6 Integrating Knowledge and Action

We must consider our planet to be on loan from our children, rather than being a gift from our ancestors ... As caretakers of our common future, we have the responsibility to seek scientifically sound policies, nationally as well as internationally. If the long-term viability of humanity is to be ensured, we have no other choice.

Gro Harlem Brundtland[1]

NAVIGATING A TRANSITION TOWARD SUSTAINABILITY

The idea of sustainable development has become a significant and dynamic force in political dialogue around the world. It emerged in the early 1980s from scientific perspectives on the relationships between society and the environment, and has evolved since in tandem with significant advances in our understanding of these relationships. Nonetheless, for the last decade and more the evolving idea of sustainable development has been shaped more by political than by scientific perspectives. Reciprocally, strategic priorities for science and technology have been little influenced by the development of sustainability thinking. The present study has been an effort to reinvigorate the needed strategic connections between science and sustainable development.

In conducting its work, the Board has focused its efforts on the next two generations, when many of the stresses between environment and development will be most acute and when a transition toward sustainability will need to take place if the earth's human population and life support systems are not to significantly damage both. This next half-century, like any future, is not knowable and will provide at least its share of surprises. But certain trends and transitions of population and habitation, wealth and consumption, technology and work, connectedness and diversity, and environmental change are likely to persist well into the coming century (Chapter 2). They provide the context for scientific analysis of some of the threats to, and opportunities for, sustainable development that the future may hold (Chapter 4). In such analysis lies the prospect for informed investment in research, capacity building, action, and policy that can make more attractive the prospects for our common journey.

In the Board's judgment, a transition to sustainability over the next two generations should aim to meet the needs of a much larger but stabilizing human population, to sustain the life support systems of the planet, and to substantially reduce hunger and poverty. For each of these dimensions of a successful transition, there is wide international agreement about minimal goals and targets.

The current trends mentioned above are likely to persist well into the coming century and could significantly undermine the prospects for sustainability. If they do, we conclude that many human needs will not be met, life support systems will be dangerously degraded, and the numbers of hungry and poor will increase. Even the most alarming current trends, however, may experience transitions that enhance the prospects for sustainability. Based on our analysis of persistent trends and plausible futures, we believe that a successful transition toward sustainability is possible over the next two generations. This transition could be achieved without miraculous technologies or drastic transformations of human societies. What will be required, however, are significant advances in basic knowledge, in the social capacity and technological capabilities to utilize it, and in the political will to turn this knowledge and know-how into action.

The individual environmental problems that have occupied most of the world's attention to date are unlikely in themselves to prevent substantial progress in a transition toward sustainability over the next two generations. Over longer time periods, unmitigated expansion of even these individual problems could certainly pose serious threats to people and the planet's life support systems. Even more troubling in the medium term, however, are the environmental threats arising from multiple, cumulative, and interactive stresses and driven by a variety of human activities. These stresses or syndromes, which result in severe environmental degradation, can be difficult to untangle from one another and complex to manage. Though often aggravated by global changes, they are shaped by the physical, ecological, and social interactions at particular places, that is, locales or regions. Developing an integrated and place-based understanding of such threats and the options for dealing with them is a central challenge for the development of a useful "sustainability science" for promoting a transition toward sustainability.

There are no maps for navigating a transition toward sustainability. Our common journey is nonetheless already under way. This Board's study has suggested the need for navigational strategies that can better integrate avowedly incomplete knowledge with necessarily experimental action into programs of adaptive management and social learning. Our goal in this chapter is to sketch such a strategy.

Why a strategic approach? "Muddling through" the changing challenges and opportunities presented by the trends discussed in Chapter 2 can take us part of the way toward sustainability goals in the future as it has in the past—especially where political systems and markets are so structured that they provide appropriate incentives and timely feedbacks. But as examples and analysis presented in earlier chapters of this report suggest, *mere* muddling through would leave untapped substantial opportunities for promoting a sustainability transition. It would also leave society unnecessarily vulnerable to a variety of foreseeable threats, as well as to the sorts of surprises that cannot be foreseen but can be prepared for.

Needed to complement the strengths and compensate for the weaknesses of "muddling through" are, therefore, strategic efforts dedicated to improving the prospects for sustainable development. Many such efforts are possible. As discussed in Chapter 1, some are well under way. Our intention here is to sketch elements of one such strategy: a strategy for mobilizing scientific knowledge in programs of purposive social learning and adaptive management committed to the promotion of a sustainability transition. We see such a strategy as a vehicle through which the science and technology community can significantly increase its contribution to the goal of "providing the energy, materials, and information to feed, house, nurture, educate, and employ many more people than are alive today—while preserving the basic life support systems of the planet, and reducing hunger and poverty."

What kind of strategy? Along with others that have studied the problem, we believe that knowledge is a crucial resource for navigating the transition toward sustainability—a resource that arms us, however imperfectly, to cope with the threats and opportunities that may be encountered along the way.[2] A capacity for long-term, intelligent investment in the production of relevant knowledge, know-how, and the capacity to use them both must therefore be a component of any strategy for the transition to sustainability. Some of that knowledge will be produced in libraries, on web sites, and in laboratories around the world. Such are the concerns before us, however, that much of what societies need to know will only emerge in the course of applying knowledge to actions. A strategy for navigating the transition toward sustainability must therefore be a strategy not just of thinking but also of doing. Our explorations suggest that such a strategy should include a spectrum of initiatives ranging from curiosity-driven research addressing fundamental processes of environmental and social change, to focused policy experiments designed to promote specific sustainability goals. We suggest a number of such initiatives below under the general headings of "Priorities for Research" and "Priorities for Action," while recognizing that in practice these realms will often blend together. We also provide an appraisal of the institutional matters that will have to be surmounted if this—or some similar—strategy for integrating knowledge and action is to realize its potential for contributing to the successful navigation of a transition toward sustainability. To be implemented, all of these initiatives would require more detailed elaboration and planning involving a wider array of groups and national perspectives than could be involved in this Board's present study. Our goal has not been to preempt that broader endeavor, but to encourage it and to suggest some initial directions.

PRIORITIES FOR RESEARCH

At least three dilemmas bedevil any effort to set priorities for scientific research in support of a sustainability transition. While these dilemmas are not unique to sustainability issues, they do pose special considerations for the strategy we seek to outline here.

First is the tension between broadly based and highly focused research strategies. This tension has been addressed in the recent NRC "Pathways" report on research priorities for understanding global environmental change.[3] Broadly based programs are desirable in light of the frequency with which important insights in one area emerge from research trying to investigate something else.[4] Moreover, they are needed to allow for the likelihood of surprising and unexpected developments in the interactions between the environment and development.[5] On the other hand, in fields as complex and multifaceted as those bearing on global change, much less the still broader field of sustainable development, there is a widespread consensus among the scientific community that much of the progress that has been achieved has come through research programs focused on "critical scientific issues and the unresolved questions that are most relevant to pressing national policy issues." [6]

A second tension exists between integrative, problem-driven research and research firmly grounded in particular disciplines. It has been recognized for more than a decade that many of the central challenges to sustainability involve multiple, interactive environmental stresses arising from multiple, overlapping human development activities.[7] Unfortunately, our collective ability to create reliable scientific knowledge about such integrated problems remains limited due to the inadequacies of observational data, the immaturity of relevant theory, and the underdevelopment of an appropriate professional community to provide meaningful criticism and peer review. In contrast, it is precisely the strengths of the established disciplines in the areas related to sustainable development that continue to make these fields our most effective engines for the generation of reliable—if more narrowly focused—scientific knowledge.

Finally, a tension exists between the quest for generalizable scientific understanding of sustainability issues and the place-specific aspects of the environment-society interactions that give rise to those very issues and generate the options for dealing with them. Again, this is not a dilemma unique to sustainability issues—it has been a central concern for scientific research in fields as diverse as agricultural production and public health for at least a generation.[8] Moreover, the tension between generalizable and place-specific understanding is increasingly confronting those seeking to provide useful research on the regional impacts of climate change and other global environmental issues.[9]

None of these tensions should be interpreted as either-or choices. Indeed, some of the most exciting and important research seems to arise precisely in circumstances where the tensions are high but successfully managed. From the Board's efforts to understand these tensions and their implications have emerged three priority tasks for advancing the research agenda of what might be called "sustainability science":

1. Develop a research framework for the science of sustainable development that integrates global and local perspectives to shape a place-based understanding of the interactions between environment and society.
2. Initiate focused research programs on a small set of understudied questions that are central to a deeper understanding of those interactions.
3. Promote better utilization of existing tools and processes for linking knowledge to action in pursuit of a sustainability transition.

We expand on these priorities in the sections that follow.

A Research Framework for Sustainability Science

Meeting the demands of a sustainability transition will require a substantial expansion in the capacity of the world's system for discovering new things. As suggested in earlier chapters of this report, the needs run broad and deep. They include the needs for both generalizable knowledge about the workings and interactions of the world's environmental, economic, and social systems, and specific understanding of particular places, problems, and solutions. Much of what societies need to know is sufficiently clear, and how to learn it is sufficiently understood, that specifically targeted research and development is surely justified. We turn to a discussion of some of these targeted areas in the following section.

But history suggests that it would be an enormous mistake to rely only or even primarily on such targeted research and development in our strategies to navigate a transition toward sustainability. Research and development are good investments. But they pay off in ways frequently unimagined by those who funded and even those who performed the seminal work. In fact, technologies have frequently transformed societies—in the nature of work, medicine, and communications. For example, a health sciences revolution is taking place as a result of our new understanding of molecular biology and genetic engineering. In addition, a transformation in communications and modeling has been brought about by the development of high-speed computers and modern communication devices.

Thus, basic research is essential for assuring that, as societies enter future stages of the transition to sustainability, markets, governments, and other players have the intellectual capital available to address the problems they face and to create the products and processes they need. If science and technology are to live up to their potential in meeting the needs of the sustainability transition, a fundamental requirement is a healthy, globally distributed system for conducting basic research across a wide range of topics and disciplines.

Precisely because of the breadth of the needed endeavor, however, a framework is also necessary to identify what the NRC "Pathways" report has called "the coherent domains of research that are likely to provide efficient and productive progress for science…" while still encompassing the range of issues that concern us.[10] What sort of research framework might be appropriate for "sustainability science"?

Intellectual Foundations

The fundamental knowledge needed to support our common journey is rooted in the core sciences of nature and society and has been nurtured in the interdisciplinary soil of scholarship and engineering practice concerned with the interactions between environment and development. Over the last generation, four related, sometimes overlapping, but nonetheless distinct, research-based components of sustainability have grown from this soil (Figure 6.1).

