EARTH SYSTEM ANALYSIS *for* SUSTAINABILITY

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Much of the media's coverage of science this year has been a retrospective narrative about the universe and our origins within it: Albert Einstein's *annus mirabilis* of publications, which upended understandings of time, space, and the atom, celebrates its centenary in 2005, and one of modern biology's key building blocks, Charles Darwin's *Origin of the Species*, has made headlines as part of a scientific-cultural divide in certain U.S. communities. While a great deal has been said about what these important scientific works have taught us, looming questions remain about our own planetary system, our interactions within it, and our ability to steer ourselves toward a sustainable future. To answer such large questions, an even more fundamental shift in humankind's research agenda, particularly regarding the analysis of the total Earth System, is in order. Fortunately, such a shift is already under way and will actually complete a millennium-scale development in the history of science.

In 1543 Nikolaus Copernicus published *De Revolutionibus Orbium Coelestium*, which set the stage for the development of modern scholarship. Not only was the Earth finally put in its correct astrophysical context, but the first principles of "exact and objective" reasoning, ultimately triumphing in the Enlightenment, were also established: The perception of cosmic reality held by Copernicus's followers (for example, Galileo, Kepler, and Newton) became dominated by the clockwork metaphor, assigning a regular trajectory governed by eternal physical laws to each particle in the universe. As well, the production of wisdom became dominated by the curiosity-driven mode, confronting the brightest minds with the ultimate riddles of creation in splendid isolation from sociopolitical interests—and from each other. Thus the great Copernican Revolution generated a paradigm in which the lonely scholar wrestles with nature to snatch some of her secrets encoded in mathematical formulae of utter beauty.

In 2001, delegates from more than 100 countries participating in the 4 major international research programs on global environmental change endorsed the Amsterdam Declaration on Global Change, which formally established the Earth System Science Partnership and set the stage for what one might call a second Copernican Revolution.[1] The concept of this novel revolution is deeply rooted in the original one yet transcends it in several crucial ways:

- The scientific eye is redirected from outer space to our "living Earth," which operates as one single hyper-complex system far from the thermodynamic equilibrium characterizing "dead" planets like Venus.[2]

- Scientific ambition is requalified by fully acknowledging the limits of understanding as highlighted by the notorious uncertainties associated with nonlinearity, complexity, and irreproducibility.[3] If the Earth System is a clockwork at all, then it is an organismic one that baffles our best anticipatory capacities.

- The scientific ethos is rebalanced by accepting that knowledge generation is inextricably embedded in the cultural historical context: There is nothing wrong with being particularly curious about the items and issues that matter most for society or recognizing that the coveted borderlines between observing subjects and scrutinized objects have often been mere constructions of a preposterous reductionism.[4] Thus, the research community becomes part of its own riddles, the research specimens become part of their own explanations, and co-production becomes the (post)normal way of coping with the cognitive "challenges of a changing Earth."[5]

The Anthropocene

The very fact that the Amsterdam Declaration resulted from an intricate cooperative process—and not from one ingenious idea of a stand-alone intellectual giant—adequately reflects the co-productive mode that will be instrumental for the much-debated "new contract between science and society."[6] Even a superficial look at the current state and dynamics of our planet indicates that the sustainability of modern civilization is at risk without such a contract. For today, we live in what may appropriately be called the "Anthropocene": a new geologic epoch in which humankind has emerged as a globally significant (and potentially intelligent) force capable of reshaping the face of the Earth past all recognition.[7]

LOOMING QUESTIONS REMAIN ABOUT OUR OWN PLANETARY SYSTEM, OUR INTERACTIONS WITHIN IT, AND OUR ABILITY TO STEER OURSELVES TOWARD A SUSTAINABLE FUTURE.

An up-to-date understanding of how human actions have brought about and are accelerating the Anthropocene is the necessary foundation for any serious effort to harness science and technology for sustainability. The recent reports of the world scientific community's decade-long research programs on global environmental change and the Earth System provide such a foundation.[8] Drawing from the works of hundreds of researchers, those reports concluded that perhaps 50 percent of the world's ice-free land surface has been transformed by human action, and the land under cropping has doubled during the past century at the expense of forests, which declined by 20 percent over the same period. Further, more than 50 percent of all accessible freshwater resources have come to be used by humankind. Fisheries remove more than 25 percent of the primary production of the oceans in the upwelling regions and 35 percent in the temperate continental shelf regions. Many enclosed seas (like the Gulf of Mexico) have been turned into virtual dead zones, and many rivers (like the Colorado, the Nile, and the Huang-He) now reach their coastlines as mere trickles due to human interference.

The same reports also confirm that more nitrogen is now fixed synthetically and applied as agricultural fertilizers than is fixed naturally in all terrestrial ecosystems. Overapplication of nitrogen fertilizers in agroindustry and nitrogen's high concentration in domestic animal manure have led to eutrophication of surface waters and groundwater in many locations around the world. These and other human activities (see below) also enhance the microbiological production of nitrous oxide (N_2O), a powerful greenhouse gas and a source of nitrogen oxide (NO) in the stratosphere, where it is strongly involved in ozone chemistry.[9]

Also affecting the Earth's atmosphere is humanity's exploitation of fossil fuels since the Industrial Revolution, which has resulted in a large pulse of air pollutants. The release of sulfur dioxide (SO_2) to the atmosphere by coal and oil burning is at least two times larger than the sum of all natural emissions, which occur mainly as marine dimethylsulfide from the oceans.

The oxidation of SO_2 to sulfuric acid has led to acidification of precipitation and lakes, causing forest damage and fish death in biologically sensitive regions such as Scandinavia, northeastern North America, and, more recently, East Asia. As a result of substantial reduction in SO_2 emissions, the situation in the former two regions has improved somewhat over the last decades; however, in East Asia, the problem has gotten worse. The release of NO into the atmosphere from fossil-fuel and biomass combustion is likewise larger than the natural inputs, adding to rainwater acidity and giving rise to photochemical ozone (smog) formation in extensive regions of the world.[10]

Humanity is also responsible for the presence of many toxic substances in the environment, particularly the 12 substances (including DDT (dichlorodiphenyltrichloroethane), PCBs (polychlorinated biphenyls), and furans (in particular, polychlorinated dibenzofuran, PCDF)) banned by the Stockholm Convention.[11] Certain other exhalations of the anthropospheric metabolism, the chlorofluorocarbon gases ($CFCl_3$ and CF_2Cl_2, collectively CFCs), are not toxic at all but have nevertheless led to the Antarctic springtime "ozone hole." CFCs would have destroyed much more of the ozone layer if international regulatory measures had not been taken to end their production by 1996. However, due to the long residence times of those gases, it will take at least another four to five decades before the ozone layer will have recovered. It is crucial to note that the discovery of maximum reduction in stratospheric ozone came as a total surprise. This phenomenon was not predicted by "traditional" science; it occurred in a section of the atmosphere furthest from the regions of CFC releases to the atmosphere and where ozone loss was thought to be impossible. The Earth System science expected to emerge from the second Copernican Revolution will have to do better by predicting at least the possibility of future "ozone holes"—that is, major disruptions of some planetary modes of operation (see the next section).

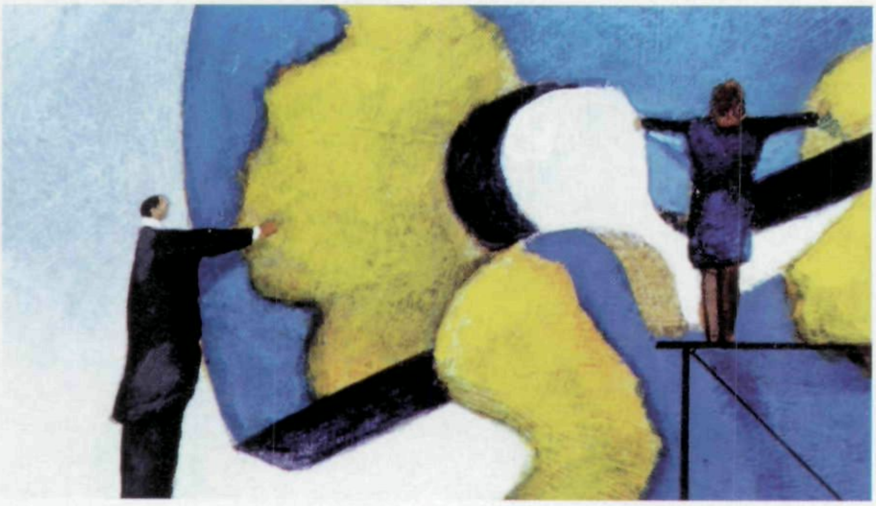
Due to fossil-fuel burning, agricultural activities, deforestation, and intensive animal husbandry, several climatically important greenhouse gases have substantially increased in the atmosphere over the past two centuries: carbon dioxide (CO_2), by more than 30 percent, and methane (CH_4), by even more than 100 percent. Such increases have in turn contributed substantially to the observed approximate 0.6°C global average temperature increase, which has been observed during the past century. The factual evidence for this development is summarized in the last assessment report of the Intergovernmental Panel of Climate Change (IPCC), which also bluntly states, "There is new and stronger evidence that most of the warming observed over the last 50 years is attributable to human activities."[12]

HUMANITY, ON AVERAGE, HAS PROSPERED THROUGH ITS CONTINUING TRANSFORMATION OF THE EARTH.

