A Transition Toward Sustainability

A Summary of findings and recommendations from the National Research Council's report *Our Common Journey*[1]

by
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Abstract

This paper discusses the challenges and opportunities facing efforts to shape a transition toward more sustainable relations between humans and their planet. It begins with a review of international goals for human development and environmental conservation, past trends in interactions between the earth's social and natural systems that set the stage for contemporary efforts to meet those goals, and some of the foreseeable problems that will have to be addressed in the years ahead. Arguing that the successful strategies for navigating a sustainability transition will necessarily be knowledge intensive, the paper discusses strategies for social learning about sustainability. It closes with a review of the institutional reforms that will be necessary to implement such strategies.

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[1] NATIONAL RESEARCH COUNCIL, BOARD ON SUSTAINABLE DEVELOPMENT. OUR COMMON JOURNEY: A TRANSITION TOWARD SUSTAINABILITY (1999) [hereinafter, NATIONAL RESEARCH COUNCIL OUR COMMON JOURNEY]. An earlier version of this paper was presented at The Ecology Law Quarterly symposium *Environment 2000 – New Issues for a New Century*, held at the University of California, Berkeley School of Law (Boalt Hall) on February 25-26, 2000. A modified version of that presentation will appear in the ECOLOGY LAW QUARTERLY in 2001.

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1 Introduction

One of the greatest challenges facing humanity at the dawn of the 21st century is learning how to better meet human needs while restoring and nurturing the planet's life support systems. Achieving advances in specific sectors of human development such as food and energy is critically important, as is making progress in addressing individual environmental problems such as the loss of biodiversity and climate warming. This paper proposes that these individual problems are better viewed as multiple dimensions of an increasingly interdependent relationship between society and environment. It is not the individual problems alone but rather their *interactions* that pose the greatest threats and opportunities for the 21st century. Therefore, the transcendent challenge before us is to craft a vision of the future that encompasses these interactions, and to develop a strategy for action that addresses them.

The most vital response to the challenge of attaining healthy interactions between multiple dimensions of human endeavor and multiple dimensions of the environment has been the idea of "sustainable development." In its present incarnation, this idea emerged in the early 1980s from scientific perspectives on the interdependent natural and social dimensions of renewable resource conservation. Since then, it has evolved in tandem with significant advances in our understanding of an increasing array of interactions between society and the environment. During its first decade, the "sustainability" concept garnered political attention and acceptance around the world, most notably with the work of the Brundtland Commission and the UN Conference on Environment and Development (UNCED), held in Rio de Janeiro in 1992. These efforts set forth the ambitious "Agenda 21," establishing goals and actions to promote improvements in human health and habitation, food security, and the environmentally sustainable use of energy, materials, and renewable resources.

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Sporadic progress was made in implementing the Agenda during the 1990s, though success was more evident at the local than at the international level. As the decade and century drew to an end, however, the difficulties of moving forward into the new millennium with the transition toward sustainability begun in the 1980s became increasingly clear. In part, those difficulties are predictably political – grounded in perennial problems of financial resources, equity, and competition with other issues for scarce social attention. In part, they also reflect fundamentally differing views on what is most important to develop, what most needs to be sustained, and what period is the most relevant for the accounting. In addition, however, a powerful impediment to moving toward more sustainable development has proved to be our ignorance about how to do so.

The political momentum that carried the idea of sustainable development so far and so quickly in public forums from Nairobi to Rio and beyond progressively distanced it from its scientific and technological (S&T) base. For example, the UN General Assembly's Special Session on "Rio +5" included only a single perfunctory mention of the S&T dimensions of the problem. Additionally, the U.S. President's Council on Sustainable Development had members from every imaginable political stakeholder group but not a single practicing scientist or engineer. As a result, even when the political and entrepreneurial will has been present, the knowledge and know-how about *how* to develop human potential while nurturing and restoring the environment often has not. It has become increasingly clear that progress toward sustainable development will be not only a politically demanding endeavor, but also a knowledge-intensive one. A transition toward sustainability, if it is to move forward at the increased pace so desperately needed in the 21st century, will have to move on two legs – one political, one scientific – both working together to propel us toward a common goal.[3]

This paper is about that "working together" – about how, as a global society, we might learn to better integrate knowledge and action in what a recent study of the U.S. National Research Council (NRC) has called *Our Common Journey* toward sustainability. This paper draws heavily on that study, conducted in the late 1990s by the NRC's Board on Sustainable Development.[4] I had the privilege to co-chair the effort, working closely with

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[3] On the necessity for a symbiotic relationship between science and politics in sustainable development, see KAI LEE, COMPASS AND GYROSCOPE: INTEGRATING SCIENCE AND POLITICS FOR THE ENVIRONMENT (1993) (arguing persuasively that while science, compass-like, can help us get our bearings and identify helpful directions, the gyroscope of politics is necessary to keep us on course).
[4] NATIONAL RESEARCH COUNCIL OUR COMMON JOURNEY, *supra* note 1.

a distinguished committee of scholars and practitioners[5]. A good bit of what is presented here I first drafted as input to the Board's deliberations. Much of the rest is drawn from the input of others to that process. Section 2 of the paper sketches the social and environmental dimensions of the sustainable development challenge. Section 3 outlines a strategy of social learning for navigating the sustainability transition, integrating elements of research, monitoring, assessment and experimental policy design. Section 4 concludes with observations on some of the institutional innovations that will be needed to implement the strategy.

