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Executive Summary

transition is under way to a world in which human populations are more crowded, more consuming, more connected, and in many parts, more diverse, than at any time in history. Current projections envisage population reaching around 9 billion people in 2050 and leveling off at 10 to 11 billion by the end of the next century—approaching nearly double that of today's 6 billion. Most of this future growth will be concentrated in the developing countries of Africa, Asia, and Latin America, where the need to reduce poverty without harming the environment will be particularly acute. Meeting even the most basic needs of a stabilizing population at least half again as large as today's implies greater production and consumption of goods and services, increased demand for land, energy, and materials, and intensified pressures on the environment and living resources. These challenges will be compounded to the extent that the resource-intensive, consumptive lifestyles currently enjoyed by many in the industrialized nations are retained by them and attained by the rest of humanity.

Can the transition to a stabilizing human population also be a transition to sustainability, in which the people living on earth over the next half-century meet their needs while nurturing and restoring the planet's life support systems? The toll of human development over the last half-century on the environment suggests that the answer may well be negative. However, there is reason for optimism. People have begun to secure more goods and services from activities ranging from agriculture to manufacturing while creating less environmental damage. In addition, efforts have grown up around the world over the last decade that have succeeded in putting sustainability issues on the global political agenda and in beginning the difficult process of translating this global interest into practices that will actually work in local and regional circumstances. Although humanity's common journey toward sustainability has not been charted with a discernible endpoint, the journey has already begun.

The reconciliation of society's developmental goals with the planet's environmental limits over the long term is the foundation of an idea known as *sustainable development.* This idea emerged in the early 1980s from scientific perspectives on the interdependence of society and environment, and has evolved since in tandem with significant advances in our understanding of this interdependence. During the concept's first decade, it garnered increasing political attention and acceptance around the world—most notably through the activities of the Brundtland Commission (1983-1987) and the United Nations Conference on Environment and Development, held in Rio de Janeiro in 1992.

As the 20th century draws to a close, however, the difficulties of actually delivering on the hopes that people around the world have attached to the idea of sustainable development have become increasingly evident. In part, these difficulties reflect political problems, grounded in questions of financial resources, equity, and the competition of other issues for the attention of decision makers. In part, they reflect differing views about what should be developed, what should be sustained, and over what period. Additionally, however, the political impetus that carried the idea of sustainable development so far and so quickly in public forums has also increasingly distanced it from its scientific and technological base. As a result, even when the political will necessary for sustainable development has been present, the knowledge and know-how to make some headway often have not.

This study, conducted by the National Research Council's Board on Sustainable Development, is an attempt to reinvigorate the essential strategic connections between scientific research, technological development, and societies' efforts to achieve environmentally sustainable improvements in human well-being. To that end, the Board seeks to illuminate critical challenges and opportunities that might be encountered in serious efforts to pursue goals of sustainable development.

Of course, *which* goals should be pursued is a normative question, not a scientific one. Our analysis, therefore, is based on goals for human well-being and environmental preservation that have been defined through recent extensive and iterative processes of international political debate and action, and sanctioned at intergovernmental conferences over the last several decades. (These goals are reviewed in some detail below.) Our choice of goals could have been different, and the goals actually pursued by society in the future will surely depart from those espoused by its diplomats in the past. Nonetheless, the Board believes that an explicit articulation of goals is necessary if the journey toward sustainability is to be more than a drifting with the powerful currents now shaping interactions between human development and the environment. Less obviously, explicit sustainability goals are required if research and development are to be focused on the most important threats and opportunities that humanity is likely to confront along the way.

This report presents a scientific exploration of the "transition toward sustainability" that would be constituted by successful efforts to attain internationally sanctioned goals for human welfare and environmental protection over the next two generations. This time horizon of analysis, a period of two generations, is necessarily somewhat arbitrary, and it inevitably de-emphasizes obstacles that become severe only over the longer run. However, in our judgment, it is over the next two generations that many of the stresses between human development and the environment will become acute. It is over this period that serious progress in a transition toward sustainability will need to take place if interactions between the earth's human population and life support systems are not to significantly damage both. Additionally, two generations is a realistic time frame for scientific and technological analysis that can provide direction, assess plausible futures, measure success—or the lack of it—along the way, and identify levers for changing course.

