? Is the Earth/human system noise driven, an example of chaotic systems that have been used in meteorology, population biology and economics, and that are now being further considered by some physicists? Does the oscillating pattern in the history of our planet's climate and number of species represent some fundamental concept similar to Turing's explanation of pattern generation in biological systems (e.g. why do zebras have stripes?) (www.pmi.princeton.edu/faculty/ECC.html). Applied mathematics is increasingly interested in nonlinear modeling systems that have a series of low-probability outcomes with great impacts. Can such an analysis help us understand the Earth system or how to perform a more enlightened decision analysis or risk assessment? Alternatively, is the system simply complex without unifying concepts similar to the genetic code? If so, how far can we go with brute force modeling given the expected enormous increase in information processing and modeling that will emerge in the next ten years? Such modeling will involve very difficult temporal and spacial scale issues given the range of phenomena that need to be considered. Alternatively, if such brute force modeling is not possible, what simplifying approaches will enable us to capture the significant elements?

All candidates for an increased understanding of the total Earth system should be tested on the past history of the evolution of Earth systems wherever possible before being applied to future predictions. The systems studies and the information gathering activities on the changing Earth systems, such as conducted by the Earth Observing System (EOS) or data collected by the U.S. Geological Survey (USGS) need to be coordinated to ensure that the needed information is acquired.

Similar efforts need to be conducted within the social sciences to help develop more quantifiable models to describe the dynamics and responses of human systems to internally and externally driven changes. These should include such key topics as population studies, resource and information flows, economic and decision making systems. While for the lay public the reduction of human systems to quantitative analyses may be troubling, it is essential that we develop as quantitative an approach to human systems as possible to provide a common language for the physical and ecological investigators to converse with each other and with their social science colleagues in order to obtain a comprehensive understanding. There is a critical need for this discourse because the questions we need to answer span the traditional disciplines. This will be a very difficult challenge but we must begin to build the bridges in order to be able to effectively translate our increased understanding into effective social action. Our universities and colleges have a critical role to play in developing our ability to carry out the need discourse. Thus, one needs to augment the current disciplinary approach to education and research with courses and new infrastructure that will enable the needed multidisciplinary efforts to succeed. The gap that currently exists between the generators of scientific knowledge and technological innovations and those responsible for designing human systems (e.g. political, legal, economic) must be closed at all levels including research, education, and actual decision making.

From the above it is clear that a direct study of the overall global system will require a very broad range of disciplines and will be extremely challenging, so it must attract the best and brightest. Initially at least it does not need to be a large effort, but rather should promote a diversity of approaches. As progress is made, investments in the most promising aspects should be appropriately increased.

Systems linkages

Because of the great complexity involved, the attempt to directly understand the Earth/human system is a very difficult, some might even say impossible, task. Yet it is critical that we advance our understanding as quickly as possible to help us make the difficult choices that lie ahead. As is the case for many other complex challenges, one can make considerable progress by identifying the key factors that underlie the complexity. For example, our study of ecosystems has already identified various areas where certain “keystone” species are essential for the survival of the overall ecosystem. Therefore, in addition to the attempt described above to extract the basic nature of the total Earth/human system and discover a conceptual simplifying framework, is the need to enhance our understanding of the key linkages (strong coupling and resonances) that characterize the overall system.

As stated earlier, the questions we need to answer will depend upon our understanding of the important connections between the various parts of the Earth/human system. Here again there may be some value in drawing an analogy with the health sciences in that we know for humans that 90% of DNA appears to have no function. In a similar manner one might expect that there are some critical sites and phenomena in the overall Earth system that, if perturbed, could have serious impacts while others may not be important for the global system. An example of the former is the El Niño effect where it is recognized that what occurs at the atmosphere/ water interface off the west coast of South America can have a serious impact on larger scale Earth system behaviors. On the other hand, comparable sized spots on the Earth have experienced massive changes in their basic character with no perceived global impact. From a more fundamental level it is a general characteristic of nonlinear systems to have certain excitations that are resonant in the sense that under certain conditions their amplitudes become very large when either driven from external perturbation or in some cases simple system noise. In mathematical terms some perturbations will experience positive feedback and grow while others will be reduced by negative feedback.