2 The challenge of sustainable development

If environment and development are intimately interdependent, it makes little sense to set goals for one without setting goals for the other. The Brundtland Commission recognized this implicitly in its 1987 report *Our Common Future* by calling for paths of social, economic and political progress that meet "the needs of the present without compromising the ability of future generations to meet their own needs."[6] Despite the dissatisfaction of many academics with the ambiguity of this conceptualization, it has resonated with a remarkable variety of groups around the world, ranging from local green organizations in Indonesia to the British Parliament to the World Business Council for Sustainable Development. Debates among such groups have tended to endorse the Brundtland position while disagreeing on the details of what is to be sustained, what is to be developed, and over what period conditions for "sustainability" should be evaluated.

2.1 Goals for a transition to sustainability

In reviewing the dominant values articulated by these various groups and embodied in formal international agreements and conventions, the National Research Council's Board on Sustainable Development found a broad consensus of views that denominated of development in terms of its ability to substantially reduce hunger and poverty while meeting human needs for food and nutrition, nurturing children, finding shelter, providing an education and securing employment. Likewise, it found broad acceptance for denominating environment in terms of the life support systems of the planet, including controlling the quality and supply of fresh water, regulating emissions into the atmosphere, protecting the oceans, and maintaining species and ecosystems.[7]

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[5] These included Robert Kates as my co-chair, Lourdes Arizpe, John Bongaarts, Ralph Cicerone, Edward Frieman, Robert Frosch, Malcom Gillis, Richard Harwood, Philip Landrigan, Kai Lee, Jerry Mahlman, Richard Mahoney, Pamela Matson, William Merrell, G. William Miller, M. Granger Morgan, Paul Raskin, John Robinson, Vernon Ruttan, Thomas Schelling, Marvalee Wake, Warren Washington, Gordon Wolman, and Berrien Moore (ex-officio). Sherburne Abbott crafted much of the study's tone and content as its Executive Director. Laura Sigman provided inspired research assistance. The study also benefited from the contributions of more than 70 workshop participants and reviewers, all of whom are named in the cover pages of the report.

[6] WORLD COMMISSION ON ENVIRONMENT AND DEVELOPMENT, OUR COMMON FUTURE 8 (1987).

[7] *See* NATIONAL RESEARCH COUNCIL OUR COMMON JOURNEY, *supra* note 1,at 39, 46 (providing a summary of the international goals adopted by the Board).

The Board addressed the time horizon issue by presenting a pragmatic argument for focusing on the prospects for sustainability over a period of a couple of generations, while acknowledging longer run concerns as well. Why? By adopting a time horizon that sees into young adulthood the grandchildren of today's decisionmakers, some degree of social meaning is achieved. The same time scale is consistent with the period likely required to move major transforming technologies (for example, energy sources) from an experimental stage to wide spread adoption, and it covers the normal replacement of much current capital stock. Thus, the Board's proposed time horizon usefully grounds the discussion in basic technologies now known while still allowing for a great deal of latitude in their possible refinement and adoption. The 50 years or so included in this "couple of generations" time horizon is not likely to be enough to bring us to a steady state of human coexistence with the biosphere – if such a state is even meaningfully imaginable. It is enough, however, to encompass substantial and measurable progress in a transition toward sustainability. Following the NRC, I therefore propose here as the centerpiece of an environmental agenda at the beginning of the 21st century:

> *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 life support systems of the planet, and to substantially reduce hunger and poverty*.[8]

2.2 The transition in historical perspective

In seeking to understand how we might promote a sustainability transition over the next couple of generations, it is useful to look back over a comparable time period at historical changes in the relationships between environment and development. Such historical trends need not persist – indeed I will point to several that seem to be undergoing significant qualitative changes – but they do provide a feel for the large, long term "currents" within which present and future efforts will have to make their way.

The overall well-being of the Earth's human population has improved dramatically over the last two generations, suggesting that the challenge of promoting a sustainability transition in part involves sustaining and accelerating what we are already doing. As noted in the UN's Human Development Report, "In the past 50 years poverty has fallen more than in the previous 500. And it has been reduced in some respects in almost all countries."[9] Since 1960, child death rates in the developing countries have been cut by more than half. Life expectancy has increased by almost 20 years. Access to safe drinking water has doubled—now being available to perhaps two thirds of the world's population. An even higher proportion now enrolls in primary school, with rates approaching 80%. Average per capita income has more than tripled; three to four billion of the world's people have experienced substantial improvements in their standard of living.[10]

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8 *Id*. at 31.
9 UNITED NATIONS DEVELOPMENT PROGRAMME, HUMAN DEVELOPMENT REPORT 1997 2 (1997).
10 NATIONAL RESEARCH COUNCIL OUR COMMON JOURNEY, *supra* note 1,at 64.

