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VISIONS OF THE 21st CENTURY: CONVENTIONAL WISDOM AND OTHER SURPRISES IN THE GLOBAL INTERACTIONS OF POPULATION, TECHNOLOGY, AND ENVIRONMENT

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The Global Environmental Policy Project (GEPP) began in 1989 as a joint effort of the Kennedy School of Government's Energy and Environmental Policy Center (EEPC) and its Science, Technology and Public Policy Program (STPP), and the Harvard Business School Negotiations Project. The Global Environmental Policy Project focuses on four subjects:

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  In recent history, regional agreements have emerged bringing together countries who share a common resource. There are lessons to be learned from the formulation and implementation of these environmental negotiations. The Project explores various global negotiations issues, including technology transfer from developed to developing countries, funding mechanisms to cover the cost of reforestation, and CO_2 emissions and reductions.

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  The analytical tools that we use to evaluate environmental impact and mitigation options were developed to combat problems with local impact and short time frames. These tools are not adequate for the examination of issues, such as global climate change, which are characterized by long-time horizons, tremendous factors of uncertainty, and a broad spectrum of perceptions among nations. The Project is developing a range of analytical techniques for the evaluation of policy options to provide governments with decision rules to assist in their selection among these options.

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VISIONS OF THE 21st CENTURY:

Conventional Wisdom and Other Surprises in the Global Interactions of Population, Technology, and Environment

by

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Executive Summary

This essay is undertaken as part of a larger effort to illuminate the opportunities and constraints that bear on the management of sustainable development in the next century. Within that broad objective, my goal in this paper is to sketch the physical context of the management problem: the ways in which human populations, their technologies, and the environments they transform set the stage on which economic, social, and political changes are played out.

As it approaches the 21st century, humanity is entering an era of chronic, large-scale, and extremely complex *syndromes* of global interdependence and change. Relative to earlier generations of problems, these emerging syndromes are characterized by profound scientific ignorance, enormous decision costs, and time and space scales that transcend those of most social institutions. The managerial challenges posed by this changing stage can only intensify over the next century as the number of people on earth, their industrial production, and their demand for agricultural products increase doubly and more.

In addressing the management challenges of global interdependence we must invent visions of the changing world we seek to manage. To be useful, such visions must eschew mechanistic predictions of what will be in favor of imaginative though disciplined

perspectives on what can be done. The importance of such visions will not lie in their details, but rather in how they are used. This essay argues that in order to shape more useful visions of possible interactions among people, technologies, and environments in the next century, four underlying issues must be addressed.

The first is space. It has become a commonplace that solutions to problems in an interdependent world require the ability to "think globally, while acting locally". In practice, however, people spend most of their time in a few places. Visions of the globe as a whole, and of the diversity of localities that make it up, are equally hard to come by. In this essay, I therefore sketch parallel pictures of global and local (or at least regional) change. To keep the exercise manageable, I focus on two contrasting regions whose high densities of present development may offer a model of things to come elsewhere in the world: Europe and the Indian subcontinent.

The second central issue is time. Global population growth has a momentum measured in generations. Many of the environmental problems that face us today involve the cumulative effects of many decades of human activity. Changes in the basic technologies that determine how we transform the physical stage of our planet can take as much as half a century from inception to full implementation on a global scale. One of our greatest challenges in shaping useful visions of the future is to see beyond the personal near term and to capture the constraints and limitations imposed by long term global change. Historical perspective has proven to be invaluable (though potentially misleading) in this regard. I therefore adopt for the visions presented here a time horizon looking a century into the past and a century into the future.

Our third issue of concern is in a sense the inverse of the first two: the central role of abrupt or discontinuous change in shaping the world stage. Most visions of the future are based on an evolutionary paradigm that involves the gradual incremental unfolding of the world system through time and, to a lesser extent, across space. But by leaving out the external shocks, nonlinear responses and discontinuous behavior so typical of social and natural systems, evolutionary perspectives leave us unprepared to interpret a host of not impossible eventualities. By leaving out the social learning called into play by the resulting surprises and crises, they also reduce the challenge of adaptive management to a sterile effort to correct past mistakes. In an effort to complement the conventional surprise-free visions of the future, I develop here an explicit look at some abrupt changes in human, technical and environmental systems that could have a major impact on global management challenges of the next century.

Fourth, an effort to provide more useful visions of the 21st century must confront the complexity and contextual richness of the reality we seek to manage. It remains extremely tempting, indeed almost necessary, to focus on a few characteristics of the human population, a couple of highly visible technologies, one or another particularly alarming environmental changes. Yet peoples, places and things <u>are</u> connected, and it is often the subtle, neglected aspects of those connections that underlie some of the most important problems and opportunities we face. In attempting to address the resulting dilemma, we encounter what historian William McNeill has called the gulf between "numbers" and "narrative" in styles of picturing past and future histories. Neither style is sufficient; both are necessary. The challenge is to experiment with ways of combining them creatively in ways that stimulate disciplined thought about the changing world around us. I therefore

conclude this essay with a proposal to adapt classical war gaming methodologies as one means of bridging this gulf in the ongoing interaction of scholars, policy analysts, and decision makers concerned with managing global change.

VISIONS OF THE 21st CENTURY:

Conventional Wisdom and Other Surprises in the Global Interactions of Population, Technology, and Environment[1]

1. Introduction

The Brundtland Commission's recent report "Our Common Future" makes a compelling case for the global connections among economic development, military security and physical environment. A central challenge of the coming decades is to learn how the interactions described by the Commission can be better managed to improve the prospects for sustainable improvements in human well-being. Management is not the same as prediction. The distinction is an important one, for management can be improved despite the enormous uncertainties and downright ignorance that will continue to make detailed predictions illusory.

This paper is undertaken as part of a larger project to illuminate the opportunities and constraints that bear on the management of sustainable development in the next century[2]. Within that broad objective, my goal here is to sketch the physical context of the management problem: the ways in which human populations, their technologies, and the environments they transform set the stage on which economic, social, and political changes are played out.

1.1 The changing stage

That physical stage is rapidly changing[3]. It holds twice as many people as it did in 1950; four times what it did in 1850. World trade has increased more than 20-fold over the last century; energy use more than 100-fold. This increasing magnitude of human activity has brought about an increasing scale and complexity of interactions among humans, their technologies and their environments. What were once local incidents of pollution shared throughout a common watershed or air basin now involve multiple nations - witness the concerns for acid deposition in Europe and North America. What were once acute episodes of relatively reversible damage now affect multiple generations - witness debates over disposal of chemical and radioactive wastes. What were once straightforward questions of ecological preservation versus economic growth now reflect complex linkages - witness the feedbacks among energy and crop production, deforestation and climate change that are evident in studies of the atmospheric greenhouse effect. What once seemed a relatively well-behaved world of smooth and predictable trends increasingly reveals a propensity for abrupt and unexpected change - witness the surprise and consternation of scientists and policy people alike confronted with the appearance of the Antarctic ozone hole.

Thus, as it approaches the 21st century, humanity is entering an era of chronic, large-scale, and extremely complex *syndromes* of global interdependence. Relative to earlier generations of problems, these emerging syndromes are characterized by profound scientific ignorance, enormous decision costs, and time and space scales that transcend those of most social institutions. The managerial challenges posed by this changing stage can only intensify over the next century as the number of people on earth, their industrial production, and their demand for agricultural products increase doubly and more.

In addressing the management challenges of global interdependence we, the people

of the world, must ultimately evolve agendas for action reflecting shared perceptions of the central issues and choices before us. But if those agendas are to reflect more than parochial views of single issues, nations, and generations, we must invent global, long term visions of the changing world we seek to manage. Such visions are not mechanistic predictions of what will be, but rather imaginative though disciplined perspectives on what could be. The importance of the visions will not lie in their details, but rather in how they are used.

Many visions of the opportunities and constraints inherent in the global interdependence of the next century exist. Making such visions more useful for management has been the subject of a major research effort I have been conducting over the last several years under the auspices of the Program on Sustainable Development of the Biosphere at the International Institute for Applied Systems Analysis. Many colleagues at IIASA and elsewhere have contributed to the findings I report below, though none should be held responsible for the particular use to which I here put our results.

1.2 The issues

The IIASA effort has suggested that in order to shape more useful visions of possible interactions among people, technologies, and environments in the next century, four underlying issues must be addressed.

The first is space. It has become a commonplace that solutions to problems in an interdependent world require the ability to "think globally, while acting locally". In practice, however, people spend most of their time in a few places -- visions of the globe as a whole, and of the diversity of localities that make it up, are equally hard to come by. In what

follows, I therefore sketch parallel pictures of global and local (or at least regional) change. To keep the exercise manageable, I focus on two contrasting regions whose high densities of present development may offer a model of things to come elsewhere in the world: Europe and the Indian subcontinent.

The second central issue is time. Global population growth has a momentum measured in generations. Many of the environmental problems that face us today involve the cumulative effects of many decades of human activity. Changes in the basic technologies that determine how we transform the physical stage of our planet can take as much as half a century from inception to full implementation on a global scale. One of our greatest challenges in shaping visions of the future is to see beyond the personal near term and to capture the constraints and limitations imposed by long term global change. Historical perspective has proven to be invaluable (though potentially misleading) in this regard. I therefore adopt for the visions presented here a time horizon looking a century into the past and a century into the future.

Our third issue of concern is in a sense the inverse of the first two: the central role of abrupt or discontinuous change in shaping the world stage. Most visions of the future are based on an evolutionary paradigm that involves the gradual incremental unfolding of the world system through time and, to a lesser extent, across space. But by leaving out the external shocks, nonlinear responses and discontinuous behavior so typical of social and natural systems, evolutionary perspectives leave us unprepared to interpret a host of not impossible eventualities. By leaving out the social learning called into play by the resulting surprises and crises, they also reduce the challenge of adaptive management to a sterile effort to correct past mistakes. In an effort to complement the conventional surprise-free

visions of the future, I develop here an explicit look at some abrupt changes in human, technical and environmental systems that could have a major impact on global management challenges of the next century.

Fourth, an effort to provide more useful visions of the 21st century must confront the complexity and contextual richness of the reality we seek to manage. It remains extremely tempting, indeed almost necessary, to focus on a few characteristics of the human population, a couple of highly visible technologies, one or another particularly alarming environmental changes. Yet peoples, places and things are connected, and it is often the subtle, neglected aspects of those connections that underlie some of the most important problems and opportunities we face. In attempting to address the resulting dilemma, we encounter what historian William McNeill has called the gulf between "numbers" and "narrative" in styles of picturing past and future histories. Neither style is sufficient; both are necessary. The challenge is to experiment with ways of combining them creatively in ways that stimulate disciplined thought about the changing world around us.

1.3 Organization of the argument

The remainder of this essay is organized as follows. Section 2 examines long term trends in the world's population, technology base and environment. A variety of historical reconstructions are used to portray changes of the past century. Standard forecasts by the UN, World Bank and other official bodies are combined to fashion a "conventional wisdom" vision of the next hundred years. The objective of this exercise is not to endorse or critique any of these forecasts. Rather, it is to illustrate the kinds of assumptions about future physical environments of the world that underlie the majority of contemporary scholarship

and government planning.

Section 3 examines strategic variants of the conventional visions portrayed in section 2. It does so by sketching a sampler of events, inventions, discoveries and developments that would be at odds with conventional wisdom, and would thus constitute surprises challenging our management skills and institutions. The objective is not to debate the likelihood of such surprises. Rather, it is to suggest how different from our conventional assumptions both the physical world and the management challenges of the next century could be.

Finally, section 4 returns to the central management theme of this essay. Its objective is to characterize an approach for using our visions of the 21st century to evaluate alternative policies and strategies. Experience with war gaming is reviewed and its possible adaptation to problems of managing global change is discussed. The central argument is that some such means of "practicing the future" will be necessary if politicians, planners, and publics are to get better at the tasks of managing an increasingly complex, interconnected and uncertain world.

2. Conventional Visions of the 21st Century: Historical trends and future change

Clearly, efforts to predict the future with any precision are indefensible. But trends do exist -- if only to be broken. And thinking of the future in light of an explicit and critical consideration of those trends, their origins, and their meanings is almost certainly better than just hoping that things will work out. In the case of population, technology and environment, history teaches us that what we as societies choose to do does indeed alter the future world we face, and the options we have within it. Unfortunately, our conscious efforts to design our choices are most often dominated by short term crises and narrow institutional or national perspectives. We therefore have a responsibility to look, as carefully as we can, about where long term, global trends may be leading us, how they might change, and what we can do now to increase the chances of managing a future that is to our liking[4].

An increasing recognition of this responsibility, coupled with the increasing scale and complexity of human activities has sparked in recent decades a growing industry of global forecasting and prediction. Differences of opinion certainly exist among different forecasting groups and institutions. More remarkable than the differences, however, is the degree of convergence that exists in the visions of likely population, technology, and environmental futures advanced by established national and international groups (eg. the UN, World Bank, International Energy Agency, Population Reference Bureau, etc.). Though we may argue about why such convergence develops, whether it is a good thing, and what it means, the fact remains that there exists some widely shared "conventional

wisdom" visions of the next century. In the following paragraphs, I sketch some of the central ground shared by those visions as they apply to population, technology and the environment, drawing on a recent project of the International Institute for Applied Systems Analysis[5]. This synthesis of the "conventional wisdom" (or, as many would have it, "the conventional foolishness") is then contrasted in section 3 with several unconventional alternative visions of the 21st century. Out of a deep conviction that past patterns of global change have a great deal of relevance for those thinking about future patterns, a historical dimension is included in the analysis.

2.1 Population

A century ago, the world's human population of about 1.5 billion people was growing at half a percent per year. A century from now, most forecasts suggest a population of about 10 billion people, with declining growth rates of significantly less than 1 percent per year. Today, with a population of a bit more than 5 billion and a growth rate that has only recently dropped below 2% per year, we are in the middle of what Kates and Burton have called "The Great Climacteric": a critical period, more persistent than a crisis, where significant change and unusual danger may occur[6]. This global pattern of maximum population growth rates in the second half of the 20th century, with slower growth rates both before and after, is expected to hold for most major regions of the world (Figure 1).

The highly uneven distribution of the human population across the earth's surface has significant implications for where its use of technologies is most intensive, and what consequences this use has for the environment[7]. The most densely populated 10% of the planet's land area provides a home for more than half of today's human population. Three

quarters of the population can be found on the most crowded 20% of the land (Figure 2). These relationships were not much different 100 years ago, nor do they seem likely change much in the coming century. Most of the earth has always been relatively empty of people; a few regions have consistently supported densities far higher than the rest (Figure 3). The big changes in distribution have occurred not at the global but at the regional scale. Fifty years ago less than 30% of the world's population lived in urban areas; by fifty years from now that fraction is expected to have doubled[8].

The quality of the human population is changing even more dramatically than its quantity. Two useful indicators are infant mortality and life expectancy at birth[9]. As a bench mark, some of today's best national values for these quality indicators are obtained in the Netherlands: infant mortality is 8 per 1000 live births and life expectancy at birth is 76 years. For the world as a whole, life expectancy at birth rose from 46 years in 1950 to 59 years in 1975, and is expected to reach about 70 years by 2025. Comparable progress can be seen in the infant mortality rate. This was halved between 1950 and 1975, and is expected to reach about 30 per thousand by 2025. Regional variations in population quality are suggested by the data for Europe and India shown in Table 1: the gap between the rich and the poor remains, but is clearly declining. To the extent that the wisdom of these conventional forecasts is born out, significant aspects of population quality in India should reach levels better than those of post-war Europe within our lifetimes.

2.2 Technology

The changes in the earth's physical stage brought about by human population growth per se are dwarfed by the changes mediated through the technologies people use to pursue their wants and needs. Over the last century, while the earth's population was tripling, its total manufacturing production rose more than 50 fold. A significant portion of this production entered international trade, which increased by a factor of 25 over the same period[10]. In general, this explosion of technology has allowed people to produce and exchange more (and more varied) goods, services, information and violence, with greater speed, at lower costs, and on an increasingly global scale. In the process technology has, quite simply, transformed the face of the earth and the life of humanity. Whether and how this continuing transformation can be managed to yield sustainable improvements in human well-being for the 21st century is one of the central questions of our time.

Despite the great richness of technological activities in which people engage, a few major areas of application are generally accepted to have the greatest direct impact on the long term, large scale relations among human populations and their physical environments.

Health and Agriculture: The continued development and application of public health technologies for water purification, vaccine administration, and the elimination of the most lethal pathogens is implicit in the dramatic improvements of life expectancy and infant mortality already quoted in the forecasts of Table 1. The studies underlying these numbers forecast no qualitative breakthroughs in health technologies available at a global scale, but neither do they allow for any qualitatively new diseases like AIDS on the global scene.