Attempts to identify such resonances and feedback mechanisms in the physical/ ecological Earth system will clearly serve two purposes. The first goal, of course, should be to identify areas in which we need to be particularly careful with any human activity that could trigger a resonant excitation. Of course, these sensitive spots or actions can have serious negative consequences but also if completely understood could serve as control points to offset potential negative developments caused by other actions either by the other Earth system excitations or human activities. These could become candidates for Earth engineering projects in the future when we better understand the overall system.

The second benefit from such a study of course is that they inform our attempts to understand the complete system and they become prominent features that proposed conceptual frameworks will need to explain. To carry out such studies will require experts in each of the subsystems to work together to identify and understand such resonances and, of course, will require funded programs that can evaluate and support such multidisciplinary activities. Again, here a comparable analysis is appropriate for the human activities: economic, health, legal, and political (policy) systems. Namely there will be certain areas that can critically influence how the overall systems will respond to increased knowledge of the tradeoffs between wealth generation and quality of life considerations and the impact on the environment.

A specific example would be the issue of the best approach for achieving needed reduction in pollutants in our atmosphere. One would clearly need to establish and integrate policy, legal, economic, and health-related approaches to achieve the needed reduction in the impact of pollutants in a cost-effective manner. The market mechanisms and legal sanctions chosen have had, and will continue to have, a profound impact on the nature of economic activity that will result. This in turn will determine the cost-benefit ratio of a particular remediation approach. An example of this was the reduction of $S0_2$ in which a market mechanism was used instead of command and control to achieve the reduction at a much lower cost. The choice of one technological approach over another for achieving a reduction can also be very important. An example of this is that if the United States had decided to subsidize mass transportation rather than financing the highway program, which supported the automobile industry, the transportation system and its impact on the environment would be considerably different than it is today. In this context the new field of industrial ecology is likely to be of increasing importance in helping to analyze industrial and government practices from a systems perspective that explicitly includes evaluation of the environmental and revenue cost impacts of various choices.

Individual systems

The organization of the current research enterprise has resulted in a very high quality understanding of individual Earth systems in isolation. One way of classifying the disciplinary work which has taken us to our current state and also, of beginning to think about how to proceed next is illustrated in Figure 11-1. In the context of that figure the classical disciplines of chemistry, physics and geology have focused on physical systems; biology and the medical sciences have focused on life systems; and social sciences and engineering have been centered on human processes. By and large the physical and biological have been thought of as natural while the purely human has been considered unnatural, at least within the context of western philosophy.

As we move ahead to build the understanding needed to provide wise planetary stewardship, we must expand our endeavors to include problems that lie at the intersections of Figure 11-1. As a parallel endeavor, we must, as described above, also continue to support the excellent disciplinary work that has produced our current state of understanding and knowledge.