These advances in human well-being, though impressive, have been uneven. There is also ample evidence that they can be stalled or reversed. And while the *proportion* of the world's population enjoying improved conditions has generally increased, the burgeoning numbers of people in many parts of the world mean that the absolute number living in poverty has actually increased. The distribution of income gains has been highly uneven, with the ratio of the income share of the richest 20% to the poorest 20% doubling over the past 30 years from 30:1 to 60:1.[11] Some regions have been largely bypassed by improving incomes. In the least developed regions, such as sub-Saharan Africa, fully half the people still live in income poverty, accompanied by periodic and even chronic hunger. The resurgence of new and old diseases throughout the world, the absolute reductions in standard of living experienced in the last decade in many eastern European countries, and the persistent poverty in even the wealthiest countries show that development progress is neither inevitable nor irreversible.

On the environmental side of the sustainable development relationship, human activities may accurately be said to have transformed the earth. On the order of half of the planet's surface has been significantly altered by human activity; half of its available freshwater is intercepted for human use, and half of its marine fisheries have been exploited at or beyond sustainable levels.[12] The atmospheric concentrations of a number of globally distributed gases central to the functioning of the earth's climate system have increased notably in response to human activities: nitrous oxide by 15%, carbon dioxide by 30%, and methane by nearly 150%.[13] Most scientists believe that these increases have caused the changes in climate observed over the last hundred years: a 0.5°C increase in globally averaged surface temperature and a 10-25cm increase in globally averaged sea-level.[14]

Although development has always affected the environment and the cumulative impact of centuries of human use can be seen in the numbers quoted above, the relative recency of the vast majority of human-induced environmental change is remarkable. Of 13 worldwide measures of human transformation of the environment reconstructed in a recent survey, only two – deforestation and terrestrial vertebrate extinctions – had changed as much in all of history up to 1950 as they have in the last half of the 20th century.[15] Over the last 50 years, humans are responsible for as much flow of nitrogen and sulfur as nature. For many heavy metals and – of course – synthetic materials, the human flux rates dominate natural fluxes by many fold. Rates of species extinction have risen to something on the order of 100 to 1000 times their background natural rates.[16] The last 10 years of the 20th century were the warmest 10 years of the 20th century, with the globally averaged

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[11] *Id.* at 67.
[12] Peter M. Vitousek et al., *Human Domination of the Earth's Ecosystems*, 277 SCI. 494 (1997).
[13] INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE, CLIMATE CHANGE 1995: THE SCIENCE OF CLIMATE CHANGE 3 (J.T. Houghton et al. eds. 1996).
[14] *Id.*
[15] Robert W. Kates et al., *The Great Transformation, in* THE EARTH AS TRANSFORMED BY HUMAN ACTION 7 (B.L. Turner II et al. eds. 1990).
[16] NATIONAL RESEARCH COUNCIL OUR COMMON JOURNEY, *supra* note 1, at 86.

temperature rising 0.25° to 0.40°C over the past 20 twenty years.[17] Moreover, many of these rates are still accelerating.

As was the case for the human development story, the global picture of human-induced environmental change hides more extreme local conditions. The German Advisory Council on Global Change has identified 16 distinct "syndromes" of regional environmental degradation occurring around the world, ranging from the over-cultivation of marginal land to industrial contamination of urban landscapes.[18] In several such regions, environmental degradation has become sufficiently extreme to directly threaten further progress in human development. A recent study found a significant number of sites –from regions as diverse as the United States and Kenya – where "current human uses and levels of well-being appear to be environmentally unsustainable over the middle- to long-term future."[19] The study also revealed two other sites–in Nepal and Mexico–that appear environmentally unsustainable in the near term, and one site – the Aral Sea region – which is already unsustainable. Moreover, as I have argued elsewhere, the large and accelerating pressures now being placed on the planet's environment, and the globalization of those pressures through widening travel and trade virtually guarantee an increase in abrupt, surprising and often undesirable responses.[20]

2.3 Looking ahead

The history of the past two generations tells us that humanity's efforts to better its own condition can be remarkably, if incompletely, successful, but in the process, however, they are capable of fundamentally transforming the planet's environment and undermining the foundations of future human development. It seems virtually inevitable that the future of the next two generations – a future that will see more people trying to produce and consume more goods on the same crowded planet -- will be exposed to an increasing risk of mutually costly collisions between environment and development.

Forecasting just what, where and when those collisions will occur is neither possible nor necessary. Many of humanity's development efforts will "muddle through" future encounters with the environment just as they have muddled through in the past. The inevitable trial and error of selecting a course of action, learning from mistakes, and making adjustments will be inspired less by efforts to think through our futures than by the necessity of acting them out. How effective, fair and efficient this muddling will be depends less on which analytic tools we adopt than it does on the social institutions we develop to provide the incentives and feedback necessary for social learning. The inevitable muddling may nonetheless be made more productive, and the likelihood of

[17] PANEL ON RECONCILING TEMPERATURE OBSERVATIONS, NATIONAL RESEARCH COUNCIL, RECONCILING OBSERVATIONS OF GLOBAL TEMPERATURE CHANGE 36 (2000).
[18] *See* GERMAN ADVISORY COUNCIL ON GLOBAL CHANGE, WORLD IN TRANSITION: THE RESEARCH CHALLENGE (1997), *available at* http://www/awi-bremmerhaven.de/WGBU.
[19] REGIONS AT RISK: COMPARISONS OF THREATENED ENVIRONMENTS 524 (Jeanne X. Kasperson et al., eds. 1995).
[20] *See* Robert W. Kates & William C. Clark, *Environmental Surprise: Expecting the Unexpected?* ENV'T, Mar. 1996, at 6 (1996).

costly and irreversible errors may be reduced, through organized efforts to assess the possible future implications of present trends. In particular, by employing a variety of modeling, assessment and scenario techniques to explore alternative paths toward particular social goals of sustainable development, we can identify some of the kinds of environmental collisions that might be encountered along the way and begin planning measures to avoid or survive them.