Health and food are closely related at local and global scales. Total world agricultural production has risen by a factor of a bit more than 5 in the last century. A further increase to twice present levels by 2030 and 3 or 4 times present levels towards the end of the next century is thought likely by many experts (Table 2). Less than half of the past increase and rather little of the future increase will come from expansion of arable land. The key factor is increased yields derived from techniques to improve genetic stocks, cultivation, fertilizer applications and control of pests and diseases. The level and character of technological inputs actually applied make a tremendous difference in the ability of the land to support people. Long term agricultural carrying capacities in India, for example, have been estimated to be two to three times higher under a regime of maximum technical inputs than a regime of minimum inputs. Even in the technologically advanced US agricultural system, aggressive programs of R&D have been estimated to double the national productive capacity that would be expected by 2030 under a continuation of present R&D funding[11]. The kinds of technological progress required to realize these forecasts vary greatly from place to place; the challenge is to design technologies appropriate for local environmental, social, and economic conditions. Generally, however, progress will be needed in agro-ecological characterization, techniques to increase the efficiency of fertilizer and water use, biotechnology, improved production systems, and training[12].

Energy: Total world energy consumption has risen by a factor of 25 in the last century, and has been predicted to increase another factor of 6 over the next hundred years (Table 2). In 1875, world energy was probably derived about equally from wood and coal with the market share of the former decreasing and the latter increasing. At

present, fossil fuels dominate the global scene -- a situation that most analysts believe will persist through the first half of the next century despite advances in biomass, solar and nuclear technologies (Figure 4). What will change is the composition of the fossil mix, with oil's share declining and that of fuels derived from coal and shale increasing. The potential share of natural gas is a subject of contemporary debate[13].

Environmental and economic pressures can be expected to continue long term trends of improvement in overall energy efficiency: the ratio of energy to GNP in the US, for example, has been halved since it peaked in the 1920's (Figure 5). This trend is likely to be associated in the future, as it has been in the past, with increasing electrification of the energy economy. Technologies that could be tightly associated with such increased electrification include superconductors, organic plasma chemistry and electrochemistry, electrochemical approaches to toxic waste management, and electric vehicle commercialization[14].

Materials: Over the past hundred years, the human use of both basic and exotic materials has increased dramatically. World iron production, for example, has grown 30 fold. Annual copper production has grown at 4.5% per year over the last century; lead at about 3.5%[15]. The use of basic chemical stocks exhibits even faster growth. European consumption of sulfuric acid increased by a factor of 40 over the last century. Since 1950, consumption of benzene has grown at 5% a year, and of organic pesticides at 18% per year[16]. The variety of materials in use has also experienced explosive growth. Something on the order of 70,00 different synthetic chemicals are now known, with 10,000 produced in commercial quantities[17].

New technologies involving composites, ceramics and other exotic materials are rapidly developing. Clearly, continuing demand for extraordinary quantities of a great variety of materials will play a significant role in setting the physical stage for the 21st century. Equally clearly, however, the long term trend of increasing material use with increasing levels of development and income has been reversed across a broad range of countries and sectors. Overall, the amount of industrial raw material needed per unit of industrial production is now less than half of what it was in 1900[18]. The basic pattern of declining intensity of materials use is illustrated for global cement use in Figure 6, and for a variety of other products in the European data of Figure 7[19]. The extent to which this "dematerialization" phenomenon is determined by income level (as suggested in Figure 6) or technical progress with time (as suggested in Figure 7) is difficult to unravel, since the two factors are so closely intertwined. In any case, however, the implications for materials use in the 21st century are profound.

Military: Military aspects of technology play a central and incompletely understood role in setting the global stage. The basic facts of the matter are straightforward, if depressing. World military expenditures have risen at an average real rate of about 4% per year since 1949, a trend that shows no signs of abating (Figure 8)[20]. Today, military expenditures consume something on the order of 4% of gross world production. Over the past decade more than $4 million million [h]as been consumed by the military sector around the world. Whether these expenditures have bought the world increased security is a matter of debate, but they have certainly increased humanity's potential for self destruction. Only a little over a century ago, the bitter and prolonged conflict of the American civil war left

600,000 dead. The improved technologies of first world war killed about 16 million people; the second world war around 20 million[21]. No one knows quite what would happen if a third world war utilized even a modest fraction of the weaponry that has been built up in recent decades. But between direct blast and fire effects of modern nuclear weapons, and the environmental changes they would likely precipitate, the military technologies of today could easily kill a thousand million people[22].

A second dimension of military technologies is less obvious but also important. A sizable fraction of total technical resources of the world have always been devoted to weapons systems. Today, a wide range of countries spend a fifth to a third of all R&D on military technology[23]. This activity certainly has had and will continue to have important civilian spinoffs -- advanced computers and semiconductor chips and electromechanical devices for automatic control are obvious examples of current interest[24]. But it is also true that military R&D may compete with civilian activities for both people and funds. Finally, the actual and potential restrictive impact of security concerns on world technology flows should not be underestimated. Better understanding of the relations between military and other technologies is needed if we are to improve our management of global change in the 21st century[25].

2.3 Environment

As noted in the section 1, the long term trend of interactions between human populations, their technologies, and the environment is one of increasing scale, complexity, and intensity. A century ago, at the beginning of the "Great Climacteric" described by Kates and Burton, only certain regional environments had been significantly transformed

by human activities. Today, there is not a place on the earth's surface where the impact of human technologies cannot be seen in changes of the physical, chemical or biotic environment. Human activities of the 21st century have the potential to dominate many of the global biogeochemical cycles, to warm the world's climate at unprecedented rates, and to eliminate a significant fraction of the earth's biodiversity.

A sampler of a few of the more important global environmental changes follows, starting with those having relatively straightforward causes and moving to the complex "syndromes" of environmental degradation noted in section 1. Due to constrains of space, I focus here on atmospheric changes, and ignore equally important issues of water pollution, deforestation, desertification and the like.

Climate change[26]: The earth's climate is strongly influenced by the atmospheric concentrations of certain "greenhouse" gases, among the most important of which are water vapor, carbon dioxide, methane, nitrous oxide, and some chlorofluorocarbons. Though the concentrations of some of these gases are significantly affected by natural fluctuations, human use of agricultural, energy, and industrial technologies has resulted over the past century in rapid increases of the total "greenhouse effect" in the atmosphere. These have been accompanied by, and may have caused, increases in global temperature of about 0.5°C and in global sea level of about 12cm. A continuation of greenhouse gas emissions could result in significant, though highly uncertain, intensification of these impacts on global climate in the next century (Figure 9). Regional impacts would vary greatly, and are even more difficult to predict. Under the forecasts summarized in Table 3, human impacts on the Indian subcontinent might well be dominated by increased coastal flooding in the

Gangetic delta and plain, and by changes in the timing and intensity of monsoon rains. Primary impacts for Europe, in contrast, could occur through rapid northern migration of climatic optima for crops and natural vegetation -- a potentially serious problem in a region where habitats are as fragmented as they have become in Europe today. An increase in summer dryness would also aggravate existing problems of water availability for many countries of the Mediterranean basin[27].

Ozone depletion in the stratosphere[28]: Ozone in the stratosphere plays an important role in the physics of the atmosphere, and provides an important shield against solar ultraviolet radiation. With less ozone, more of the ultraviolet radiation would reach the earth's surface where it can cause significant harm to materials, plants, and people. The stratospheric ozone concentration is controlled through complex physical and chemical processes involving a number of gases -- among them, chlorofluorocarbons, halons, methane, nitrous oxide and carbon dioxide -- that are now being influenced by human activity. Measurement difficulties have plagued efforts to assess possible ozone depletion. It now seems, however, that for the period of 1969-1986 global ozone depletion may have been on the order of 2-3%[29]. At the regional scale, a spectacular and unexpected decrease of 50% in total column ozone has occurred over the Antarctic in the last decade. Looking into the future, simple models forecast a wide range of possible additional declines in global ozone values by the middle of the next century. The median estimate of about 5% would be only slightly altered by full implementation of the present Montreal Protocol on Protection of the Ozone Layer (Figure 10)[30]. Depletion would be greatest at high latitudes, with the total loss over the Indian subcontinent perhaps half that over Europe[31].

Air pollution and forest damage: Of the many large scale environmental changes of recent years, none is so visually dramatic as the syndrome of extensive forest damage now evident in North America, Europe, and China. The causes of the damage are complex and poorly understood[32]. Most studies, however, agree that some combination of atmospheric pollutants is involved. Most often named are tropospheric ozone, acid deposition, sulfur and nitrogen oxides, nitrate and ammonia, and heavy metals. Where the "Waldsterben" phenomenon is most advanced in central Europe, the volume of wood now showing signs of decline is more than 5 times the volume annually harvested. For many of the most severely affected countries and species, the ratio is greater than 10 (Figure 11)[33]. In other words, vastly more of Europe's forest is now at risk to air pollutants than to direct harvest by man. This situation will almost certainly deteriorate further by the middle of the next century, although present agreements to reduce sulfur emissions by 30% will help and stronger measures being contemplated would help even more (Figure 12)[34].

Though the character and, probably, the causation of forest damage differ among regions, there is every reason to expect that the current situation in Europe, with its uniquely long and intense history of industrial air pollution, provides the best available forecasting model of possible future developments elsewhere. Further development of existing damage can be expected in eastern North America and southern China. Potential problem areas for the future, identified on the basis of soil sensitivity and expected future industrial activity, include South America's Caribbean coast and the South Atlantic coast from Buenos Aires to Rio de Janeiro, Africa's Gulf of Guinea coast, India's west coast, and the Malaysian archipelago[35].

Syndromes of environmental degradation: One of the most difficult tasks we must face in managing the interactions among human activities and the environment is to comprehend the connections among changes. Fossil fuel combustion, for example, has an impact on each of the environmental components treated above -- yet we persist in assessing the impacts of alternative energy policies one at a time. Conversely, many human and natural processes influence each property of the environment -- yet we frequently conduct assessments process by process. One interesting experiment in picturing the missing connections is presented in Figure 13. These figures summarize a massive multidisciplinary study of long term impacts of world development on the atmosphere[36].

Each cell in the figures represents the impact of a particular natural or human source of change on a particular environmental component for a given period and region. Data for past periods are derived from historical studies, while those for the future are based on standard forecasts such as those presented above. Knowledge about the effects of various levels of impact is used to color code the results on a qualitative severity scale. "Summing" across columns gives the "Total (environmental) impact" of a given source. "Summing" across rows gives the "Environmental quality assessment" for a given component. Row and column totals combine in the lower left hand corner to give a history of changes in overall environmental quality for the region in question. In this example, Europe shows a long history of increasing impacts, slowed but never reversed by technological improvements in pollution control. India begins to experience environmental problems later, but their rate of onset is faster and the overall environmental situation by the end of the 21st century is as bad as Europe's. Many details of the study underlying these figures

could be debated, and the importance of subjective value assumptions in performing the "summations" is clear. Nonetheless, some sort of synoptic effort in the directions suggested here will be necessary if we are to come to terms with the next century's tightly linked syndromes of environment - development interactions.

3. Alternative Visions of the 21st Century: the Role of Surprise

The forecasts summarized in the previous section represent a cross-section of the "conventional wisdom" currently advanced by prestigious national and international organizations concerning likely future changes in human populations, their technologies and the natural environment. They explicitly presume an absence of global scale wars or economic depression over the next century, and more generally are free of radical departures from historical trends. But as noted in the introduction, significant change often does occur in abrupt or discontinuous bursts. And, as the Canadian biologist C.S. Holling has argued, if there is no framework of expectation or understanding then these abrupt changes are perceived as surprises -- as catastrophes, crises or opportunities[37].

Surprise-free forecasts are therefore necessary but insufficient tools for efforts to improve the management of long-term interactions between humans and their environment. The problem in providing alternatives is not that analysts have been unaware of the shortcomings of surprise-free thinking, but rather that they lack, in the words of Harvard's Harvey Brooks,

> usable methodologies to deal with discontinuities and random events. The multiplicity of conceivable surprises is so large and heterogeneous that the analyst despairs of deciding where to begin, and instead proceeds in the hope that in the longer sweep of history surprises and discontinuities will average out, leaving smoother long-term trends that can... provide a basis for reasonable approximations of the future[38].

But real history turns out to be far from an "averaging out". The distinguished historian W.H. McNeill concluded his remarks at a symposium on "Resources for an Uncertain

Future" as follows:

> I believe historians' preoccupation with catastrophe might be useful to economists, if they care to listen. Extreme cases, breakdowns, abrupt interruptions of established market relations - these are not staples of economic theory, and are, I believe, usually dismissed by statistically minded analysts of the norm and its fluctuations. But human societies are a species of equilibrium, and equilibria are liable to catastrophe when, under special limiting conditions, small inputs may produce very large, often unforseen, and frequently irreversible outputs... As an historian contemplating the richly catastrophic career of humanity across the centuries, venture to recommend to economists a more attentive consideration of [catastrophe] models -- at least when trying to contemplate the deeper past and long-range future[39].

A central challenge for management as we approach the 21st century is therefore to develop methods, models and concepts necessary to move beyond surprise-free analyses to a more realistic treatment of the complex interactions among people, technologies and environments.

3.1 Approaches to the study of surprise

The "catastrophe" theories and their relatives referred to by McNeill have played an important role in providing an alternative paradigm to surprise-free analysis. But to move beyond the empty generalities and vague analogies which have so inflated the "catastrophe" literature, it will be necessary to assemble a great deal of carefully documented case material, to fashion a family of specific techniques and explanatory models, and to develop a basic theory of surprise.

As an example of what can be done on the empirical side, Harvey Brooks has devised a "typology of surprises in technology, institutions, and development"[40]. He characterizes the kinds of surprise that arise in socio-technical systems as follows:

- Unexpected discrete events, such as the oil shocks of 1973 and 1979, the Three Mile Island reactor accident, political coups or revolutions, major natural catastrophes, accidental wars.

- Discontinuities in long-term trends, such as the acceleration of USA oil imports between 1966 and 1973, the onset of the stagflation phenomenon in the OECD countries in the 1970s, the decline in the ratio of energy consumption growth to GNP growth in the OECD countries after 1973.

- The sudden emergence into political consciousness of new information, such as the relation between fluorocarbon production and stratospheric ozone, the deterioration of central European forests apparently due to air pollution, the discovery of recombinant DNA technique, the discovery of asbestos-related cancer of industrial workers.

Brooks has collected a large number of examples under each of these categories, and has taken some initial steps in shaping a theory that accounts for their major features. More generally, Torsten Hagerstrand and Robert Kates, have cataloged following possible techniques for constructing surprise rich scenarios of future change[41]:

1) Contrariness: How can the surprise-free assumptions be changed?

2) Perceived expert surprise: What are the tails of the distributions of relevant tasks, events, and outcomes?

3) Imaging: Given an unlikely future, what sequence of events might be used to reach it?

4) System dynamics: How could known current trends produce counterintuitive results due to interaction?

5) Surprise theory: Are there underlying principles that would let us understand unexpected events and developments?

6) Historical retrodiction: Are the seeds of future surprises always present with hindsight, and how can they be recognized?

Summarized in the remainder of this section are the results of two preliminary and experimental efforts to get on with the task of building surprise rich scenarios. The first employed a mix of the first three techniques outlined by Hagerstrand and Kates, and concentrates on social change. The second adopted a systems dynamics approach (number 4 above) in exploring possible environmental surprises. The section concludes with some speculations on the prospects for a theory of surprise (number 5 above). The results obtained, it should go without saying, should be treated as points of departure for further thinking and analysis, not as predictions of what is likely to occur.

3.2 The Friibergh Surprises

As part of the continuing IIASA effort to explore and evaluate approaches for surprise-rich analysis of global futures, a workshop was held at Friibergh Manor in Sweden in 1986[42]. The workshop brought together historians, natural scientists and social scientists from Europe, North America, and Africa. Its objective was to write a number of "future histories" of the next century that would differ significantly from the conventional visions described in section 2, above. The basic methodology evaluated through the workshop was to review the conventional forecasts, then to postulate a set of states of the world in 2075 sufficiently different from the conventional wisdom as to be judged by workshop participants to be "surprising" or unlikely, and finally to attempt to construct plausible sequences of events connecting these surprising futures to the world of today. Participants endeavored to make individual events in the sequences as plausible as possible -- the intention was to discover the extent to which a surprising century could emerge as the cumulative product of a sequence of relatively unsurprising days and years. Independent working groups wrote their own "future histories" for each postulated state of the world in 2075. Results were then compared, critiqued, and a composite history constructed. The effort was global in perspective, but with particular attention paid to developments in Europe and the Indian subcontinent.