The metaphors of "journey" and "navigation" in the work reported here were adopted with serious intent. They reflect the Board's view that any successful quest for sustainability will be a collective, uncertain and adaptive endeavor in which society's discovering of where it wants to go is intertwined with how it might try to get there. Also, they reflect the view that the pathways of a transition to sustainability cannot be charted fully in advance. Instead, they will have to be navigated adaptively at many scales and in many places. Intelligent adjustments in view of the unfolding results of our research and policies, and of the overall course of development, can be made through the process of social learning. Such learning requires some clearly articulated goals for the journey toward sustainability, better understanding of the past and persistent trends of social and environmental change, improved tools for looking along alternative pathways, and clearer understanding of the possible environmental and social threats and opportunities ahead. Ultimately, success in achieving a sustainability transition will be determined not by the possession of knowledge, but by using it, and using it intelligently in setting goals, providing needed indicators and incentives, capturing and diffusing innovation, carefully examining alternatives, establishing effective institutions, and, most generally, encouraging good decisions and taking appropriate actions.

GOALS FOR THE TRANSITION TO SUSTAINABILITY

In the Board's judgment, the primary goals of a transition toward sustainability over the next two generations should be 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 sustainability transition, international conventions and agreements reflect a broad consensus about minimal goals and targets, though there is seldom analysis of these goals' implications, their potential interactions with one another, or their competing claims on scarce resources. Our analysis documents these goals and the uneven progress that has been made in meeting them.

In particular, in the area of human needs, internationally agreed-on targets exist for providing food and nutrition, nurturing children, finding shelter, and providing an education, but not for finding employment. There is an implicit hierarchy of needs that favors children and people in disasters and that favors feeding and nurturing first, followed by education, housing, and employment.

Compared to targets for meeting human needs, quantitative targets for preserving life support systems are fewer, more modest, and more contested. Global targets now exist for ozone-depleting substances and greenhouse gases, and regional targets exist for some air pollutants. Absolute prohibitions (zero targets) exist for ocean dumping of radioactive wastes and some toxics, for the taking and/or sale of a few large mammals (whales, elephants, seals), migratory birds when breeding or endangered, and certain regional fishing stocks. Water, land resources, and ecosystems such as arid lands and forests have, at best, qualitative targets for the achievement of sustainable management or restoration. International standards exist for many toxic materials, organic pollutants, and heavy metals that threaten human health, but not for ecosystem health.

TRENDS AND TRANSITIONS

Certain current trends 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 and could significantly undermine the prospects for sustainability. If they do persist, many human needs will not be met, life support systems will be dangerously degraded, and the numbers of hungry and poor will increase. Among the social trends reviewed by the Board that merit particular attention are expanding urbanization, growing disparities of wealth, wasteful consumption, increasing connectedness, and shifts in the distribution of power. Environmental trends of special concern include the buildup of long-lived greenhouse gases in the atmosphere and associated climate changes, the decline of valued marine fisheries; increasing regional shortfalls in the quality and quantity of fresh water; expanding tropical deforestation; the continuing loss of species, ecosystems, and their services; the emergence and reemergence of serious diseases; and more generally, the increasing human dominance of natural systems. Some of these current trends present significant opportunities for advancing a transition toward sustainability, as well as threats to that transition. All, however, bear watching.

Even the most alarming current trends, however, may experience transitions that enhance the prospects for sustainability. Trends are rarely constant. Breaks or inflections in long-term trends mark periods of transition. Some transitions relevant to the prospects for sustainability are already under way to varying degrees in specific places and regions around the globe: the demographic transition from high to low birth and death rates; the health transition from early death by infectious diseases to late death by cancer, heart disease, and stroke; the economic transition from state to market control; the civil society transition from single-party, military, or state-run institutions to multiparty politics and a rich mix of governmental and nongovernmental institutions. Environmentally, some significant positive transitions have occurred in specific regions. These include shifts from increasing to decreasing rates of emissions for specific pollutants, from deforestation to reforestation, and from shrinking to expanding ranges for certain endangered species. Individual, local trend reversals such as these clearly do not make a sustainability transition. But they do show that efforts to catalyze or accelerate relevant shifts can have significant implications for meeting human needs in ways that sustain the life support systems of the planet.

EXPLORING THE FUTURE

The Board evaluated various tools (integrated assessment models, scenarios, regional information systems) that could be used to explore what the future may hold and to test the likelihood of achieving the goals it set, under varied assumptions about human development and the environment. The purpose of these tools is not to predict the future, but rather to structure and discipline thinking about future possibilities in the light of present knowledge and intentions. They can be used to explore what contingencies society may face, assess how well society is prepared to deal with those contingencies, and identify indicators for which society should be watchful.