There is no question that humanity has done quite well by its transformation of the planet. Supported by great technological and medical advancements as well as by access to plentiful natural resources, we have colonized most places on Earth and even set foot on the Moon. The transformations of the last century helped humanity increase the amount of cropland by a factor of 2, the number of people living on the planet by a factor of 4, water use by a factor of more than 8, energy use by a factor of 16, and industrial output by a factor of more than 40.[13] The quality of human life also increased, with average life expectancy up more than 40 percent in the last 50 years; literacy up more than 20 percent in the last 35 years; and substantial improvements in the female/male ratio in primary education, the number of people living in democratic countries, and the increased commitment of the international community to protect civilians from internal conflict and defend the rights of national minorities.[14] The uneven distribution of these increases, their tenuous character, and the continued suffering of peoples left or falling behind are stark reminders that much more remains to be done. However, the fact remains that humanity, on average, has prospered through its continuing transformation of the Earth. The question is whether past trends of increasing prosperity can be broadened and sustained as the Anthropocene matures.

The prognosis for continued and sustainable improvements in human well-being on a transformed planet Earth is, at best, guarded. The U.S. National Academy of Sciences has concluded that over the next 50 years, human population can be expected to increase by perhaps 50 percent. Associated with such an increase, the demand for food production could well increase by 80 percent, for urban infrastructure by 100 percent, and for energy services by substantially more than 200 percent.[15] The resulting intensification of pressures on an already stressed biosphere could be overwhelming.

For example, depending on the scenarios of future energy use and model uncertainties, the increasing emissions and resulting growth in atmospheric concentrations of CO_2 are estimated by IPCC to cause a rise in global average temperature by 1.4°–5.8°C during this century. This warming will be accompanied by sea-level rise of 9–88 centimeters by 2100 and of 0.5–10 meters by the end of the current millennium. As a matter of fact, recent analyses of ice flow dynamics in Greenland and Antarctica suggest that anthropogenic sea change may occur even earlier and faster than IPCC has predicted.[16] According to NASA climatologist James E. Hansen, considering only the warming of the globe over the past 50 years plus the warming already in the pipeline—together more than 1°C—the Earth will return halfway to temperature conditions of the last interglacial, the Eemian (120,000–130,000 years ago), when global sea levels were 5–6 meters higher than at present.[17] However, greater warming is expected if humanity cannot drastically curtail the emissions of CO_2 and other greenhouse gases. The impact of current human activities is projected to last over very long periods. According to the Belgian climatologists Marie-France Loutre and André Berger, because of past and future anthropogenic



emissions of CO_2, climate may depart significantly from its natural course over the next 50,000 years.[18] But scientific research needs to find out—as soon as possible—what "significantly" means in this context.

Earth System Analysis

Is it possible to develop a robust understanding of the complex Earth System just in time for steering our planet safely through the Anthropocene? The answer is by no means a definite "yes," yet there are various signs of hope. Earth System science is perpetually advanced by thousands of research projects involving tens of thousands of investigators across the globe, and Earth System analysis is emerging as the conceptual, integrating part of the overall enterprise: It is a transdiscipline striving to perceive the big picture, to ask and answer the genuine systems questions, and to identify the prime pathways toward global sustainability in strategy space (that is, the sum of likely decision outcomes available to all relevant actors).[19]

A recent Dahlem Conference[20] assembled an exceptional collection of scholars from all corners of the scientific community to review the state of the pertinent art and to set the agenda for the further development of the field.[21] The conference was organized as an attempt to describe the coevolution of matter and life on Earth since its very formation and to explain—as far as possible—the planet's systemic properties in the various stages of that coevolution. Four working groups set out to tackle the intimidating intellectual challenges involved, covering, respectively, long-term geosphere-biosphere coevolution and astrobiology, possible states and modes of operation of the Quaternary Earth System, Earth System dynamics in the Anthropocene, and sustainability.

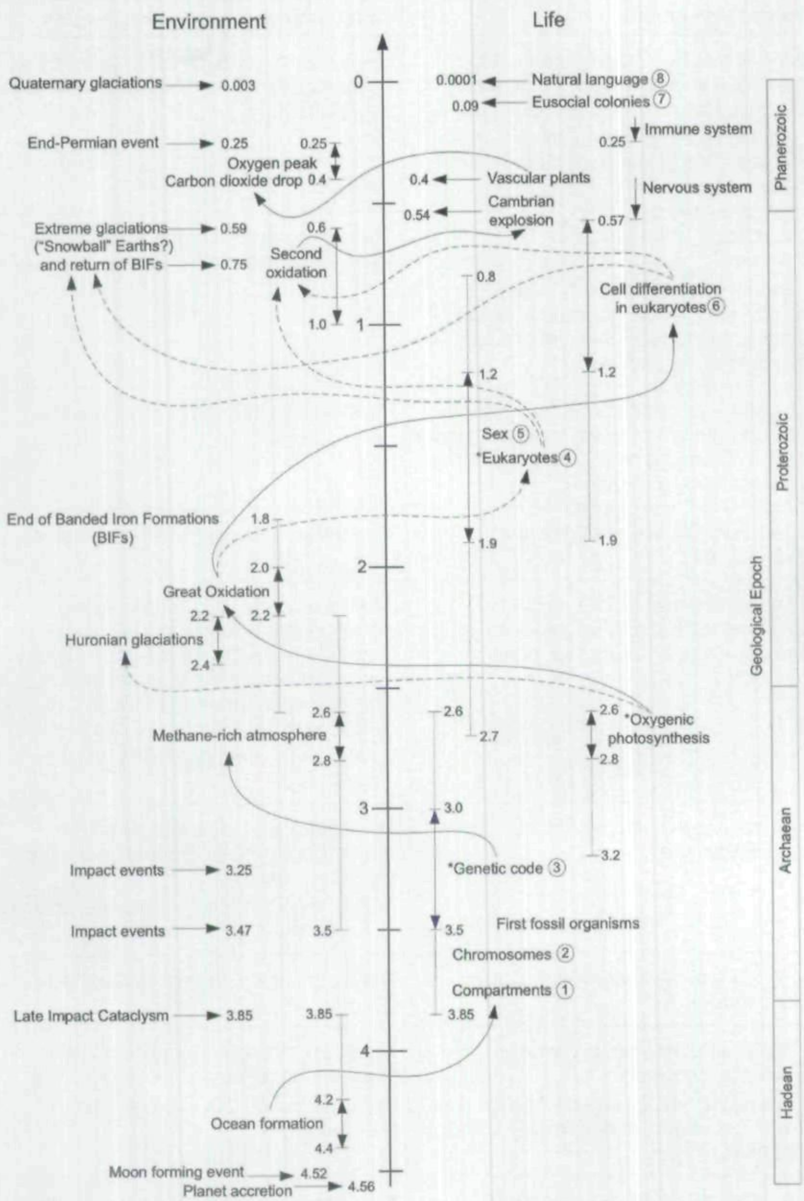
Long-Term Geosphere-Biosphere Coevolution and Astrobiology