In the space available here, I can sketch only a summary of two of the Friibergh Scenarios. Regrettably, these summaries omit the rich contextual narratives which give the originals an aura of both verisimilitude and playfulness -- an example of the narrative vs. numbers tension noted in section 1. It may be worth pointing out, however, that most of the normally sober and skeptical scholars involved in the Friibergh effort came away

convinced by the process of building these scenarios that the future histories they constructed were surprisingly compelling in their internal momentum and logic. The implication is that even worlds as different from our present imaginings as those described below require little more than a persistent bias to events for their fulfillment. In other words, very surprising futures turned out to be surprisingly easy to shape. The meaning of this finding -- confirmed by other work in scenario analysis and war gaming[43] -- for efforts to think broadly about the 21st century are debatable, but probably important.

Friibergh I - "The Big Shift": The leitmotif of the first scenario of global change developed at Friibergh is a shift of the center of the world economy to South and East Asia. A number of factors contributed to reversal of 20th century core - periphery relations. One was a "noble decline" of Europe and America, brought on through an increasing unwillingness of nations, ethnic groups and individuals to look beyond short term gains in material welfare and economic security. The resulting failure to develop the new social and economic structures that the 21st century demanded was reflected in the collapse of Europe's 1992 experiment, and the transient nature of the Gorbachev era in the USSR. The Cold War was not so much resolved as rendered irrelevant, fading into insignificance relative to the internal problems of the former superpowers.

In contrast, India, China and their neighbors traverse the 21st century as increasingly dynamic and expansive societies, successful in resolving many of the problems that confront them. This was in part due to an advantageous international situation, but resulted largely from radical political actions and social innovations taken at the national and regional level. A vigorous new social synthesis of the most successful approaches to organization of work

that had been developed in the 20th century, plus the region's traditional religious and community values emerged. This proved successful in guiding development, mobilizing the masses, and keeping social tensions within limits manageable by the authoritarian but pragmatic central governments of the region. Even the great calamity of the period -- the loss of much of coastal Bangladesh to rising sea level --had the long-term effect of diminishing local power struggles and promoting integration of the region.

Some quantitative results of these developments are presented in Table 2 and Figure 14. By 2075, this world-turned upside down had a population of about 8 billion people. Growth of population largely stabilized due to the radical improvements in personal well-being in South and East Asia. Global energy use and agricultural production also increased somewhat less than in the conventional wisdom forecasts of the late 20th century. By most meaningful measures, the gap between North and South declined dramatically.

Friibergh 2 - "The Big Load": In this scenario, the declining rates of global population growth that so influenced forecasts of the late 20th century prove to be a transient and local anomaly. By 2075 there are 20 billion people alive on the planet. A variety of factors contributed to the failure of the 20th century's population control efforts, among them ethnic competition within nations and China's explicit reversal of its slow-growth policies. Most spectacular, however, was a backlash response -- fanned

by suspicions of intentional genocide -- to the belated discovery that a male contraceptive distributed widely in the third world during the early 21st century invoked permanent rather than temporary sterility in men working under extreme tropical conditions.

To the surprise of many, however, technological and economic growth were stimulated rather than swamped by the expanding population. Rapid progress -- though incremental rather than revolutionary -- in solar energy and bioengineering technologies were crucial. By the end of the century, most people were doing about as well as they were expected to under the conventional forecasts of world only half as densely inhabited that were prevalent at a hundred years before (see Table 2 and Figure 14).

The "Big Load" imposed great stresses on environmental and social systems. But the world of the mid 21st century was nonetheless held together through a system granting high ethnic autonomy at the local level and a "new international order" of nongovernmental institutions coordinating economic and environmental measures at the global level. Transnational religious and business organizations were central to this system, with nation states becoming increasingly preoccupied with symbolic and security functions. A great deal of migration took place in this crowded world, especially into sparsely settled areas like Siberia, Amazonia and -- after the elimination of the tse-tse fly and a variety of water borne diseases -- much of central Africa. After a period of ineffective if draconian measures to regulate the flow of people, however, states also relegate this function to nongovernmental mechanisms and the market.

3.3 The Laxenburg Surprises

The possibility of abrupt and unexpected environmental change at large scales is now taken seriously in the natural sciences, if for no other reason than the totally unexpected appearance over the last decade of the hole in the ozone layer above Antarctica (Figure 15), and the rapid onset of forest die-back in parts of Europe. The possibilities of

catastrophic sea level rises associated with collapse of the West Antarctic ice sheet, and of rapid rearrangements of North Atlantic ocean circulation and climate have also received wide public attention. Nonetheless, no systematic study of not-impossible environmental surprises has yet been attempted.

Although environmental change was not absent from the Friibergh scenarios, the methods used in the Friibergh experiments did not attempt to utilize any deep understanding of the possible sources of abrupt or discontinuous change in the natural environment. A second workshop was therefore held, this time at Laxenburg Austria's Institute for Applied Systems Analysis, to outline a set of not impossible environmental surprises for the next century. Participants were drawn from ecology, oceanography, atmospheric chemistry and climatology. Source material constituted both historical documentation of abrupt changes that had happened before and thus might recur, and understanding of causal processes that might, through interaction, produce unexpected results. As in the case of the Friibergh experiments, the objective was not to predict the likely, but rather to expand perceptions of the not-impossible[44].

Once again, space constraints for this essay allow me only to summarize a few of the Laxenburg results. Missing will be both the sense of adventure that permeated this communal effort to second guess the unknown, and the detailed critical analyses that make these particular imaginings more than entertaining science fictions. Most important, however, I know of no way to convey the feeling of many participants that they were working on something that was simultaneously important for serious people to understand and indecent for serious scholars to study. The willingness of the group to move forward on the experiment despite that tension is encouraging.

Laxenburg 1 - Amazonian Fire Forests[45]: The central event of the first Laxenburg scenario was a series of catastrophic fires that occurred in the Amazonian basin in the mid 21st century, similar in character to, but vastly more extensive than, those that had ravaged Borneo in the 1980's. Surprisingly, however, the forest that grew back in the wake of these fires was not the humid rain forest of classical Amazonia, but an open woodland associated with annual dry periods and maintained by periodic fires. In subsequent years, this fire-maintained woodland encroached rapidly on the remaining rain forest, leaving only patchy remanents by century end.

In retrospect, it seems reasonably clear how the Amazonian collapse developed. No processes unknown to scientists of the late 20th century were involved; it was rather the unlikely but wholly plausible systems interaction of several processes that did the job. Since the late 20th century it had been known that about half of the 2-3 meters of rain that falls in the Amazonian basin each year was recycled internally through the rapid evapotranspiration pathways provided by the forest. This internal recycling significantly mitigated the seasonality of water availability in the Amazon system. Such a positive feed-back loop between the amount of rainfall and the huge area of tropical vegetation it supported had long been recognized to pose a theoretical possibility of disruption with unpredictable consequences. The basic hypothesis was that some external processes could lead to a reduction in the water vapor available to the system. Total rainfall would then decrease, the buffering character of the forest would be adversely affected, and the seasonality of water availability would increase. These changes would feed back on themselves, producing an incrementally altered forest system, recycling incrementally less

water, and increasing stress during the increasingly extreme periods of annual dryness. Eventually, a critical point would be reached at which any number of events might trigger an abrupt transition into a radically different system of vegetation, recycling much less of the region's water.

In the event, two human-induced processes that set the stage for the collapse of Amazonia, one global, one regional. At the global scale, the slowly warming climate resulting from the greenhouse effect resulted in intensification of the overall hydrological cycle. But although more rain fell in Amazonia than at present, it fell less frequently and more intensely. This increased water stress on forests, especially in the dry season. Added to this globally induced stress were the regional effects of forest clearing and the resulting decrease in water-recycling capacity of the basin. With the stage set by this increasing stress on the positive feedback loops of Amazonia's hydrological system, it was only a matter of time until some event triggered catastrophic change. As had been the case in Borneo in the 1980's that triggering event turned out to be a massive fire, probably precipitated by the acute episodes of dryness that have for centuries been associated with the periodic "El Niño" or Southern Oscillation in ocean temperatures[46]. These fires sufficiently disrupted the forest's ability to recycle water that the trees growing back in their aftermath faced significantly dryer conditions than their predecessors. As in many other regions of the world, this relatively dry forest, once established, was stable -- supporting the periodic fires that assured its own regeneration[47]. This abrupt, catastrophic, and irreversible change of today's Amazonian rain forest into a much less diverse and productive Amazonian fire forest eventually resulted in the loss of a significant fraction of the western hemisphere's biodiversity, and the conversion of a humid, highly productive

ecosystem into an area of periodic drought and diminished carrying capacity.

Laxenburg 2 - Degradation of the troposphere[48]: In the latter years of the 20th century, high concentrations of tropospheric ozone became chronic in industrialized urban areas, with occasional acute episodes over larger areas. In the early 21st century, these pockets of high concentrations exploded outward into a chronic, continent-scale phenomenon of ozone stress throughout much of the developed and developing world. By 2025 average background ozone concentrations in many rural areas were equivalent to the worst months experienced by the Ruhr Valley or Los Angeles in the 1980s. The complex syndrome of atmospheric degradation accompanying these changes accelerated through the remainder of the century, despite some marked successes in regulating individual pollutants. The cumulative damage to human health, crops, forests, and development in general exceeded anything seen in the 20th century.

Again, in retrospect it was fairly clear how unexpected interactions among individually understood processes had combined to produce the rapid alteration of global tropospheric chemistry. The central actors in this transformation turned out to be methane, the oxides of nitrogen, and hydroxyl radicals. Hydroxyl radicals are extremely scarce but extremely effective "cleaners" that remove from the atmosphere a range of obnoxious chemicals including carbon monoxide, hydrocarbons, and some of the sulfur compounds involved in acid rain. Methane (CH_4) had been increasing at a rate of about 1% per year through much of the 20th century. Conventional wisdom at the time ascribed this rise to growing cultivation of rice and ruminants and, to a lesser extent, to direct release from industrial coking and fossil fuel production operations (leakage from coal seems and gas

transport plus gas flaring). In clean air, methane is oxidized to carbon dioxide, in the process consuming both ozone and the hydroxyl radical. In air polluted with high levels of nitrogen oxides, however, the oxidation of methane proceeds by a different path that releases both the hydroxyl radical and ozone to the atmosphere. As we entered the 21st century, the atmospheric concentration of methane grew at an accelerating rate. In addition to the known sources mentioned earlier, this was due to the unexpected increase of methane releases from Canadian and Siberian tundra. (Those normally unproductive landscapes, it turned out, were being fertilized -- and their methane production thus increased -- by the long range transport of nitrogen oxide compounds from the industrialized areas of the northern hemisphere). In the relatively clean air of the equatorial regions and southern hemisphere, oxidation of the increased amounts of methane depleted the available hydroxyl radicals. This left the polluted northern latitudes, with their hydroxyl-producing chemistry, as the principal location of further methane oxidation. In the process, however, the high nitrogen oxide concentrations in those latitudes assured substantial net production of ozone over virtually all the inhabited land areas of the northern hemisphere. By the end of first quarter of the century, the depression of hydroxyl concentrations in the low and southern latitudes, coupled with increased biomass burning and industrial activity in the same regions, allowed nitrogen oxides to accumulate there. These eventually reached the threshold concentration above which methane oxidation is a net producer of ozone; ozone concentrations therefore began to climb even in these relatively clean areas. The final contributor to this scenario was the further acceleration of methane releases from the northern latitudes that began about mid century in response to climate warming. (Both increased tundra productivity and the release of previously

frozen methane clathrates from the bottom of the Arctic Ocean contributed to this response). This methane release initiated a positive feedback -- warmer temperatures produced more methane which warmed the temperatures even more -- which, as a by-product, churned out even more ozone into the global troposphere.

3.4 Towards a general understanding of surprise?

Surprising futures of the sort summarized above could be spun out indefinitely. And although more such spinning would almost certainly provide useful counterpoint to the conventional wisdoms that so often blinker our perspectives on the future, a more systematic treatment of the nature and origins of abrupt change in complex systems, and of social reactions of surprise, is nonetheless badly needed.

In the beginnings of work towards such a theory of surprise, CS Holling has emphasized the critical importance of processes operating on multiple time scales[49]. In particular, he argues that the abrupt change of one or more "fast" variables (for example, the fraction of water recirculated or the ozone levels in the "Laxenburg" scenarios described above) can often be understood as a consequence of specific alterations in the underlying system structure that result from continuous change of one or more "slow" variables (for example, the deforestation or the methane rises in the examples). Elsewhere, Holling has summarized a large body of empirical work on the key features of environmental systems that exhibit abrupt change[50]. I paraphrase his conclusions as follows:

1) There can be a number of locally stable equilibria and stability domains around these equilibria due to the existence of significant nonlinear processes

in the system.

2) Abrupt jumps between the stability domains can be triggered by exogenous events. The size of these domains is a measure of the sensitivity to such events.

3) The stability domains themselves expand, contract, and disappear in response to changes in slow variables... and, quite independently of exogenous events, force the system to move between domains.

4) Different scales of variability emerge from the details of the system. There can be conditions of low equilibrium with little variability. And there can be dynamic disequilibrium in which there is no global equilibrium condition and the system moves in a catastrophic manner between stability domains. Finally, there exists the possibility of chaotic behavior.

5) Abrupt change is thus an integral property of the system. For long periods change is gradual and abrupt behavior is inhibited. Conditions are eventually reached, however, when an abrupt jump event becomes increasingly likely and ultimately inevitable.

The potential utility of Holling's approach for complex systems of interactions between people and environments can be illustrated by current debates over the impacts

of climatic variability and change on society. Martin Parry has characterized the problem as follows:

> What, for example, were the real "causes" of the Sahelian crisis... meteorological drought or enhanced vulnerability due to economic and political developments insensitive to an environment that has always been changeable[51]?

He points a way to its resolution, however, with a distinction

> ...between contingently necessary and contingently sufficient conditions for an occurrence. It is probable that increased vulnerability was a necessary condition (or precondition) for the Sahelian disaster; without it the economic system might have been more resilient to the meteorological drought. It was not, however, a sufficient condition, because it required a further event... to precipitate the effect[52].

In the conceptual framework introduced by Holling, the "contingently necessary" economic and political developments would thus seem to play the stage-setting role of slow variables. Meteorological drought is one possible candidate for the exogenous triggering event. And the disaster of ensuing famine is the abrupt change that society, lacking an adequate framework of understanding, reacts to with surprise.

Whether this perspective on abrupt change can help to develop tools and understanding that will be useful in managing the interactions among human populations, their technologies, and the environment remains to be seen. At a minimum, however, it focusses attention of the need to assess, much more systematically than has been the case, those "slow variable" processes that might be significantly involved in setting the stage for interactions of people and their environments. In the final section of this paper, I suggest

how our nascent understanding of surprise might be utilized for improved management of the interactions among people, their technologies, and environments.

4. Practicing the Future

This essay, along with its companions in the Visions project, has attempted to sketch a broad range of not-impossible futures that humanity could find itself contending with in the 21st century. An indefinite number of additional visions is surely possible, each emphasizing a different set of actors, interactions, and uncertainties. The central challenge is not, however, comprehensively to describe or rank all such alternatives. Rather, it is to design management skills that will help us to deal with the wide range of contingencies they represent -- skills that will help us in turning the future's unforseen opportunities to our advantage, and in controlling its unforeseeable dangers within tolerable limits. Much calculation and analysis can doubtless aid in this task. But there is a limit to how much improvement can be expected from theoretical studies divorced from actual conditions of use. And no management tool or concept has value independent of the skills of its user -- skills that can only be learned through long and continuing practice. If the visions suggested here are to evolve into something of practical value for societies, societies must find ways of putting them to work. Only such exercises in application can produce a realistic feel of how various policies and management strategies might best be applied, of what are their actual strengths and limitations, and of where they can best be improved[53].

What might such exercises look like? What skills would they try to develop? How would they provide opportunities to apply and test our incomplete understanding of the world's changing physical stage and possible policy responses to it?

The need for practice: Practicing with Earth itself obviously has its drawbacks. Scientists may speak of the human releases of carbon dioxide to the atmosphere as "a great geophysical experiment", but the results of this particular experiment may come in a bit late to be of much use for those living in the test tube. The obvious alternative of practicing on various mathematical models of the Earth also leaves much to be desired. Any notion of confidently predicting the practical consequences of alternative response options wilts under the numbing scale and complexity of today's interactions among people, their technologies, and the environment, plus the profound uncertainties that remain in our scientific understanding of those interactions. Moreover, even in simpler contexts, formal models have generally not been conducive to the close interaction among scientists, politicians, and other people that would be such an important aspect of the social learning that will be required to cope with global change in the 21st century.