The first is essentially biological, emphasizing the intertwined fates of humanity and the natural resource base on which it depends for sustenance. This branch of research originated in the conservationist thinking of the 19th and early 20th centuries.[11] Internationally, it began to take shape in 1973 with the pathbreaking *Ecological Principles for Economic Development*, blossomed in 1980 as the *World Conservation Strategy* (which first popularized the term "sustainable development"), matured to em-

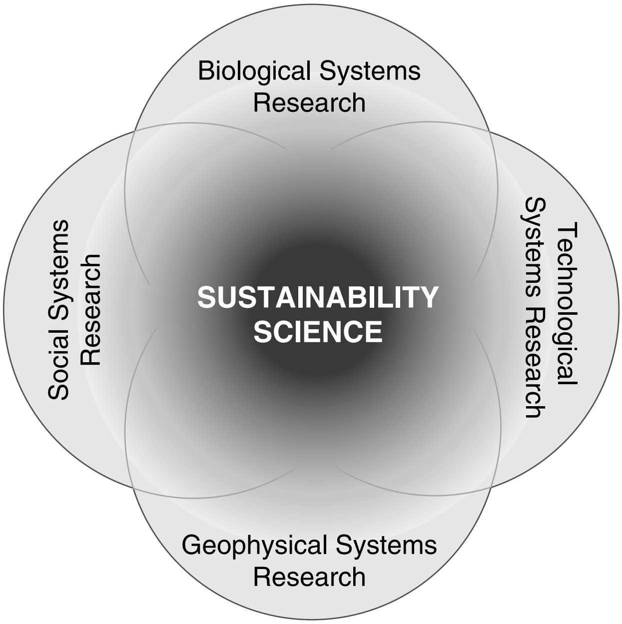

FIGURE 6.1 Four interlinked, research-based components of sustainability science.

brace the social dimensions of resource use with the report *Caring for the Earth*, and now supports the international DIVERSITAS program on biodiversity and sustainable use of the earth's biotic resources.[12] Within the United States, recent offshoots of this branch of research include the *Sustainable Biosphere Initiative* of the Ecological Society of America and the *Teeming with Life* initiative of the President's Council of Advisors on Science and Technology.[13]

A second branch of research relevant to sustainability has been essentially geophysical, emphasizing the interconnections among the earth's climate and biogeochemical cycles, including their response to perturbation by human activities. This branch originated and has remained grounded in efforts to understand the earth as a system. Early impetus was provided by projects undertaken during the International Geophysical Year of 1957 and by concerns about human-induced changes to the global climate and stratosphere, concerns that took shape in the late 1960s. An international, interdisciplinary approach to research on earth systems science was nurtured through the 1970s by early studies of the International Council for Science's Scientific Committee on Problems of the Environment (SCOPE), and given form and strength with the emergence of the World Meteorological Organization's World Climate Research Program in 1979 and the International Council for Science's International Geosphere-Biosphere Program in 1986. U.S. contributions to and pursuit of this earth systems science agenda, which began with NASA's global habitability program in the early 1980s, have recently been reviewed in the "Pathways" report of the National Research Council.[14]

A third branch of relevant research has been primarily social, focusing on how human institutions, economic systems, and beliefs shape the interactions between societies and the environment. This branch is rooted in geographers' efforts to sort out long-term, large-scale relationships among resources, landscapes, and development. At an early stage, this branch of research produced divergent shoots, addressing topics as different as the economics of natural resource use, institutions for governing environmental "commons," the determinants of human vulnerability to environmental hazards or risks, and methods for environmental impact assessment and policy design. Interdisciplinary studies seeking to integrate these disparate strands became widespread in the 1970s, especially in the area of natural resource management, and were drawn into early efforts to understand global issues such as climate change.[15] By the mid-1980s, a wide variety of social science programs had begun to address issues of global environmental change.[16] A comprehensive international effort was launched in 1990, and today is moving forward as the International Human Dimensions Program.[17] Recent reviews of the content and concerns of this line of research are available.[18]

Finally, a fourth branch of relevant research has been the development of basic technological knowledge and the design of products and processes for producing more social goods with less environmental harm. This effort has occurred in several overlapping areas, such as energy technology, emissions control and treatment technologies, and green process and product design. It has involved many efforts, including both market- and regulatory-driven development in industry, technology spillovers among industrial sectors (e.g., the use of aero-derivitive gas turbines for electric power generation), and collaborative research among private institutes, government laboratories, universities, and nonprofit organizations. [19] As engineering practice, this branch reaches back into the earliest work on sanitation, air pollution control, and agricultural practices for soil conservation. By the early 1980s, such practices had been codified as basic engineering principles for pollution prevention, addressing both end-of-pipe treatment and disposal technologies.[20] In addition, basic technology research in the areas of energy, materials, biology, and information have led to efficiency improvements and materials substitutions that continue to reduce the environmental pressures associated with the production of social goods and services.[21] Finally, a broader systems perspective on technology, environment, and development began to emerge in the mid-1980s, focused not on individual technologies or processes but rather on minimizing waste produced by whole sectors of human activity.[22] Under the rubrics of "industrial ecology" and "industrial transformation," this systems approach to environmental engineering has become a centerpiece of both international and U.S. research programs on global change.[23]

Integrative Science

A research framework for sustainability science will need to build on these established branches of scholarship and their respective research programs, practices, and observation systems. Assuring the health of these foundational programs and their priority endeavors is therefore a fundamental prerequisite for sustainability science. But sustainability science will need to be broader yet, spanning the individual branches to ask how, over the large scale and the long term, the earth, its ecosystems, and its people can interact for mutual sustenance.

In keeping with our exploratory theme, we neither know how such science will evolve or if its ambitious rubric—sustainability science—will ever take hold. We do know, however, from the material reviewed in Chapter 4 and elsewhere[24] that many of the most problematic threats to people and their life support systems arise from multiple, cumulative, and interactive stresses resulting from a variety of human activities. Sustainability science will therefore have to be above all else *integrative* science—science committed to bridging barriers that separate traditional modes of inquiry. In particular, it will need to integrate across the discipline-based branches of relevant research described above—geophysical, biological, social, and technological. The same can be said for sectoral approaches that continue to treat such interconnected human activities as energy, agriculture, habitation, and transportation separately. In addition, sustainability science will need to integrate across geographic scales to eliminate the sometimes convenient but ultimately artificial distinctions between global and local perspectives. Finally, it will need to integrate across styles of knowledge creation, bridging the gulf that separates the detached practice of scholarship from the engaged practice of engineering and management.

Fortunately, integrative research approaches to address environment and development issues at the ecosystem scale are not wholly new.[25] Today, for example, forest management strives to encompass social systems and natural resources in an inclusive and interacting systems framework .[26] In addition, integrated water management approaches are forming a new paradigm in water management, and research has been undertaken to understand the interactions of urban, agricultural, industrial, and natural ecosystem requirements for water resources, and the policy implications for water management.[27] In agriculture, especially in systems designed for high-yield, successful production is more likely when crop selection, pest management, irrigation systems, and local culture are considered (see Chapter 3).[28] At a broader scale, the international global change research program has made tremendous progress in the task of integrating previously separate disciplines. For example, 15 years ago atmospheric chemists and biologists had not combined their knowledge to study atmospheric change, despite the fact that biological processes exert major regulation on atmospheric composition. Furthermore, neither had been well integrated into atmospheric physics, oceanography, or climate research. Today, these disciplines are much more closely linked, and integrated research, analysis, and assessment are at the heart of our understanding of global change.[29]

But if the first steps toward an integrative science of sustainability have been taken, the great leaps forward lie ahead. While the international global change research community has made great headway in linking the relevant natural science disciplines, it has made far less progress—despite significant national and international effort—in understanding the interactions of natural and social systems. The same can be said about the incorporation of biodiversity considerations in contemporary global climate change studies. As a result, the scientific community now knows much about what emissions cause various global environmental changes, but too little about what drives those emissions, what impacts they will have on people and other species, and what to do about them. Likewise, although integrated forest ecosystem management programs have progressed to the point of including people in the ecosystem at a local scale, there is much less progress in planning and assessment at broader regional scales, where issues such as air and water pollution and determinants of human population migration and density distribution begin to exert tremendous control. In short, if there is no longer much doubt about *whether* integrative approaches to research are needed in support of a sustainability transition, *how* to achieve such integration in rigorous and useful research programs remains problematical. For if in many cases systems are strongly coupled, then how is one to avoid the practical impossibility of having to study everything in order to know anything? We describe below one approach to this dilemma that our studies have suggested is especially worth pursuing: integrating research for sustainability not around particular disciplines or sectors, but rather around the study of interactions between development and environment in particular places.

Place-Based Science

In Chapter 4, we argued that the major threats and opportunities of the sustainability transition are not only multiple, cumulative, and interactive, but also place-based. In other words, it is in specific regions with distinctive social and ecological attributes that the critical threats to sustainability emerge, and where a successful transition will need to be based. Fortunately, "place" also provides a conceptual and operational framework within which progress in integrative understanding and management are possible (Figure 6.2). Not surprisingly, for the examples of threats and opportunities emerging from the interactions of multiple sectoral activities and environmental components as characterized in Chapter 4, we found the best examples of analytic and policy progress in work on particular places.

To argue that sustainability science will be integrative and place-based is to beg the question for the time being of what constitutes an appropriate classification of "place." In part, the distinction is surely one of scale. In Chapter 5, for example, we suggested that indicators of planetary circulation made sense at a global scale, and those of critical unsustainability at a regional scale, while productive landscapes and ecosystems require more localized indicators. A grand query of sustainability science will be these scale relationships. Understanding the links between macroscale and microscale phenomena is one of the great querries of our age in a wide array of sciences.[30] The pursuit of such understanding will also be a central task of sustainability science.

Whatever spatial scales turn out to be most appropriate for examining particular sustainability issues, however, there remains the task of classifying the "kinds" of pressures and stresses that occur at those scales. While any such classification is necessarily somewhat arbitrary, and will lump together places exhibiting differences, without some classification scientists are left with the dismal prospect of approaching each "place" as though it were altogether unique. One approach to this dilemma certainly worth pursuing in a "place-based" framework for sustainability science has been put forward in the concept of recurrent "degradation syndromes" (See Box 6.1).

However defined, sustainability science as a place-based science will benefit from the many ongoing efforts to regionalize environment-development relationships. The START (SysTem for Analysis, Research and Training) initiative of the International Geosphere-Biosphere Program, the World Climate Research Program, and the International Human

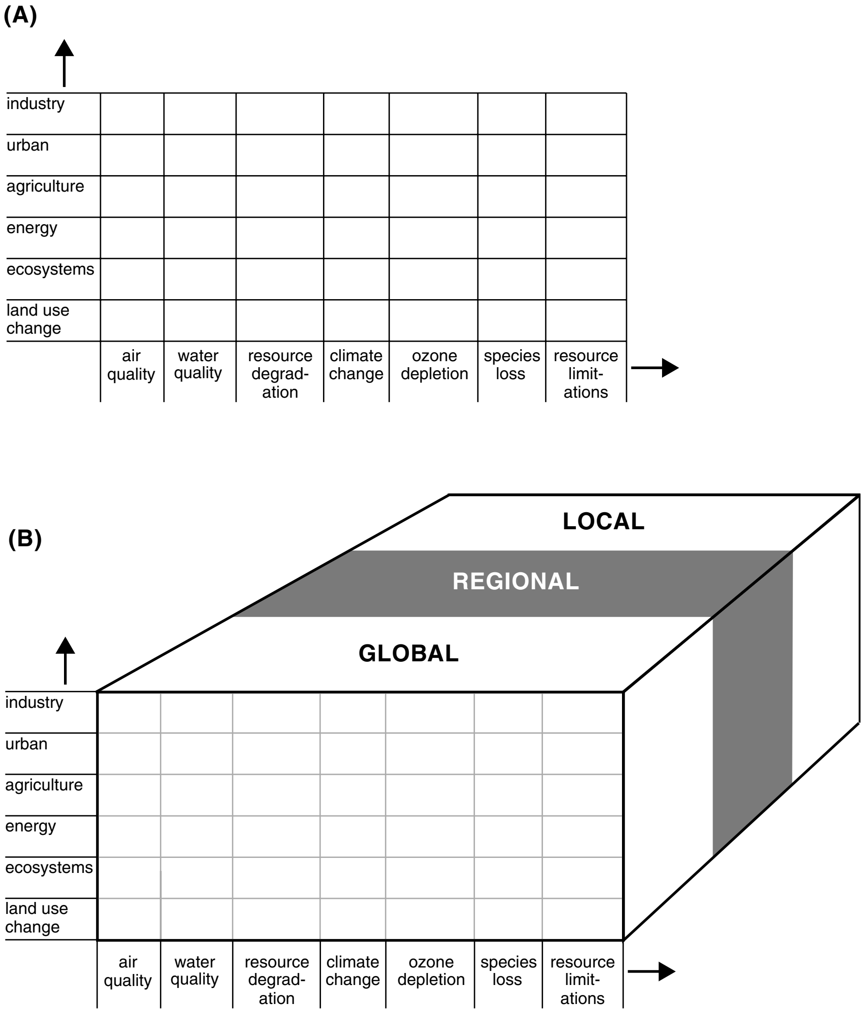

FIGURE 6.2 (A) Traditional approach to sustainability research, in which the effects of multiple human activities on environmental changes are assessed separately. (B) Place-based, integrative approach to sustainability science. Most challenges and opportunities exist at midrange scales.