A remarkable clash of scientific cultures was staged in this group, where global change researchers met with space researchers primarily interested in the existence and habitability of other planets inside and outside the solar system. The common themes were the general possibility of intelligent life in our universe and the long-term, large-scale coevolution of dead and living matter through complex self-organization processes far from thermodynamic equilibrium. The group addressed a number of exciting issues, such as the evolutionary topology of the biosphere, the interactive development of environmental dynamics and information processing through the great planetary transitions, the terraforming potential provided by Mars, the probability of the emergence of intelligence, and the failure of the SETI project (thus far) to track down messages from extraterrestrial civilizations. The Gaia theory served as an integrating factor and unifying metaphor in the group's debates.[22]

The admittedly fascinating issues directly connected to astrobiology cannot be dealt with here, but other discussion strands that came from this group are highly relevant for global sustainability in the future and deserve elaboration: Within the framework of Earth System analysis, the Anthropocene can be perceived as the latest step on the grand coevolutionary ladder of entwined transitions of information-processing (that is, active) life and force-driven (that is, passive) environment. If we go back in time, we soon encounter the rise of the "hydraulic societies" in the valleys of the Nile, Euphrates, Tigris, and Indus Rivers, which were probably founded in response to the great drying of the African-Asian regions approximately 6,000 years ago. Before this, organized hunting by *Homo sapiens* caused mass extinctions of the prehistoric fauna: Language provided the novel inheritance system that allowed the emergence of a society capable of exerting such an environmental pressure, resting on complex, negotiated division of labor. Earlier, the evolution of hominids in the East African Rift valley was shaped by rapidly changing ambient conditions. Such entwined environment-information transitions have characterized Earth's history since its beginning approximately four billion years ago. The pertinent "coevolution cartoon" is depicted in Figure 1 on page 15.

Studying and understanding the Earth System dynamics encapsulated in the diagram should provide us with valuable hints about the potential planetary-scale developments triggered by the Anthropocene. For instance, unabated global

Figure 1. Earth's coevolutionary ladder



NOTE: Arrows from one side of the time line to the other indicate necessary conditions or potential causal connections between the evolution of life and changes in the environment or vice versa. Solid lines characterize well-established connections, while broken lines flag more controversial connections. Error bars indicate uncertainties in timing.

SOURCE: T. M. Lenton, et al., "Group Report: Long-term Geosphere-Biosphere Coeveolution and Astrobiology," in H. J. Schellnhuber, P. J. Crutzen, W. C. Clark, M. Claussen, and H. Held, eds., *Earth System Analysis for Sustainability: Report on the 91st Dahlem Workshop* (Cambridge, MA, and London: The MIT Press in cooperation with Dahlem University Press, 2004), 111–40.

warming would not only transform the planetary biosphere beyond recognition but probably also enforce the redesign of humanity's worldwide self-organization under fierce adaptation pressures. (This challenging subject will be addressed further at the very end of the article.)

Quaternary Earth System Dynamics

While the first working group looked at the total history of the Earth System, the second group did a "time slice analysis" to understand the planetary machinery in a specific epoch, the Quaternary (approximately the last two million years before the establishment of modern civilization). This period in Earth's development is remarkable because the global machinery was in a state very similar to the contemporary one then—yet without human interference with crucial biogeophysicochemical inventories and processes. Special emphasis was given to the stability and variability of our planet's Quaternary mode of operation, an analysis clearly involving the identification and quantification of major feedback loops, phase thresholds, and other critical elements. An important discussion was held between stability optimists (led by the geologists) and stability pessimists (led by the climatologists), and the arguments expressed during this debate resulted in very specific demands for high-quality data for settling the case.

The latter intellectual controversy is characterized in Table 1 on page 16, which summarizes the state of disagreement with respect to a shortlist of important Quaternary issues.[24]

There was unanimous support, however, for the advancement of Earth System modeling as the only way to really understand the roller-coaster glaciation dynamics of that epoch. The solution of the "ice-age mystery"—that is, why did the eternal, tiny gravitation-driven variations in the Earth-Sun constellation begin to generate such massive effects a few million years ago?—would catapult the second Copernican Revolution forward. In fact, simulation models seem to be poised for providing a satisfactory answer soon.[25]

Table 1. Bounded consensus tableau for Quaternary mode of operation

Item	Points of agreement	Outstanding or unresolved issues
Ice and sea level	Buildup of massive North American and Eurasian ice sheets as well as increases in existing ice sheets during glacial times. Ice buildup resulted in a maximum ~130 meter reduction in sea level during glacial periods.	Mechanisms accounting for buildup and destabilization of ice sheets are not fully established.
Dominant periods observed in the records	Orbital forcing is the probable "pacemaker." 20- and 40-kiloannum (ka; 1 ka is 1000 years) cycles may be reasonably linear responses to precessional and obliquity orbital forcing, respectively.	There is no agreed explanation for the strong response at the 100-ka orbital cycle.
Transition into the Quaternary	~2.6 mega-annum (Ma; 1 Ma is 1 million years) B.P. (before present) transition from smaller $\partial^{18}O$ variations at ~20 ka period to larger variations at ~40 ka.	The cause of the transition is disputed.
Mid-Pleistocene transition	~900 ka B.P. transition to dominant period ~100 ka.	The cause of the transition is disputed.
Carbon dioxide (CO_2), other greenhouse gases, and temperature are highly correlated on orbital timescales.	Positive feedbacks link CO_2 and temperature. CO_2 oscillates between bounds ~190 parts per million (ppm) to 280 ppm.	The influence of CO_2 on temperature is well understood, but the influence of temperature on CO_2 is still unresolved. A number of competing theories exist about why the ocean takes up more CO_2 during cold phases. What sets the bounds of CO_2 variation is not resolved.
Dust and hydrological cycle	Glacial periods are drier and dustier than interglacial periods.	The influence of temperature on the hydrological cycle is broadly understood, but details are not. Dust in the Vostok core precedes changes in temperature.
Terrestrial vegetation	Terrestrial biota have lower biomass in glacial periods.	The extent of the change is disputed.
Feedbacks	Positive feedbacks amplify climate sensitivity to insolation. Feedbacks include ice albedo, water vapor, land surface albedo, methane (CH_4), and atmospheric CO_2.	The strength and importance of some of these are uncertain. Mechanisms for CO_2 feedback are uncertain.
Suborbital changes	Rapid warming events are recorded in Greenland ice cores during last glacial period (Dansgaard/Oeschger events). The dominant theory is that these are related to changes in ocean circulation in the North Atlantic. Cold events are associated with ice-rafter debris layers (Heinrich events), indicating massive amounts of iceberg calving.	It is unclear what triggers the changes in ocean circulation.

SOURCE: A. J. Watson, et al., "Group Report: Possible States and Modes of Operation of the Quaternary Earth System," in H. J. Schellnhuber, P. J. Crutzen, W. C. Clark, M. Claussen, and H. Held, eds., *Earth System Analysis for Sustainability: Report on the 91st Dahlem Workshop* (Cambridge, MA, and London: The MIT Press in cooperation with Dahlem University Press, 2004), 192–93.

Earth System Dynamics in the Anthropocene

Almost everything on Earth has changed with the advent of *Homo sapiens* and the establishment of the modern anthroposphere. The third working group made the heroic effort to describe how the human factor has already modified the planet's Quaternary mode of operation to identify potential anthropogenic phase transitions ahead, to specify the scientific advancements necessary for timely anticipation of dangerous Anthropocene dynamics, and to assess the prospects of large-scale technological fixes of the accelerating sustainability crisis all around us. An in-depth analysis of the notorious climate sensitivity conundrum and a thorough delineation of Earth System geography in the Anthropocene (intercomparing the role of the mid-latitudes to the tropics and the polar regions) were among the highlights in the group's deliberations.