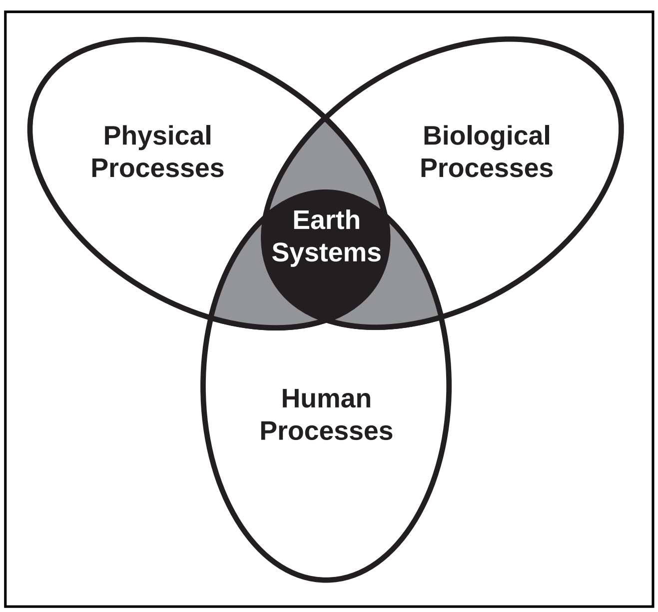

Figure 11-1. Classification scheme for disciplinary and interdisciplinary investigation of earth systems.

1. The physical system

—*Atmospheric gases.* By far the most prominent example of our understanding of the physical systems of our planet as they pertain to Earth Stewardship has to do with the chemical composition of the atmosphere and its relationship to the average temperature of the atmosphere. While there is still debate concerning the impact of changes in the chemical composition of the atmosphere, it is well established that in the history of our planet, changes related to glacial and interglacial periods have included significant changes in the concentration of CO_2 and other atmospheric gases. The relationship between the temperature distribution at Earth's surface and changes in the composition of the atmosphere is currently a rapidly advancing field. Since the first report by the Intergovernmental Panel on Climate Change in 1990, the scientific community has advanced from a statement that it would be on the order of a decade before confident statements could be made with regard to the anthropogenic signal in atmospherically driven changes in temperature, to the cautious statement of the second IPCC assessment released in 1996 that indicates a human signal is present in current changes in climate. That rapid change in confidence reflects dramatic advances in our understanding of the warming effects of greenhouse gases and the compensating cooling effects of atmospheric aerosols and in our ability to construct computer models of increasing spatial resolution that incorporate our rapidly advancing understanding of atmospheric chemistry and physics.

—*El Niño /Southern Oscillation.* El Niño is an oceanographic phenomenon in which the thermocline along the western coast of South America deepens and results in significant climatic variability throughout the eastern Pacific Rim. The Southern Oscillation is an episodic change in the large-scale atmospheric pressure of the southwestern Pacific region. The associated changes in pressure change the atmospheric circulation and also result in significant climatic variability.

Circulation of the atmosphere and of the ocean are both fluid dynamics problems albeit with dramatically different scaling considerations. In classical studies of these two systems, they were considered independently with the unstudied system serving only as a boundary condition for the system of interest. The realization that the El Niño and Southern Oscillation phenomena are fundamentally linked has led to dramatic advances in our understanding of seasonal-to-interannual climate variability. That work has been driven by focused study of the coupling between the atmosphere and ocean circulation systems and has opened the possibility of understanding of the atmosphere/ ocean system as a whole. Our current understanding is such that we can predict sea-surface temperature in the central Pacific 12–18 months in advance with useful confidence (Cane et al. 1994). From that prediction we can also make statements with confidence concerning the climate in specific regions spanning the globe.

2. The life system

—*Historical biodiversity.* Over the roughly 4.5 billion years that Earth has supported life, there have been dramatic changes in the character and diversity of that life. Perhaps the most dramatic change in the character of life on Earth is also related to the most fundamental change in the composition of the atmosphere: the emergence of photosynthesizing organisms and the development of free oxygen in the atmosphere.

The fossil record that supports most of what we know about extinction and species origination is most reliable following the evolution of shelled organisms about 600 million years ago. These organisms emerged in a radiation that produced most of the major phyla and dramatically increased the number of species. Since that time species extinctions have been nearly as common as originations.

On occasion in the history of Earth there have been events in which the majority of the species extant have been extinguished. The largest of these occurred about 250 million years ago and removed about 52% of the families. Efforts to extrapolate that number to species yields extinctions on the order of 77% to 96%. The mass extinction at the end of the Cretaceous (~65 million years ago) is believed to have been caused by an asteroid impact. Even in this relatively recent event there is debate concerning the mechanisms of mass extinction. Current estimates of the number of species range an order of magnitude (~3–~30 million). The current state of understanding indicates that current extinction rates related to the destruction of habitats probably far exceeds the background rate.