BOX 6.1 Degradation Syndromes

The "degradation syndromes" concept was originally developed by Canadian scientists to classify regional ecosystems under stress (Rapport et al. 1981; Regier and Baskerville 1986) and later applied to the analysis of global change in the NRC's 1986 assessment of initial priorities for U.S. contributions to the International Geosphere-Biosphere Program (NRC 1988, pp. 161ff). More recently, the degradation syndrome concept was substantially elaborated by the German Advisory Council on Global Change (WBGU): "… interactions in certain regions between human societies and the environment frequently operate along typical lines. These functional patterns (*syndromes*) are unfavorable and characteristic constellations of natural and civilizational trends and their respective interactions, and can be identified in many regions of the world." (WBGU 1997, pp. 112)

The Council's report goes on to postulate the 16 global change syndromes listed below, and to develop an elaborate set of criteria for ranking their relative importance for various societies (WBGU, Box 18). It also employs the syndromes as a framework for defining priorities for future research.

"Utilization" Syndromes

1. Overcultivation of marginal land: *Sahel Syndrome*
2. Overexploitation of natural ecosystems: *Overexploitation Syndrome*
3. Environmental degradation through abandonment of traditional agricultural practices: *Rural Exodus Syndrome*
4. Nonsustainable agroindustrial use of soils and bodies of water: *Dust Bowl Syndrome*
5. Environmental degradation through depletion of nonrenewable resources: *Katanga Syndrome*
6. Development and destruction of nature for recreational ends: *Mass Tourism Syndrome*
7. Environmental destruction through war and military action: *Scorched Earth Syndrome*

"Develoment" Syndromes

8. Environmental damage of natural landscapes as a result of large-scale projects: *Aral Sea Syndrome*
9. Environmental degradation through the introduction of inappropriate farming methods: *Green Revolution Syndrome*
10. Disregard for environmental standards in the course of rapid economic growth: *Asian Tigers Syndrome*
11. Environmental degradation through uncontrolled urban growth: *Favela Syndrome*
12. Destruction of landscapes through planned expansion of urban infrastructures: *Urban Sprawl Syndrome*
13. Singular anthropogenic environmental disasters with long-term impacts: *Major Accident Syndrome*

"Sink" Syndromes

14. Environmental degradation through large-scale diffusion of long-lived substances: *Smokestack Syndrome*
15. Environmental degradation through controlled and uncontrolled disposal of waste: *Waste Dumping Syndrome*
16. Local contamination of environmental assets at industrial locations: *Contaminated Land Syndrome*

Dimensions Program on global environmental change has focused on the regional dimensions of global change since its inception.[31] It is now addressing issues ranging from determinants of land use change to industrial transformation to implications of environmental change for national security. The flagship international scientific assessment of climate change by the Intergovernmental Panel on Climate Change produced an addendum of 10 regions to its second assessment [32] and will base its third assessment on such regional analyses. The recommendations of the German Advisory Council on Global Change have already been noted (see Box 6.1). In the United States, the first assessment of climate change and impacts is being done for 19 regions.[33] Analogous efforts are under way in the European Union, as well as Canada and a number of other countries.[34] Implicit in many of these efforts is the search for parsimony—the identification of the smallest number of regions that can capture the diversity of nature-society relationships and still be manageable without constraining scientific understanding, organizational capacity, and budget. Common to all these approaches is a need for basic advances in our ability to understand interactive, cumulative effects of global change in particular regional contexts. Promoting such advances across a broad front is perhaps the central challenge of a place-based, integrative sustainability science.

Focused Research Programs

It would be premature here to suggest a comprehensive research agenda for a still-nascent sustainability science. The potentially vast scope of such an agenda was explored in ICSU's conference on "An Agenda of Science for Environment and Development into the 21st Century," conducted in 1991 as part of the preparations for the UN Conference on Environment and Development in Rio de Janiero.[35] The chapter on "Science for Sustainable Development" in "Agenda 21" carried forward this broad conception of research needs, and has served as a template for subsequent progress reports by the UN Commission on Sustainable Development. Those reports, and others reviewed above, show that several research programs relevant to sustainability have grown notably over the last decade, especially within the four central branches of scholarship described in the preceding section. Much research in what might well be seen as the sustainability science agenda is clearly moving along now. It remains true, however, that the very breadth of the science that could contribute to understanding long-term, large-scale interactions between environment and society brought with it the risk that the overall research program actually carried out would remain relatively diffuse, underfunded, and unproductive. Evidence presented at the 1997 UN General Assembly's Rio+5 review[36] for the most part bore out this expectation. Several opportunities for international efforts to address these issues and reinvigorate a science agenda for environment and development were scheduled for the turn of the century. These include the 1999 World Conference on Science arranged by UNESCO and ICSU in Budapest and the Conference on the Transition to Sustainability planned by the InterAcademy Panel on International Issues for the year 2000 in Japan.[37]

In hopes of contributing to such efforts, this Board followed the thrust of recent NRC reviews of global change research that have "consistently emphasized the need … to focus on critical scientific issues and unresolved questions that are most relevant to pressing national policy issues." [38] In particular, we list below seven critical areas of inquiry that are central to the pursuit of a sustainability transition and are amenable to research. Most are understudied in existing research programs. The causes for this relative lack of attention are varied: only now are some of the relevant sciences matured to the point of being able to address some of the critical questions; some critical questions fall between disciplines; and some of these questions acquire new urgency in the context of a transition to sustainability. Independent of the reasons for current neglect, we set these seven issues forward as candidates for focused research programs in sustainability science.

Critical Loads and Carrying Capacities

To pursue the goal of "preserving the basic life support systems of the planet" is, among other things, to look for limits beyond which those systems should not be pushed. Both process understanding and practical experience suggest that relatively sharp boundaries do sometimes exist separating relatively normal and radically transformed states of life support systems.[39] Moreover, scientists know that the abrupt changes associated with the crossing of such boundaries provide special "windows of opportunity" for mobilizing political action and institutional reform.[40] Finally, the indicator systems discussed in Chapter 5 lose much of their attraction if they provide no signal of the approach of a "dangerous threshold" or nonlinear relationship between the indicator variable and adverse environmental or social consequences.

For all of these reasons, it should not be surprising that efforts to establish "safety" limits for the earth's life-support and ecological systems are long-standing and widespread. Under various circumstances, these efforts have sought to specify critical indicator values in each of the "pressure," "state," and "response" categories described in Chapter 5. Debates about the "carrying capacities" of the earth and its component ecosystems for domestic animals or the people that herd them have been active since at least the 17th century.[41] Efforts to determine the shape of dose-response relationships for human health effects at low levels of exposure to radiation and chemical pollutants suggest that there may be practical limits to how far the conventional predictive risk assessment paradigm can be pushed. This ambition to identify safe levels for "state" indicators has led European states to specify "critical loads" for the deposition of acidifying compounds on ecosystems.[42] It shows up again in the Framework Convention on Climate Change, which calls for "stabilization of greenhouse gas concentrations … at a level that would prevent dangerous anthropogenic interference with the climate system."[43] Finally, some scholars have sought to identify critical thresholds of damage beyond which whole regional ecosystems lose their ability for self-renewal and slide inexorably into deeper and deeper degradation.[44]

While many of these efforts to specify safety limits for human pressures on the biosphere have been helpful, the Board's inquiries found that the underlying concepts have proven to be contentious, ambiguous, and frustrating. Carrying capacities turn out to depend on available technologies and consumption practices. Efforts to specify actual critical loads or safety levels are undermined by the heterogeneity of the environment and populations at risk. In addition, thresholds turn out to be less often absolute than relative. Finally, a good case can be made that the viability of ecosystems depends less on critical levels that may be exceeded during particular episodes of stress than on the longer term regime of stresses that includes, but cannot be reduced to, such single-valued characteristics.[45]

We encountered all these difficulties in the present study, as we failed in our effort to develop criteria that could provide a "bright line" test for significant degradation of regional ecosystems and their life-support functions (see Chapter 4). Though we had no trouble identifying cases in which life support systems had been degraded or even destroyed, we were unable to turn the concepts of "critical loads," "carrying capacities," and their cousins into useful tools for navigating the transition toward sustainability. This is clearly an area that needs further work. Either a robust scientific foundation needs to be built under the idea of "safe limits," or the scientific community needs to come up with alternative concepts for guiding action toward sustainability. The historical experience of efforts to determine whether threshold or linear responses best characterize dose-hazard relationships for human health and exposure to radiation suggest that this will not be an easy task.[46]

Understanding and Monitoring the Transitions

The persistent trends in environment and development that we have discussed in this report (Chapters 2 and 3) can, if properly understood, serve as important guides to a sustainability transition. They are the great currents of our uncharted sea—large-scale, persistent forces that will shape, though not fully determine, our paths to the future. Over the last two decades, many of the global trends most important for the sustainability transition have become much better documented and understood. These advances have occurred in both the social and environmental realms, and in studies of their interactions.[47]

The search for fundamental *transitions*—or breaks in trends—in the relationships between society and environment has been harder. In this report we have identified one powerful transition that is both credible and interesting: the change in population regimes from those of high birth and death rates to those of low birth and death rates. This transition is *credible* because it meets scientific criteria: it is partly supported by theory, matches the data well, and has predictive power. It is *interesting* because it appears to be not simply a continuous trend, but rather a transition from one relatively stable state of affairs to another. Several other candidate "transitions" seem almost as compelling: in settlement regimes, the transition from predominantly rural to predominantly urban regimes; in agricultural productivity, the transition from increases in production deriving from additions in the amount of land farmed to increases deriving from additions to local yields based on knowledge and its use (e.g., physical inputs such as fertilizers and pesticides). Other possible transitions were noted—for example, the globalization of the economy and changes in consumption patterns, energy intensity, pollution per unit value produced by the economy, and the role of the state in global governance—that are surely interesting, but are not as well understood or as globally documented as the others. Improving that documentation and understanding, especially for those transitions that transcend the normal disciplinary boundaries of scholarship, should be a priority objective for sustainability science (see Chapter 5 on indicators).

Consumption Patterns: Determinants and Alternatives

One of the biggest obstacles for a successful transition to sustainability is the desire of so many people for lifestyles requiring much larger flows of energy and materials. Yet relatively little work has been done in addressing consumption in this fundamental sense, as energy and materials, rather than in terms of "final" consumer goods and services. For example, although much work has been done on documenting trends of dematerialization and decarbonization,[48] an explanatory theory to account for variations in rates of decreasing mass per unit of service has not yet been developed. There is also the need for methodology to separate out resource-depleting or environmentally damaging consumption from general consumption, and to substitute modes of consumption that are less damaging and depleting of energy and materials for the more damaging ones. Little-studied of late, but particularly important in activities as diverse as agriculture and air conditioning, is the systemic potential for substituting information for energy and material use.

Turning to the demand side of consumption, advertising and culture appear remarkably effective in encouraging emulation of high-consumption lifestyles. Nonetheless, the human behavior driving consumption is still poorly understood, especially the potential for alternative consumption patterns, and the value systems that would support them.[49] A small but growing effort has explored people's satisfaction with their current levels of consumption and their willingness to substitute other values for material things.[50] Such values include reducing work time for more leisure, social, or family time, diminishing household burdens on environment, and enjoying simplified life styles.[51] A rigorous, comparative research program is needed into how the values underlying alternative consumption patterns are formed, stabilized, and undermined in contemporary societies.[52]

Finally, it is clear that any number of economic interventions—tax policies, removal or introduction of subsidies, tariffs, and trade restrictions, more effective use of markets, market intervention through regulatory initiatives, among others—may have an impact on consumption. Unfortunately, societies have an inadequate understanding of the responses of complex and interconnected economies (and the vested interests therein) to such interventions, so that there will be tremendous concerns and some danger in implementing such mechanisms, and in learning from their actual performance.

Incentives for Technical Innovation

Innovative technologies that produce more human value with less environmental damage will surely be a central element of any transition to sustainability. When the economic benefits of such technologies can be captured by private parties, markets offer the most efficient way to move the basic knowledge created by research into practical new products and processes. Many new products and capabilities that will contribute to a successful sustainability transition—from efficient heat pump technology to systems for recycling aluminum cans—are already being widely adopted as a result of success in the marketplace. Markets, however, do not always produce the desirable products and processes, or the desirable solutions to social allocation problems. The conditions associated with such market failure include unpriced externalities, public goods, and insecure or uncertain property rights.* Standard remedies are equally well known, generally involving government regulation of externalities, provision of public goods, or enforcement of property rights.