A substantial part of the discussions in this group focused on the confirmed and suspected "Achilles' heels," or tipping elements, in the planetary system. The crucial question was whether those critical elements most susceptible to triggering by human actions can be identified in good time to avoid abrupt—and most likely devastating—global change.[26]

For illustration, a biogeophysical subset of potential tipping elements/processes in the Earth System is compiled in Figure 2 on page 18. Its entries are underpinned by research results of rather varying conclusiveness, and the collection is far from complete. In fact, new suspects are identified by global change research almost every year, such as the Indian monsoon, which may be pushed into a see-saw dynamics by the combined driving forces of anthropogenic global warming, anthropogenic regional air pollution, and anthropogenic local land-surface transformation.[27]

At a recent climate change conference in Exeter, England, convened on behalf of British Prime Minister Tony Blair as a stepping stone toward the July 2005 G8 Summit,[28] many of the items in Figure 2 were scrutinized, and a novel critical element of highest importance was flagged: The direct acidification of the oceans due to anthropogenic atmospheric CO_2 enrichment is likely to trigger dramatic changes in marine ecosystem structure and marine biogeochemical cycles. Human interference has already brought about an average oceanic pH reduction of 0.1 units since the industrial revolution, and model calculations suggest that business-as-usual burning of fossil fuels could provoke a staggering further reduction of more than 0.7 units—outdoing all acidity changes during the last 300 million years.[29]

THE DIRECT ACIDIFICATION OF THE OCEANS DUE TO ANTHROPOGENIC ATMOSPHERIC CO_2 ENRICHMENT IS LIKELY TO TRIGGER DRAMATIC CHANGES IN MARINE ECOSYSTEM STRUCTURE AND MARINE BIOGEOCHEMICAL CYCLES.

Yet we may be heading for additional trouble: Various newspapers reported growing concerns among Russian ecologists that the Siberian forests—the largest boreal ecosystem on Earth—has become highly vulnerable to conflagration under the multiple stresses of global change.[30] In 2003, 22 million hectares of spruce, larch, fir, scots pine, and oak were destroyed or damaged by fire. On one day in June that year, a U.S. satellite recorded 157 fires across almost 11 million hectares, sending a plume of smoke that reached Kyoto, Japan, approximately 5,000 kilometers away. A (partial) collapse of the Siberian forests in response to climate change would accelerate the latter by adding enormous amounts of CO_2 to the atmosphere and thus contribute to a self-amplifying greenhouse dynamics.[31]

While the criticality analysis of the planetary ecosphere is making good progress and promises to eventually support global stewardship, the complementary criticality analysis of the anthroposphere has not yet begun: What are the irreplaceable components of the global industrial metabolism? On which agricultural region will future world food production crucially depend? Are there institutions that can preserve/establish social cohesion and international equity throughout the globalization process? Which of the current mega-cities are bound to implode ultimately, and where will the new planetary centers of knowledge production lie? What technologies have the potential to transform radically humanity's interactions with its natural resources and its life-support systems? Genuine Earth System analysis for sustainability needs to address all these questions, but there will be no quick answers under business-as-usual conditions. A crash program on the caliber and scale of the Manhattan Project may actually be necessary to deliver before all windows of opportunity close down.

Sustainability

The most difficult task of all remained for members of the fourth group, who were to transgress the borderline between purely analytical reasoning and solution-driven strategic thinking. In other words, the group tried to identify pathways toward global sustainability, to evaluate the conceivable management schemes for steering our planet clear of the Anthropocene crisis, and to imagine all the scientific, technological, socioeconomic, and institutional innovations necessary for implementing the right strategy. A number of heated debates ensued over issues such as adaptive management; participatory decisionmaking; integrated systems of production, consumption, and distribution; capacity building for coping with environmental change; and upscaling of successful local/regional institutional designs. The discussions culminated in two interrelated strands: The group strove to sketch the crucial features of a future science-policy dialogue that allows for the true co-production of sustainability wisdom, and it attempted to derive the pertinent conclusions for the novel organization of science and technology in the twenty-first century.

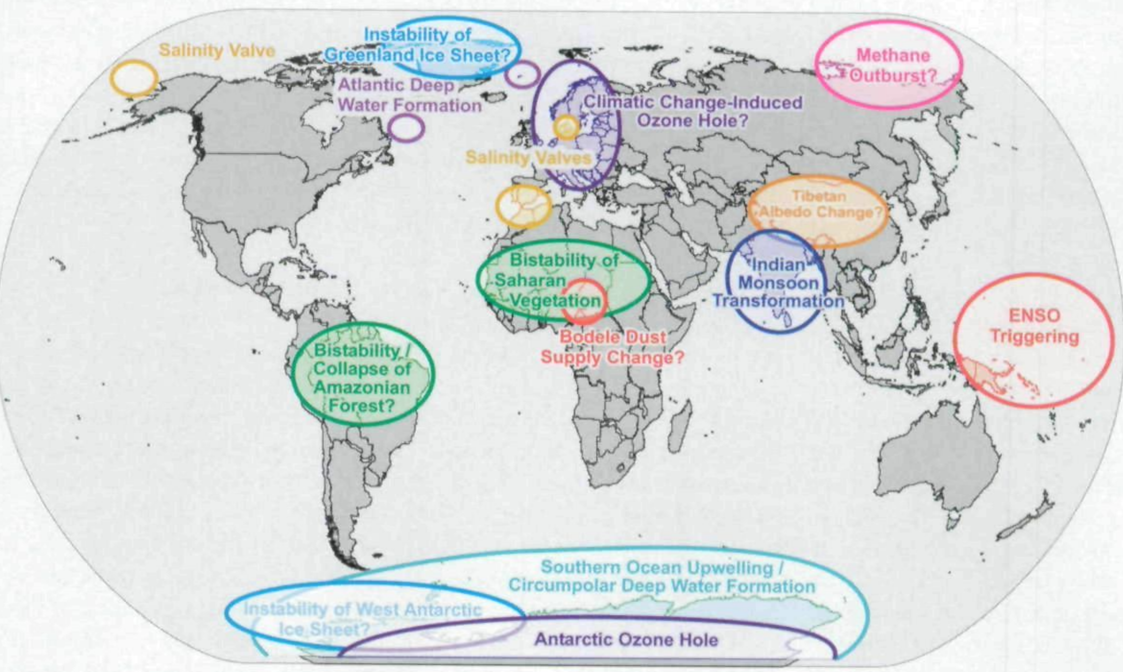
The group specifically focused on the nature and potential role of participatory decisionmaking at the Earth System level. Participatory decisionmaking has been promoted as being capable of resolving many global and regional environmental problems. There are many benefits of such participation—not the least of which is securing people's rights in industrialized societies. However, can we presuppose that such inclusive systems automatically, or even usually, achieve outcomes consistent with fostering the long-term sustainability of the Earth System? There are many reasons to believe, in fact, that such processes are inherently ill-equipped to grapple with the complex dynamics that span large spatial and temporal scales. There may be a tension between "rightness of procedure" and "goodness of outcome."[32]

Despite the difficulties, for reasons outlined below, it is important to support participatory decisionmaking whenever possible—without supposing that such processes would usually be democratic in the strictest sense of the word. Negotiation of the values society holds or will hold is legitimately within the purview of every stakeholder or citizen. Therefore, scientists ought not have, per se, a stronger voice in that negotiation than any other citizen, yet they should have a dominant role in determining the likelihood of various future scenarios and their courses and impacts (both beneficial and harmful). Similarly, others with specialized knowledge (for example, lawyers, historians, and economists) will have particular roles to play. Final decisions that weigh scientific, economic, political, social, and cultural considerations are ultimately in the hands of legitimately recognized representatives or leaders—when they exist. Many countries, unfortunately, lack such legitimate leadership.

A number of factors are relevant to a consideration of the role of participatory decisionmaking in addressing Earth System issues; for the most part, they can be divided into the following three categories:

• *Rationale*. Wide participation on the part of the interested parties may be advocated for normative or instrumental reasons. Normatively, participation may simply be regarded as good in itself. Instrumentally, participation may generate creative input into decisionmaking processes or increase the willingness of affected parties to implement or comply with commitments made during decisionmaking processes.

Figure 2. A world map of global change Achilles' heels



SOURCE: H. J. Schellnhuber, 2005.

• *Types of participation.* Different types of participation may be more or less relevant to decisionmaking on Earth System issues. For example, interested or affected parties may be allowed to vote or merely comment, participate in setting agendas or making final choices among options, or have equal or differential weight in making choices.

• *Types of decisions.* Participation on the part of interested or affected parties may be more important for some types of decisions than others. For example, participation is highly important in making basic value decisions (such as choices regarding social justice versus economic growth) but relatively less important in making highly technical decisions (such as how to measure concentrations of greenhouse gases in the Earth's atmosphere). In practice, most decisions or choices are likely to fall somewhere between these extremes. It would be helpful to place different types of choices on this spectrum and to make decisions about appropriate levels and types of participation accordingly.