The central analytic challenge facing such efforts is to provide useful integration. How far such integration is from normal assessment practice was illustrated in the mid-1980s by Paul Crutzen and Thomas Graedel in their contributions to the sustainable development program at the International Institute for Applied Systems Analysis (IIASA).[21] As suggested by Figure 1A, inspired by their work, the overall assessment goal is to assess the impacts of the full range of natural processes and human development activities on the full range of environmental components. This sort of fully integrated assessment is increasingly being attempted at regional scales as suggested by the German "degradation syndromes" work referred to earlier, the regional evaluations of UNEP's *Global Environmental Outlook 2000*,[22] and a number of cases cited in the BSD's *Our Common Journey*. Such integrative efforts, however, remain rare and underdeveloped. Instead, most studies have focused on single cells of the Crutzen-Graedel matrix: the impact of a single human activity on a single dimension of the environment. More ambitiously, some studies, such as the IPCC climate assessments, have focused on a single "column" environmental problem and sought to evaluate the impacts of multiple human activities and natural fluctuations on that problem.[23] Alternatively, other efforts such as the recent World Commission on Dams have focused on a particular "row" of human activity and sought to evaluate its multiple environmental impacts.[24]

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2.3.1 Comparing environmental problems

Between these simple "column" or "row" assessments and fully integrated approaches lie a number of summary reviews and comparative efforts. The most conventional of these have surveyed a range of environmental problems and attempted to identify those raising the greatest concerns for particular times and places. Figure 2 summarizes the results of eight such assessments performed over the last two generations, reflecting perspectives from India, the United States, and a variety of international governmental and non-governmental institutions. The results suggest that some problems, such as groundwater contamination and forest degradation, cause nearly universal concern. Others problems, such as indoor air pollution, show up less often. Over time, the early

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[21] P.J. Crutzen & T.E. Graedel, *The Role of Atmospheric Chemistry in Environment-Development Interactions*, *in* SUSTAINABLE DEVELOPMENT OF THE BIOSPHERE 213 (William C. Clark & R. E. Munn eds. 1986).

[22] *See* UNITED NATIONS ENVIRONMENT PROGRAMME, GLOBAL ENVIRONMENTAL OUTLOOK 2000, *at* http://www.grida.no/geo2000/ov-e/ov-e.pdf.

[23] *See* INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE, *available at* http://www.ipcc.ch/.

[24] *See* WORLD COMMISSION ON DAMS, *available at* http://www.dams.org/.

focus on the depletion of natural resources and contamination of the environment has shifted toward concern for the integrity of ecosystems. Overall, this analysis suggests that for most people of the world, water and air pollution are top priority issues. For many of the more developed nations, climate change and ozone depletion are also ranked highly. Developing nations, in contrast, have focused more on droughts and floods, disease epidemics, and the degradation of local living resources.

This historical overview suggests, above all else, that our principal environmental preoccupations tend to be shaped heavily by where, and when, we sit. Long-term strategies for promoting transitions toward sustainability need to account for this contextual dependence and to resist the temptation to become fixated on a few "charmed problems" (such as climate change in current times).

A second approach to looking ahead at the possible obstacles facing a transition toward sustainability has focused not on particular environmental problems but rather on particular dimensions of human development and their overall environmental implications. This is the approach taken by the Brundtland Commission in its *Our Common Future* report and, more recently, by the BSD in *Our Common Journey*. The results of the BSD study – focused on particular areas of possible policy intervention – are worth summarizing here as a point of departure for my later discussion of transition strategies and institutions.

2.3.2 Human population and settlement

Of all the transitions in relations between development and the environment marking the end of the 20^{th} century, those in human demography are the most striking. For most of the last two generations (and long before), each passing year added more people to the earth's population than did the year before. For most of the next two generations (and long after), each passing year will almost certainly add fewer. In addition, we are passing from a history in which human populations have been predominantly rural, through a present that has become —and a future that will be —predominantly urban. And we are moving from a century dominated by its children to an era dominated by a new majority of aging adults. As a result of all these changes, the earth's human population is unlikely to double again in the foreseeable future. Nonetheless, it may well reach eight or nine billion people by 2050 before leveling off at perhaps 10 to 11 billion people by the end of the century. Moreover, its urban population will almost certainly more than double, growing from the present three billion city dwellers to perhaps seven billion by 2050 and more than eight billion by the end of the century.[25]