The range of historical and current estimates and the lack of certainty concerning mechanism are symptoms of the great difficulty associated with making statements concerning the diversity of life on Earth. Much work remains to be done on such fundamental questions as the continuity versus episodicity of extinction and the role of extinction events in the long-term processes of evolution.

—*The diversity/stability debate.* Much of the ongoing debate concerning current biodiversity issues is centered on the relationship between the magnitude of biodiversity and the function and stability of ecosystems. In particular the working hypothesis is that greater biodiversity leads to greater stability in ecological systems. While there are studies that seem to demonstrate this principle for particular ecosystems (Tilman and Downing 1994), the mechanisms that would underlie such a relationship remain elusive. This is primarily due to the difficulty in doing controlled experiments in open systems with large numbers of free parameters.

At a recent meeting at the Biosphere 2 Center in Oracle, Arizona, a group of leading ecologists began to consider how facilities such as Biosphere 2 might address such complex issues as the relationship between diversity and stability. In particular, discussion of the role that large experimental facilities such as Biosphere 2 might play in isolating underlying mechanisms was begun.

3. The human system

—*Political economy.* If it has no other effect, the Rio conference clearly articulated the inextricable link between environment and development. Beyond the physical sciences, it may well be that economists have been the most vocal in their discussions of greenhouse warming and resource use issues. As noted above, the most vociferous debates concerning stewardship in the 21st century are those surrounding how we should act in the face of our growing understanding of the relationship between anthropogenic forcing and planetary function.

Economics seems to be the driving force of today’s environmental destruction. Since World War II the world has used resources voraciously in the pursuit of industrial growth. The situation can be described as the industrial countries overconsuming resources, which are overextracted and exported by developing countries and traded at prices that are often below social costs. The disparity in the use of resources—such as petroleum or agricultural commodities—between industrial and developing regions, the North and the South, is a central problem in economics (Chichilnisky 1994). The key issue now is how to achieve a swift transition to a more sustainable pattern of economic progress, one that avoids replicating resource-intensive patterns of industrialization. There are sound reasons to avoid resource-intensive economic development in the South. Latin America and Africa have followed traditional resource-intensive patterns of growth and lost ground. The successful Asian model has been more knowledge-intensive. It is vital that we achieve a swift transition to knowledge-intensive economic progress, one that uses human capital as the main engine of growth and is compatible with the conservation of the ecological infrastructures that support human life on Earth.

A ray of hope is the advent of a "knowledge revolution" in selected regions, based on explosive increases in the productivity of human capital and on the use of information technology as a fuel (Chichilnisky 1996). In any case the development of forward-looking economic institutions that improve the connections between markets and the environment seems essential to achieve a harmonious relation between humans and the biosphere.

—*Industrial ecology.* An emerging paradigm for guiding the design and evolution of industrial economies is the analogy between industrial systems and ecological systems. The analogy draws primarily on the model of an industrial sector as a process that transforms inputs into outputs. To the extent that the outputs from one activity can be the inputs to another, the need for external sources and sinks can be reduced. In the limit, an economy would require only incoming energy and would emit only entropy. In the largest sense, this must be the long-term state for the planet as a whole. For finite (but depending on the fuel source, possibly very long) periods of time, we can use energy and materials at a rate that is greater than incoming solar radiation, but this only reflects the fact that we have great reserves of energy that has been stored over geologic time.

As an emerging discipline, industrial ecology considers flows of materials and energy through economic systems and searches for ways to minimize the overall impact of that economy on the health of Earth as a whole. Thus there may be situations where the waste or toxicity of a sub-element of an industrial system actually increases. Such increases will be more than offset through improvements in the system as a whole. The methods and units of analysis in industrial ecology are still in their infancy, but their foundation as an integrative endeavor is firmly established. This larger picture has implications that span from individual manufacturing processes to the organization of economies themselves.