More useful means of practicing how to cope with complex interactions of environments and societies are badly needed. Considerable attention has been devoted to these needs over the last 5 years in an experimental program at the International Institute for Applied Systems Analysis's. Following an extensive review and evaluation of experience with alternative approaches[54], the IIASA effort developed a program of "policy exercises": organized efforts that bring together policy people, scientists, and technologists to practice writing "future histories" of plausible interactions between societies' development activities and the global environment[55]. Trial efforts have been conducted on problems of long term interactions between development and environment in Europe, and on the implications for the world forest products industry of pollution-induced die-back in Europe's forests. Further efforts are planned to deal with policies for managing climate change.

Some of the tentative conclusions and perspectives from this work are summarized below.

Political exercises and gaming: Policy exercises are derived from approaches developed in support of political- military strategic planning during the late 1950's and early 1960's[56]. At that time, experience had shown that formal models were inadequate to capture the contingencies, the unquantifiable factors, and the contextual richness that seemed central to the main lines of political evolution between the great powers in the period 1955- 1965. The models also tended to strengthen rather than relax the barrier between analysts and practitioners of political and military strategy. In attempting to design more useful integrative approaches, Herbert Goldhamer of the Rand Corporation realized that his

> problem was similar to that confronting historians. He was faced with the task of writing a 'future history' to clarify his ideas about the motives and influences affecting the behavior of great powers, their leaders, and others in the real political world[57].

The method devised by Goldhamer and his colleagues to write these future histories was dubbed "political gaming". Teams of human (as opposed to computer) participants were confronted with generally realistic problem scenarios and required to work through responses both to the scenario and to the moves made by other teams. The role of "Nature", which determines the impact on conditions of play resulting from the moves of the teams, the injection of unexpected events, the introduction of constraints on allowable responses, and so on, was played by the control team responsible for organizing the exercise[58].

Garry Brewer has described four "difficult questions that eluded or exceed the capacity of alternative analytic tools" that were explored by the original political exercises[59]. These questions sufficiently resemble those that confront us in learning to cope with global interactions of people, technologies and environment to warrant quoting here:

- What political options could be imagined in light of the conflict situations portrayed? What likely consequences would each have?

- Could political inventiveness be fostered by having those actually responsible assume their roles in a controlled, gamed environment? Would the quality of political ideas stimulated be as good or better than those obtained conventionally?

- Could the game identify particularly important, but poorly understood, topics or questions for further study and resolution? What discoveries flow from this type of analysis that do not from others?

- Could the game sensitize responsible officials to make potential decisions more realistic, especially with respect to likely political and policy consequences?

Future histories of global change: Experience with political gaming indicated that each of the preceding questions could be given an answer of "yes, but only under favorable

conditions"[60]. The same experience led to several additional conclusions suggesting that the political exercises might serve as a basis for designing policy exercises to practice social responses to the carbon dioxide question and other environmental problems. Several of the most important of these potential linkages between exercises in political and broader social/ environmental policy are summarized below.

- The political games were found to perform better than alternative approaches in studying "poorly understood dynamic processes... [and] institutional interactions" and in "opening participation to many with different perspectives and special competences, on a continuing basis over time"[61]. The need to accommodate multiple political and environmental perspectives in efforts to learn effective responses to global change is central to the Visions project. The "poorly understood" nature of our knowledge of long term, large scale environmental processes and institutional responses likewise requires no further elaboration.

- "The selection of competent professionals to participate in the political exercise proved to be critically important. This situation is analogous to that in chess or other games when inferior players tend to consolidate their own bad habits rather than being stimulated to improved or inspired play"[62]. To be useful, policy exercises on global change questions would almost certainly have to involve several of the very top scientists involved in recent environmental assessment plus their opposite numbers from the world of politics, finance, and industry. The political gaming experience suggests that there is little point in carrying out such exercises using second rate consultants and middle level bureaucrats. But

securing the participation of sufficiently senior and innovative people may not be as difficult as it sounds. For environmental problems in general and the greenhouse question in particular, some of the best scientists and best policy people have been expressing a growing dissatisfaction over their inability to address each other except through stultifying layers of reports and bureaucracy, or in ritualized and guarded public encounters. The recent Villach-Bellagio workshop series is one response to this dissatisfaction[63]. Carefully designed policy exercises might constitute the next step in providing the channels and forums of communication they seek.

- "[O]ne of the most useful aspects of the political game was its provision of an orderly framework within which a great deal of written analysis and discussion took place... [O]ral or written discussion of political problems that arise during the game is one of its most valuable features"[64]. Finding a way to order, to evaluate, and ultimately to use the great volume of literature now being generated on the scientific and practical aspects of global change is becoming increasingly urgent. The occasional grand Conference has a role to play in linking theory to its practical implications, but that role is limited. As I have argued repeatedly, we need different opportunities to practice using the awkward tools our limited understanding has provided, and to learn how they can best be applied to the practical problems than confront us. Policy exercises could provide such opportunities.

- The "future history" orientation of the games' output makes them an excellent vehicle for exploring response options in terms of the time sequences of coordinated action they imply. The requirement that such actions taken in the games be internally consistent,

and that ways be found to sustain them in the face of new problems, other groups' policy agendas, and wavering social will has often proved to be among the most powerful tools of policy analysis[65]. Some preliminary work in exploring time sequence constraints on social responses to the question of the greenhouse effect has been done in connection with the market penetration times of nonfossil energy technologies[66]. This has yielded some of the more useful insights yet available on what energy policy can and cannot do about the practical implications of climate change. Policy exercises could be designed that would allow such market penetration findings to be explored in a more general context of the time characteristics for other responses and background changes discussed in this essay.

- The political games helped to refine future research priorities for technical participants and their staffs by exposing them to the kinds of questions their political masters would need answered under a range of often unconventional but still plausible future histories. This is an extremely important result since "[t]he game... may under favorable circumstances make more effective use of existing knowledge than other modes of intellectual collaboration, but it would be placing an intolerable burden on it to treat it as a machine that displaces theoretical thought and empirical research"[67]. Likewise, policy exercises would in no sense be a substitute for the careful research on basic science and response options that are required to improve the basic tools that can be used in fashioning effective social responses. But the exercises might help the research community to learn which answers -- which tools -- are likely to be most needed by policy people across a wide range of plausible future histories.

If experience with political exercises is any guide, we should expect that many of the ostensibly useful answers now being sought by scientists and analysts are ones for which no policy people are ever likely to ask the relevant questions. (My own bet is that most work on cost/ benefit estimates of "the" impacts of environmental changes will fall in this category of answers no one ever asks for). Conversely, we are likely to find a number of urgent questions emerging in the course of the policy exercises that scientists could have studied, but haven't. I suspect that the design of global environmental monitoring and data systems would benefit tremendously from such policy experiments. In the final analysis, however, it is only by working through specific future histories of global change that we will have an opportunity to move beyond mere individual opinions to a critical, perhaps even consensual, assessment of what might turn out to be truly usable knowledge.

In conclusion: The debate about human induced changes in the global system has now reached a stage at which further advances in coping with its practical implications will require much closer integration of political, economic, technical and environmental perspectives than has until now been the case. Some form of policy exercise, aimed at writing future histories of global change and social response, seems to offer some prospect for fostering such integration. As one outcome of the Visions project, several experimental policy exercises might profitably be conducted, each involving perhaps a dozen of the most informed and creative scholars and policy people concerned with particular aspects of global change. The only way to discover whether we would really learn something useful from such an experiment will be to try it. At a minimum, I suspect it would be fun.

Table 1: Population quality indicators

Variable	Area[1]	Year[2]		
		1950	1975	2025
Life expectancy at birth (years)	W	46	59	71
	I	39	53	72
	E	65	72	77
Infant mortality rate (/1000)	W	156	77	30
	I	190	126	35
	E	62	19	7

[1] Area: W=world; E=Europe without Russia; I=Indian subcontinent

[2] Figures for 2025 are for the "Conventional wisdom" scenario described in the text.

Table 2: Relative indices of development under alternative scenarios

Variable	Area	Year and Scenario[3]			
		1875	2075 CW	2075 F1	2075
F2					
Population size (1975=100)	W	36	250	190	500
	I	38	310	240	450
	E	53	145	100	300
Agricultural production (1975=100)	W	18	380	250	750
	I	32	420	500	650
	E	54	230	260	200
Agricultural land (1975=100)	W	52	120	120	150
	I	50	105	95	105
	E	89	90	130	70
Enegy use (1975=100)	W	4	580	500	1200
	I	14	1030	1600	1600
	E	10	455	130	700

[3] Figures for 2075 result from the following scenarios, as described in the text: CW=conventional wisdom; F1=Friibergh 1 ("The Big Shift"); F2= Friibergh 2 ("The Big Load").

Table 3: Regional scenarios for climate change[a]

Region[b]	Temperature change[c] (as a multiple of global average) Summer	Winter	Precipitation change[d]
High latitudes (60-90°)	0.5x to 0.7x	2.0x to 2.4x	Enhanced in winter
Mid latitudes (30-60°)	0.8x to 1.0x	1.2x to 1.4x	Possible reduced in summer
Low latitudes (0-30°)	0.9x to 0.7x	0.9x to 0.7x	Enhanced in zones of heavy rain now

[a]From J. Jäger. 1988. *Developing policies for responding to climatic change.* WCIP-1. [WMO/TD-No.225]. (Geneva: World Meteorological Organization).

[b]The figures in this table are taken from computer modelling results for the Northern Hemisphere. Low latitude trends are likely to be similar for the Southern Hemisphere. The mid-latitudes of the Southern Hemisphere may differ due to the smaller landmass. The high latitudes of the Southern Hemisphere could respond much differently from Arctic areas because of the high altitude and land-based nature of the Antarctic.

[c]Regional temperature changes are presented here as multiples of the globally and annually averaged temperature changes shown in Fig. 9. Thus, for example, if from Fig. 9 one assumes that the globally averaged annual temperature change for the year 2040 could be 2.0°C, then the table entry says that high latitude winter temperatures in the same year might have risen by a multiple of 2.0 to 2.4, to temperatures between 4.0° and 4.8° C. Similarly, a rate of change in the global mean temperature of 0.3°C/decade from Fig. 9 would translate via this table to a rate of change in high latitude winter temperatures of 0.6° to 0.7°/decade. The temperature figures cited in this table are taken from two general circulation models of the earth's atmosphere, selected to reflect the range of results being obtained from today's most advanced scientific studies. In particular, for each range of temperature multiples given in the table, the first value is drawn from J. Hansen et al. 1984. Climatic sensitivity: analysis of feedback mechanisms. (In) J. Hansen and T. Takahashi, eds., *Climate processes and climate sensitivity.* (Washington, DC: American Geophysical Union). The second value in each range comes from the work of S. Manabe and R.J. Stouffer. 1980. Sensitivity of a global climate model to an increase of CO_2 concentration in the atmosphere. *J. Geophys. Res. 85*: 5529-5554.

[d]Precipitation is among the most difficult properties of climate to model or predict. The qualitative assessments quoted here are nonetheless supported by a number of studies. In particular, they are drawn from J. Mitchell et al. 1987: On CO_2 climate sensitivity and model dependence of results. *Quart. Journal of the Royal Meteorological Society 113*: 293-322.

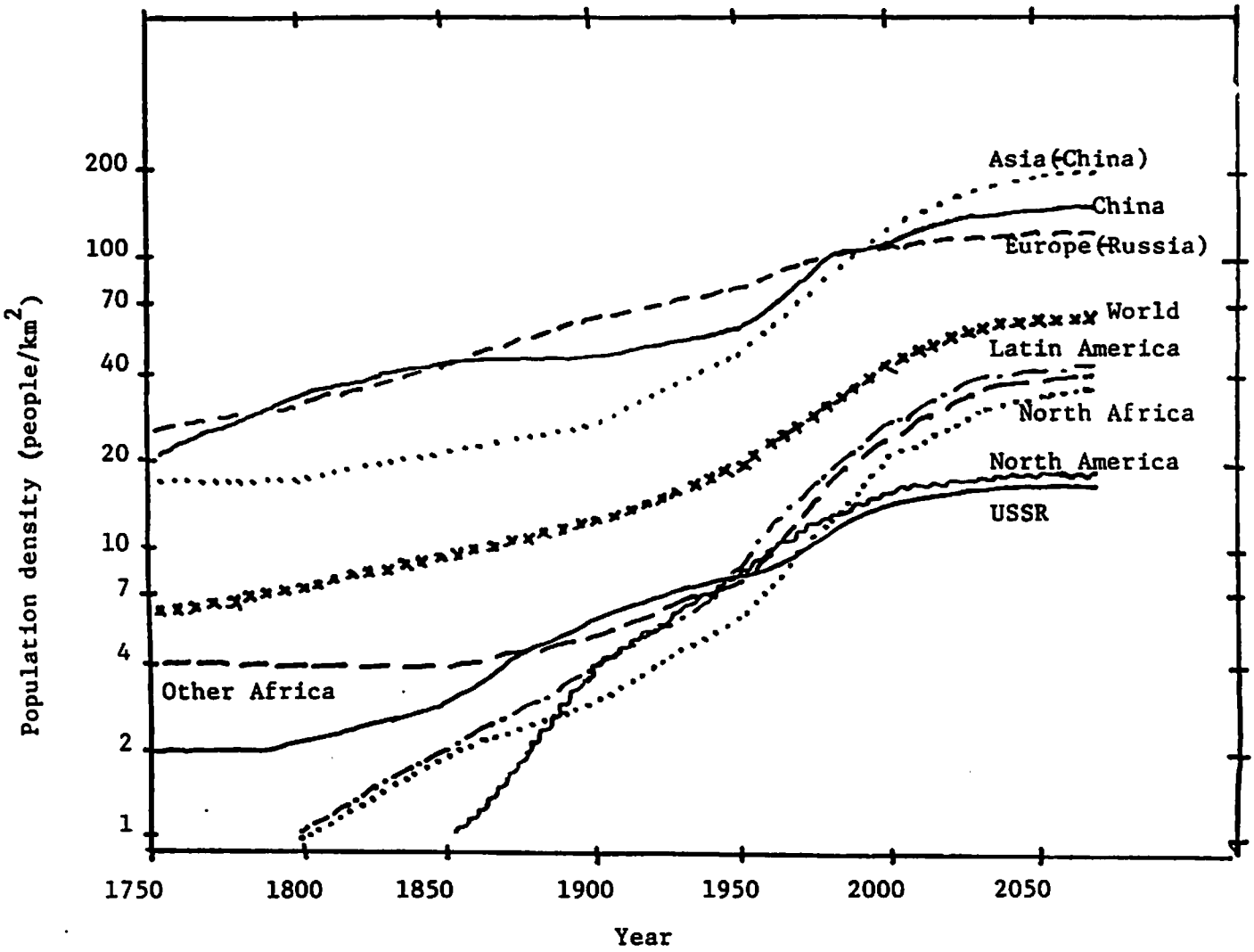


Figure 1: History and projections of human population densities for the world as a whole and for large regions. Units are people per square kilometer of land surface, plotted on a logarithmic scale. Source: W.C. Clark. 1986. Sustainable development of the biosphere: themes for a research program. Pp. 3-48 in W.C. Clark and R.E. Munn, eds. Sustainable development of the biosphere. (Cambridge: Cambridge University Press).