A number of additional challenges emerge when applying participatory decisionmaking to problems of sustainable development. First, it is difficult to include all interested or affected groups: Members of future generations will be irrevocably affected by our actions but cannot be strongly or accurately represented. In addition, even for present-day stakeholders, identifying and enlisting those who should be involved can be daunting, because potential participants extend from individuals to entire nations. Second, it proves challenging to convey the complex science involved to those who must negotiate what values should prevail (all citizens) and those who must make decisions. There are no simple answers to this challenge, and it must be recognized that many, if not most, of the participants making decisions about our complex world do so with a limited scientific understanding as well as with diverse perceptions, opinions, and interests regarding what should be done. Third, participatory processes may favor "consensus" solutions that reflect the need for political compromise and incrementalism, rather than reflecting environmental exigencies that make such compromises environmentally and socially intolerable, even when the majority of participants wish to avoid such an outcome. Finally, the inherent disparity among interested parties ultimately tends to favor the rich and powerful, both within a society and between societies. Participatory processes devoted to questions of sustainable development will have to find a way to strengthen and perhaps (given the forces orienting us toward the rich and powerful) favor the poor and disenfranchised.

A NUMBER OF CHALLENGES EMERGE WHEN APPLYING PARTICIPATORY DECISIONMAKING TO PROBLEMS OF SUSTAINABLE DEVELOPMENT.

Participatory processes can broaden the legitimacy accorded to environmental decisionmaking and thereby increase the concern and commitment of a range of actors in society to the goal of sustainability. At the Earth System level, however, the processes must be designed in ways that ensure that the political exigencies of participation do not override the environmental exigencies of the problem being addressed.

Emerging Keys to Global Sustainability

We cannot predict whether a worldwide transition to sustainability will be achieved before the crucial windows of opportunity close down one by one. The problem may be that there are actually too many "solutions" available for coping with the Anthropocene crisis, so humankind might remain foolish enough to adopt no particular one at all. Global systems analysis should help to overcome this dilemma by highlighting key elements in strategy space that can bring about sustainability and meet certain criteria such as optimality, timeliness, and equity. It may be sufficient, however, to simply single out a few approaches that really can work—and to forget about the possibly more sophisticated and noble rest. The few approaches that follow may be instrumental in attaining sustainability due to their systemic character.

Political Upscaling: The Earth Alliance

Why is it so difficult to deal with global problems like climate change? The obvious answer is that the political actors currently trying to solve these problems through negotiations are the more than 200 nation-states on Earth. This means that the challenges of the twenty-first century and beyond are addressed by institutional structures shaped in the nineteenth century. Moreover, the institution vested with nominal authority over issues of international governance, the United Nations, is in the midst of a deep motivational and organizational crisis and has not managed so far to adequately reflect the paramount importance of global sustainability issues in its institutional makeup. For instance, the United Nations Environment Programme (UNEP) and the Commission for Sustainable Development (CSD) are relatively inferior components within the overall architecture, short on power and resources.

There are some indications, however, that this unsatisfactory state of affairs may be changed soon. UN Secretary-General Kofi A. Annan has asked for more integrated structures dealing with environmental protection in the UN System, and environmental secretaries of state from several European countries have asked, in an open letter published in various newspapers in May 2005, for a proper UN environmental organization of comparative weight as the World Health Organization (WHO) and the Food and Agriculture Organization of the United Nations (FAO).[33] These political statements support a much broader and bolder vision developed a few years ago by the German Advisory Council on Global Change (Wissenschaftlicher Beirat der Bundesregierung Globale Umweltveränderungen, WBGU), namely the notion of an "Earth Alliance," as described in the box to the right.

WHY IS IT SO DIFFICULT TO DEAL WITH GLOBAL PROBLEMS LIKE CLIMATE CHANGE?

The Forgotten Integration: Reviving Rio

In its last report,[34] WBGU went one decisive step further: The council pointed out that the institutional structure (sketched in the box) would constitute an ideal platform for redeeming the grand promise made by the statesmen and women of the world in 1992 at the UN Conference on Environment and Development held in Rio de Janeiro—namely, to unite global environmental policy with global development policy for bringing about planetary-scale sustainability. In the wake of the 2002 World Summit on Sustainable Development in Johannesburg, however, especially through the formulation of the Millennium Development Goals (MDGs), the vessel launched at Rio became increasingly tilted away from its environmental board.

The critical issue of poverty reduction has recently gained center stage on the international agenda, as evidenced by the UN Millennium Project report *Investing in Development: A Practical Plan to Achieve the Millennium Development Goals*, for which economist Jeffrey Sachs was lead author.[35] However, the issue's prominence must be tempered with the realization that the MDGs (and particularly their necessary longer-term extrapolations) will not be achieved if global environmental change is treated as a marginal issue within the wide development field. Neither will they be reached if decisionmakers fail to exploit the tremendous synergies that can be released by an integrated sustainability policy. The central WBGU thesis is "poverty reduction *through* environmental protection," not "poverty reduction *instead* of environmental protection" as certain neoclassical economists tend to argue. In fact, WBGU envisages a global "virtual circle" dynamics.

Under this paradigm, serious environmental concerns in the industrialized world (such as fears about the tipping phenomena associated with global warming) lead to heavily increased investments in the developing world (through the Clean Development Mechanism under the Kyoto Protocol, for instance); generate, as a crucial "side effect," sustainable economic growth there; reduce, in turn, the pressures on natural resources; emancipate the peoples in the developing world from short-term thinking imposed on them by sheer need; and thus, finally, enable developing countries to join the "preservation club" of the industrialized world. It almost goes without saying that environmental protec-

THE EARTH ALLIANCE

The German Advisory Council on Global Change's (WBGU) vision of an Earth Alliance to reform the architecture of international environmental institutions and organizations builds on existing structures and develops them further as needed.[1] As sketched in the figures below, the Earth Alliance comprises three crosscutting areas interlinked in terms of essentials like information, communication, coordination, and finances. First, to enhance the assessment of environmental problems, WBGU proposes the establishment of an independent entity with the task of issuing (early) warnings of development trajectories that harbor particularly high risks. Second, WBGU recommends changes in the organizational hub of international environmental policy. This centers on the stepwise establishment of an international environmental organization—involving the coordination and cooperation function of a strengthened the United Nations Environment Programme (UNEP), with closer networking among the secretariats of the international environmental conventions and their (in some instances yet to be established) scientific advisory bodies. Third, in addition to legal certainty and good governance, sufficient financial resources are necessary to counter growing global challenges successfully. However, the reluctance of the industrialized countries to provide adequate funding—which has become increasingly entrenched over the years—poses an obstacle to the raising of adequate funds to protect global environmental resources. WBGU recommends that innovative avenues for funding global environmental policy be pursued increasingly.[2]