These expected increases in numbers and concentrations of people on the planet – though slower and less severe than forecast even a decade ago – are nonetheless likely to seriously challenge efforts to achieve the social and environmental goals outlined at the beginning of this essay. The Board concluded that the space, resources, and waste

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[25] NATIONAL RESEARCH COUNCIL OUR COMMON JOURNEY, *supra* note 1, at 61.

disposal necessary to provide for the needs of another four billion people over the next 50 years seem unlikely to be available without significantly degrading the earth's life support systems unless humans successfully develop quite different patterns of consumption and production.. Since virtually all of this increase will be accommodated in urban areas —the equivalent of building about 40 San Franciscos every year for the next half century —the challenges of providing municipal air and water quality, sanitation, and garbage disposal will be particularly acute. For mature, slowly growing, and wealthy urban areas, we almost know-how to combine the technology, financing and administration necessary to provide such waste services. For the young, rapidly growing, and generally under-financed urban infrastructures that will arise to accommodate four billion more city dwellers over the next 50 years,[26] we do not —at least without exacting a steep price in human well being and environmental quality.

2.3.3 Agriculture and food security

Developing secure supplies of food for a population that, over the next 50 years, will grow to 50% again as large as today's is a daunting challenge. The Board's analysis suggested that world demand for food could easily double over this period, depending on the diets of our children and grandchildren. Meeting these overall needs while reducing chronic hunger will require that paths of development negotiate a wide variety of potential barriers and roadblocks, both institutional and environmental. Most of these challenges differ in degree, rather than in kind, from those that have confronted the agricultural sector for the last half century. Significantly, the slowing of population growth around the world frees us to think in terms of strategies for sustaining certain absolute amounts of food production rather than perpetually sustaining rates of increase. More controversially, the increasing urbanization of the world's population may let us begin to think of the agricultural system more as producer of affordable food, and less as a last-resort producer of income for the otherwise unemployed.

Opportunities for improving production, distribution and access in the food and agriculture system are substantial but not unlimited. The opportunities are clearest in the globally traded staples (maize, wheat, rice, etc.) where the private sector is playing an increasing role in both the development of new technologies and the marketing of resulting product. Prospects for improvements in regional staples (for example, cassava, sorghum, millet) are much less encouraging, despite the central role these crops play in providing food security for much of the world's poorest population.

More generally, many of the sources of the last half century's phenomenal improvements in agricultural production now appear to be nearing their limits. Rates at which new land is being brought into cultivation, or under irrigation, are declining —partly because the prime sites are long since taken, partly because of increasing competition from other uses. Soil fertility continues to decline as a result of inappropriate management in many areas and, even where stabilized, is perennially at risk Fertilizer and biocide applications are yielding lower returns in many areas, are barely holding their own elsewhere, and in some cases their overuse has contributed to the severe degradation of

[26] NATIONAL RESEARCH COUNCIL OUR COMMON JOURNEY, *supra* note 1, at 305.

agricultural production and food security. Yield ceilings are emerging for major crops that have historically responded well to continuing improvements in "green revolution" technologies. Perhaps most alarming, in the face of these challenges, investments are declining in the global agricultural research system that has been responsible for much of our progress over the past several decades. Substantial private sector investment will almost certainly be necessary to reinvigorate this research system. But as the recent biotechnology debacles show, such investment is a risky business. Learning how to make private investment in agriculture attractive and effective over the long haul—particularly with regard to those aspects of the system most important for enhancing food security and reducing hunger—remains a daunting task for the coming decades.

2.3.4 Energy and materials

The Board's analysis suggested that over the next two generations, global demand for goods and services is likely to increase two- to four-fold. The material and energy use associated with meeting this demand seems less likely than previously thought to be constrained by absolute resource shortages, provided that reasonably functioning markets and R&D systems are maintained. But even under such optimistic assumptions, the energy and materials needed to meet the demands of the next two generations could significantly undermine the planet's life support systems and the prospects for sustainable improvements in human well-being by overburdening its capacity for waste disposal. We see these threats today at multiple levels, from the global risk of climate change due to the excessive emission of greenhouse gases to the local hazards associated with urban garbage disposal.

The fundamental challenge for today and for the future is the same challenge posed by the Brundtland Commission in the 1980s: to produce more with less. In practice, efforts to meet this challenge have moved along three related but distinct paths: (1) technological substitution to reduce the use of particularly hazardous substances, (2) efficiency improvements in the conversion of energy and materials into end uses, and (3) the reduction of "leakages" in the overall material system through recycling and reuse. In all of these areas, substantial progress is being made. At a global level, the intensity of commercial energy use (that is, energy used to produce a unit of economic product) is declining, as is the intensity of carbon in that energy. Similar global trends of "dematerialization" are evident for a wide range of materials. Generally, high levels of economic growth mean that despite these efficiency improvements, absolute amounts of energy and most materials are nonetheless still increasing globally. There are exceptions—the extraction of certain problematic metals such as lead and copper may have peaked; emissions to the environment almost certainly have. But the absolute quantity of materials released into the environment as a result of human activities continues to grow and has already exceeded flows associated with natural processes across a wide range of substances. In many cases, such as sulfur emissions from fossil fuels, these human flows have degraded the performance of crucial life support systems on a continental scale. The potential for future damage is significant, growing, and spreading from the long-industrialized to the newly industrializing portions of the world.[27]

2.3.5 Living resources

Pressures on living resources are increasing across the board, putting at risk not only future supplies of food and fiber but also a host of other services ranging from watershed protection and climate maintenance to pollination and the control of disease organisms. These pressures are driven by excessive harvest demands, the persistence of a frontier mentality in an increasingly crowded world, heavy-handed recreational activities, and perturbations to the chemical and radiation environments of the planet.