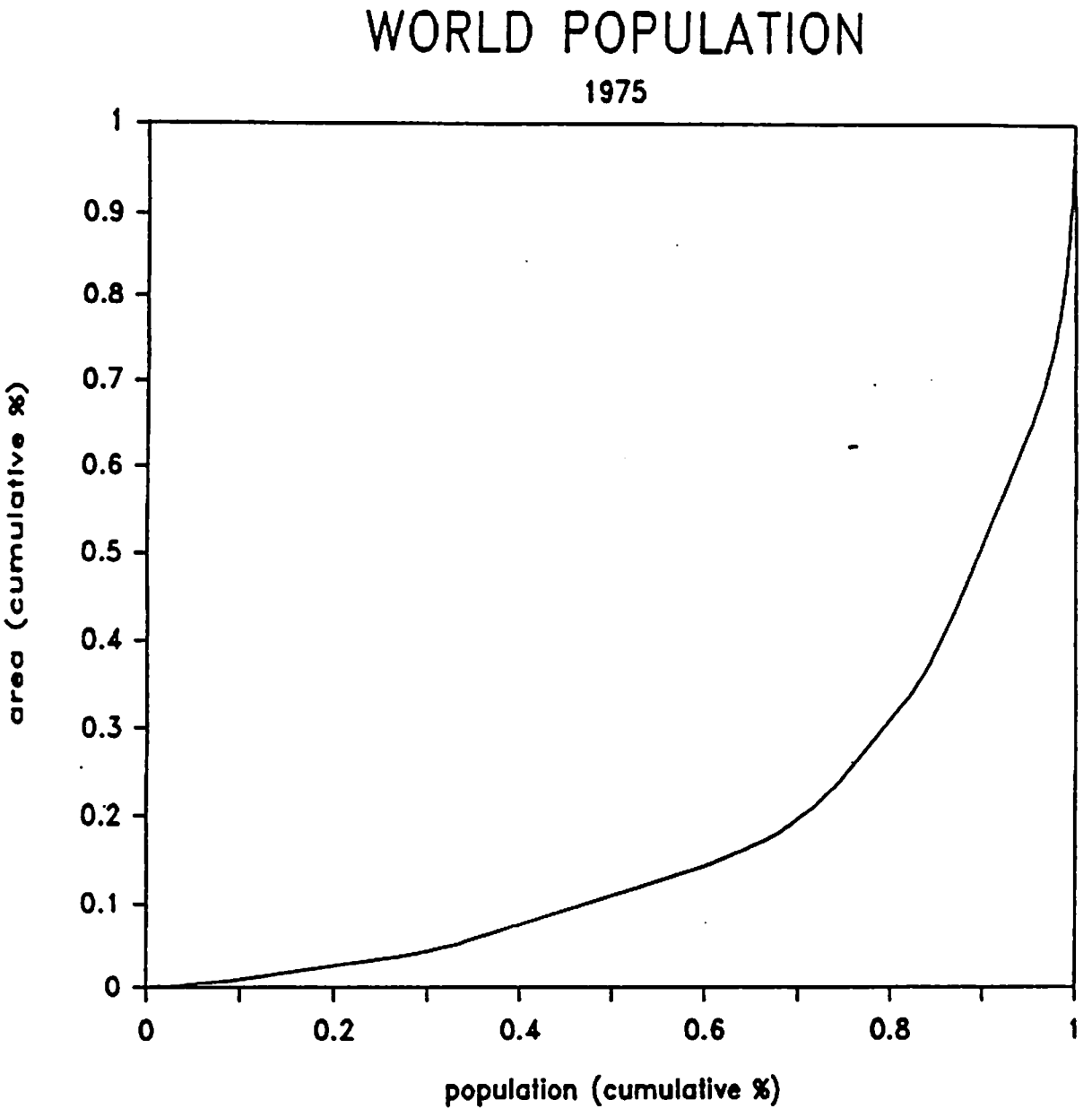


Figure 2: Cumulative distribution of human population on the earth's land surface. These "Lorenz" curves are formed by ranking the countries of the earth from most densely to least densely populated, then plotting the cumulative proportion that occurs on increasing fractions of the earth's total land area. Thus, for example, the most crowded 10% of the earth provides a home for almost 60% of its population. The curve shown here is for 1975. The curve derived from conventional forecasts of population in 2075 is virtually indistinguishable from this one. Source: As for Fig. 1.

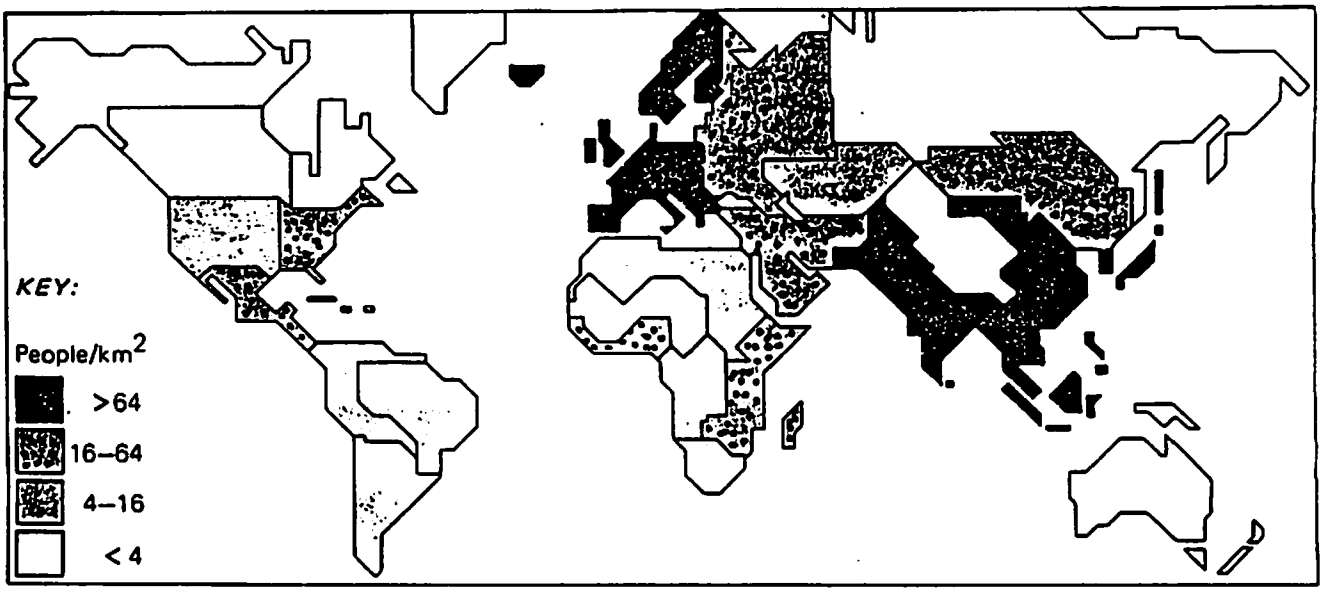


Figure 3: Geographical distribution of current population density, mapped for areas of about 5 million square kilometers. Note that the density scale is geometric. Source: As for Figure 1.

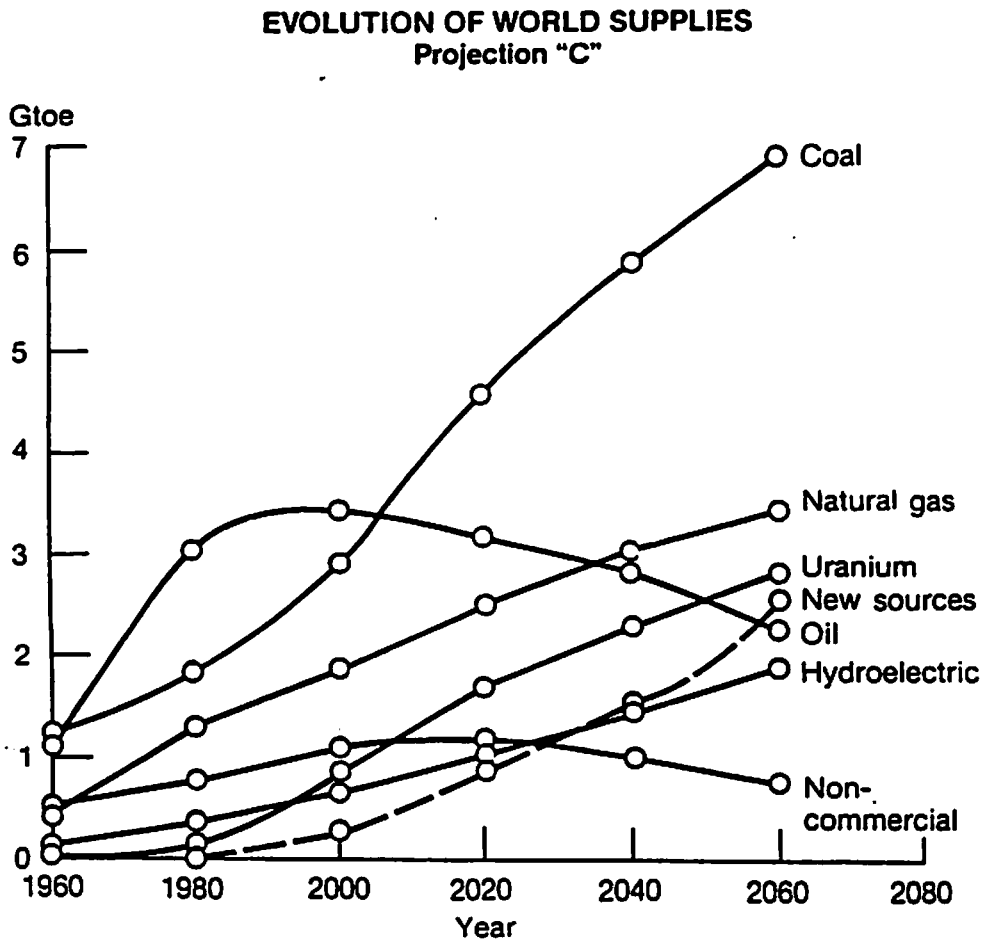


Figure 4: Evolution of world energy supplies under the "conventional" projection "c" made by the World Energy Conference's Conservation Commission in 1986. Source: C. Starr. 1988. Implications of continuing electrification. Paper presented at symposium "An energy agenda for the 1990's", National Academy of Engineering, Irvine CA, May 1988.

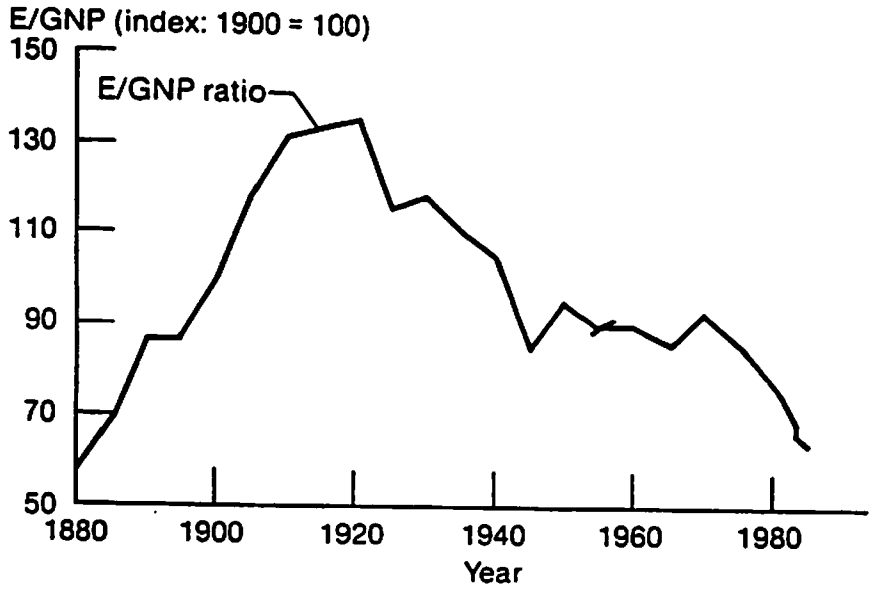


Figure 5: Long term trends in intensity of energy use for the United States, measured as the ratio of total energy use to GNP. Source: As for Fig. 4.

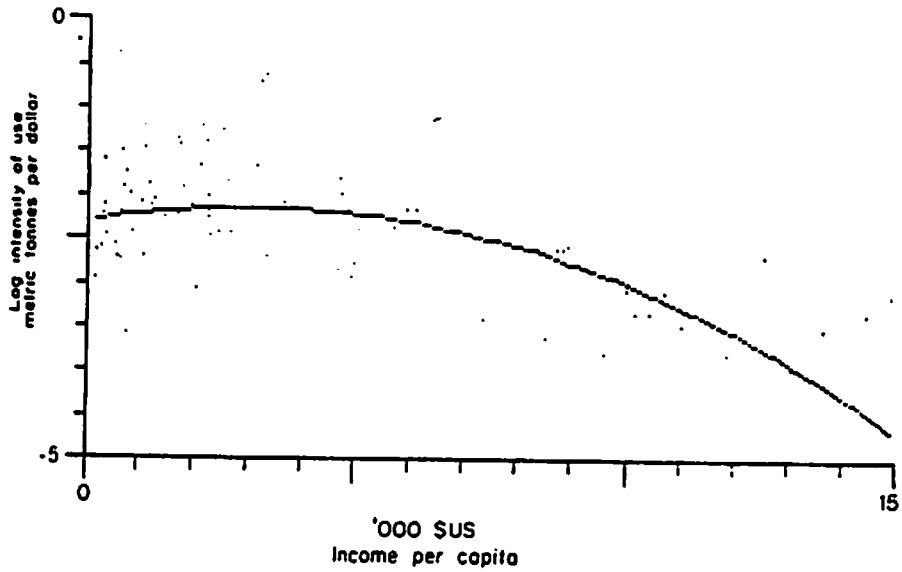


Figure 6: Patterns in intensity of cement use for the world, measured as the (log of) metric tons of cement used per dollar of GNP for various countries of the world today. The trend shows decreasing intensity with increasing wealth. Source: W.G.B. Phillips. 1987. Factors affecting the long-term availability of bulk materials. (in) Digby J. McLaren and B.J. Skinner. Resources and World Development. [Dahlem Workshop Report: Physical, chemical and earth sciences No. 6]. (Wiley, Chichester).pp. 327-345.

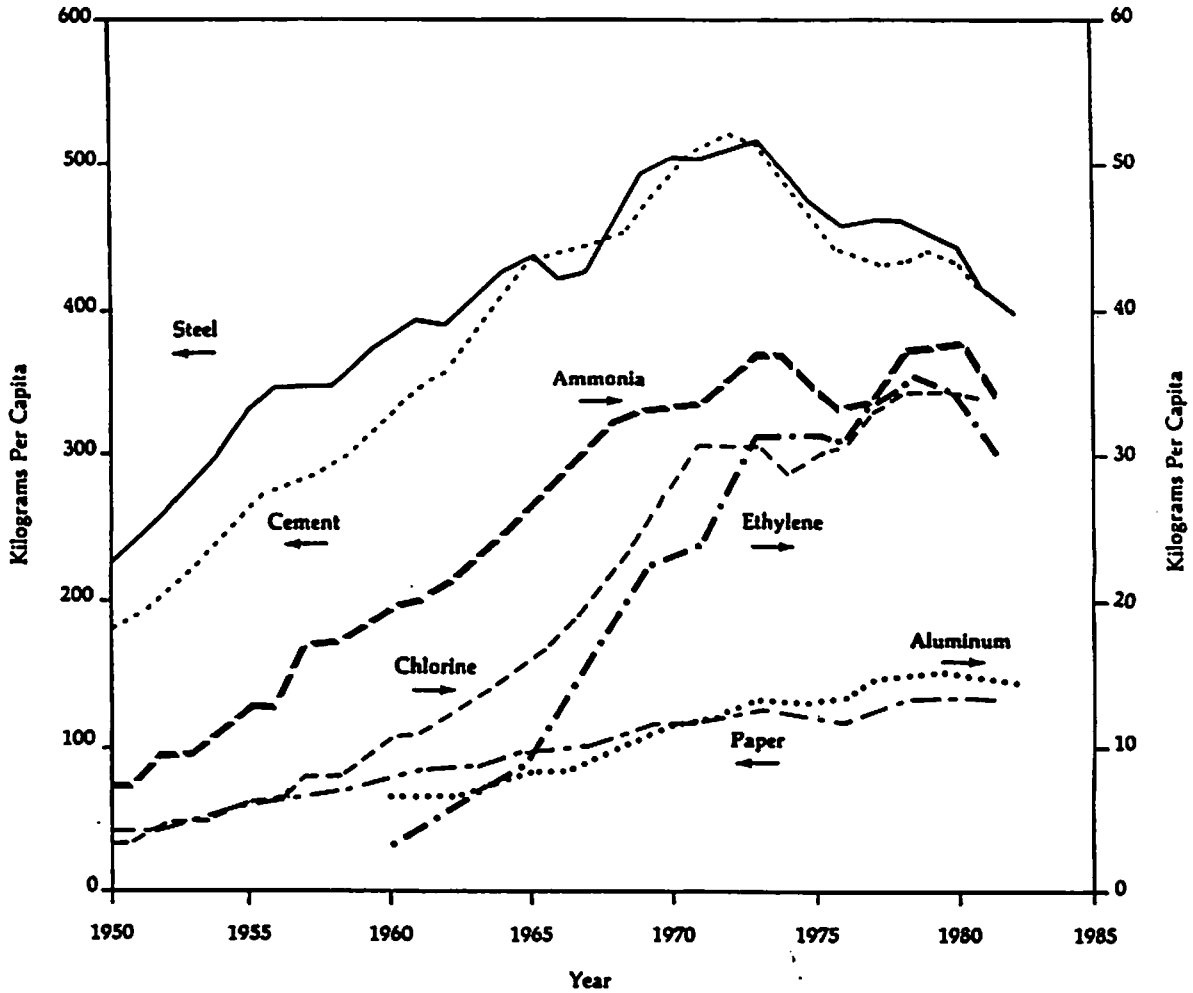


Figure 7: Long term trends in intensity of material use for Western Europe, measured as kilograms per capita. Source: M. Ross, E.D. Larson and R.H. Williams. 1988. Energy demand and materials flow in the economy. Energy, the international journal. (in press).