Integrated assessment models seek to link in a consistent fashion formal models of the environment and society. The accumulating experience suggests that the models can make a difference in society's ability to address complex interactions between environment and development by providing analytic insight through problem redefinition and by directly informing policy making through supporting international environmental negotiations (e.g., whaling and stratospheric ozone depletion). Models can also be useful probes of uncertainties and their significance in exploring the possible future implications of current decisions. Deliberate simplification of such complex models can be an important part of strategies for exploring the future. But the art of providing useful simplifications remains demanding and underdeveloped.

Long-range development scenarios are summary stories of how the world might unfold. They are useful for organizing scientific insight, gauging emerging risks, and challenging the imagination. Scenarios are told in the language of words as well as numbers, because some critical dimensions—assumptions about culture, values, lifestyles, and social institutions—require qualitative description. Scenarios do not predict the future; they provide insight into the present. Experience suggests that scenarios to support the study of global futures and the requirements for a transition to sustainability should be rigorous, reflecting the insights of science and modeling. But scenario building must also recognize that the story of the future is not a mere projection of current trends and understanding. The spectrum of scenarios to consider should contrast long-range visions that reflect the uncertainty about how the global system might unfold, the possibility of surprise, and a range of pathways to a sustainable future.

Regional information systems constitute a third tool. These systems harness scientific knowledge to support policy decisions affecting the long-term interactions of development and environment, and often contain elements of scenario development and integrated modeling. Experience in developing such information systems shows that a regional scale approach grounded in ecosystem knowledge and cooperative and adaptive management constitutes an infrastructure for social learning—a way to lay out scientific knowledge in a form that can be accessible to non-specialists. As such, these systems provide a mode of communication and negotiation that can draw opponents together for learning as well as conflict resolution, allowing learning to continue as action proceeds. Work at the regional scale shows that the way human and natural systems interact can be studied and acted upon within an integrated framework.

Although the future is unknowable, **based on our analysis of**

persistent trends and plausible futures, the Board believes 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. There is ample evidence from attitudinal surveys and grassroots activities that the public supports and demands such progress.

ENVIRONMENTAL THREATS AND OPPORTUNITIES

Knowledge about the most significant potential obstacles to sustainability is needed along with an awareness of the opportunities for deflecting, adapting to, or mitigating the threats. The most serious threats are those that affect the ability of multiple sectors of society to move ahead toward the normative goals for sustainability; have cumulative or delayed consequences, with effects felt over a long time; are irreversible or difficult to change; or have a notable potential to interact with each other to damage earth's life support systems. The Board attempted several approaches to identify significant environmental threats, including (1) a review of comparative rankings of the severity of environmental hazards for particular times and places; (2) expert assessment of the challenges and opportunities of human activities in several developmental sectors that the Brundtland Commission identified as critical (human population and well-being, urban systems, agricultural production, industry, energy, and living resources); and finally, (3) evaluation of how these threats and opportunities may change when multiple activities from different sectors interact with complex environmental systems (e.g. freshwater systems, atmosphere and climate, and species and ecosystems).

Overall, hazard rankings suggest that, for most nations of the world, water and air pollution are the top priority issues; for most of the more industrialized nations, ozone depletion and climate change are also ranked highly; while for many of the less-industrialized countries, droughts or floods, disease epidemics, and the availability of local living resources are crucial. The rankings, however, tend to depend on the circumstances of the assessed region, focus on the problem rather than the cause, and do not address interactions. The analysis of common challenges to development showed that while some progress had been made in each sector (e.g., lowering fertility to improve the balance between population and resources; increasing opportunities for health and education; providing water, air, and sanitation services in urban centers; expanding food production; reducing and reusing materials; using energy more efficiently; and implementing conservation measures for living resources), many of the remaining challenges are at least as serious as they were 10 years ago.

In addition, our review of hazards and sectors showed that most decision making and much research about threats has chosen to treat environmental perturbations and associated human activities in relatively discrete categories such as "soil erosion," "fisheries depletion," and "acid rain." Such categorization is also apparent in the organization of ministries, regulation, and research administration around the world. Both understanding and management have benefited substantially from these approaches. However, much has been missed, and many of the challenges in seeking a sustainability transition lie in the interactions among environmental and human activities that were previously treated as separate and distinct.