Although significant progress has been made in mitigating some of these pressures and in reducing or even reversing their negative impacts, the prospect for conserving our living resources and the services they provide can only be described as dismal. Societies have, of course, long been aware that over-harvest of living resources can undermine subsequent prospects for human development and have long attempted to construct regimes to restrict harvests of forests, fisheries and wildlife below "sustainable yield" levels. It has become increasingly clear, however, that direct harvest is only one of the pressures placed by humans on living resources. Land use change and habitat destruction often cause even greater damage to the living systems on which our fates so closely depend. The most obvious successes in countering these pressures over the last two generations have been the protection of a few high profile vertebrate species and a number of especially attractive or unique places. But the ultimate ineffectiveness of protection measures targeted at single links or locations in the complex web of life is becoming ever clearer. Almost nowhere has the challenge of conserving whole ecosystems been met. Only recently have we realized the immense cost of our failure to appreciate the magnitude and multidimensionality of the tasks involved in conserving living resources. This realization has been brought home to us through system scale collapses in places as diverse as the Great Lakes, the Columbia Basin, and the Aral Sea. Learning how to make intensive use of whole ecosystems while maintaining or restoring their underlying ecological integrity is surely one of the most daunting tasks before us. Indeed, we are only beginning to develop a consensus on relevant measures by which the success or failure of such system scale conservation efforts could be evaluated.[28]

2.3.6 Interactions

Over the last several decades most of the research and policies addressing the environment and development issues have focused on one or another of the problems or

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[27] *See* Alan McDonald, *Combating Acid Deposition and Climate Change*, ENV'T, Apr. 1999, at 4.
[28] *See*, *e.g.*, NATIONAL RESEARCH COUNCIL, COMMITTEE TO EVALUATE INDICATORS FOR MONITORING AQUATIC AND TERRESTRIAL ENVIRONMENTS, ECOLOGICAL INDICATORS FOR THE NATION (2000); Robin O'Malley & Kate Wing, *Forging a New Tool for Ecosystem Reporting* ENVIRONMENT, Apr. 2000, at 20; Edward Ayensu et al., *International Ecosystem Assessment,* 286 SCI. 685-86 (1999).

sectoral activities noted above. Both understanding and management have benefited substantially from these focused approaches. But the interactions among problems and activities are real; the interdependence of environment and development runs deep. As pointed out in the NRC's sustainability transition study:

> *no longer can we ask about the consequences of climate change on agricultural systems; instead, we must ask about the combined effects of climate change, increased climate variability, elevated carbon dioxide, soil quality changes, crop management changes, and tropospheric and stratospheric ozone changes on crop productivity*.[29]

Efforts to improve crop productivity can, in turn, be expected to have consequences not only for human well-being but for most of the dimensions of the environment that are listed above as causes of changes in that productivity. Just as future efforts to comprehend and manage sustainable development will require greater attention to multiple interacting effects, so will they require a deeper appreciation of the multiple interacting stresses impinging on environmental systems.

2.3.7 Conclusion

The prospects for moving forward toward a sustainability transition over the next two generations are not great, but there remains room for informed optimism. 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. Even the most alarming current trends, however, may experience transformations that enhance the prospects for sustainability. Based on its analysis of persistent trends and plausible futures, the NRC's Board on Sustainable Development concluded 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*.[30]

Moreover, it continued:

> *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*

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[29] NATIONAL RESEARCH COUNCIL OUR COMMON JOURNEY, *supra* note 1, at 209.
[30] NATIONAL RESEARCH COUNCIL, OUR COMMON JOURNEY, *supra* note 1, at 7.

> *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*.[31]

The Board noted that the resulting "syndromes of degradation" are difficult to untangle and profoundly difficult to manage. Though often aggravated by global changes, they are shaped by characteristics reflecting the particular physical, ecological and social interactions of specific regions and locales. This realization led to one of the Board's core conclusions:

> *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*.[32]

In the next two sections, I turn to a consideration of strategies and institutions for meeting this challenge.

3 Strategies for learning[33]

There are no maps for navigating a transition toward sustainability. Nonetheless, the "common journey" described by the Board on Sustainable Development is already underway. The Board's study has suggested the need for navigational strategies that can better integrate avowedly incomplete knowledge and necessarily experimental action into programs of adaptive management and social learning.

Why a strategic approach? "Muddling through" the challenges and opportunities presented by the trends noted above can take us part of the way toward sustainability goals in the future, just as it has in the past —especially where political systems and markets are so structured that they provide appropriate incentives and timely feedbacks. *Mere* muddling through, however, would leave substantial opportunities for promoting a sustainability transition untapped. 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.