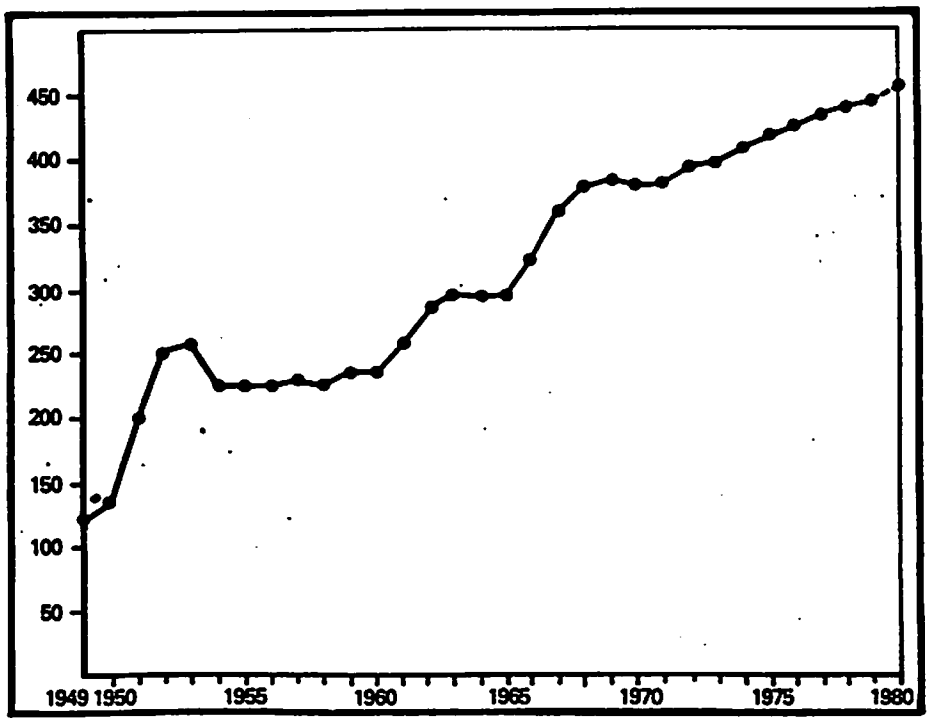
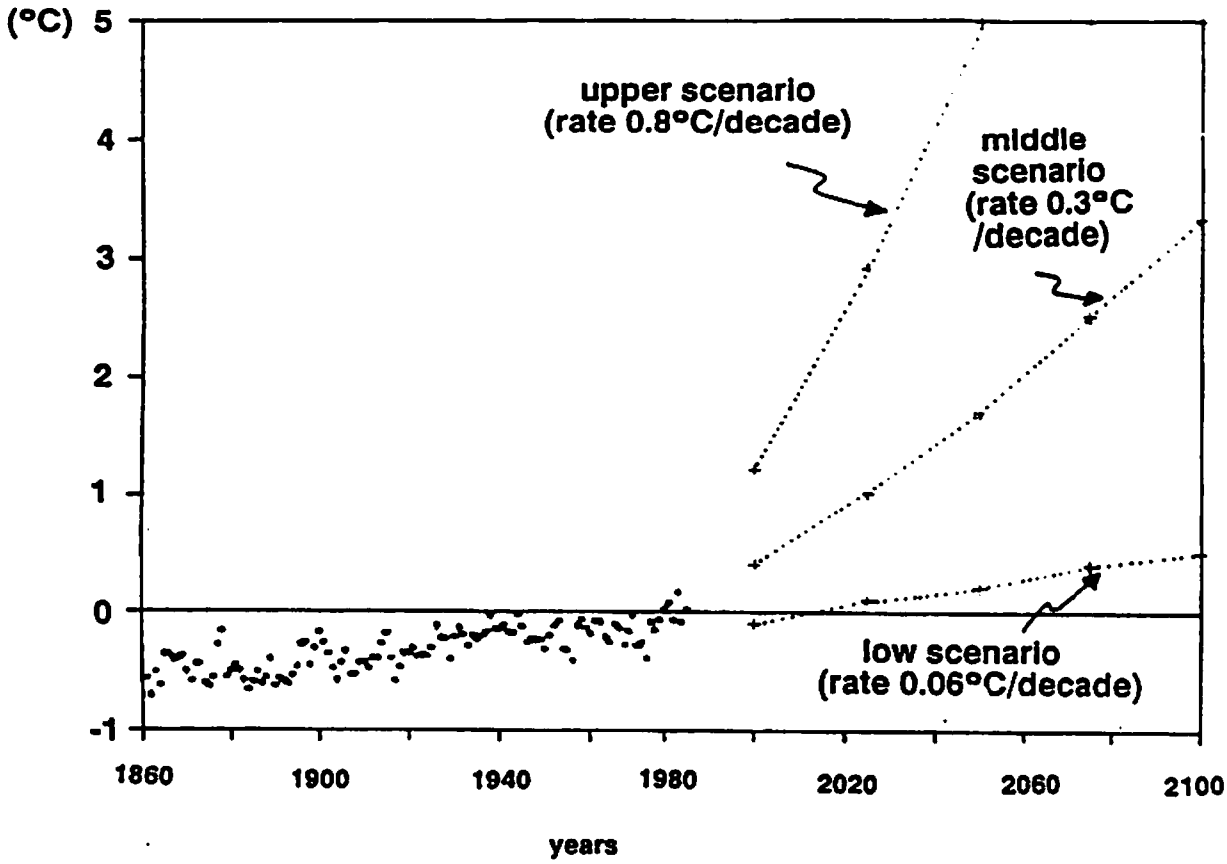


Figure 8: Trends in total world military expenditure. The units are US $ thousand million, in constant 1978 prices and exchange rates. Source: Stockholm International Peace Institute. 1981. World armaments and disarmament yearbook: 1981. (London: Taylor and Francis, Ltd.)

Figure 9: The greenhouse effect: scenarios of temperature and sea level change. The figure shows scenarios of changes in (above) globally averaged temperature and (below) sea-level that might develop in response to continued emissions of atmospheric greenhouse gases. The values are plotted as differences from the 1985 values. The middle curve of each panel reflects a scenario of continued present trends of emissions, including implementation of the Montreal Protocol on chlorofluorocarbons. There is a 5/10 chance that the actual path of climate change could lie below the middle curve. The upper curve of each panel reflects a scenario of accelerated greenhouse gas emissions and a relatively high climate sensitivity as predicted by some models. The lower curve of each panel reflects a scenario of radically curtailed emissions and a relatively low climate sensitivity. There is a 9/10 chance that the actual future pattern of greenhouse gas induced climate change will fall outside the bounds of these scenarios. Sources: Observed temperature data were provided by P.D. Jones; observed sea-level data by V. Gornitz. The scenarios are taken from J. Jäger. 1988. Developing policies for responding to climatic change. [Summary of discussions and recommendations of workshops held in Villach and Bellagio, 1987]. WCIP - 1; WMO/TD- No. 225. (Geneva: World Meteorological Organization and United Nations Environment Program).


(°C)
5
4
3
2
1
0
-1
upper scenario
(rate 0.8°C/decade)
middle
scenario
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low scenario
(rate 0.06°C/decade)
1860
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1940
1980
2020
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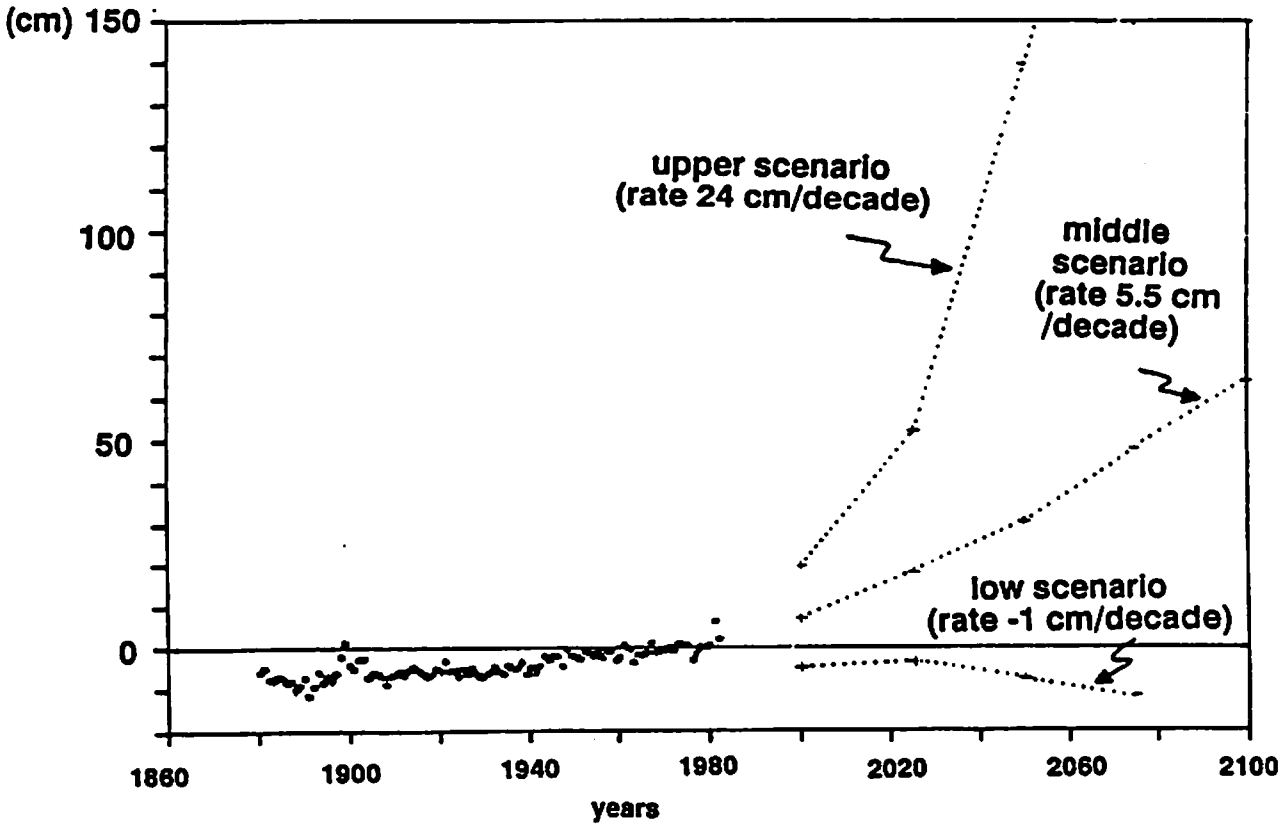
2100
years


(cm)
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upper scenario
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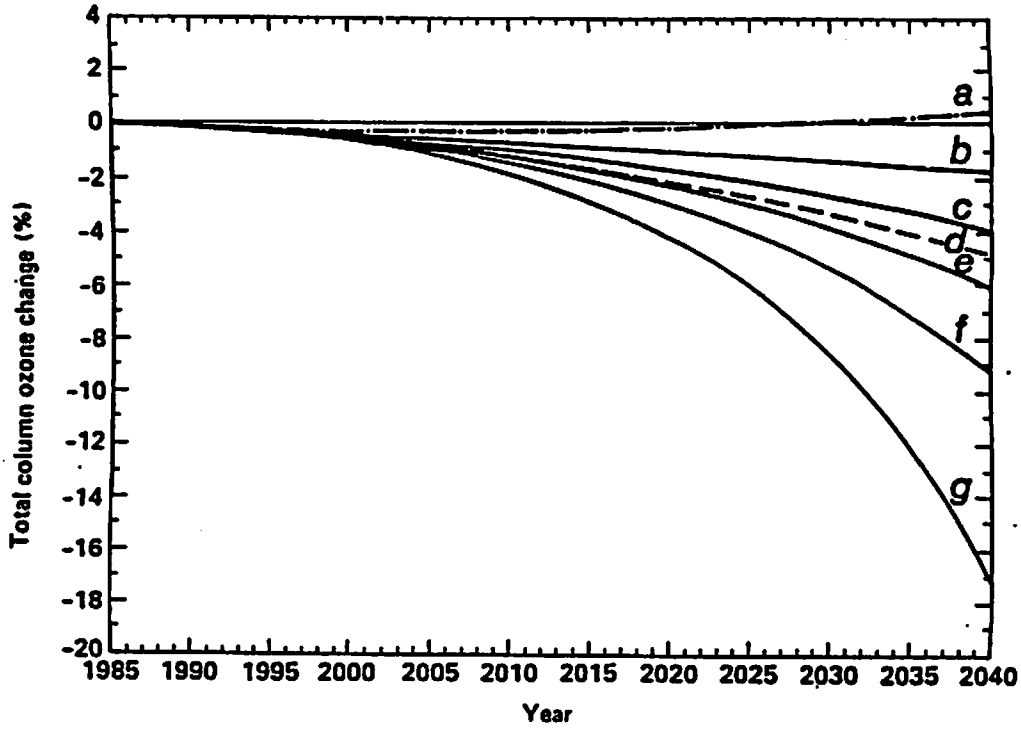

Figure 10: Stratospheric ozone depletion. Scenarios for average global change in total column ozone under a range of emission scenarios for gases with a potential for ozone depletion. The middle scenario 'd' is analogous to the middle scenario of Figure 9, ie. it assumes current trends of all emissions, plus implementation of the Montreal Protocol. There is a 9/10 chance that the actual depletion will lie outside the envelope set by the outer scenarios 'a' and 'g'. Source: J.K. Hammitt et al. 1987. Future emission scenarios for chemicals that may deplete stratospheric ozone. Nature 330: 711-716.

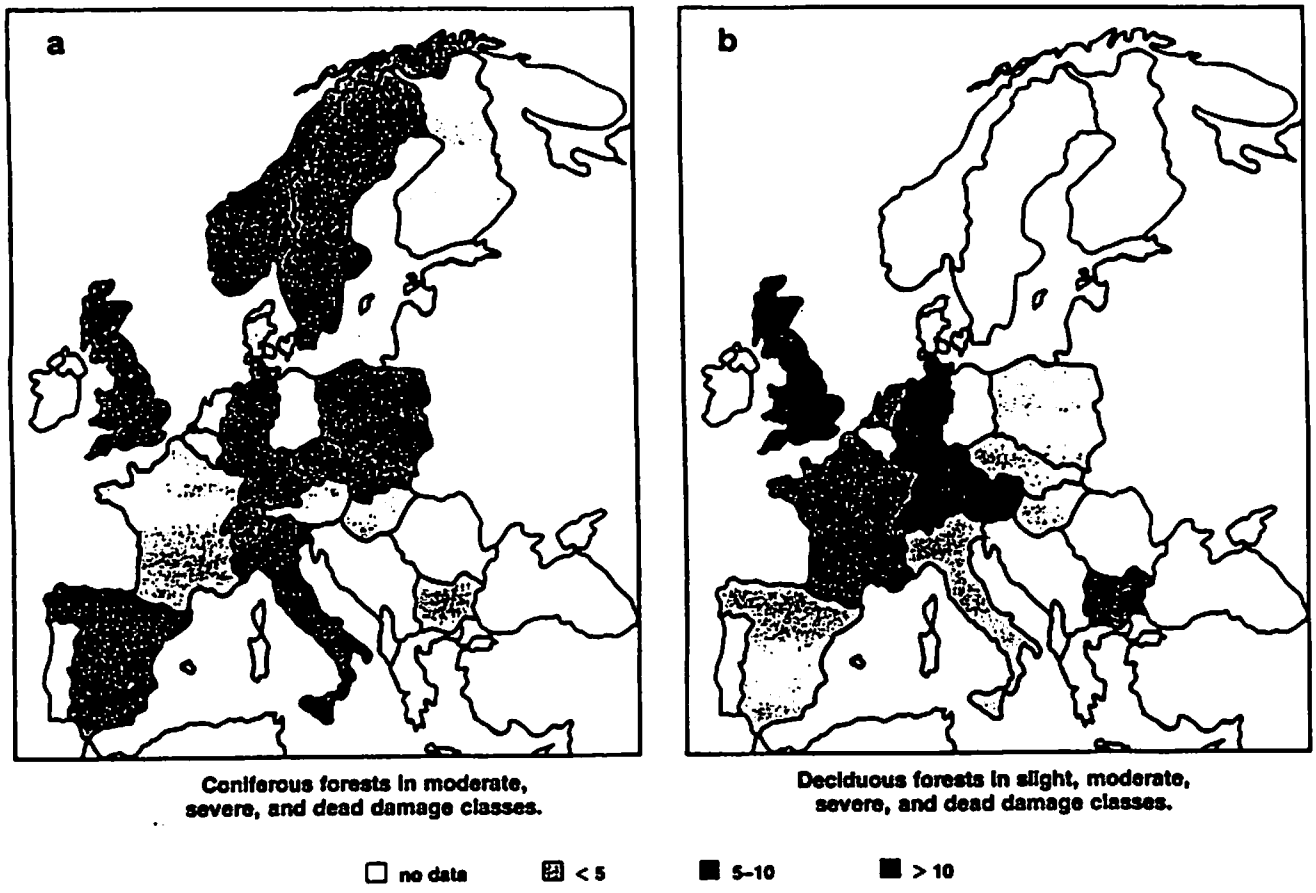

Figure 11: Forest damage in Europe, mid 1980s. Figure shows national-level data for ratio of volume of damaged forest to volume of forest harvested annually. Thus, in the middle category plotted, 5-10 times more trees are now showing signs of damage than are cut each year. Source: S. Nilsson and P. Duinker. 1987. The extent of forest decline in Europe: a synthesis of survey results. Environment 29(9): 4-9, 30-31.