The Board concludes that most of 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, 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 promoting a transition toward sustainability.**

REPORTING ON THE TRANSITION

Indicators are essential to inform society over the coming decades how, and to what extent, progress is being made in navigating a transition toward sustainability. Regularly repeated observations of natural and social phenomena facilitate the provision of systematic feedback. They provide both quantitative and qualitative descriptions of human well-being, the economy, and impacts of human activities upon the natural world.

Numerous efforts are now underway to collect, analyze, and aggregate the information needed to form sets of indicators of environmental, societal, and technological change. On an ecological scale, these efforts range in coverage from watersheds to the whole planet, and on a political scale from municipal to international institutions and activities. **Nonetheless, the Board finds that there is no consensus on the appropriateness of the current sets of indicators or the scientific basis for choosing among them.** Their effectiveness is limited by the lack of agreement on the meaning of sustainable development, on the appropriate level of specificity or aggregation for optimal indicators, and on the preferred use of existing as opposed to desired data sets.

For reporting on a sustainability transition, however, it is clear that multiple indicators are needed to chart progress toward the goals for meeting human needs and preserving life support systems, and to evaluate the efficacy of actions taken to attain these goals. Thus, specific indicators of human welfare will be required on global and regional scales. Many of these indicators are already available. Selecting indicators of life support systems will be more difficult. In this report, the Board suggests three levels of indicators: planetary circulatory systems, regional zones of critical vulnerability, and local inventories of productive landscapes and ecosystems. Monitoring planetary circulatory systems captures changes in the Earth's biogeochemical cycles and its networks of human communication, technology, trade, and travel. Critical zones of human-environment vulnerability are characterized in ways that capture the regional interactions of specific ecosystems, human activities, social and economic capacity to respond and adapt, and the feasibility of reversing damage. Local inventories assist conservation by capturing the effects of human settlements on environmental services and resources, and on the prospects for sustaining species, habitats, and ecosystems.

To characterize the effectiveness of actions undertaken to reach the goals, at least four approaches seem promising and deserving of further study: maintaining national capital accounts; conducting policy assessments; monitoring essential trends and transitions; and surprise diagnosis. One approach to national capital accounts uses economic accounting to assess the value of three types of national resources—natural, human, and produced capital. This analytical framework draws attention to transformations among forms of wealth, and acknowledges and highlights the importance of undervalued natural capital. The second approach, policy assessment, supports adaptive management by attending to the details of policy implementation (e.g., data gathering) such that lessons can be learned from any policies instituted—even those that fail. The third approach measures progress that has been made by monitoring essential trends and transitions—such as those in demographics, consumption patterns, and energy-intensity and pollution per unit of economic output. Finally, surprise diagnoses—the search for and evaluation of unanticipated indicator patterns such as the stratospheric ozone hole—are essential for identifying mistakes and omissions of analysis.

INTEGRATING KNOWLEDGE AND ACTION

Because the pathway to sustainability cannot be charted in advance, it will have to be navigated through trial and error and conscious experimentation. The urgent need is to design strategies and institutions that can better integrate incomplete knowledge with experimental action into programs of adaptive management and social learning. A capacity for long-term, intelligent investment in the production of relevant knowledge, know-how, and the use of both must be a component of any strategy for the transition to sustainability. In short, this strategy must be one not just of thinking but also of doing. Our explorations suggest that this strategy should include a spectrum of initiatives, from curiosity-driven research addressing fundamental processes of environmental and social change, to focused policy experiments designed to promote specific sustainability goals.

Tensions exist between broadly based and highly focused research strategies; between integrative, problem-driven research and research firmly grounded in particular disciplines; and between the quest for generalizable scientific understanding of sustainability issues and the localized knowledge of environment-society interactions that give rise to those issues and generate the options for dealing with them. These understandable tensions must be addressed.

Priorities for Research: Sustainability Science

From the Board's efforts to address these tensions, three priority tasks emerged for advancing the research agenda of what might be called "sustainability science."