Therefore, strategic efforts dedicated to improving the prospects for sustainable development are needed to complement the strengths and compensate for the weaknesses of "muddling through." Many such efforts are possible; some are well underway. My

[31] *Id.* at 8.
[32] *Id*.
[33] The remainder of this paper incorporates material originally prepared by the author for the National Research Council OUR COMMON JOURNEY study (*supra* note 1) and appears in slightly altered form in Chapter 6 of that study. This material is included in the article in order to provide examples of specific approaches toward addressing the general problems discussed in Sections 1 and 2 of this paper.

intention here is to sketch elements of one such strategy: a strategy for mobilizing scientific knowledge to pursue programs of purposive social learning and adaptive management committed to the promotion of a sustainability transition.

Why a knowledge-based strategy in a world where political and economic constraints to sustainability often seem so binding? Because knowledge is not only a crucial resource for navigating the uncertain transition toward sustainability, it is also a resource that can be increased significantly through relatively small investments of economic and political capital.[34] Enhancing our capacity for long-term, intelligent investment in the production of relevant knowledge and know-how and the capacity to use them must therefore be a component of any strategy for the transition toward sustainability.

Where is that investment most needed? Much of it clearly belongs in the classic sites of knowledge creation and communication that have served us so well over the past several generations: laboratories, universities, libraries and a variety of international programs that together create powerful knowledge networks. The challenges before us, however, are such that much of what we need to know will only emerge by applying knowledge to action in the field. A knowledge-based strategy for navigating the transition toward sustainability must therefore be a strategy not just of thinking, but also of doing. The Board's explorations suggested that such a strategy should include a spectrum of initiatives ranging from curiosity-driven research addressing fundamental processes of environmental and social change to policy driven research and experiments designed to promote specific sustainability goals. The Board recommended a number of such initiatives, which I summarize below.

3.1 Basic Research

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 sections of this article, the needs run broad and deep. They include both generalizable knowledge about the workings and interactions of the world's environmental, economic, and social systems, as well as specific understanding of particular places, problems and solutions. Much of what we need to know is sufficiently well understood that targeted applications of knowledge to policy is surely justified. I 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 exclusively on such targeted research and development strategies. Research and development are good investments but they pay off in ways frequently unimagined by those who funded and even performed the seminal work. Thus, basic research is essential for assuring that as we enter future stages of the transition toward sustainability, markets, governments, and other players have the intellectual capital available to address the problems they face and to create the products and processes necessary to solve those problems. If science and technology are to live up to their

[34] WORLD BANK, WORLD DEVELOPMENT REPORT 1998: KNOWLEDGE FOR DEVELOPMENT (1997); UNITED NATIONS, UN COMMISSION FOR SCIENCE AND TECHNOLOGY FOR DEVELOPMENT, KNOWLEDGE SOCIETIES: INFORMATION TECHNOLOGY FOR SUSTAINABLE DEVELOPMENT (1998).

potential in meeting the needs of the sustainability transition, they must function within 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.[35] What sort of framework might be appropriate for conceptualizing basic research needs and opportunities for "sustainability science?"

3.1.1 Historical foundations

Over the last generation, four related and sometimes overlapping but nonetheless distinct branches of research-based programs relevant to sustainability have developed. (See Figure 3.)

The first is essentially ecological, emphasizing the intertwined fates of humanity and the natural resource base on which it depends for sustenance. This branch originated in the conservationist thinking of the 19th and early 20th centuries. Internationally, it began to take shape in 1973 with the path-breaking *Ecological Principles for Economic Development*, blossomed in 1980 as the *World Conservation Strategy* (which first popularized the term "sustainable development"), matured to embrace the social dimensions of resource use with the report *Caring for the Earth* in 1991, and now supports the international *Diversitas* program on biodiversity and sustainable use of the earth's biotic resources.[36] Within the United States, recent offshoots of this branch include the *Sustainable Biosphere Initiative* of the Ecological Society of America and the *Teaming with Life* initiative of the President's Council of Advisors on Science and Technology.[37]

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

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[35] NATIONAL RESEARCH COUNCIL, COMMITTEE ON GLOBAL CHANGE RESEARCH, GLOBAL ENVIRONMENTAL CHANGE: RESEARCH PATHWAYS FOR THE NEXT DECADE, OVERVIEW 9 (1998). *See also*, International Human Dimensions Programme on Global Environmental Change, *About IHDP*, *available at* http://www.uni-bonn.de/ihdp/ABOUT.HTML.

[36] *See* William Mark Adams, GREEN DEVELOPMENT: ENVIRONMENT AND SUSTAINABILITY IN THE THIRD WORLD (1990); INTERNATIONAL UNION FOR CONSERVATION OF NATURE AND NATURAL RESOURCES, UNITED NATIONS ENVIRONMENT PROGRAMME, AND WORLD WIDE FUND FOR NATURE, WORLD CONSERVATION STRATEGY: LIVING RESOURCE CONSERVATION FOR SUSTAINABLE DEVELOPMENT (1980); WORLD CONSERVATION UNION, UNITED NATIONS ENVIRONMENT PROGRAMME, AND WORLD WIDE FUND FOR NATURE, CARING FOR THE EARTH: A STRATEGY FOR SUSTAINABLE LIVING. (1991); Diversitas, *About Diversitas, available at* http://www.lmcp.jussieu.fr/icsu/DIVERSITAS/About/index.html.