More systematic application of existing remedies for market failure would surely help to align incentives for technical innovation with the needs of a transition toward sustainability—for example, through the realistic pricing of water used for agriculture and industry. But as necessary as such measures may be, they are almost certainly insufficient. The spatial and temporal extent of sustainability issues means that incentives must function across national boundaries and across generations—exactly the domain in which the national governments responsible for most past remedies to market failure are least likely to be helpful. The information-intensive character of much of the innovation needed to navigate a transition poses extraordinary hurdles for handling intellectual property rights, as can be seen in recent debates over biotechnology. In addition, a global trend to commercialize data is manifest in emerging national legislation (proposed in the United States; ratified in Europe as the European Database Directive) and international organization discussions (e.g., World Meteorological Organization, World Intellectual Property Organization) on intellectual property rights. These bills and agreements are of great concern to the international scientific and technical communities because they could give database producers perpetual and exclusive rights to the contents of their databases, without regard to fair use exceptions such as research and education.[53] A concerted research program on the kinds of incentives, market and otherwise, needed to promote technological innovations for a sustainability transition, on the options for providing such incentives in a highly uncertain, multi-actor, globalizing world, and on their actual performance in that world is surely worth pursuing.

Institutions for Navigating a Transition Toward Sustainability

If institutions are the norms, expectations, and rules through which societies figure out what to do and organize themselves to get things

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*"Externalities" are relationships among actors that are not taken into account in the market transactions between them. An example is the pollution from one actor's energy production falling on another. "Public goods" are those whose benefits can be taken advantage of, not only by those who invested in the goods' provision, but also by others who did not. An example is the construction of sewage treatment plants. "Property rights" issues arise when a potential investor in a technology or sustainable use practice cannot retain the benefits of that investment. Open access commons such as ocean fisheries are a well-known example, where a current "investment" in restricted, but sustainable, fishing levels are not recouped in later harvests because the investor cannot assure that others will exercise the same restraint.

done, then the institutions with which society will navigate the transition toward sustainability may be quite different from those with which it has the most experience to date. As noted elsewhere in this report, those institutions will likely be less government-centered than in the past, involving as well substantial roles for a variety of private sector and non-profit actors. [54] Moreover, they could well be less centered at the level of nation-states, spanning instead scales from the local to the global. Finally, they will almost certainly be substantially more information-intensive than the institutions of the past, with increasing tasks of monitoring, assessment, and reporting.[55] Within these emerging multi-actor, multi-scalar, information-rich institutions, initiatives are less likely to be pushed by the familiar individual actor groups—a UN agency, a national government, or a single firm or sector—than by ad hoc networks of advocates temporarily united around a shared purpose.[56]

Today, we have very limited understanding of what these emergent institutions are or might be. We know even less about the factors determining their effectiveness in promoting a sustainability transition, though issues of participation, credibility, capacity, and linkage immediately come to the fore. Nonetheless, recent work has begun to sketch the outlines of what a long-term research program on institutions for a sustainability transition might include.[57] Central to this emerging agenda is the need for a better understanding of when enlightened self interest provides sufficient grounds for state and nonstate actors to engage in behaviors promoting a sustainability transition, when various forms of collective action are also necessary, and how such collective action can be promoted.[58] A focused effort to develop and pursue this emerging institutional agenda is needed.

Indicator Systems

We have argued in this report that an informed dialogue on goals for the transition toward sustainability is necessary if societies are to take some measure of responsibility for where they ought to be headed, rather than merely acquiescing to where the currents of demographic, economic, and environmental transformation take them. But even in the best of circumstances, goals alone are only distant intentions. To become operationally useful, they need to be translated into specific indicators that can be monitored, reported on, and evaluated throughout the journey. Seen in this manner, indicators become part of an information feedback system through which societies can assess progress, adjust directions, and obtain warnings of unsustainability.

Chapter 5 reviewed the vast range of efforts that have been carried out around the world to develop indicator systems relevant to the sustainability transition. These range from global accounts of people and carbon, through regionally integrated "sustainability" metrics, through corporate environmental audits. Although further conceptual development of such indicators systems will be important, the most pressing need is to facilitate the wider application of existing knowledge about indicators to specific management situations. The experience reviewed in this report suggests that to be used, such applications need to be developed in ways that involve stakeholders and ultimate users as well as the technical community. The same experience also suggests, however, that user-driven indicator systems can often overlook some of the more strategic functions of indicators we outlined in Chapter 5. We believe that a research effort focused on bridging this gap between practice-driven and theory-driven indicator systems for sustainability could reap significant benefits.

Assessment Tools

In Chapter 3, we described the need for methods and processes to perform "what if" explorations of possible trends, transitions, and policy options. We presented examples of how the tools of integrated assessment models, scenarios, and regional information systems had helped to integrate knowledge and action in a variety of efforts to promote sustainability. Despite their potential contributions to the navigation of a transition toward sustainability, however, the best assessment methods are not nearly as widely used as they might be. Several steps could help to remedy this.

First, the international development of a set of reference scenarios could play a significant role in developing a common understanding of a sustainability transition, just as has been done in the narrower case of stratospheric ozone depletion. The focus of such scenario efforts should be on the interactions among the needs of future generations, and the impacts on life support systems of satisfying these needs through technologies and institutions of the future. Examples of what such explorations might entail are provided in a number of recent publications.[59] Further development of scenarios should be encouraged by establishing a global scenarios forum, learning from the experience of groups such as the IPCC Special Report on Emissions Scenarios, the Energy Modeling Forum, the Global Scenario Group of the Stockholm Environment Institute[60] and other similar efforts. Whatever the specific character of the forum, the goal should be to bring into the discussion broad expertise in environment and development, as well as representatives from multiple regions and nations.

A second assessment initiative stems from the growing realization that the credibility of international science-based assessments (e.g., the IPCC assessment of climate change) and their use by individual countries is strongly conditioned by the extent of a country's meaningful participation in the assessment.[61] This same lesson has been repeatedly learned at national and local levels, and is a central issue for ongoing U.S. national efforts to conduct regions-based assessments of global change.[62] Critical experimentation with a variety of methods for achieving legitimacy-enhancing participation without undue cost to scientific credibility is badly needed.[63] New information technology may have much to offer such experiments. But empirical data on the conditions under which, and the degree to which, remote engagement can replace face-to-face interaction in legitimacy-building participation efforts remains almost nonexistent.[64]

Integrative methods that bring a variety of disciplinary perspectives into the formulation of assessment questions and strategies must also be developed. Fortunately, there is substantial activity on this front, with truly integrative approaches replacing earlier models that simply used the social sciences to supplement assessments framed primarily by the natural sciences.[65]

Finally, much of the knowledge and decision making necessary for navigating a transition toward sustainability is, as we have noted, tied to particular places and circumstances. Scenarios and assessment models used in support of sustainability efforts therefore require both global perspective and local context. Bridging multiple scales of analysis has long been a particularly vexing problem in both the natural and social sciences. Despite these difficulties, however, recent progress has been seen in pragmatic efforts to bring global sustainability perspectives to bear on practical problems of ecosystem, watershed, and community management.[66] Some of these, such as recent efforts dealing with sustainable futures for the Columbia Basin and Alpine regions of Europe, have become quite sophisticated in their integration of global modeling with local stakeholder perspectives, knowledge bases, and decision-making needs.[67] Such experience needs to be codified so that it can be assessed, adapted, and learned from in capacity-building efforts throughout the world.

Toward More Usable Knowledge

A great deal of knowledge, know-how, and capacity for learning relevant to sustainable development has already been assembled in various observation systems, laboratories, and management regimes around the world. Unfortunately, relatively little of this rich resource is currently utilized in even a fraction of the situations where it could contribute to navigating the transition to sustainability successfully. Even as the science and technology community pursues new research and development endeavors of the sort described elsewhere in this chapter, it therefore faces the additional task of promoting better use of what is already known.

In general, the need is for two-way, dynamic processes for transforming what one person, group, firm, or nation knows into something useful for the particular challenges and opportunities faced by another. Increasingly, such processes are taking the form of collaborations or partnerships rather than the one-directional "pipeline" model that characterized earlier efforts in information diffusion and technology transfer. Newly emerging information technologies almost certainly have a role to play in making such collaborations both effective and global in reach. Much remains to be understood, however, about the potential opportunities and risks posed by these new technologies, and about the social and technological infrastructures needed to assure their effective and equitable use.[68] Effective two-way collaborations have emerged in engineering, agricultural development, and renewable resource management as well as research-intensive private sector activities. There is a continuing need for advancing our understanding of what underlies these effective collaborations in moving knowledge into action, for making that understanding part of the normal training for professionals engaged in research, and for applying it systematically in promoting better and more widespread use of what is already known to the pursuits of a sustainability transition.

One implication of the emerging "collaborative" view of knowledge and technology dissemination is already clear, however. Making knowledge more usable means enhancing the capacity of groups around the world not only to obtain and interpret it, but also to critique it and adapt it to their own place-specific contexts. This is as true for the current undertakings of shaping useful assessments of climate change as it has been for the classical concerns of agricultural extension. And it is as important—if not more so—for the nongovernmental organizations, private enterprises, and regional authorities destined for central roles in the sustainability transition as it is for the national governmental bodies that have been the conventional focus of capacity-building efforts. Aggressive and inclusive fostering of local capacity in science and technology must therefore be a centerpiece of any strategy for the sustainability transition. This has been generally recognized in international discussions on measures for promoting sustainable development. Programs to do something with this realization nonetheless remain largely inadequate.[69]

As we discuss below, the successful production and application of the knowledge needed for a sustainability transition will require significant strengthening of institutional capacity in at least four areas: linking long-term research programs to societal goals; coupling global, national, and local institutions into effective research systems; linking academia, government, and the private sector in collaborative research partnerships; and integrating disciplinary knowledge in place-based, problem-driven research efforts. None of these needs are unique to sustainability science; strengthening our institutional capacity to address them will benefit society more broadly as well. The specific institutional forms and processes needed will be a function of the particular problems and places involved. Nonetheless, several general needs for the development of institutional capacity seem clear.

Linking Long-Term Research Programs to Societal Goals

As we have repeatedly emphasized in this report, some of the knowledge and know-how needed for navigating the transition to sustainability will be produced without need of strategic design or priority setting by governments or international bodies. Given adequate support for curiosity-driven research, incentives for private sector research, and spillovers from short-term research on immediate problems, much of value will be discovered and disseminated. Nonetheless, there remains a great deal of knowledge that would be useful—and may be necessary—to meet the goals of the transition, yet which is unlikely to be produced through such channels. These types of knowledge include most monitoring data with large geographical coverage, much "public good" understanding about the interactions of social and environmental systems (i.e., understanding useful to everyone once it is discovered by someone), and certain know-how lacking near-term prospects of generating competitive returns on investment. To create and disseminate such knowledge, society needs the institutional capacity to design and sustain the full array of long-term monitoring, research, and development programs that are required to attain sustainability goals.

In the United States, as in most other countries, the lack of such capacity is generally acknowledged.[70] Creating it will require, first of all, institutional structures that can promote the articulation of a broadly shared, politically viable consensus on sustainability goals. Second, it will need mechanisms for designing, setting priorities, and providing stable funding for the research programs that could help to achieve those goals. Successful efforts to link long-term research programs to social goals are not without precedent, having been carried out internationally in the effort to eliminate smallpox, and domestically in the U.S. in certain areas of the space program (e.g., Apollo), defense (e.g., the Atlas rocket development), and health (e.g., polio). Submissions to the 1977 UN General Assembly Special Session showed that a number of countries have made substantial progress toward articulating goals relevant to sustainability.[71] And the

European Union's Fifth Framework Program for research and development (1998-2002) makes the link between sustainability goals and priority research programs explicit.[72]

Forging similar long-term linkages in the U.S. political context will be particularly difficult given the government's fractionation of domestic and international policy making.[73] The Carnegie Commission advanced a number of general recommendations for enhancing the nation's capacity to link science and technology to societal goals in 1992; a number of followup efforts are now in play.[74] Most of these entail some form of coordinated effort involving a number of congressional committees and federal agencies under leadership of the White House offices of Science and Technology Policy and Management and Budget. Focused efforts are now needed to adapt the general recommendations emerging from these various efforts to the challenges of designing and implementing particular long-term research programs in support of sustainability goals.