- **Develop a research framework that integrates global and local perspectives to shape a "place-based" understanding of the interactions between environment and society.** The framework should build on the intellectual foundations of the geophysical, biological, social, and technological sciences, and on their interdisciplinary research programs, such as earth systems science and industrial ecology. It will need to integrate across geographic scales to combine global, regional, and local perspectives as needed in understanding what is going on in the particular places where people live, work, and govern. Establishing a place-based sustainability science will also provide a conceptual and operational approach for monitoring progress in integrated understanding and management.
- **Initiate focused research programs on a small set of understudied**

questions that are central to a deeper understanding of interactions between society and the environment. The concepts of critical loads and carrying capacities have proven sufficiently problematical that further efforts are needed to determine whether scientifically meaningful "limits" can be established beyond which the life support systems of the planet cannot safely be pushed. Improving the understanding and documentation of transitions will be necessary as these transitions unfold (e.g., changes in population growth patterns, globalization of the economy, energy and materials intensity in human activities, and governance). In addition, more exploration will be needed of the determinants of and alternatives to consumption patterns; the incentives (in markets, remedies for market failure, and information) for technical innovation that produces more of human value with less environmental damage; and the institutions, indicator systems, and assessment tools for navigating a sustainablity transition.

- **Promote better utilization of existing tools and processes for linking knowledge to action in pursuit of a transition to sustainability.** A great deal of knowledge, know-how, and capacity for learning about sustainable development is already assembled in various observational systems, laboratories, and management regimes around the world—but these resources are not widely known or used. The successful production and use of the knowledge needed for a sustainability transition will require significant strengthening of institutional capacity in at least four areas: the linking of 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.

Priorities for Action: Knowledge-Action Collaboratives

Developing the knowledge, assessment tools and methods, and institutional understanding needed for a sustainability transition is a central task for science and technology. But enough is already known to undertake early priorities for action. For the challenges in the core sectoral areas of sustainable development identified more than a decade ago by the Brundtland Commission —human population and well-being, cities, agriculture, energy and materials, and living resources— the Board has identified appropriate next steps by integrating what is known about a sector with what can be done. This means integrating both the lessons learned from the last decade and the projected needs and know-how over the coming decades with both the policy actions that can move society along a positive pathway and the indicators that can monitor our progress.

It also means creating new and strengthening existing "knowledge-action collaboratives" that bring together the many diverse and sector-specific groups that have the knowledge and know-how and the means to implement it.

Priorities for action include the following:

• **Accelerate current trends in fertility reduction.** After reviewing the continuing trends of reduction in fertility and the potential for accelerated reductions, the Board believes that achieving a 10 percent reduction in the population now projected for 2050 is a desirable and attainable goal. While growth rates are declining, because the current growth rate (still higher than replacement level) is applied to a fast-increasing population base, absolute population growth will continue to have tremendous momentum over the next two decades. World population size is expected to increase by 3 billion people by 2050. This number can be reduced by meeting the large unmet need for contraceptives worldwide, by postponing having children through education and job opportunities, and by reducing desired family size while increasing the care and education of smaller numbers of children. Moreover, the lack of access to family planning contributes significantly to maternal and infant mortality, an additional burden on human well-being. Allowing families to avoid the unwanted births, enhancing the status of women to delay childbearing, and nurturing children would result in a billion fewer people and substantially ease the transition toward sustainability.

• **Accommodate an expected doubling to tripling of the urban system in a habitable, efficient, and environmentally friendly manner.** The urban proportion of the world's population is projected to grow from 50 percent to 80 percent or more over the next two generations, with 4 billion people added to the 3 billion people living in cities today. The cities emerging from this unprecedented growth in urban populations must meet the needs for housing, nurturing, educating and employing these 4 billion new urban dwellers. Providing them with adequate water, sanitation, and clean air may be one of the most daunting and under-appreciated challenges of the first half of the 21st century. Nonetheless, by learning how to utilize the potential efficiencies provided by increasing population densities and the opportunity to build anew, these cities could meet human needs while reducing their relative "ecological footprint" and providing more environmentally friendly engines of development.

• **Reverse declining trends in agricultural production in Africa; sustain 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. A collaborative effort involving

African governments, the African scientific community, African farmers, and nongovernmental organizations will be needed to address the causes and the responsive actions to achieve the technical capacity and implementation needed. At the same time, over the two generations to come, meeting the challenge of feeding the burgeoning world population as a whole and reducing hunger while sustaining life support systems will require a dramatic overall advance in food production, distribution, and access. Sustainable increases in output per hectare of two to three times present levels will be required by 2050. Productivity must be increased on robust areas and restored to degraded lands, while damage to fragile land areas is reduced. New biology-based technologies and implementation will be needed to meet these challenges, renewing yield increases and diminishing negative environmental and social consequences.