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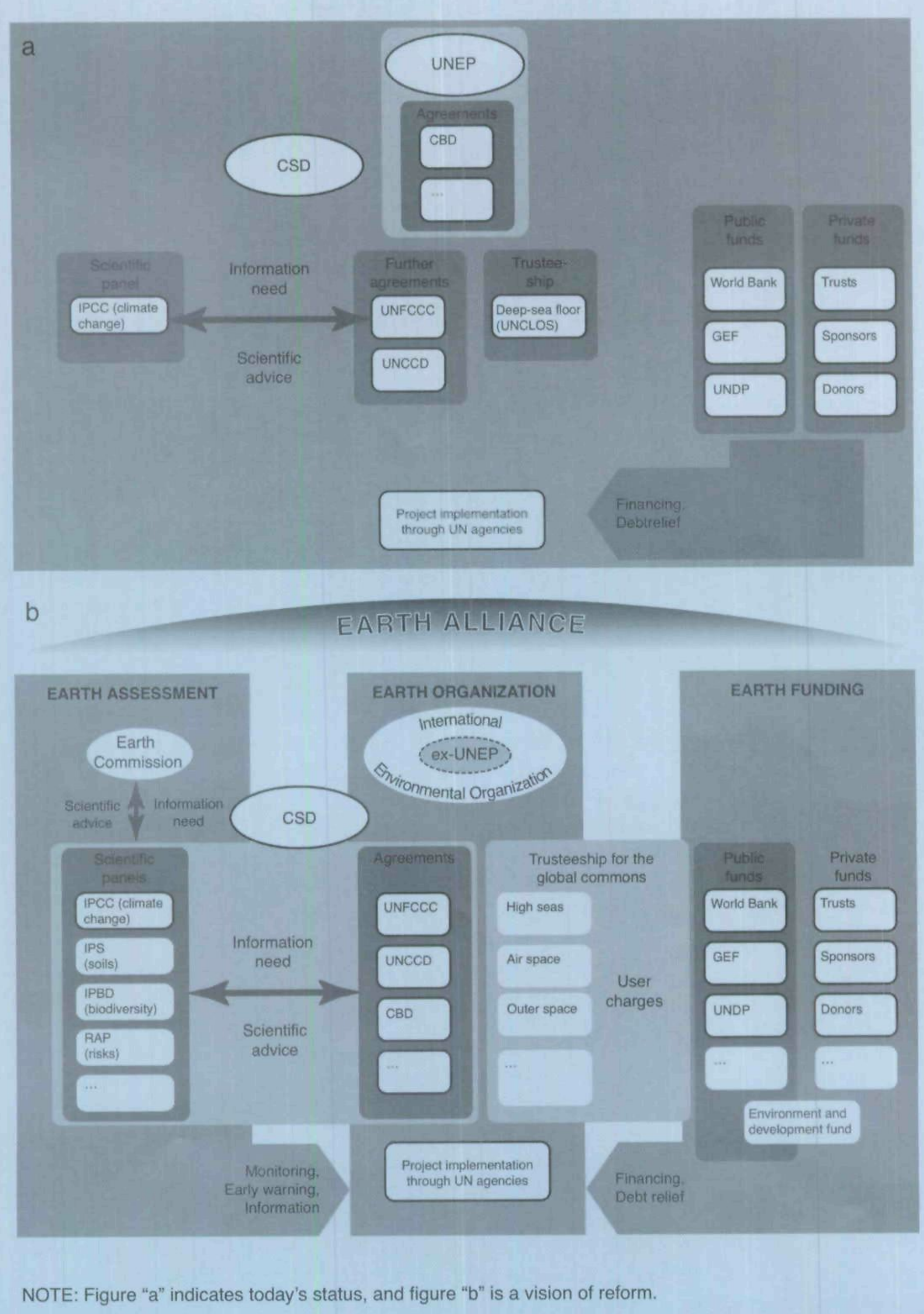
1. German Advisory Council on Global Change (WBGU), *Charging the Use of the Global Commons* (Berlin: WBGU, 2002).

2. WBGU, *World in Transition: Fighting Poverty through Environmental Policy* (London: Earthscan, forthcoming 2005).



NOTE: Figure "a" indicates today's status, and figure "b" is a vision of reform.

SOURCE: German Advisory Council on Global Change (WBGU), *World in Transition: New Structures for Global Environmental Policy* (London and Sterling, VA: Earthscan, 2001).

tion policies implemented by developed countries (like greenhouse gas emission reductions) are the absolute precondition for keeping the vulnerability of developing countries within a manageable range. A systems-analytic sketch of such a "Rio strategy" (or sustainability strategy) is given in Figure 3 on page 23.[36]

Political Downscaling: Coalitions of Cities

If the concerted planetary management by nation-states under the roof of the United Nations (that is, at a global governance level) is unfeasible, then there is still the option to reverse direction entirely for approaching sustainability: A bottom-up strategy motivating and connecting willing subnational actors and bodies worldwide seems to provide a much better perspective in a political universe where one single country is able to slow down (or even stop) all well-meaning multilateral initiatives. The grassroots heroes in the climate change battle, for instance, could be the cities that are prepared to face the global change challenges overshadowing all their longer-term planning schemes.

City governments already observe worrying changes in their local climates and environments, which will generally have worse impacts than corresponding developments in sparsely populated areas and are likely to jeopardize even the viability of the cities themselves. The temperature rise in urban domains may exceed by 5°C those in the surrounding countryside, where anthropogenic warming is expected to amount to 4°–6°C on most of the continents. This notorious heat island effect, which is greatest in the evening, comes largely from buildings that emit and store heat. But of greater concern for the well-being of humans, other animals, and plants is the prospect that heat waves will become much more frequent according to the latest scientific estimates and could lead to the recurrence of the disastrous ambient conditions experienced in London and Paris in 2003.[37] In addition, there are negative synergies: Heat waves are likely to be associated with strong inversion conditions that will trap air pollution in urban domains and assist the lateral transport of ozone and similarly toxic gases between neighboring cities. An equally serious environmental effect of climate change in densely populated areas is the greater likelihood of flooding caused by intense, more frequent rainfall events, by sea level rise, and by the relentless anthropogenic expansion of impervious surfaces. In the last 10 years, the United Kingdom and continental Europe have experienced some of the largest floods ever recorded, provoking enormous economic losses. The 2002 Elbe River flood alone caused damages costing more than US$15 billion.

THE CRITICAL ISSUE OF POVERTY REDUCTION HAS RECENTLY GAINED CENTER STAGE ON THE INTERNATIONAL AGENDA.

But lessons have been learned about reducing the future impacts of floods by using temporary and permanent structures, more resilient building designs and, above all, better planning of built-up areas. In Houston, for example, ecological communities are working with nature to reduce the need for concrete flood structures. In Hamburg, the dykes are being raised to ensure the long-term viability of the port, and in London, the Thames River barrier may eventually be increased. There are, however, other areas in the United Kingdom and throughout the world where cities and rural communities will have to retreat from the coast and watch their settlements disappear—perhaps the ultimate democratic challenge for a local community. The hot spots of the sustainability challenge are, in fact, the coastal mega-cities in the developing world, where the two dominating trends of global change, namely climate change (implying sea-level rise) and urbanization (driven by socioeconomic globalization), collide to wreak havoc.

On the other hand, cities themselves hold the key to environmental protection—if national governments allow (or even encourage) them to use it: Greater London consumes more energy than do small nations such as Portugal or Greece, and London's mayor has now set up a regional climate change agency to massively reduce the city's greenhouse gas emissions. Toronto has pioneered city-wide energy-saving schemes, and Singapore has initiated congestion charging to reduce automobile carbon emissions—as well as to deal with traffic jams. Increasingly throughout the world, urban planning is required to have as its objective the sustainability of local communities. Seattle is spearheading a cities coalition in the United States to fight global warming, even beyond the obligations that would have arisen from the Kyoto Protocol had the United States ratified it. Because of their significant regulatory and executive autonomy, cities can often do what entire nation-states cannot agree to do. So, climate protection may be pioneered in the next decades by hundreds of willing city governments[38]—joining forces with other subnational entities (such as the State of California, if recent speeches by Governor Arnold Schwarzenegger will translate into policy) and supranational entities (including international corporations such as BP and HSBC). Earth System analysis for sustainability needs to carefully explore the potential benefits (and risks) involved in such a change of course.

Ultimate (Un-)Sustainability: Auto-Evolution

The Anthropocene can be perceived as a period of accelerated coevolution, driven forward at an unprecedented pace by an unprecedented force, namely *Homo sapiens*' collective intelligence. The current anthropogenic transformation of the ecosphere (in particular, anthropogenic climate change) will create cascades of impacts on natural and socioeconomic systems, which—in turn—will provoke higher-order cascades of adjustments and responses. This will most likely also result in a major reinvention of the driving force itself: human culture.

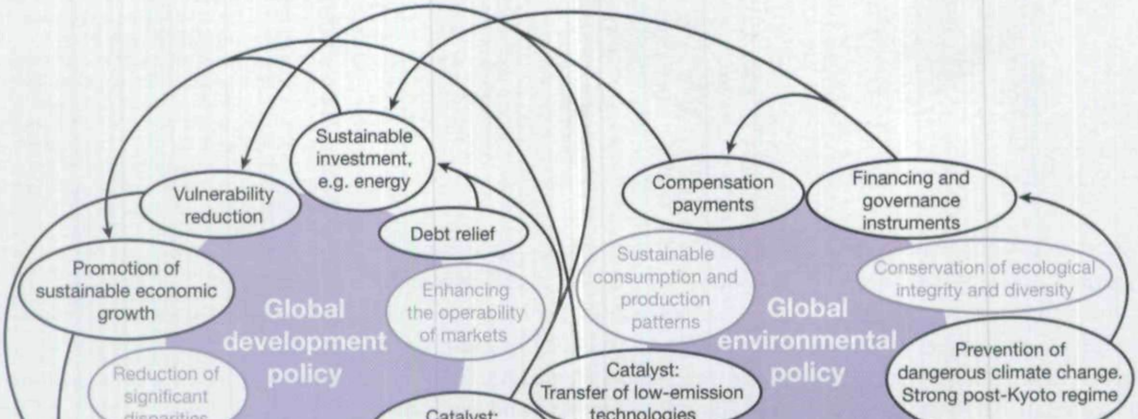
The need to adapt will undoubtedly transform our ways of satisfying the basic needs for food, freshwater, health, shelter, and mobility. For instance, new geostrategic modes of agricultural production will have to be established under the combined stresses of global warming, soil degradation, and biodiversity loss. The current ratio of terrestrial versus marine protein harvesting might need a fundamental revision. On the other hand, meter-scale sea-level rise and progressive ocean acidification[39] may considerably complicate such a revision and require the restructuring of most of the planet's coastal zones.