Integrating Global, National, and Local Institutions into Effective Research Systems

The knowledge base to support a transition to sustainability will have to be attuned to the unique characteristics of particular places and issues. At the same time, it must be able draw on research that addresses phenomena of regional or even global scale. Societies need arrangements that connect the local end-users—including corporations, farmers, households, land use planning commissions, and regional research centers—and the international science and technology community into a global research system. This system needs to link local use and the best that international science has to offer in a way that provides relevant scientific guidance for a sustainability transition. In this sense, sustainability science is like the agricultural science that supported the Green Revolution, or the health science that has brought about the reduction of many infectious diseases. The analogy is an important one, for it highlights both the potential and the pitfalls of problem-driven research systems that span multiple geographic scales.[75] The design of an integrated research system of sustainability science will have to evolve on its own course. Nonetheless, the following elements seem almost certain to play a role and merit serious attention.

At the international level, sustainability science would benefit from a set of international research institutes somewhat analogous to the CGIAR (Consultative Group on International Agricultural Research) of The World Bank, Food and Agricultural Organization of the United Nations (FAO), UN Development Program (UNDP), and UN Environment Program

(UNEP) with centers located in regions reflecting major sustainability challenges. One such CGIAR-derived approach has in fact been recommended.[76] The new efforts could well be based in or affiliated with the regionally oriented START centers of the IGBP, WCRP, and IHDP, or related institutions such as the Inter-American Institute for Global Change Research. Mandates for each institute should almost certainly include research responsibility for one or more sustainability science issues of particular relevance to the region in which it is located, and responsibility for global leadership on an issue particularly relevant to its region, but with clear relevance to a larger community.

If the international institutes are to be effective, they must be able to work with strong national research systems. Such systems must have the capacity to set priorities, mobilize resources, carry out the necessary R&D, and assess progress in areas such as energy, agriculture, environment, and other priority areas outlined here. National capacity is also important in producing the knowledge and analysis needed by national governments and national constituencies to make decisions about research priorities and technology development and investment, and to establish policies and programs that will advance the sustainability transition. In the United States, a national mechanism should be developed to promote research and development on critical issues that do not fall within the charter of established mechanisms. The Science and Technology Centers of the National Science Foundation, and the military's earlier ARPA (Advanced Research Projects Agency) materials and computer labs might provide informative models for consideration in the design of such collaborations.[77]

In addition to national capacity, all countries, except for the very smallest, will need decentralized research (and education and training) capacity at the regional, local, and firm level. With appropriate incentives, decentralized systems can make important contributions to the generation, transfer, and communication of locally relevant knowledge. The network should be organized and funded in a manner that provides incentives for it to contribute to local-level sustainability concerns (e.g., the eutrophication of lakes or contamination of groundwater) by performing what has been termed "routine science" (e.g., monitoring or operational research) and technology development.

Linking Academia, Government, and the Private Sector in Collaborative Partnerships

Linkages are also needed that facilitate collaboration among academics, governmental and private sectors, and nongovernmental actors in research partnerships to promote the sustainability transition. It is by now generally accepted that one of the greatest shortcomings in the efforts to enhance worldwide agricultural production through the CGIAR system was the failure to provide incentives and institutional arrangements that would link private sector actors into that system.[78] Similar difficulties have plagued efforts to enhance family planning and basic public health around the world. Even efforts to transfer relatively discrete technologies across national borders have been shown to require collaborative, two-way partnerships among public and private interests if they are to have much hope of success.[79] Societies need to enhance these collaborative efforts if substantial opportunities to harness science and technology to the sustainability transition are not to be lost.

Multisector research and development partnerships need not be formally codified. Many of the most successful collaborations consist almost entirely of the flow of people among sectors, with young university-trained scientists and engineers heading into the commercial world, business people serving terms in government, and so on.[80] While these exchanges often work reasonably well within nations, there is a case to be made for substantial strengthening of mechanisms to promote two-way exchanges of scientists and engineers across national as well as sectoral boundaries.

However successful informal partnerships of these sorts may be, the need will remain to foster more structured cross-sectoral partnerships to promote sustainability science. Although national governments have a role to play in such endeavors, it seems likely that an important locus for integration may be at the subnational level, where organizational arrangements can be more readily tailored to specific needs and opportunities.[81] This emphasis on cross-scale issues in institutional design reemphasizes the point made earlier about the importance of tending to linkages among local, national, and global actors in the science and technology system. Especially as such linkages extend across national boundaries, creative institutional designs will be needed to assure that incentives for participation in research partnerships remain high and stable. This seems to be one area in which the contributions of dedicated private foundations could be particularly effective.

Integrating Disciplinary Knowledge in Place-Based, Problem-Driven Research Efforts

Finally, sustainability science will require progress in institutional designs that foster integration of research planning and support across disciplines and sectoral missions to address system interactions in particular regions and locales.

This need runs counter to deeply held organizational biases that emphasize individual intellectual disciplines within academia, and individual sectoral missions within governments. Thus, it is vastly easier to mount a study of the people or plants or hydrology or soils of a watershed than of their interactions. Studies of the implications of energy use on one region and land use change on another are more likely than an integrated study of how all human activities on a particular landscape affect it jointly. A variety of arrangements involving Presidential initiatives, lead agencies, multi-agency coordinating committees and task forces, and other mechanisms have been tried in the U.S. science policy structure to address these issues, none with uniform success.

That said, substantial progress has been made over the last decade in bridging disciplinary and even occasionally sectoral perspectives in addressing problems of global environmental change.[82] Even this limited progress, however, has proven tenuous and enormously difficult to sustain.[83] And it has not fared at all well in providing long-term support for the integrative, place-based science that this Board has identified as central to the successful navigation of the transition toward sustainability. A priority for enhancing institutional capacity to foster sustainability science is therefore the design of an S&T policy system that puts control of more research funds in the hands of place-based institutions with a mission of promoting integrative, policy-driven knowledge and know-how. Some precedent for such an approach exists in the old land-grant agricultural colleges and in a variety of novel regional partnerships of academia, government, and industry that have emerged in areas of high technology R&D. Internationally, institutions such as the START system could—if properly supported—provide the testing ground for such integrative, place-based efforts.

PRIORITIES FOR ACTION

This section applies the strategy sketched above to the core sectoral challenges for sustainable development identified more than a decade ago by the Brundtland Commission. For each sector—population, settlements, agriculture, energy and materials, and living resources—we begin by recapitulating the Brundtland Commission's call for action. We then draw from our own studies of developments since the Brundtland report to suggest plausible, high-priority sectoral goals for a sustainability transition, assess the knowledge most needed for the journey, and propose specific steps that could help society to move along a suitable pathway. In some sectors, such as population, enough is known to suggest specific policy measures. In others, such as urban systems, where the needed knowledge is less fully developed, enough is known to suggest where to look for guidance. In all cases, what is needed is the iterative, adaptive approach outlined in our strategy for navigation where science both in-forms action and learns as much as possible from the encounter. Activities related to many of our action priorities are under way with varying but generally inadequate levels of support around the world. Our intent is not to ignore, much less compete with such initiatives, but rather to help focus attention on a few areas where significantly increased concentration or activity seems warranted. Implementation of our recommendations will therefore be a task not only for the National Research Council and its national and international partners in science, but also for the many "knowledge-action collaboratives" involving the international science community, governments, non-governmental organizations, and the private sector around the world.

Human population: Accelerate current trends in fertility reduction

> "Giving people the means to choose the size of their families is not just a method of keeping population in balance with resources; it is a way of assuring—especially for women—the basic human right of self-determination. The extent to which facilities for exercising such choices are made available is itself a measure of a nation's development." WCED, 1987

By the middle of the next century, in just 50 years, global population is currently projected to be about 9 billion in the UN mid-range forecast, with much higher and somewhat lower populations within the current range of projections. These projections are based on the assumed trajectory of the demographic transition, with fertility reduced to a level just adequate for replacement over the next generation. Could, and should, the pace of this fertility reduction be increased? In many ways, smaller generations could ease a transition to sustainability. By reducing the number of people to feed, nurture, house, educate, and employ, the tasks become less daunting. Consumption of energy and materials would be reduced while available investment for both human development and economic growth would be potentially increased. On the other hand, too much fertility reduction, accomplished too quickly, can clearly bring on transition problems of its own. Especially troublesome are those associated with the creation of populations characterized by high ratios of elderly people relative to productive workers. On balance, however, for most parts of the world still exhibiting high fertility, accelerating the rates of reduction will almost certainly ease the transition toward sustainability.

Goals

An achievable goal for population is to accelerate current trends in fertility reduction. After reviewing the continuing reduction in fertility and the potential for accelerated reductions (notably, in addressing the unwanted childbearing due to lack of available contraception), we believe that achieving a 10 percent reduction in the population now projected for 2050 is a desirable and attainable goal.[84] Nearly a billion less people would ease the transition toward sustainability.

Knowledge

As noted in Chapter 4, the three major sources of high fertility and continued rapid population growth are the unmet need for contraception, the still high desired family size, and the large number of young people entering reproductive age. Improving access to contraceptive services, and linking these to reproductive and child health services can over the next decade reduce the unmet needs for contraception. On the whole, enough is now known about providing access to such services to meet these needs in the course of a decade. The potential of private markets to deliver contraceptives, however, has not been fully explored by national programs. In other areas, more knowledge is called for. Thus, more needs to be learned about the factors that determine desired family size and the nature and effectiveness of incentives to postpone marriage and delay reproduction. Fundamental research on the factors influencing the timing and speed of the demographic transition is also still required. For example, while diminished fertility seems to correlate with increasing income over the long term, it also seems to respond to shorter term diminution in income. Further, fertility has dropped below replacement in most industrial countries (contrary to the constant replacement assumption of most projections) and future trends are uncertain. And, a better understanding is needed of the implications that enhanced fertility reduction rates and age-specific mortality factors such as AIDS will have for social issues related to the future age distributions of the populations they create.

Actions

Despite these knowledge needs, societies know enough to seek a reduction of the 2056 projected levels of population by 10 percent. Research and decomposition analyses have shown that such reductions should be possible. Desired family size diminishes with increased incomes, child survival, educational and employment opportunities for women, and access to birth control. As discussed in Chapter 4, all of these measures tend to be correlated and each—separately and together—has been hypothesized as a key lever in fertility reduction. In practice, attaining the reductions will require behavioral as well as cultural changes, with much energetic and coordinated action by national governments, international organizations, and other institutions, as well as by individuals.

Over the short-term, the most obvious strategy is to meet the unsatisfied demand for contraception by increasing the knowledge about and availability of existing technologies to those who might want to use them. Over the medium term, strategies are needed to aim for reduced family size through efforts to enhance the status of women, particularly developing incentive structures for educating girls and women. Education is a reasonably well-known and tested intervention, with additional critical benefits for individuals and societies; but accelerating education for women will require new and sustained efforts. Finally, looking over the longer term, the most promising effect would be achieved by delaying the onset and increasing the spacing of childbearing. Postponing having children through education and job opportunities (thereby, in most societies encouraging marriage at a later age) and addressing such difficult issues as adolescent sexuality have the potential to slow population momentum. But more specific programs—such as the novel program in Hyderabad, India, that provides dowries to empower young women to stay in school and to postpone marriage—are needed. All these actions require a level of collaboration not usually found—bringing together initiatives in family planning, reproductive health, education, women's rights, adolescent pregnancy, and employment to accelerate fertility reduction.