- **Accelerate improvements in the use of energy and materials.** A reasonable goal for the sustainability transition is to double the historical rate of improvements in energy and materials use. These improvements include both the long-term reduction in the amount of carbon produced per unit of energy ("decarbonization") and, more generally, in the amount of energy or material used per unit of product (efficiency or intensity). Research and development should continue on the many efforts under way to improve household energy-efficiency, build low-polluting, energy-efficient automobiles, and reduce waste, as well as to minimize the throughput of energy and materials from industrial processes through reuse, recycling, and the substitution of services for products. In designing and evaluating institutions and incentives to encourage sustainable energy technologies, it will be important to carefully examine system implications for these technologies over their full life cycles, using such strategies as material balance modeling and economic input-output analysis together with consideration of environmental loadings. Without such 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.

- **Restore degraded ecosystems while conserving biodiversity elsewhere.** For the human-dominated ecosystems (forests, grasslands, agricultural, urban, and coastal environments) undergoing degradation from multiple demands and stresses, the goal should be to work toward restoring and maintaining these systems' functions and integrity. Their services, including genetic diversity, and their human uses both need to be sustained over the long term. Greater understanding is needed of how biological systems work, how to stem the continued loss of habitats, and how ecosystems can be restored and managed at the landscape or regional scale. This will require knowledge of the socioeconomic determinants of overexploitation, the appropriate valuation of ecosystem services, and sustainable management and harvesting techniques. Those ecosystems that have been the least influenced by human activities represent the last reserves of the earth's biodiversity. For future generations, these systems provide a treasure of stored biodiversity and of ethical, aesthetic, and spiritual qualities. For these systems, the goal should be to protect and conserve biological diversity, both by dramatically reducing current rates of land conversion and by more rigorously identifying and selecting protected areas.

Achievements in one sector do not imply improvements in other sectors or in the situation overall. For example, efforts to preserve natural ecosystems for ethical or aesthetic reasons, or for the goods and services they provide to humans, may ultimately fail if they do not account for the longer-term changes likely to be introduced by atmospheric pollution, climate change, water shortages, or human population enchroachment. **The Board therefore also proposes integrated approaches to research and actions at the regional scale related to water, atmosphere and climate, and species and ecosystems.** The need is to develop both a thorough understanding of the most critical interactions and an integrated strategy for planning and management. This will require evaluation of ongoing experiments in integrative research, more focused effort on such research at all spatial scales, and new frameworks for improving interactions among partners in industry, academia, foundations, and other organizations.

There is no precedent for the ambitious enterprise of mobilizing science and technology to ensure a transition to sustainability. Nevertheless, 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 United States is a major consumer of global resources. Moreover, sustainable communities have not been realized across the U.S. landscape. Carrying out this enterprise successfully will require collaborative efforts across many dimensions of science and society.

Implementation of the recommendations in this report will be a task not only for the National Research Council and its U.S. partners in science, but also for the international science community, governments, foundations, voluntary organizations, and the private sector working together through innovative knowledge-action collaboratives. Our goal here has not been to preempt any broader endeavors involving these national and international partners, but rather to encourage them and to suggest some initial directions for our common journey toward sustainability.

Introduction

e are in the midst of a transition to a world in which human populations are more crowded, more consuming, more connected, and in many parts of the world, more diverse, than at any time in history. Current projections envisage population reaching around 9 billion people in 2050 and leveling off at 10 to 11 billion by the end of the next century—close to double that of today's 6 billion.[1] Most of this future growth will be concentrated in the developing countries of Africa, Asia, and Latin America, where the need to reduce poverty without harm to the environment will be particularly acute. Meeting even the most basic needs of a stabilized population at least half again as large as today's implies greater production and consumption of goods and services, increased demand for land, energy, and materials, and intensified pressures on the environment and living resources. These challenges will be compounded to the extent that the resource-intensive, consumptive lifestyles currently enjoyed by many in the industrialized nations are retained by them and attained by the rest of humanity.

Can the transition to a stable human population also be a transition to sustainability, in which the people living on earth over the next half-century meet their needs while nurturing and restoring the planet's life support systems? The toll of human development over the last half-century on the environment suggests that the answer may well be "no." The examples of Appalachian coal country, the Aral Sea, or the Southeast Asian forest fires serve as vivid reminders of how devastating to both society and the environment the implications of heedless development can be. On a more optimistic note, people have begun learning how to secure more social "goods" while creating fewer environmental "bads" in activities ranging from agriculture to manufacturing to recreation. A remarkable number of efforts have grown up around the world over the last decade that have succeeded in putting sustainability issues on the global political agenda—and in beginning the actual search for specific pathways toward sustainability in many local contexts. If, at the close of the 20th century, the end of our common voyage toward sustainability has not yet been charted, much less brought into sight, the journey has at least begun.