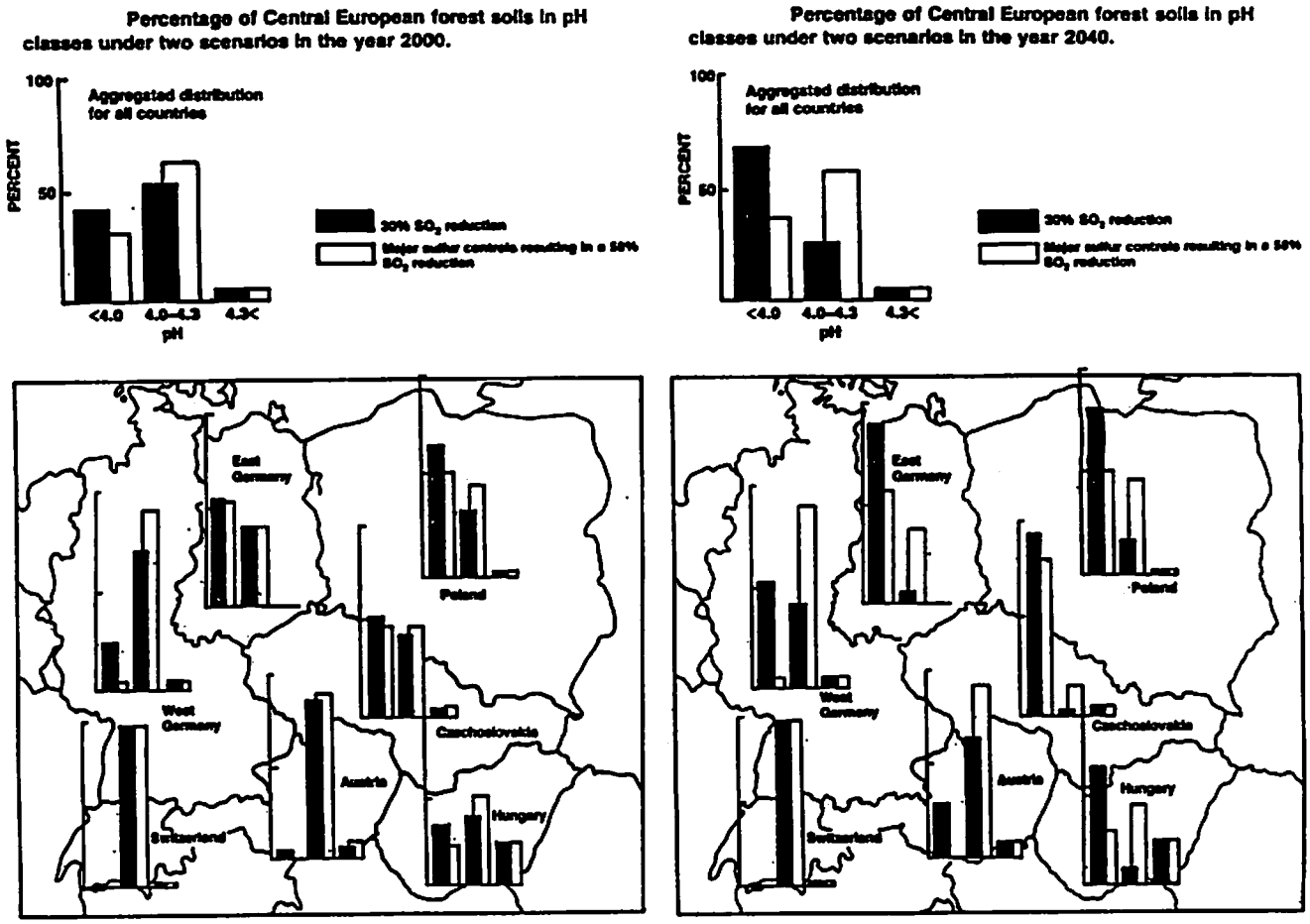

Figure 12: Acid deposition in the future. Figure shows national level statistics for percentage of forest soils in various pH classes expected under alternative scenarios of fossil fuel use. Source: J. Alcamo et al. 1987. Acidification in Europe: a simulation model for evaluating control strategies. Ambio 16: 232-45, as reproduced in L. Hordijk. 1988. Linking science and policy: a model approach to acid rain. Environment 30(2): 16-20, 40-42.

Figure 13a,b: Synoptic assessment of long term trends of environmental change in Europe and the Gangetic Plain of India, under a "conventional wisdom" scenario of continued population growth, technical change, and pollutant emissions. See text, pg. 11, for details. Source: J. Darmstadter et al. 1987. Impacts of world development on selected characteristics of the atmosphere: an integrative approach. (2 vols.). ORNL/Sub/86-22033/1. (Oak Ridge, TN: Oak Ridge National Laboratory, for Resources for the Future, Washington.). Copies available from RFF. The conceptualization and execution of the synoptic figures developed under the leadership of study coauthor Thomas Graedel of ATT-Bell Labs.

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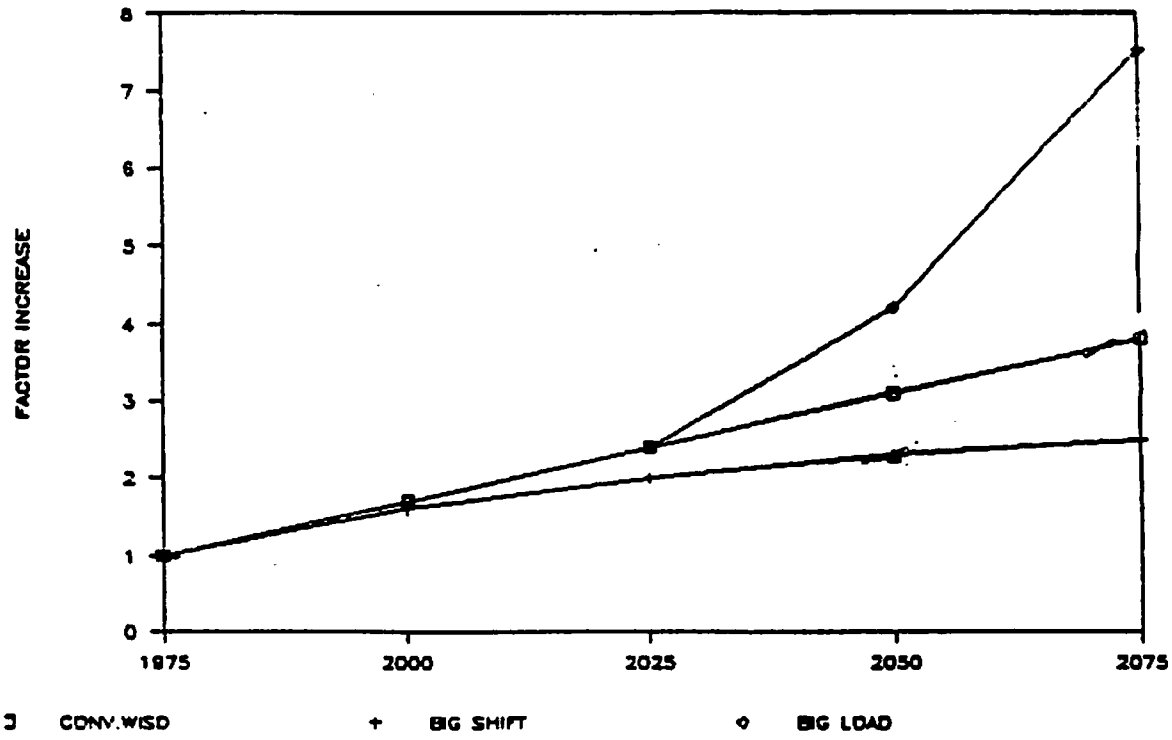
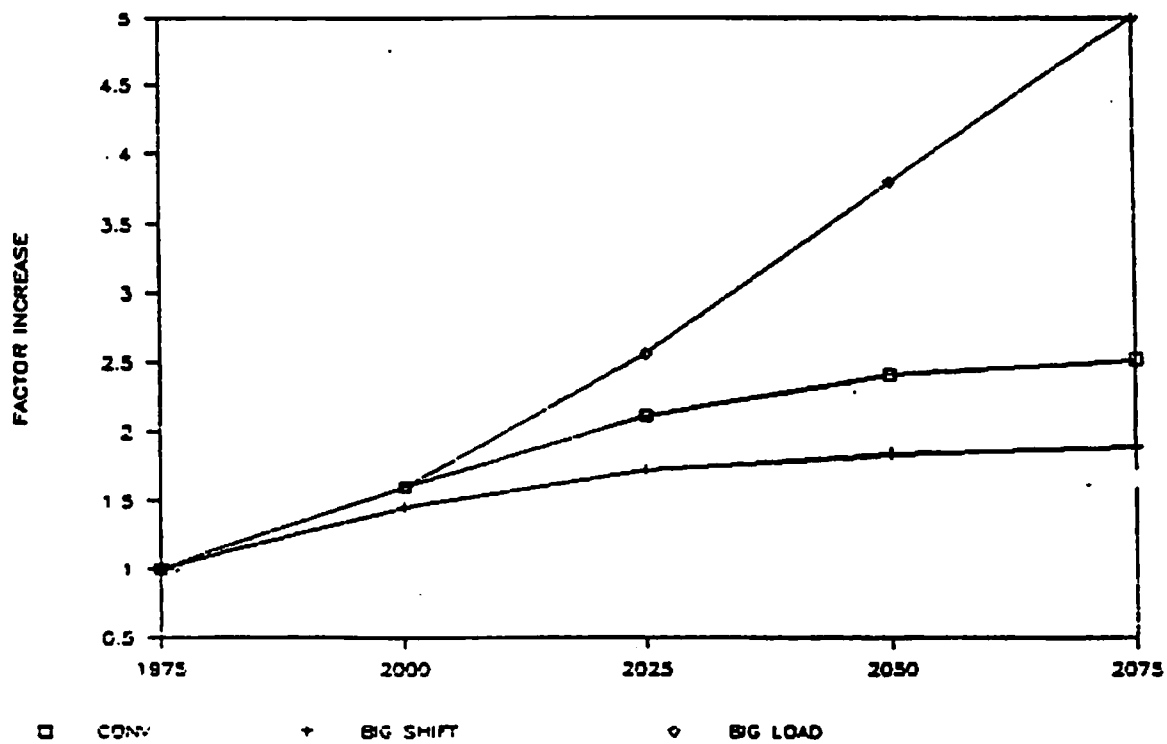
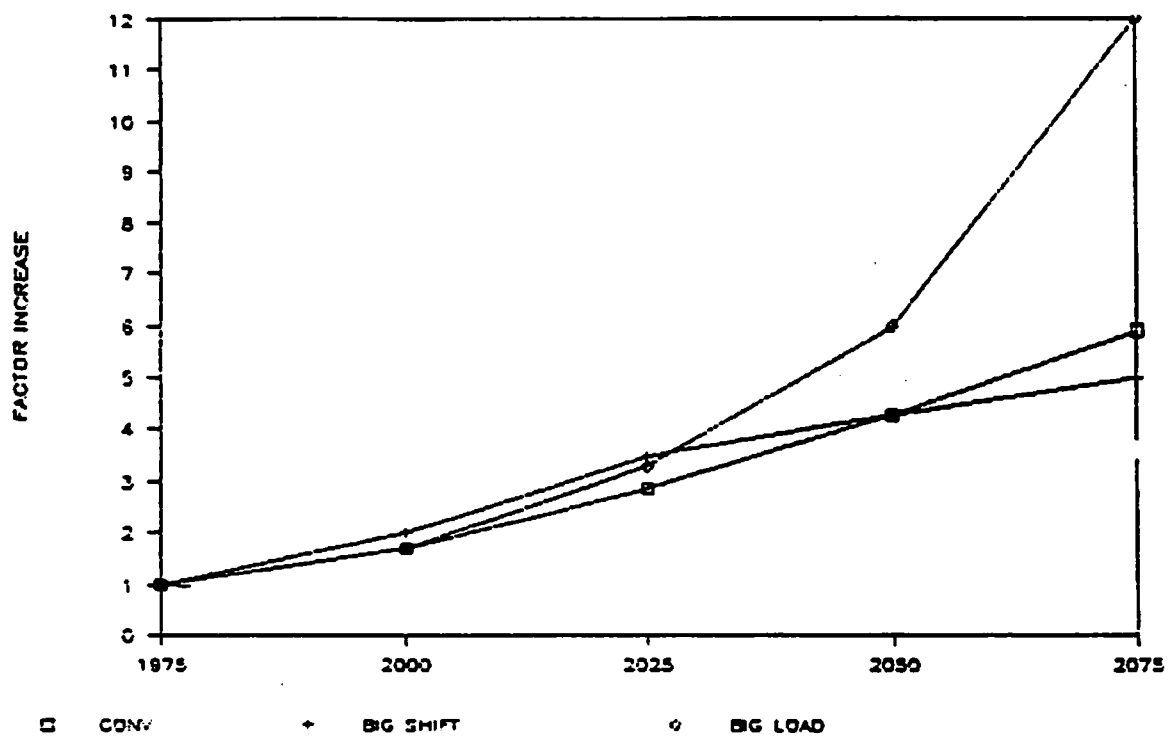


Global agricultural production in different scenarios

Figure 14a,b,c: The Friibergh Scenarios. The figure plots factor increases in global population, energy use, and agricultural production associated with the two Friibergh Surprises ("Big Load" and "Big Shift") described in the text. Source: S. Anderberg. 1988. The Friibergh Scenarios. (in) F. Toth et al. (eds). Scenarios of socioeconomic development for studies of global environmental change: a critical review. (Laxenburg, Austria: International Institute for Applied Systems Analysis).