Cities: Accommodate an expected doubling to tripling of the urban system in a habitable, efficient, and environmentally friendly manner

> "In many developing countries, cities have thus grown far beyond anything imagined only a few decades ago—and at speeds without historic precedent... These projections put the urban challenge firmly in the developing countries. In the space of 15 years ...the developing world will have to increase by 65 percent its capacity to produce and manage its urban infrastructure, services, and shelter—merely to maintain present conditions." WCED, 1987

Over the next two generations, the human population is expected to become predominantly urban, with the great majority of new human settlement expected in urbanized areas in developing countries. Using current projections for population and rates of urbanization, the transition will be from a world with 3 billion people in cities to one with 7 billion in cities—a doubling to tripling of urban systems. Almost all of this growth will take place in and around existing cities; truly new cities such as Abuja and Brasilia have been and are likely to continue to be rare.

The challenges posed by this projected urban population growth are daunting.[85] Nonetheless, a number of opportunities present themselves and stem in part from the same trends that present challenges. The growth of high-density cities provides an opportunity for economic and energy-efficient provision of services and infrastructure (e.g., the marginal cost of providing each additional unit of public service is lower in urban areas than in rural areas). The fact that growth will be rapid means that most of the infrastructure will be built in the next several decades, providing an opportunity to build modern and efficient facilities. Key to these opportunities, of course, is the foresight, will, and capital required to take advantage of them.

Goals

An achievable goal is to accommodate a doubling to tripling of the urban system in a habitable, efficient, and environmentally friendly manner. The cities emerging from such growth should meet the needs for housing, nurturing, educating, and employing the 4 billion additional persons expected to be urban dwellers by the middle of the 21st century. By utilizing the potential efficiencies provided by both increased density and the opportunity to build anew, these cities should meet human needs while reducing their "ecological footprint" and providing more environmentally friendly engines of development.

Knowledge

Cities are very complex places. The knowledge and know-how required to expand and manage them are diffused across a broad range of disciplines, practitioners, and institutions. The urban social sciences study the forces, needs, and impacts of growth; architects, engineers, and planners address the built environment's form and function. These professions, as well as politicians, developers, financiers, and the construction industry create the built environment. Environmental scientists seek to maintain the needed ecosystem services and lessen the impacts of cities on their own environs. Habitability, efficiency, and environmental health are all goals of clusters of disciplines and professions. An extensive literature related to each is available.[86] Lacking, however, is the knowledge and know-how for sustainable cities that brings these goals together to drive research and development programs to better meet urban residents' needs, reduce hunger and poverty, and lessen stresses on life support systems. For example, not enough is known about the tradeoffs among sustainability goals as cities grow to different sizes, in different configurations, or at different rates. Lacking even more is the understanding of how to manage such tradeoffs within the realities of the urban politics and economics that characterize different regions of the world. For example, better understanding is needed of the relation between the growth of cities and the development of capital markets in developing countries that can mobilize funds for housing.

Actions

Humanity is in the midst of a transition from a world with 3 billion people in cities to one with 7 billion in cities, mostly in developing countries. Over the next two generations, the equivalent of nearly 1,000 great cities will be built, in and about existing cities—an average of almost 20 of these cities every year. The challenge that faces urban areas and all high-density population areas is to achieve settlement patterns that make efficient use of land and infrastructure and impose reduced burdens on material and energy use, while providing satisfactory levels of living. This challenge poses both an enormous necessity and a grand opportunity to seek new behaviors, institutions, policies (public and private), technologies, urban forms, environmental management (water, wastes, air quality), and infrastructure configurations to move urban areas toward sustainability. Now is the time to bring together the science and technology of habitability, efficiency, and environment with the practice of planning, building, and financing the cities of tomorrow. Such a collaborative partnership of disciplines, professions, and major institutions of finance and development can seek the needed knowledge to urgently address this still dimly recognized enormous challenge and opportunity, which is only dimly recognized today.

Agricultural production: Reverse the declining trends in agricultural production in Africa; sustain historic trends elsewhere

> "Global food security depends not only on raising global food production, but on reducing distortions in the structure of the world food market and on shifting the focus of food production to food-deficit countries, regions and households." WCED, 1987

The last 50 years have seen an increase in agricultural production that has outpaced population growth, reduced hunger, and improved diets almost everywhere around the world. The great failure has been Africa, where per capita production has generally been declining over the last several decades. Food demand in the next 50 years will continue to rise in response to population growth, per capita income growth, and attempts to reduce the undernutrition of the very poor. Meeting the challenge of feeding the population and reducing hunger while sustaining life support systems will require dramatic advances both in food production, on which we focus here, and in food distribution and access. The Brundtland Commission recognized the multiplicity of strategies that would be required to meet the challenge. Yet the past 15 years have seen stagnation in real spending on international agricultural research and increasing indications that societies' capabilities for rising food production are inadequate worldwide, with a special problem in Africa.[87]

Goals

An achievable goal is to reverse declining trends in agricultural production in Africa while sustaining historic trends elsewhere. The most critical near-term aspect of this goal is to reverse the decline in agricultural production capability in Sub-Saharan Africa, the only region where population growth has outpaced growth in agricultural production.

Knowledge

The gains in agricultural production during this century were made possible by the ability of public and private sector research institutions to incorporate new knowledge and technology into new production materials and new production practices that could be transmitted to producers. Advances in education, both in schooling and in nonformal education (such as agricultural extension), have been important factors in enabling farm families to utilize the new knowledge and technology more productively. In recent decades, the production increases associated with the Green Revolution technologies of improved seed, nutrients, and pest control have slowed, while numerous social and environmental concerns about those technologies have been raised. Thus, the next 50 years are seen as requiring a "green-green" revolution, in which new biology-based technologies are used to renew yield increases and diminish negative environmental and social effects.[88] Whether such knowledge—and the institutions necessary to produce and apply it—can be created quickly enough to enable a transition toward sustainability remains a subject of much debate.

Actions

Societies know enough to take many of the needed actions now. The challenge that faces agriculture is to intensify production on robust soil areas, to reduce the intensity of agricultural use on fragile land areas, and to restore productivity on degraded lands. Sustainable increases in output per hectare of about two (perhaps three) times present levels will be required by 2050. Substantial progress has been made by developing countries in Asia and Latin America in establishing the institutional capacity to achieve these objectives. In addition, food production and food quality improvements have been introduced in many regions through biotechnology, agricultural runoff prevention from minimum tillage practices, efficient water use by targeted application, and reduction of farm inputs from precision applications based on computer analysis.

Africa, however, remains the only major region where growth in production lags behind growth in demand. Why this should be so remains a puzzle to African governments and aid agencies, as well as to students of African economic development. It is possible to point to the difficult problems of managing agricultural soil resources, the constraints resulting from traditional land tenure institutions, limited agricultural capacity, urban bias in agricultural and food policy, and to a lack of stability in economic governance and political institutions. But the weights that should be given to these several factors and the actions that must be taken to "get agriculture moving" is a source of substantial disagreement. A collaborative effort involving African governments, the African scientific community, African farmers, and nongovernmental organizations will be needed to address the underlying causes and the actions that are needed for the countries of Sub-Saharan Africa to implement the technical and institutional changes required to get agriculture moving, and to build the agriculturally based development required for an African transition toward sustainability.

Industry and energy: Accelerate improvements in the use of energy and materials

> "If industrial development is to be sustainable over the long term, it will have to change radically in terms of the quality of that development… In general, industries and industrial operations should be encouraged that are more efficient in terms of resource use, that generate less pollution and waste, that are based on the use of renewable rather than non-renewable resources, and that minimize irreversible adverse impacts on human health and the environment…. The period ahead must be regarded as transitional from an era in which energy has been used in an unsustainable manner. A generally acceptable pathway to a safe and sustainable energy future has not yet been found." WCED, 1987

The extraction of raw materials and their conversion into material products of all kinds requires large amounts of energy and poses great environmental burdens and damages. In a more crowded and more consuming world, one required transition is toward the production of the goods and services to meet the far greater needs and wants of human society with a much smaller environmental impact. This achievement will require a smaller loss to the environment of the basic ingredients of energy and materials that sustain life, and a system of production and delivery that is less disruptive of environmental systems. In the 10 years since the Brundtland challenge to industry to produce more with less, there have been substantial improvements in this direction both by industry and by consumers. But this trend toward greater efficiency and dematerialization must be accomplished universally and at much faster rates than the historical ones described in Chapter 2 if it is to offset the rapid increases in production forecast for the next decades. The energy system has been moving toward improved end-use efficiency and declining emissions of carbon dioxide per unit of energy production, but rapid rates of population and economic growth have outstripped these trends of increasing efficiency and decarbonization.

Goals

An achievable goal is to accelerate efficiency improvements in the use of energy and materials. Some analysts have set improvement goals on the basis of an increase in the eco-efficiency ratio of a process, firm, or economy: useful (saleable) outputs divided by resource inputs (materials and energy).[89] Long-term rates of improvement in energy efficiency has averaged about 1 to 2 percent per year since the beginning of the Industrial Revolution. A reasonable energy goal for the transition toward sustainability discussed in this report may be to double this historical rate of energy efficiency improvement. Others have suggested as much as a 10-fold increase in eco-efficiency for materials use in the developed world over the same 50 years.[90] Aggregate goals do not distinguish among resources with high and low environmental impacts. Instead, they point generally in the right direction, leaving freedom for experimentation with diverse methods, while conveying a simple but essential message.

Knowledge

Research and development should focus on improving processes and generating technologies that can reduce the energy and materials required per unit of economic output, as in the many efforts under way to improve household energy efficiency; build low-polluting, energy-efficient automobiles; and reduce waste. The emergent field of study and action known as industrial ecology seeks to use the mechanisms of markets, competition, and efficiency to minimize the throughput of energy and materials and the output of wastes from industrial processes. The means include improved eco-efficiency, reuse, recycling, and the substitution of services for products. Many new energy technologies are being developed—for example, fuel cells, photoelectric conversion systems, carbon separation and sequestration technologies, advanced storage technologies, high-temperature superconductors, and advanced power electronics. Much, if not enough, is known about the kinds of research partnerships and incentives that will most effectively and efficiently move such promising developments into the "pre-competitive" stage of product demonstration. Still more is understood about the factors influencing the rate and pattern of adoption of new technologies once they become competitive in open markets. Great challenges remain, however, in the middle ground in understanding the institutional and incentive requirements for bringing promising technologies from the pre-competitive into competitive stages of their development.

In designing and evaluating institutions and incentives to encourage sustainable technologies, it is important to consider their implications carefully at a system level over the technologies' full life cycles, using such strategies as material balance modeling and economic input-output analysis coupled to evaluation of environmental loadings. Without such a systematic assessment, policies that appear to promote better solutions may in the long run have serious undesirable consequences, such as creating difficult problems for the recycling and disposal of materials.

Over the long term, there is a great opportunity to increase human sustenance without increasing environmental burdens through new basic and applied knowledge in the science and engineering of biological processes, new energy sources and transmission technologies, new materials, and more generally in the substitution of information for energy and materials.

Actions

Businesses are likely to pursue reductions in the intensity of energy and materials use if provided with the needed incentives such as the potential to reduce costs or regulatory provisions. Approaches to accelerate efficiency trends through industry leaders (some already committed to "green" practices) and through trade and industry associations (e.g., the Conference Board, the International Organization for Standardization [ISO]) seem likely to have major effects on large and medium size firms. Attracting the interest of the large numbers of small firms in long-established industries, most of which have little capacity for investment in change, will be more difficult and require special efforts.

Even when consumer and public attitudes are neutral, or in favor of change, however, the barriers to efficiency improvements that are embodied in subsidies, statutes and regulations are likely to be difficult to reverse. This will be especially true of those involving long-standing differential incentives, or those that will penalize some industries in favor of others. However, given current trends toward "green" attitudes to recycling and green advertising by product and service suppliers, the pressure by environmental organizations and by government, especially if coordinated, might be effective in encouraging change.

To achieve the increased efficiency objective with respect to energy provisions, ways must be found to reflect the full environmental costs of various fuels through the marketplace. This can be done through means that include fuel use taxes, fuel-efficiency standards for appliances and motor vehicle fleets, and green energy requirements on electric power systems. Direct "externality" taxes on fuels are believed by most economists to be much more efficient, and to produce fewer perverse incentives, than indirect methods, though they tend to be politically unpopular in some countries.