In recent years, the science and technology community has not been a particularly prominent participant on this journey. This has not always been the case. Early thinking on sustainability issues—for example, the World Conservation Strategy[2]—was firmly grounded in a scientific understanding of the workings and limits of resources and environmental systems. But, with the possible exception of the ozone protocols, the central thrusts of many recent sustainability initiatives have been shaped more by political than scientific ideas. Major recent innovations have come in the realm of policies and institutions, rather than knowledge and know-how. Relatively little progress has been made in developing a scientific understanding of the obstacles facing any transition to sustainability, the technological opportunities for pursuing this goal, or the use of modern sensing and information systems for providing navigational aids along the way.

The principal national and international reports have thus tended to address science and technology as necessary, potentially expensive, but otherwise unproblematic inputs to the process of sustainable development. As inputs, science and technology have been addressed either as highly specific requirements (e.g., methods for the safe disposal of nuclear wastes) or as the most general needs (e.g., enhanced scientific understanding, better technology transfer, more useful policy assessments, improved environmental prediction, more complete monitoring and reporting, or strengthened capacity). Moreover, overall investments in research and development have been declining in recent years for a variety of reasons. Thus, we approach the 21st century with less than might be hoped for in the way of a useful strategic appraisal of how the knowledge and know-how most crucial to successfully navigating the transition toward sustainability is to be identified or of how the capacity to create the needed science and technology is to be developed and sustained.

This report and the processes involved in its preparation and dissemination seek to help reengage the science and technology community as a committed partner in the ongoing global effort to achieve sustainable development. This report is the result of a nearly four-year study of the

National Research Council's Board on Sustainable Development. The Board is composed of 25 members with expertise in diverse topics relating to sustainability, including population demographics, agronomy, agriculture, geography, meteorology, atmospheric chemistry, oceanography, ecology, integrative biology, modeling, hydrology, economics, industry, international finance, energy research, engineering, political science, anthropology, health, and public policy. Since its formation in 1994, the Board has held three workshops (Environmental Barriers to Sustainable Development, December 1996; Decomposition of Complex Issues in Sustainable Development, February 1997; Food Security: Sustaining the Potential, May 1997), two week-long summer studies (Scouting the Rapids, Bar Harbor, Maine, August 1996; Science for the Sustainability Transition, Woods Hole, Massachusetts, July 1997) and other meetings; and the Board has commissioned several papers. The concepts and broad findings of this study were presented at a Symposium on The Transition to Sustainability, which was held at the 135^{th} Annual Meeting of the National Academy of Sciences, in April 1998.

The Board has an ambitious plan for disseminating the messages of the report both within the United States and to the international science and technology communities. In particular, we have suggested that the InterAcademy Panel on International Issues (IAP)—an informal network of academies of science—take up the issue of sustainability as a major thrust of its program over the next several years. In pursuit of this goal, the Board will present its report as a contribution to an IAP Conference on the Transition to Sustainability, being held in Tokyo on May 15-19, 2000. It is hoped that this conference will set in motion a number of international initiatives that reengage the scientific and technical communities in the dialog on sustainability.

We adopted the metaphors of "journey" and "navigation" in the work reported here with serious intent. They reflect our conviction that any successful quest for sustainability will necessarily be a collective, uncertain, and adaptive endeavor in which society's discovering of where it wants to go and how it might try to get there will be inextricably intertwined. Humanity is no more master of its fate in interactions with the environment than is a canoeist shooting the rapids of a turbulent river—a vivid image used to suggest the challenges to policy in seeking sustainable development.[3] But if we do not suffer the delusion of having total control of the future, neither are we fatalists who believe that the skills of the canoeist, boat builder, and mapmaker are irrelevant to the journey's outcome. Instead, as evidenced by many successful explorations from the Beagle to the Hubble, science and technology, we believe, are the necessary complements to inspired leadership, creative imagination, and good luck. The objective of this report is to suggest how the science and technology enterprise can increase society's chances of undertaking and achieving our common journey of a transition toward sustainability.