The need to mitigate or limit global change to manageable dimensions will undoubtedly bring about the reorganization of humanity in geographical, cultural, and political space. For instance, the containment of energy and material demands requires a reassessment of all production and consumption modes and a revaluation of the urban-rural nexus. The handling of environmental problems striking at all scales asks for novel institutional structures, connecting global with local decisionmaking.

Thus, ironically, modern humanity's reckless exploitation of the ecosphere might trigger the transition to a new global form of social aggregation, which University of Sussex zoologist Alison Jolly dubbed the "Fifth Step" of emergent self-organization of matter.[40]

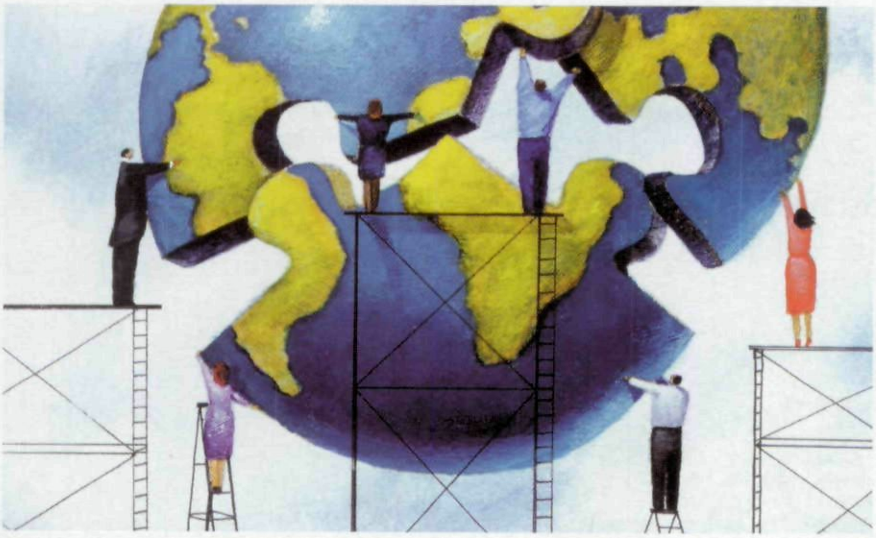
While this further step up the coevolution ladder would be an altogether positive

Figure 3. Climate-focused sustainability strategy generating positive feedback loops between environmental and development policies



SOURCE: German Advisory Council on Global Change (WBGU), *World in Transition: Fighting Poverty through Environmental Policy* (London: Earthscan, forthcoming 2005).

outcome of the Anthropocene crisis, the latter may provoke other planetary-scale responses of a more questionable character. For instance, the global warming threat has prompted a number of respected scientists to consider "geoengineering schemes"[41] for counteracting anthropogenic climate forcing. These schemes range from quite dubious proposals (like manipulating planetary insolation through gigantic mirrors in outer space) to potentially feasible suggestions based on solid science (like the massive extraction of anthropospheric CO_2 through physicochemical precipitation[42] or the judicious injection of SO_2 into the stratosphere[43]).



But there are also first discussions about "macro-adaptation" options like diverting rivers for compensating precipitation pattern shifts or assisting ecosystems migration in response to global change by establishing transnational unfragmented bio-corridors (for instance, across the Central American isthmus).

These are just a few possible roads toward medium-term Earth System management, but where will these roads ultimately lead to? Is there something like a common vanishing point? Stanislaw Lem has dreamt up such a point in his science-fiction novel *Solaris*, where information-processing life and geophysical forces eventually merge into one single planetary entity. Lem's ingenious construction is good intellectual fun but hardly a robust answer to the coevolution riddle. However, it is timely to start thinking about the longer-term prospects of the Earth System as guided (or misguided) by a "Global Subject,"[44] that is, a post-Anthropocene Leviathan representing humanity's collective self-conscious willpower.

Earth System management could explore the following options:

• *Planetary design*—the fixation or amendment of the ecosphere according to humanity's preferences (using, inter alia, geoengineering and nanotechnology);

• *Pure auto-evolution*—the fixation or amendment of humanity by itself (for example, through gene technology), partially in response to environmental pressures, partially for completely independent reasons, and guided by purely cultural criteria (related, for example, to health or aesthetics standards); and

• *Controlled coevolution*—the establishment of a process where humanity perpetually reinvents itself, nature, and the respective interactions—either spontaneously (on the pertinent time scales) or in agreement with some unshakable principles laid down once and for all.

It is critical to emphasize that the last scenario is the most realistic and desirable one. Wise stewardship could translate this pathway into "sustainable auto-evolution," with the right balance between conservation and innovation, nature and civilization, and responsiveness and autonomy. The immense challenge is to start seeking those criteria and principles that might define the "sustainability" of such an Earth System future, where information-processing organic matter would ultimately rule and shape its cosmos without any constraints except the most fundamental laws of physics. So let us consider launching the first explorative ship ever to sail into this uncharted ocean.

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College Cambridge; an honorary professor in the Department of Applied Mathematics and Theoretical Physics, University of Cambridge; and the J. M. Burgers Visiting Professor at the Delft University of Technology, Delft, Netherlands. He is also director of Lighthill Institute of Mathematical Sciences. He was director-general and chief executive of the Meteorological Office (the Met Office) in Exeter, UK, from 1992–1997 and was appointed as a working peer in the House of Lords, with the title Baron Hunt of Chesterton, in 2000.

NOTES

1. The four international research programs that endorsed the Amsterdam Declaration and now make up the Earth System Science Partnership are the International Geosphere-Biosphere Programme (IGBP), the International Human Dimensions Programme on Global Environmental Change (IHDP), the World Climate Research Programme (WCRP), and the international biodiversity program DIVERSITAS. For more information on the partnership, see http://www.essp.org/; and B. Moore III, A. Underdal, P. Lemke, and M. Loreau, "The Amsterdam Declaration on Global Change," in W. Steffen, J. Jäger, D. J. Carson, and C. Bradshaw, eds., *Challenges of a Changing Earth: Proceedings of the Global Change Open Science Conference, Amsterdam, The Netherlands, 10–13 July 2001* (Berlin, Heidelberg, and New York: Springer, 2002). For more information on the term "second Copernican Revolution," see H. J. Schellnhuber, "'Earth System' Analysis and the Second Copernican Revolution," *Nature*, 2 December 1999 (Millennium supplement), C19–C23.

2. J. Lovelock, "The Living Earth," *Nature*, 18 December 2003, 769–70.

3. H. J. Schellnhuber, "Coping with Earth System Complexity and Irregularity," in Steffen, Jäger, Carson, and Bradshaw, note 1 above, page 151.

4. H. Nowotny, P. Scott, and M. Gibbons, *Re-Thinking Science: Knowledge and the Public in an Age of Uncertainty* (Cambridge, UK: Polity Press, 2001).

5. Steffen, Jäger, Carson, and Bradshaw, note 1 above.

6. J. Lubchenco, "Entering the Century of the Environment: A New Social Contract for Science," *Science*, 23 January 1998, 491–97.

7. P. J. Crutzen, "Geology of Mankind," *Nature*, 3 January 2002, 23.

8. See, in particular, the recent IGBP book series published by Springer (Berlin). The series' flagship volume is W. Steffen et al., *Global Change and the Earth System: A Planet Under Pressure* (Berlin: Springer, 2004).