In the short term, societies need to promote more rapid adoption of existing in-use efficiency technologies and practices worldwide. Many efficient technologies are already available to be used in places around the world where they are needed. But societies also need to move beyond simply using what is available to promoting some technologies in a demonstration phase that encourages further development of these technologies. Renewables seem to show enough promise to rate some special nurturing in this category. For the longer term, societies need to commit to fostering and supporting a broadly based, collaborative program of basic energy research and development, involving both public and private sectors in all the varied ways made possible by trends toward deregulation and multiple scale developments. Finally, experience has suggested that a transition toward sustainability will be hastened by research on materials. This should be a broad program, driven by our knowledge that materials innovations will be important for increased production and product efficiency, not simply by a quest for the particular materials that societies now need. These individual research initiatives can usefully be viewed as a portfolio within which technology choices for the future can be based on an integrated view of sustainable production.

Living resources: Restore degraded ecosystems while conserving diversity elsewhere

> "The challenge facing nations today is no longer deciding whether conservation (of living natural resources) is a good idea, but rather how it can be implemented in the national interest and within the means available in each country.... the economic values inherent in the genetic materials of species are alone enough to justify species preservation." WCED, 1987

Species, ecosystems, and their services are critical elements of the life support systems of the planet and represent important natural capital for the human economic and social enterprise. Humans have become integral parts of most of the earth's ecosystems.[91] As described in Chapter 4, human activities that modify ecosystems, primarily land use change and overharvesting of renewable resources, constitute the major threats to sustaining these systems. As described in Chapter 2, unprecedentedly high rates of species extinctions are being driven primarily by continuing loss of habitat. Changes in species and ecosystems also imply losses in natural capital stocks. One estimated value of U.S. species (agricultural crops and livestock, hunted animals, forest products) to the worldwide economy is $434 billion.[92] The value of marine fisheries for human consumption worldwide is estimated to be between $50 and $100 billion.[93] One estimate of ecosystem services on a global basis has generated a value of $33 trillion/year.[94] Unfortunately, species valuation is rudimentary. Also, numbers alone often do not lead to preservation (see Box 6.2). Nonetheless, expansion of the human population and human activities threatens many living resources and ecosystems. Humanity must not await the arrival of future generations before taking action to preserve the present stock of biodiversity.

Goals

An achievable goal is to restore degraded systems while conserving diversity elsewhere. For the human-dominated ecosystems undergoing degradation from multiple demands and stresses, the goal should be to work toward restoring and maintaining their function and integrity so that their services and use for humans may be sustained over long time frames. Other ecosystems have been less influenced by human activities.

Box 6.2 Valuation of Rain Forests

There has been much speculation about natural product chemistry and the potential value of rainforests for pharmaceuticals. If rain forests were an extremely rich and valuable source of pharmaceutical precursor opportunities, their preservation should be assured by market forces, which would not allow their destruction. Unfortunately, they have been only occasionally found to be such a resource. Indeed, one study valuing biodiversity for use in pharmaceutical research cites the "maximum possible value of a marginal species is slightly less than $10,000,"[95] which is not enough to mobilize corporate attention for preservation. Thus, the preservation of species must be assured through other interventions, both scientific and political.

Some of them represent the last reserves of earth's biological diversity, providing a treasure for future generations as a storehouse of biodiversity and because of their aesthetic and spiritual qualities. For these systems, the goal is to protect and conserve biological diversity, both by dramatically reducing current rates of land conversion and by planning for conservation.

Knowledge

Much is known about ecosystem function and how ecosystems and species respond to anthropogenic changes. Some of that information has already been integrated into management approaches. A growing number of recent efforts have integrated knowledge of ecosystem processes and the services they provide into both conservation and development planning. Most of these management approaches are in fact experiments, and adaptive learning is a requisite characteristic of them. The field of restoration ecology, for example, is yielding information about successes and failures as well as providing critical knowledge to help reverse the trend of habitat modification and to establish new habitats for biodiversity. In addition, knowledge from conservation biology is used in managing protected areas, as well as in identifying appropriate species-rich habitats for conservation purposes. To apply these approaches more widely will require additional research, learning, and information dissemination at the interface between the social sciences, natural sciences, and technology.

Beyond these applications, new knowledge is needed in three general areas—fundamental understanding, ecosystem management, and monitoring. In the realm of fundamental understanding of how biological systems work, better knowledge is needed of both the dynamics of population processes and the seasonal and interannual variations in ecosystem processes. We also need an increased understanding of the roles of genes, species, and functional groups in ecosystem processes; the response of ecosystems, species, and population dynamics to multiple and interacting anthropogenic changes; and an assessment of what kinds of species and ecosystems are distributed worldwide and how they can be best used and valued by people.[96]

A second general area of needed information addresses how ecosystems can best be managed at the landscape or regional scale, while accommodating human needs and activities (sometimes termed "ecosystem management"). New knowledge is required to understand the components of decision making for land and resource use across scales and political boundaries; identify the socioeconomic determinants of overexploitation; develop the ability to predict and correctly value the services provided by ecosystems; and develop more sustainable management and harvesting techniques. Moreover, new institutions may be required to integrate the diverse range of knowledge.

Finally, in the area of monitoring, research that allows evaluating the usefulness of the indicator species concept and the concept of fragile or sentinel ecosystems is needed. Monitoring programs must make better use of ecological knowledge gleaned from basic research programs. In addition, evaluations of comparable methods for data gathering and analysis, the strengths and weaknesses of current and future remote-sensing systems, and the criteria for species and habitat protection and use will be necessary before reliable monitoring systems can be developed.

Actions

Enough is already known to better manage human-dominated ecosystems and to preserve biodiversity. Restoration ecology and conservation biology have grown both in theory and in experience through applications to problems of protecting and managing species and ecosystems. Land conservation is made possible through easements, joint partnerships, "debt-for-nature swaps," grants from the Global Environment Facility, and other transactions. Nevertheless, there are lingering tensions or debates about preservation versus conservation* (e.g., wildlife parks in Kenya), best practices, incentives, and the valuation of natural resources. Resolution of these and related issues will require a better integration of the biological and social sciences, including better understanding of the beliefs, attitudes, and needs of local communities, the private sector, and governments.

The restoration of degraded systems will require focusing on better management of human-dominated systems, including using ecological knowledge in decision making and removing incentives that encourage exploitation of systems and replacing them with incentives that sustain the systems. Examples of successful land restoration abound, and with application of new biotechnologies such as phytoremediation, even the most seriously damaged terrestrial ecosystems have a chance for restoration and recovery of values and services. More attention should also be focused on restoring "marginal" lands of low agricultural value and use, because such areas with lower quality soils may support higher biodiversity than more heavily exploited agricultural lands with higher quality soils.[97] These and other "manipulation" experiments are underway to evaluate the applications of ecology in restoring degraded systems; the management of forests, agriculture, and oceans, while retaining

*To preserve is to protect from any change, whereas to conserve is to use with regard to dangers of overuse.

ecosystem services; the effects of species reintroductions (e.g., recovering marine mammal populations) and species invasions (e.g., exotics) on ecosystem structure and functioning; and multiple-use management in forests, protected areas, and coastal and marine ecosystems.

A comprehensive, comparative analysis is needed to determine what these experiments reveal for adaptive management and what useful information is transferable from one species, one ecosystem, or one scale to another. This knowledge—together with removal of the incentives for forestry, irrigation, and fisheries that encourage land degradation or overexploitation of living resources—would help restore degraded systems, encourage the sustainable use of renewable resources, and build natural capital for future generations.

Biodiversity can be managed in part by setting aside protected areas. Unfortunately, many existing protected sites were established because of convenience, threat of overuse, or aesthetic reasons, not because of biodiversity. Fortunately, many programs are under way to evaluate important areas for protecting species diversity (e.g., identification of "hot spots," or areas of high biodiversity at greatest risks of disturbance; and establishment of wilderness areas, or ecosystems protected from human interference); engage local communities in conservation efforts (e.g., UNESCO's Biosphere Reserves); and establish buffer zones around protected areas as transition zones. These efforts provide opportunities for identifying appropriate sites for long-term protection of biodiversity and for balancing the ecological needs of species with the economic needs of society.

Integrative Interactions: Water, Atmosphere and Climate, Species and Ecosystems

Our elaboration of navigational needs in each of the Brundtland "sectors" demonstrates that it is possible to identify appropriate next steps in each sector through the integration of what societies know—both the lessons learned over the last decade and the projected needs for knowledge and know-how over the coming decades—with what societies can do, namely, the policy actions that move us in the right directions and the indicators that can monitor their progress. Achievements in each of the sectors toward the specified goals will improve our chances of attaining the overall goals of a sustainability transition. But it is clear that achievements in one sector do not imply improvements in others, and that the interactions among the sectors also must be taken into account in terms of the resources they require and the environmental effects to which they contribute. To meet our normative goals, an integrated approach is necessary.

For example, as we discussed in Chapter 4, progress in reducing a pollution-causing gas emission from one sector may not reduce urban or regional smog, because gaseous emissions from many sectors, including stationary and mobile combustion sources, industry, agriculture, and natural ecosystems together contribute to the atmospheric chemistry that produces regional air pollution. Also, improvements in the efficiency of water use and reuse and the water quality at its outflow in urban systems may be meaningless to downstream users if similar efficiency improvements are not made in adjacent agricultural areas. Likewise, efforts to preserve natural ecosystems for ethical or aesthetic reasons, or for the goods and services they provide us, may ultimately fail if these efforts do not account for the longer term changes likely to be introduced by atmospheric pollution, climate change, or human population encroachment.

These examples and others in Chapter 4 argue strongly for the need to develop both a thorough understanding of the most critical interactions, often at a regional scale, and an integrated strategy for planning and management that is focused on sustaining critical life support systems. Such strategies require research and policies that go beyond the typical framework of sectoral or scientific disciplines. For example, any integrated approach to sustaining the world's water supplies must extend from hydrology and engineering to consider water resources in the context of the interacting physical, biological, chemical, and human systems that control water cycling and use at a landscape scale. An integrated perspective, therefore, takes into account land use, water quality, ecosystem processes and protection, as well as urban and economic requirements. Similarly, any approach to the sustainability of atmosphere and climate requires the integration of industrial, energy, urban, and agricultural planning and management.

Knowledge

An integrative strategy for the sustainability transition is one that views, studies, and manages the world as a dynamic, interacting system. Such a strategy is already under development and application, albeit in its very early steps. It must be built on the knowledge and know-how of the individual disciplines and sectors addressed above. Indeed, it is the advanced state of knowledge in those areas that allow integrative approaches to proceed. However, the strategy now required demands a new way of working and thinking, including new concepts and theories that link the areas of knowledge and that account for feedbacks and interactions among both biophysical and social systems.

Researchers and managers have begun developing and testing such approaches under the various names of ecosystem management, adaptive management, integrated conservation and development planning, integrated water resource planning, and so on. For example, the U.S. Forest Service is carrying out a series of regional integrated forest planning and management efforts, including work in the Appalachians, Columbia River, and Sierra Nevada.[98] Also, several U.S. funding agencies have in the past few years initiated research opportunities that aim to integrate across disciplines and sectors.[99] To date, the results and application of these activities toward sustainability science are unclear. Perhaps the most important outcome of these early efforts will be the emergence of a new body of theory about how to ask integrative questions, acquire and integrate knowledge, and apply that knowledge using adaptive approaches.

Actions

For issues in energy, agriculture, human population, and living resources, discussed earlier in this section and in the report, the immediate actions to be taken build on a long record of advancement in knowledge and know-how and in concepts and theories. In the area of integrative science, the scientific community has much less experience, and in many ways our immediate action must be to learn by doing and redoing. There are several dimensions to this action. First, we must ask in rigorous and careful ways about the determinants of success or failure in our ongoing experiments in integrative research (see, e.g., the earlier discussion in this chapter of research on degraded ecosystems), a point that we have also made more generally in this report about social learning and adaptive management. Second, much more effort must be focused on truly integrative research at all spatial scales. While funding institutions around the world are increasingly willing to provide resources for patching together different kinds of disciplinary information, fewer funding agencies have been willing to invest in studies that are interdisciplinary and integrative from their inception, and it is these studies that have the best chance of developing the conceptual underpinnings of integrative science. Third, new frameworks for interactions among industry, academia, foundations, and other nongovernmental organizations must be developed in which all partners contribute to the analysis of sustainability at local to regional scales.