Conclusion

The above general description for approaching the study of global systems will help provide the basis for global planning, global engineering and global mitigation. They, in turn, together with more local and regional approaches, provide the basis for wise stewardship of our planet. The main thesis is that we will need to make some very difficult choices within the foreseeable future for which we currently lack the basic underlying physical, ecological, and human system knowledge and the engineering and social tools to implement them. This is not because a catastrophe is predicted, because a central tenet of this paper is that enough is not known to make such a prediction for the Earth system as a whole. Rather it is suggested that in any case difficult choices will be forced upon us by sociopolitical considerations and we need to be careful. These choices have the potential for great impact on the world's wealth generation capacity and biosphere. Mistakes will be very costly in terms of wealth generation and the environment and can have a large impact on social or biosphere stability and thus U.S. and global security.

While not the focus of this paper, it is clear that in the course of obtaining the knowledge we will be redefining our relationship to other species and our role and responsibilities as wise stewards. The spiritual, ethical, and existential dimensions of the changes this will provoke have the potential to be as profound as the impact of Copernicus and Galileo on our perception of our place in the universe. In the end, that impact can be as important as the increased direct knowledge of the Earth/human system to our future well-being and security.

Next steps

There are two reasons that a "going-to-the-moon" systems' approach is more appropriate than the current significant, but fragmented and insufficient efforts. The first is that there are large potential threats to U.S. and global security that could occur as a result of our initiating actions whose consequences are unknown. Can we really afford to continue to gamble? Given what is at stake it would seem appropriate to approach the task of obtaining the needed knowledge and tools with a sense of urgency. Second, the knowledge, engineering and social tools we need require an integrated approach. This paper has described in very general terms, the systems research that needs to be pursued. As explicitly suggested in the introduction, there are questions that need to be answered in order to implement wise stewardship and thus avoid threats to U.S. and global security. The following process is a suggestion to be followed to determine the specific types of programs and levels of effort:

(1) Determine a list of critical systems-related questions evaluated both for importance and for likelihood of obtaining the answer with a research effort.

(2) For each of the critical questions (ranked on the basis of the sum of the rankings of importance and likelihood of progress) develop a research agenda that specifies the types of studies and levels of effort. For important questions where progress will be difficult given the lags in state of knowledge and tools, develop a priority list for longer term investments in knowledge-base building and tool development. In describing the proposed programs, for each question, one should determine the physical, biological and social science components so that one can translate increased knowledge to useful action.

The "going-to-the -moon" character of the proposed efforts might suggest the need for a separate organization to coordinate the program as well as to establish the needed accountability to ensure that the necessary progress is made in a cost-effective manner.

References

Ausebel, J. H. 1996. The liberation of the environment. *Daedalus*, 125(3), 1–17.

Cane, M. A., G. Eshel, and R. W. Buckland. 1994. Forecasting Zimbabwean maize yield using eastern equatorial Pacific sea surface temperature. *Nature* 370:204–205.

Chichilnisky, G. 1994. North–South trade and the global environment. *American Economic Review.*

Chichilnisky, G. 1996. The Knowledge Revolution. *Journal of International Trade and Economic Development.*

Costanza, R., R. d'Arge, R. de Groot, S, Farber, M. Grasso, B. Hannon, S. Naeem, K. Limburg, J. Paruelo, R. V. O'Neill, R. Raskin, P. Sutton, P., and M. van den Belt. The total value of the world's ecosystem services and natural capital. *Science* (submitted November 1996)

Raup, D. M. 1988. Diversity crises in the geological past. In *Biodiversity* (51–57), edited by E. O. Wilson and E. M. Peters. Washington, D.C.: National Academy Press.

Tilman, D. and J. A. Downing. 1994. Biodiversity and stability in grasslands. *Nature* 367:363–365.

.