9. An excellent review of global impacts of land use is provided by J. A. Foley et al., "Global Consequences of Land Use," *Science*, 22 July 2005, 570–74.

10. For a fuller examination of the effects of ozone pollution and policy challenges to combat it, see M. Bernstein and D. Whitman, "Smog Alert: The Challenges of Battling Ozone Pollution," in this issue (*Environment*, October 2005), pages 28–41.

11. J. Kaiser and M. Enserik, "Treaty Takes a POP at the Dirty Dozen," *Science*, 15 December 2000, 2053.

12. Intergovernmental Panel on Climate Change (IPCC), *Climate Change 2001: Synthesis Report: Third Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge, UK, and New York: Cambridge University Press, 2001). See, in particular, page 5.

13. J. R. McNeill, *Something New Under the Sun: An Environmental History of the Twentieth-Century World* (New York: W.W. Norton, 2000).

14. R. W. Kates and T. M. Parris, "Long-Term Trends and a Sustainability Transition," *Proceedings of the National Academy of Sciences of the United States of America* 100, no. 14 (2003): 8062–67.

15. National Research Council, Board on Sustainable Development, *Our Common Journey: A Transition toward Sustainability* (Washington, DC: National Academy Press, 1999), 20.

16. J. E. Hansen, "A Slippery Slope: How Much Global Warming Constitutes 'Dangerous Anthropogenic Interference'?" *Climatic Change* 68, no. 3 (2005): 269–79; and M. Oppenheimer and R. B. Alley, "The West Antarctic Ice Sheet and Long Term Climate Policy," *Climatic Change* 64, no. 1–2 (2004): 1–10.

17. J. Hansen, "Defusing the Global Warming Time Bomb," *Scientific American*, March 2004, 68–77.

18. See, for example, M. F. Loutre and A. Berger, "Future Climatic Changes: Are We Entering An Exceptionally Long Interglacial?" *Climatic Change* 46, no. 1–2 (2000): 61–90. Note that the "natural" climate development is largely determined by the Milankovich mechanism, that is, the quasi-periodic variation of planetary insulation as governed by the laws of astrophysics.

19. H. J. Schellnhuber, note 1 above, C19; H. J. Schellnhuber and V. Wenzel, *Earth System Analysis: Integrating Science for Sustainability* (Berlin: Springer, 1998); and H. J. Schellnhuber and D. Sahagian, "The Twenty-Three GAIM Questions," *Global Change Newsletter*, April 2002, 20.

20. The Dahlem Conferences are a special-format workshop series, dedicated to the most advanced frontiers of interdisciplinary science and named after their traditional venue, a district of Berlin.

21. H. J. Schellnhuber, P. J. Crutzen, W. C. Clark, M. Claussen, and H. Held, eds., *Earth System Analysis for Sustainability: Report on the 91st Dahlem Workshop* (Cambridge, MA, and London: The MIT Press in cooperation with Dahlem University Press, 2004).

22. See, for example, J. Lovelock, *The Ages of Gaia: A Biography of Our Living Earth* (Oxford: Oxford University Press, 2000). *Environment* published a vivid debate of the Gaia theory in its May 1990 issue. See S. H. Schneider, "Debating Gaia," *Environment*, May 1990, 4–9, 29–32.

23. For a thorough discussion of this matter, see T. M. Lenton, et al., "Group Report: Long-term Geosphere-Biosphere Coevolution and Astrobiology," in Schellnhuber, Crutzen, Clark, Claussen, and Held, note 21 above, pages 111–40. A stylized summary of that discussion is given in T. M. Lenton, H. J. Schellnhuber, and E. Szathmáry, "Climbing the Co-evolution Ladder," *Nature*, 21 October 2004, 913.

24. A. J. Watson, et al., "Group Report: Possible States and Modes of Operation of the Quaternary Earth System," in Schellnhuber, Crutzen, Clark, Claussen, and Held, note 21 above, pages 189–210.

25. A promising approach employs Earth System models of intermediate complexity (EMICs) like the CLIMBER family operated at the Potsdam Institute. For an interesting recent result, see G. H. Haug et al., "North Pacific Seasonality and the Glaciation of North America 2.7 Million Years Ago," *Nature*, 24 February 2005, 821–25.

26. See also W. Steffen et al., "Abrupt Changes: The Achilles' Heels of the Earth System," *Environment*, April 2004, 8–20.

27. K. Zickfeld, B. Knopf, V. Petoukhov, and H. J. Schellnhuber, "Is the Indian Summer Monsoon Stable against Global Change?" *Geophysical Research Letters* 32, no. 15 (2005): L15707.

28. A full account of this landmark meeting will be given in H. J. Schellnhuber et al., eds., *Avoiding Dangerous Climate Change* (Cambridge, UK: Cambridge University Press, forthcoming 2005).

29. K. Caldeira and M. E. Wickett, "Oceanography: Anthropogenic Carbon and Ocean pH," *Nature*, 25 September 2003, 365.

30. See, for instance, T. Radford, "Huge Rise in Siberian Forest Fires Puts Planet at Risk, Scientists Warn," *The Guardian*, 31 May 2005, 2.

31. Note that lax laws are likely to aggravate the problem, since many fires in Siberia appear to have been set by arsonists for creating more salvage timber as reported by BBC News, "Fire Threat to Siberia's Forests," *BBC News Online*, 31 May 2005, http://news.bbc.co.uk/2/hi/europe/4596651.stm.

32. A. Sen, *Inequality Reexamined* (Oxford: Oxford University Press, 1995).

33. See, for example, United Nations Secretary-General, *In Larger Freedom: Towards Development, Security and Human Rights for All: Report of the Secretary-General to the UN General Assembly, 21 March 2005*, http://www.un.org/largerfreedom/; and C. Narbona Ruiz, S. Lepeltier, and J. Trittin, "Die Umwelt muss in den Mittelpunkt" ("The Environment Must Take Center Stage"), *Frankfurter Rundschau*, 27 May 2005, 7.

34. Wissenschaftlicher Beirat der Bundesregierung Globale Umweltveränderungen (WBGU) (German Advisory Council on Global Change), *World in Transition: New Structures for Global Environmental Policy* (London and Sterling, VA: Earthscan, 2001).

35. UN Millennium Project, *Investing in Development: A Practical Plan to Achieve the Millennium Development Goals: UN Millennium Project, Report to the UN Secretary-General* (New York: United Nations, 2005), http://www.unmillenniumproject.org/.

36. Note that a revival of the "Rio spirit" must have major institutional implications, such as the replacement of the increasingly inadequate UN Economic and Social Council (ECOSOC) by a "Council for Global Development and Environment." (See WBGU, *World in Transition: Fighting Poverty through Environmental Policy* (London: Earthscan, forthcoming 2005.)

37. In the summer of 2003, a total of 20,000–30,000 people died in Europe—mainly in the big cities and particularly the elderly and vulnerable—as a result of extremely high temperatures. See R. S. Kovats, T. Wolf, and B. Menne, "Heatwave of August 2003 in Europe: Provisional Estimates of the Impact on Mortality," *Eurosurveillance Weekly*, 11 March 2004. Yet much higher temperatures are likely to become standard in Asian cities in the wake of climate change.

38. For instance, on 5 June 2005, mayors from around the world signed the Urban Environmental Accords. See United Nations World Environment Day 2005 news release, "Mayors Sign Historic Environmental Accords," http://www.wed2005.org/5.1.php?news_id=30.

39. The Royal Society, *Ocean Acidification Due to Increasing Atmospheric Carbon Dioxide*, policy document 12/05 (London: The Royal Society, 2005).

40. A. Jolly, "The Fifth Step," *New Scientist*, 25 December 1999, 78–79.

41. S. H. Schneider, "Geoengineering: Could—or Should—We Do It?" *Climatic Change* 33, no. 3 (1996): 291–302.

42. K. S. Lackner, "A Guide to CO_2 Sequestration," *Science*, 13 June 2003, 1677–78.

43. P. J. Crutzen, "Towards a Global Experiment on Climate Control?" *Climatic Change*, forthcoming 2005.

44. Schellnhuber, note 1 above, page C19; and W. Lucht and R. K. Pachauri, "The Mental Component of the Earth System," in Schellnhuber, Crutzen, Clark, Claussen, and Held, note 21 above.