TOWARD A SUSTAINABILITY TRANSITION

The challenge of mobilizing science and technology for a transition toward sustainability is daunting. Relevant knowledge needs to be integrated from the natural and social sciences, engineering, and management practice. Approaches to learning how to navigate the transition need to extend from the most basic research, to the active design and interpretation of large-scale policy experiments, to the informed diffusion of technologies around the world. Collaboration needs to occur across scales, extending from the local to the global, and across industrial sectors, nonstate actors, and governments. Judgments about priorities need to balance a respect for individual initiative and the inevitability of surprise with a responsiveness to urgent national and international needs.

The United States does not have in its national history a precedent for conducting such an enterprise. However, the role of science and technology in the agricultural, defense, and health complexes may provide partial and instructive analogies. Each of these broad areas has involved collaboration among an extended community of universities, businesses, and government agencies to address a specific set of social problems. Each also has involved the development of mission-oriented laboratories and experiment "stations" (e.g., agricultural experiment stations in the United States). These latter institutions were essential in promoting the development of hospitable settings in which a critical mass of scientists and engineers could come together, conduct world-class research on unconventional, problem-driven topics, and receive recognition from their peers in the larger R&D community—settings now in short supply for the kind of sustainability science that we believe is increasingly needed.[100]

An assessment of the extent and implications of similarities between the agriculture, defense, and health complexes and the needs of sustainability science was beyond the charge of this study and has yet to be undertaken. What this study has suggested is that the magnitude of the challenges to science posed by sustainability concerns in the 21st century may well be as great as the challenges posed by food, health, and security concerns in the 20th century. It is therefore past time to begin thinking about the institutional capacity for funding and promoting sustainability science in terms that are commensurate with the magnitude of the task ahead.

In establishing the Board on Sustainable Development and this project, the National Academies undertook their own experiment in social learning. There was great risk of failure. The legacy of the Academies' experiment—a commitment to sustainable development, to the pursuit of a sustainability science, and to the implications for future work—probably poses a more formidable challenge than the initial task of laying out the strategic framework contained in these pages. In the national history of the scientific enterprise, the National Academies have no precedent for conducting nor following up this type of study. Instead, they will need to continue the process of social learning by exercising their convening role to pursue priorities for research; help establish collaborative partnerships to advance the priorities for action; and work internationally with the scientific and technical community and the private sector. The United States has a special obligation to join and help guide the journey. In addition to having a robust scientific and technological capacity, the US public is a major consumer of global resources. Moreover, sustainable communities have not been realized across the US landscape.

Today, we have an opportunity to shape a sustainable world, if not necessarily for our children or grandchildren alive today, quite possibly for our great-grandchildren. All societies must seize the opportunity by applying what they know toward what they should do. Our common journey toward—or away from—sustainability has already begun.

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ENDNOTES

1 Editorial in *Science*, Vol. 277, July (1997).
2 see, e.g., World Bank (1997); UN (1998).
3 NRC (1998a).
4 Schelling (1996).
5 Kates and Clark (1996).
6 NRC (1998a), p. 18; see also NRC (1995).
7 Clark and Munn (1986); UNEP et al. (1998).
8 E.g., Ruttan (1994).
9 NRC (1998a); Watson et al. (1998).
10 NRC (1998a), p. 9.
11 Adams (1990).
12 *Ecological Principles*, IUCN et al. (1980, 1991); *World Conservation Strategy*, IUCN et al. (1991); *Caring for the Earth* (1991); DIVERSITAS (1998).
13 *Sustainable Biosphere Initiative,* ESA (1998); *Teeming with Life,* PCAST (1998).
14 Global habitability program, Goody (1982); "Pathways" report, NRC (1998a).
15 Natural resource management, e.g., Holling (1978); global issues, e.g., Williams (1978).
16 See, e.g., the review in NRC (1988), pp. 196ff.
17 IHDP (1998).
18 See Rayner and Malone (1998) and NRC (1999a).
19 For a history of these efforts, see, e.g., Helm (1990); NAE (1993, 1994, 1996, 1997a,b, 1998, 1999); NRC (1996d).
20 E.g., NRC (1985).
21 E.g., NRC (1997b); PCAST (1997, 1999).
22 E.g., NAE (1994).
23 NRC (1998a); EU (1998); IHDP (1998).
24 E.g., NRC (1998a), UNEP et al. (1998).
25 E.g., Gunderson et al. (1995); NRC (1996a).
26 E.g. Johnson et al. (1998).
27 NRC (1998d).
28 Studies of rice paddies as ecosystems discovered that pest species can be controlled with a multispecies community ecology regime that uses far less pesticide while allowing higher yields. Insights from the study of culture and ecology have led to a new vision of how humans can feed themselves with lower impacts on life support systems vital to the well-being of a rural society (see Lansing 1991).
29 Houghton et al. (1996; NRC 1998a).
30 Gibson et al. (1998); Root and Schneider (1995); Wilbanks and Kates, forthcoming; Cash and Moser (1998); Gunderson et al. (1995); Rosswall et al. (1988); Clark (1985); NRC (1998c); Turner et al. (1990).
31 IGBP (1991, 1994); IHDP (1998); START, http://www.igbp.kva.se/start.html.
32 Watson et al. (1998).
33 USGCRP (forthcoming); See http://www.nacc.usgcrp.gov/.
34 These include the European Union's Fifth Framework Program for research, EU (1998), http:www.cordis.lu/fp5/home.html; the Canadian Tri-Council Eco-Research Program, http:www.sdri.ubc.ca/gbfp/tricerp.html; and the Inter-American Institute for Global Change Research, HtmlResAnchor http://www.iai.int/. For a broad overview of other initiatives see UNCSD (1997).
35 Dooge et al. (1992).
36 UNCSD (1997).

37 Information on the "World Conference on Science: Science for the 21st Century, A New Commitment" is provided on UNESCO's web page http://www.unesco.org; information on the "Conference on the Transition to Sustainability" is provided on http://www4.nationalacademies.org/oia/iap/IAPHome.nsf/all/2000+Conference. Visited 8/27/99.

38 NRC (1998a), p. 18.

39 Holling (1986); Clark (1988).

40 Kingdon (1984); Baumgartner and Jones (1993); Burton et al. (1993); Gunderson et al. (1995).

41 Hardin (1968); Cohen (1995); Daily and Ehrlich (1996).

42 Nilsson and Grennfelt (1988); Skeffington and Wilson (1988); Bull (1991); Posch and de Vries (1999).

43 FCCC (1992), Article 2.

44 E.g., Kasperson et al. (1995).

45 See also Cohen (1995); Posch and de Vries (1999).

46 NRC (1981, 1998b).

47 Landes (1998); NRC (1998a); Grübler (1998); Turner et al. (1990).

48 E.g., Herman et al. (1989); Nakicenovic (1996); Wernick et al. (1996); NRC (1997b); Grübler (1998).

49 NRC (1997b); Kates (1999); Policy Research Project on Sustainable Development (1998).

50 Kempton et al. (1995); Merck Family Fund (1995).

51 Durning (1992); Center for a New American Dream (1997-1999).

52 UNDP (1998).

53 NRC (1997a).

54 Mathews (1997).

55 Nye and Keohane (1998).

56 E.g., Keck and Sikkink (1998).

57 Ostrum (1990); Haas et al. (1993); NRC (1997b); Rayner and Malone (1998); Francis and Lerner (1996).

58 Sandler (1997).

59 E.g., Raskin et al. (1998); Hammond (1998); Bossel (1998).

60 The Global Scenario Group (GSG), part of the Stockholm Environment Institute's Polestar Project, was established to engage a diverse group of development professionals in a long-term commitment to examining the requirements for sustainability. It is an independent, international, and interdisciplinary body that represents a variety of geographic and professional experiences and engages in an ongoing process of global and regional scenario development, policy analysis, and public education.

61 Fritz (1998); GEA (1997).

62 USGCRP (forthcoming); See http://www.nacc.usgcrp.gov.

63 As an example of such work, see *Interactive Social Science: Environmental Research*, the report of a workshop sponsored by the Economic and Social Research Council's Global Environmental Change Programme (UK) and the Social Sciences and Humanities Research Council (Canada), University of Sussex, Brighton, UK, 2-4 March 1998.

64 NCEDR (1998).

65 Dowlatabadi and Morgan (1993); Rotmans and Dowlatabadi (1998); NRC (1998a).

66 E.g.,. Gunderson et al. (1995); PCSD (1997); UN (1999).

67 Cebon et al. (1998); NRC (1996a); Miles (1995).

68 UN (1998).

69 UNCSD (1997).

70 E.g., Carnegie Commission on Science, Technology and Government (1992).

71 UN (1999).

72 EU (1998).

73 Porter and Vernon (1989).

74 E.g. NSTC (1995); NRC (1996); NSB (1999).

75 Ruttan (1994); Strong (1998).

76 In 1992, the Carnegie Commission on Science, Technology, and Government suggested establishing a Consultative Group for Research on the Environment (CGREEN), patterned after the Consultative Group on International Agricultural Research to Integrate Environmental Science. Carnegie Commission (1992, pp. 22ff).

77 The Advanced Research Projects Agency (ARPA), later named the Defense Advanced Research Projects Agency, was established by the U.S. Department of Defense in 1958 to foster and fund cutting-edge research related to defense needs. The ARPA-supported work in universities led to development of the Internet and optical communications, among other accomplishments. For an account of ARPA's support of the development of what became the Internet, see Hughes (1998).

78 Bell et al. (1994); Strong (1998).

79 Norberg-Bohm et al. (1990); Norberg-Bohm et al. (1992).

80 Branscomb (1998).

81 U.S. House of Representatives (1998); Guston (1997).

82 USGCRP (1998); NRC (1998d).

83 NRC (1998a).

84 This conclusion is based also on discussions at the board's 1997 Workshop on the Decomposition of Complex Issues in Sustainable Development, held at The H. John Heinz III Center for Science, Economics and the Environment, Washington DC, February 27-28, 1997.

85 In the years since the Brundtland report, there have been dramatic successes in efforts to improve water, air, and sanitation services in urban systems. But the number of city dwellers without decent housing or adequate water and exposed to poor sanitation and air pollution has grown (World Bank 1992, Ch. 4) to 600 million, while another 100 million have no home at all (UN 1997, Chs. 1-16). Meeting the housing and employment needs for these urban dwellers and the billions yet to come will inevitably lead to massive conversion of the productive agricultural and forest resources adjacent to the city and along the connecting highways and rail lines. More distant water resources will be diverted or polluted, and airborne pollutants will cross continents and national boundaries.

86 E.g., NAE (1988); UN (1997); NRC (1996b, 1998c).

87 Declining research spending, Alston et al. (1998b), p. 61; food production capabilities, Alston et al. (1998a,b).

88 Green Revolution, Conway (1997); bioengineering of crops, Kendall et al. (1997).

89 See, e.g., NAE (1999a,b); UNEP (1998); WRI (1998).

90 Raskin et al. (1998).

91 Recently, the U.S. National Science Foundation began support of studies focused on human-dominated ecosystems. The long-term ecology of urban environments is being studied in Phoenix, Arizona, and Baltimore, Maryland, as part of the NSF's Long Term Ecological Research (LTER) program. (See NSF 1997 and Chapter 5 of this report.)

92 PCAST (1998).

93 Kaufman and Dayton (1997).

94 Costanza and Folke (1997).

95 Simpson et al. (1996), p. 177.

96 PCAST (1998); NSB/NSF (1999).

97 Dobson et al. (1997).

98 U.S. Department of Agriculture, National Forest Service, http://www.usfs.gov.

99 E.g., NSF's Water and Watersheds Program, NASA's Land Use/Land Cover Change Program.

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