Global population trends in different scenarios



Global energy use in different scenarios

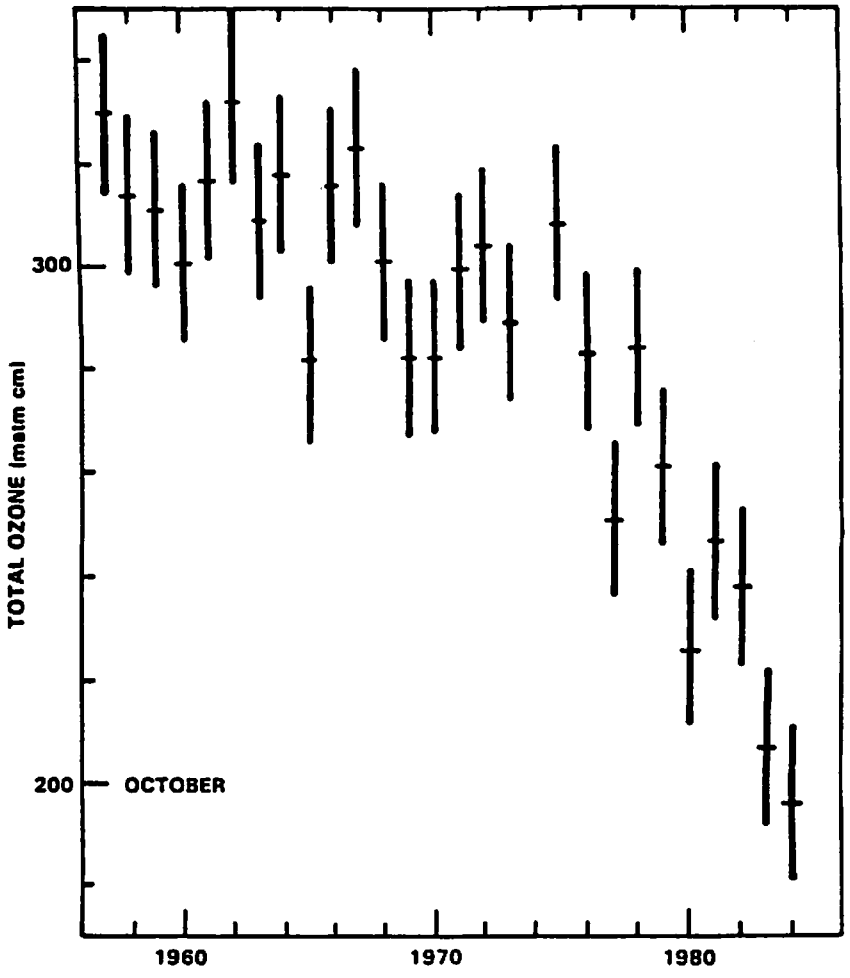


Figure 15: Antarctic ozone depletion. Monthly means of total ozone at Halley Bay for October of the years 1957 through 1984. Source: US National Aeronautics and Space Administration (NASA) 1986. Present state of knowledge of the upper atmosphere; an assessment report. NASA Ref. Publ. 1162. (Washington, DC: NASA).

NOTES

1. This paper draws heavily on work conducted in the program on "Sustainable development of the biosphere", led by the author at the International Institute for Applied Systems Analysis from 1984 to 1987, and since that time directed by Dr. Alan Solomon. Some of the material used here is based on earlier versions that have appeared in various project documents, notably W.C. Clark. 1985. On the practical implications of the carbon dioxide question. WP-85-43. (Laxenburg, Austria: IIASA); and W.C. Clark. 1986. Sustainable development of the biosphere: themes for a research program. Pp. 3-53 in W.C. Clark and R.E. Munn. 1986. Sustainable development of the biosphere. (Cambridge: Cambridge University Press). Material quoted from these documents is used with permission.

2. The original version of this paper was prepared for the Project on "Visions of Canada in the Year 2000" of the Economic Council of Canada.

3. For the data quoted here, plus a wealth of long-term, global data on technical change and development, see W.W. Rostow. 1978. The world economy: history and prospect. (Austin: University of Texas Press). Note that the objections to Rostow's central thesis in this book (ie. those concerning universal stages of economic development) in no way undermine the value of the basic data and perspectives presented.

4. For a development of this perspective, see S. Ramo. 1988. Globalization of industry and implications for the future. Pp. 12-31 in J. Muroyama and H.G. Stever, eds. Globalization of technology: international perspectives. (Washington, DC: National Academy Press).

5. Unless otherwise noted, the material and data used here are taken from F. Toth, E. Hizsnyik-Toth, and W.C. Clark, eds. 1988. Scenarios of socioeconomic development for studies of global environmental change: a critical review. (Laxenburg, Austria: International Institute for Applied Systems Analysis).

6. R.W. Kates and I. Burton. 1986. The great climacteric 1798-2048: transition to a just and sustainable human environment. In R.W. Kates and I. Burton, eds. Geography, resources and environment. Vol. 2: Essays on themes from the work of G.F. White. (Chicago: Univ. of Chicago Press).

7. For the analysis behind data summarized here, see Clark, 1986, op. cit.

8. United Nations. 1985. Estimates and projections of urban, rural and city populations, 1950-2025: the 1982 assessment. (New York: United Nations); United Nations. 1980. Patterns of urban and rural population growth. (New York: United Nations).

9. Many attempts have been made to identify quality of life indicators more useful than the per capita GNP figures so often encountered in contemporary debates. While other choices are possible, I follow here the recommendations of the recent Wingspread Conference on "Agenda for the year 2000" and use infant mortality and life expectancy at birth. Some measure of literacy should be added as well, but time series data on the subject are notoriously difficult to handle. Figures cited here come from computerized data files of the UN.

10. See Rostow, op. cit.

11. Glenn L. Johnston and Sylvan H. Wittwer. 1984. Agricultural technology until 2030: prospects, priorities and policies. Michigan State University, Agricultural Experiment Station, Special Report No. 12.

12. P.A. Oram. 1988. Ecological approaches to sustainable agriculture in developing countries. Environment (in press); E.T. York. 1988. Research to achieve sustainable food production in developing countries. Environment (in press).

13. Chauncy Starr. 1988. Implications of continuing electrification. (in) National Academy of Engineering, An energy agenda for the 1990's. (Washington, DC: National Academy Press).

14. Starr, op. cit.

15. Mining annual review. 1985. Metals output and prices - a historical review. pp. 22-25. (London: London Mining Journal Books, Ltd).

16. US Council on Environmental Quality. 1981. Environmental trends. (Washington: US Government Printing Office).

17. US National Research Council. 1979. Toxic substances in the environment. (in) Science and technology: a five-year outlook. (San Francisco: WH Freeman). ch. 9.

18. Estimate by International Monetary Fund, quoted in U. Columbo. 1988. The technology revolution and the global economy. (in) Muroyama and Stever, eds. Globalization of technology. (Washington, DC: National Academy Press). pp. 23-31.

19. The global cement data are from W.G.B. Phillips. 1987. Factors affecting the long-term availability of bulk materials. (in) Digby J. McLaren and B.J. Skinner. Resources and World Development. [Dahlem Workshop Report: Physical, chemical and earth sciences No. 6]. (Wiley, Chichester).pp. 327-345. The European data are from M. Ross, E.D. Larson and R.H. Williams. 1988. Energy demand and materials flow in the economy. Energy, the international journal. (in press).

20. Stockholm International Peace Institute. 1981. World armaments and disarmament yearbook: 1981. (London: Taylor and Francis, Ltd.)

21. L.F. Richardson. 1960. Statistics of deadly quarrels. (Pittsburgh: Boxwood).

22. S. Bergstron et al. 1983. Effects of a nuclear war on health and health services. Report of the International Committee of Experts in Medical Sciences and Public Health. WHO Pub. A36.12 (World Health Org.: Geneva).

23. U.S. National Science Foundation. 1988. Science and engineering indicators - 1987. (Washington, DC: US Government Printing Office).

24. S. Ramo. 1988. Globalization of industry and implications for the future. (In) Muroyama and Stever (eds). pp. 12-22.

25. One effort to reach such understanding is being pursued in the program on "Dual-use technologies: balancing economic and security interests in federal R&D investment strategies" being conducted by Prof. Lewis Branscomb and colleagues at Harvard's Kennedy School of Government.

26. Except as noted, findings and data used in this paragraph are drawn from J. Jäger. 1988. Developing policies for responding to climatic change. [Summary of discussions and recommendations of workshops held in Villach and Bellagio, 1987]. WCIP - 1; WMO/TD- No. 225. (Geneva: World Meteorological Organization and United Nations Environment Program).

27. Floor Brouwer and Malin Falkenmark. 1988. Water availability in Europe. [Paper prepared for the Eighth International Symposium on Forecasting, June 12-15, 1988; Amsterdam]. (Laxenburg, Austria: International Institute for Applied Systems Analysis).

28. Unless otherwise noted, material for this section is drawn from US National Aeronautics and Space Administration (NASA) 1986. Present state of knowledge of the upper atmosphere: an assessment report. NASA Ref. Publ. 1162. (Washington, DC: NASA), and NASA. 1988. Executive summary of the Ozone trends panel report. [released 15 March, 1988]. (Washington, DC: NASA).

29. Reliable data are available only for the mid latitudes of the Northern Hemisphere. The quoted figure is for total column ozone in these latitudes, and reflects the total decline over the entire period.

30. J.K. Hammitt et al. 1987. Future emission scenarios for chemicals that may deplete stratospheric ozone. Nature 330: 711-716.

31. F. Stordal and I. Isaksen. 1986. Ozone perturbations due to increases in N_2O, CH_4, and chlorocarbons: two-dimensional time-dependent calculations. (In) J. Titus (ed). Effects of changes in stratospheric ozone and global climate. (Washington, DC: Environmental Protection Administration).

32. Excellent reviews is provided in World Resources Institute. 1986. World Resources 1986: an assessment of the resource base that supports the global economy. (New York: Basic Books). ch. 12. The European perspective is summarized in a series of articles published in Environment: S. Nilsson and P. Duinker. 1987. The extent of forest decline in Europe: a synthesis of survey results. Environment 29(9): 4-9, 30-31; B. Prinz. 1987. Causes of forest damage: major hypotheses and factors. Environment 29(9): 10-15, 32-37; H. Dovland. 1987. Monitoring European transboundary air pollution. Environment 29(10): 10-15, 27; P.H. Sand. 1987. International policy responses to air pollution in Europe. Environment 29(10): 16-20, 28-29; L. Hordijk. 1988. Linking science and policy: a model approach to acid rain. Environment 30(2): 16-20, 40-42.

33. S. Nilsson and P. Duinker. 1987. The extent of forest decline in Europe. Environment 29(9): 4-9, 30-31.

34. J. Alcamo et al. 1987. Acidification in Europe: a simulation model for evaluating control strategies. Ambio 16: 232-45.

35. H. Rodhe and R. Herrera (eds). 1988. Acidification in tropical countries. [SCOPE 36]. (Chichester, UK: John Wiley and Sons).

36. J. Darmstadter et al. 1987. Impacts of world development on selected characteristics of the atmosphere: an integrative approach. (2 vols.). ORNL/Sub/86-22033/1. (Oak Ridge, TN: Oak Ridge National Laboratory, for Resources for the Future, Washington.). Copies available from RFF. The conceptualization and execution of the synoptic figures developed under the leadership of study coauthor Thomas Graedel of ATT-Bell Labs.

37. C.S. Holling. 1985. Canada - IIASA biosphere project: a proposal. [Unpublished MS]. (Vancouver, Canada: University of British Columbia).

38. H. Brooks. 1986. The typology of surprises in technology, institutions and development. (In) Clark and Munn (eds.), p. 326.

39. W.H. McNeill. 1978. Coping with an uncertain future: historical perspective. (in) C. Hitch (ed). Resources for an uncertain future. (Baltimore: Johns Hopkins Univ. Press). pp. 59-67.

40. Harvey Brooks. 1986. The typology of surprises in technology, institutions, and development. Pp. 325-348 in Clark and Munn, eds., op. cit.

41. Torsten Hagerstrand and Robert Kates. 1986. Unpublished manuscript

quoted in W.C. Clark. 1986. Sustainable development of the biosphere: themes for a research program. Pp. 7-48 in Clark and Munn, eds. op. cit.

42. A full report of the methods and results of the Friibergh workshop, plus an evaluation of the exercise, has been published by the host organization, the Swedish Council for Planning and Coordination of Research. (U. Svedin and B. Aniansson. 1987. Surprising futures: notes from an international workshop on long-term world development. [Friibergh Manor, Switzerland, January 1986]. Stockholm: Swedish Council for Planning and Coordination of Research. Box 7610, S-113 85, Stockholm, Sweden). Refinements of the basic Friibergh Scenarios, including a quantification of their basic trends, have recently been published by IIASA. (S. Anderberg. 1988. The Friibergh Scenarios. (in) F. Toth et al. (eds). Scenarios of socioeconomic development for studies of global environmental change: a critical review. Laxenburg, Austria: International Institute for Applied Systems Analysis).

43. See, for example, G. Brewer. 1986. Methods of synthesis - policy exercises. (in) Clark and Munn (eds). Sustainable development of the biosphere. (Cambridge: Cambridge University Press). ch. 17.

44. Results of this workshop are being readied for publication by the author.

45. The material reported here was developed by Robert Dickinson of the National Center for Atmospheric Research and Hank Shuggart of the University of Virginia, drawing on the following publications: H. Sioli. 1984. Former and recent utilizations of Amazonia and their impact on the environment. Pp. 692-706 in H. Sioli, ed. The Amazon: limnology and landscape ecology of a mighty tropical river and its basin. (Dordrecht, Holland: W. Junk, Publ.); E. Salati. 1987. The forest and the hydrological cycle. Pp. 273-296 in R.E. Dickinson, ed. The geophysiology of Amazonia. (New York: John Wiley and Sons).

46. J.P. Malingreau et al. 1985. Remote sensing of forest fires: Kalimantan and North Borneo 1982-83. Ambio 14(6).

47. Examples, cited at the Laxenburg workshop by Prof. H. Shuggart of the University of Virginia, include the fire-prone forests of the southern United States versus the southern hardwood forest; the sclerophylous fienboss heathland of the Cape of Good Hope versus the subtropical African rainforest; and the sclerophylous Eucalyptus forests of Tasmania versus the temperate rain forest.

48. Discussions on this scenario were initiated at the workshop by Paul Crutzen of the Max-Planck Institute for Chemistry, based in part on P. Crutzen. 1987. Role of the tropics in atmospheric chemistry. Pp. 107-130 in R.E. Dickinson, ed. (op. cit.).

49. CS Holling. 1986. The resilience of terrestrial ecosystems: local surprise and global change. Pp. 292-317 in Clark and Munn, eds. (op. cit).

50. Holling, op. cit. See also CS Holling. 1973. Resilience and stability of ecological systems. Annual review of ecology and systematics 4: 1-23.

51. M. Parry. 1986. Some implications of climatic change for human development. Pp. 378-407 in Clark and Munn, op. cit.

52. Parry, op. cit.

53. For a broader discussion of this treatment of policy analysis and management as "craft work", see J.R. Ravetz. 1971. Scientific knowledge and its social problems. (Oxford: Clarendon Press); A. Wildavsky. 1979. Speaking truth to power: the art and craft of policy analysis. (Boston: Little, Brown); and C.E. Lindblom and D.K. Cohen. 1979. Usable knowledge: social science and social problem solving. (New Haven: Yale Univ. Press).

54. G.Brewer. 1986. Methods for synthesis: policy exercises. Pp. 455-473 in Clark and Munn, eds., op. cit.; D.H. Meadows and J.M. Robinson. 1985. The electronic oracle: computer models and social decisions. (Chichester, UK: John Wiley and Sons).

55. F. Toth. 1987. Practicing the future. Parts 1 and 2. Working paper. (Laxenburg, Austria: International Institute for Applied Systems Analysis).

56. H. Goldhamer and H. Speier. 1959. Some observations on political gaming. World politics 12: 72-83.

57. G. Brewer and M. Shubik. 1979. The war game: a critique of military problem solving. (Cambridge: Harvard Univ. Press). p. 101. See also T.B. Allen. 1987. War games. (New York: McGraw Hill).

58. Exercises of this sort have been described under the term "free-form, manual games" in the American literature. See Goldhamer and Spear, op. cit.; T.A. Brown and E.W. Paxson. 1975. A retrospective look at some strategy and force evaluation games. R-1619-RR. (Santa Monica, CA: The Rand Corp.); Brewer and Shubik, op. cit.; Brewer, 1986, op. cit.; Allen, op. cit.

59. Brewer, 1986, op. cit.

60. Brown and Paxson, op. cit.; Brewer and Shubik, op. cit.

61. Brewer, 1986, op. cit.

62. Brewer and Shubik, op. cit., p. 101.

63. J. Jäger, op. cit.

64. Goldhamer and Speier, op. cit., pp. 77-8.

65. Thomas Schelling. 1984. Private communication to the author.

66. See C. Marchetti. 1979. Multicompetition and the diffusion of new technology in the energy system. Chemical economy and engineering review 11: 7-13; C. Marchetti and N. Nakicenovic. 1979. The dynamics of energy systems and the logistic substitution model. IIASA RR-79-13. (Laxenburg, Austria: International Institute for Applied Systems Analysis); A.M. Perry et al. 1982. Energy supply and demand implications of carbon dioxide. Energy 7: 991-1004.; J. Edmonds and J. Reilly. 1985. Global energy: assessing the future. (Oxford: Oxford Univ. Press); J.Lauerman. 1985. Market penetration as an impediment to replacement of fossil fuels in the carbon dioxide environment problem. [Paper presented to Humphrey Inst. Symposium on Greenhouse Policy Options, Minneapolis, May 1984].

67. H. Goldhamer. 1973. Private communication to Brewer and Shubik, op. cit., quoted on their p. 103.