We are too aware of the host of shortcomings in the present study. Despite our commitment to international perspectives, except for members from Canada and Mexico, the Board has been essentially a group of U.S. nationals examining a global issue with regard to which local conditions, traditions, and perceptions matter very much. Despite our understanding of how greatly the prospects for any transition to sustainability depend on substantial international political stability and effective domestic governance, we have not explored the political threats or all possible social threats (e.g., terrorism, violence) to such conditions or how they might be mitigated. Despite our belief that poverty alleviation is central to the challenges of sustainability, we have not focused on the economic programs needed to increase productivity of the abjectly poor segments of the world's population. And despite our conviction that taking on the challenges of sustainability is an inherently interdisciplinary activity, we have been better at mobilizing the insights of some disciplines than others in our work. Finally, we are aware that the questions posed and issues addressed in this report are hardly new. Much is known about population, cities, land transformation, agriculture, ecology, and other phenomena that we discuss here only in the most general of terms. We are equally aware that much of what is known is not applied—for a variety of political, economic, and cultural reasons.

Thus, in this report we have found ourselves both emphasizing the necessity of better applying what is known and arguing that the capacity to produce new knowledge will become increasingly important as pressures on societies and the life support systems of the planet become more intense. More of the same in science and technology or in politics is unlikely to meet the reasonable aspirations of people throughout the globe. But we believe that the scientific and technical community must play an important role in helping societies to realize these aspirations. We believe there are no ready answers to questions of whether or how billions of people in societies all over the globe can achieve their hopes for a better quality of life without severely degrading life support systems. At the same time, we also believe that failure to engage the issues in a truly serious way is shirking both our technical responsibilities and our public duties. Nevertheless, we sit at the Board's table as experts in particular fields, not as advocates of particular causes. This study represents our attempt to seriously engage the issues and to offer a few suggestions for next steps in what appears to be the right direction.

To this end, Chapter 1 develops the Board's concept of a transition to sustainability and the roles of science, technology, and values in outfitting and navigating the journey toward it. Chapter 2 provides an historically based map of the persistent, large-scale currents of social and environmental change into which the voyage is launched, and with which it will have to contend. Chapter 3 reviews the range of modeling, assessment, and scenario methods available for looking ahead at possible development pathways and their implications for sustainability. Chapter 4 draws on current scientific understanding to outline some of the most significant environmental threats and opportunities that the voyage might encounter. Chapter 5 explores the contributions that appropriate monitoring and indicator systems might make for our abilities to proceed in a turbulent world of surprise and inevitable policy failures. Chapter 6 presents a vision of how knowledge and action could be better integrated in a strategy for navigating toward sustainability, and priorities for research and action to promote the life and livelihood goals of our common journey.

ENDNOTES

[1] UN (United Nations). 1999 (forthcoming). *Word population prospects: The 1998 revision*. New York: United National Population Division.

[2] IUCN (The World Conservation Union), UNEP (United Nations Environment Programme), WWF (World Wildlife Fund), FAO (Food and Agriculture Organization of the United Nations), and UNESCO (United Nations Educational, Scientific, and Cultural Organization). 1980. *World conservation strategy: Living resource conservation for sustainable development*. Gland, Switzerland: IUCN.

[3] William Ruckelshaus, former Administrator of the U.S. Environmental Protection Agency and member of the World Commission on Environment and Development, the well-known "Brundtland Commission," 1989. Toward a sustainable world. Scientific American 261, No. 3:166-74.

1 Our Common Journey

The test of our progress is not whether we add more to the abundance of those who have much; it is whether we provide enough for those who have too little.

Franklin Delano Roosevelt (Second Inaugural Address, January 20, 1937)

ver the last two decades, as appreciation of the challenge of "sustainable development" has very rapidly grown, the term has been used with diverse and evolving meanings in public debate and the scholarly literature. At the outset of our analysis, we therefore look at these various uses of the term. Next, we review action that has been taken in pursuit of sustainability goals since the 1987 publication of the World Commission on Environment and Development's report (often called "the Brundtland report") *Our Common Future*. In the heart of this chapter, we develop our concept of a "transition toward sustainability"—a transition over the early decades of the 21st century in which a stabilizing world population comes to meet its needs by moving away from actions that degrade the planet's life support systems and living resources, while moving toward those that sustain and restore these systems and resources. Moreover, this transition would move away from actions that widen disparities in human welfare and toward measures that reduce hunger and poverty. Ours is a normative vision of sustainability, which in our view is defined by the joint objectives of meeting human needs while preserving life support systems and reducing hunger and poverty. This vision is firmly anchored in the goals and aspirations of the world community as expressed through major international conventions and commissions of the past decade. Finally, in this chapter, we close with a brief exposition of the role of science and technology in this transition—a role that we see above all as one of fostering rapid and effective social learning.