[37] Ecological Society of America, *The Sustainable Biosphere Initiative, available at* http://esa.sdsc.edu/sbi.htm (1998); PRESIDENT'S COMMITTEE OF ADVISORS ON SCIENCE AND TECHNOLOGY, TEAMING WITH LIFE: INVESTING IN SCIENCE TO UNDERSTAND AND USE AMERICA'S LIVING CAPITAL (1998).

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 that began to take 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 Scientific Committee on Problems of the Environment, and was given form and strength with the emergence of the World Climate Research Program in 1979 and the International Geosphere-Biosphere Program in 1986. U.S. contributions to this earth systems science agenda were shaped by NASA's global habitability program in the early 1980s and have recently been reviewed in the "Pathways" report of the National Research Council.[38]

A third branch of relevant research has been primarily social, focusing on how human institutions, economics 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. Early on, it produced somewhat 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,[39] and were drawn into early efforts to understand global issues such as climate change.[40] By the mid-1980s, a wide variety of social science programs had begun to address issues of global environmental change.[41] A comprehensive international effort was launched in 1990, and today is moving forward as the International Human Dimensions Programme on Global Environmental Change.[42] Recent reviews of the substantive content and concerns of this line of research are available.[43]

Finally, a fourth branch of relevant research has focused on the development of basic technological knowledge and on the design of products and processes for producing more social goods with less environmental harm. This effort has occurred in 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 spill-overs between industrial sectors (for example, the use of aero-derivitive gas turbines for electric power generation), and collaborative research (between private institutes, government laboratories,

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[38] THE EXECUTIVE COMMITTEE OF A WORKSHOP HELD AT WOODS HOLE, MA, JUNE 16-21, 1982 (Richard Goody, Chairman), GLOBAL CHANGE: IMPACTS ON HABITABILITY (1980); NATIONAL RESEARCH COUNCIL, COMMITTEE ON GLOBAL CHANGE RESEARCH, *supra* note 27, at 9.

[39] *See*, *e.g*., ADAPTIVE ENVIRONMENTAL ASSESSMENT AND MANAGEMENT (C. S. Holling ed. 1978).

[40] *See*, *e.g*., CARBON DIOXIDE, CLIMATE AND SOCIETY (Jill Williams, ed. 1978).

[41] *E.g.*, NATIONAL RESEARCH COUNCIL, COMMITTEE FOR AN INTERNATIONAL GEOSPHERE-BIOSPHERE PROGRAM, GLOBAL CHANGE IN THE GEOSPHERE-BIOSPHERE: INITIAL PRIORITIES FOR AN IGBP (1986).

[42] International Human Dimensions Programme on Global Environmental Change, *About IHDP, available at* http://www.uni-bonn.de/ihdp/ABOUT.HTML.

[43] HUMAN CHOICE AND CLIMATE CHANGE (Steve Rayner & Elizabeth L. Malone eds. 1998); COMMITTEE ON THE HUMAN DIMENSIONS OF GLOBAL CHANGE ET AL., HUMAN DIMENSIONS OF GLOBAL CHANGE: RESEARCH PATHWAYS FOR THE NEXT DECADE (1999).

universities, and non-profit organizations) (see NRC and NAE reports dating from the late 1980s for history).[44] 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.[45] 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.[46] Finally, a broader systems perspective on technology, environment and development began to emerge in the mid-1980s, focusing not on individual technologies or processes but rather on minimizing waste produced by whole sectors of human activity.[47] 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.[48]

The Board concluded that a research framework for sustainability science will need to build on these established branches of scholarship together with their respective research programs, practices and observation systems. Assuring the health of these foundational programs and their priorities 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 large scales and the long-term the earth, its ecosystems and its people can interact for mutual sustenance.

3.1.2 Integrative futures

As noted in Section 2 and elsewhere, 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.[49] Sustainability science will therefore

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[44] *E.g.,* NATIONAL ACADEMY OF ENGINEERING, THE ECOLOGY OF INDUSTRY: SECTORS AND LINKAGES (Deanna J. Richards & Greg Pearson eds. 1998); BOARD ON SUSTAINABLE DEVELOPMENT, NATIONAL RESEARCH COUNCIL, *supra* note 1, at 199 (citing numerous sources).

[45] *See* BOARD ON ENVIRONMENTAL STUDIES AND TOXICOLOGY & COMMISSION ON BEHAVIORAL AND SOCIAL SCIENCES AND EDUCATION, NATIONAL RESEARCH COUNCIL, REDUCING HAZARDOUS WASTE GENERATION: AN EVALUATION AND CALL TO ACTION (1985).

[46] *See* COMMITTEE ON THE HUMAN DIMENSIONS OF GLOBAL CHANGE, NATIONAL RESEARCH COUNCIL, ENVIRONMENTALLY SIGNIFICANT CONSUMPTION: RESEARCH DIRECTIONS (Paul C. Stern et al. eds. 1997); PANEL ON ENERGY RESEARCH AND DEVELOPMENT, PRESIDENT'S COMMITTEE OF ADVISORS ON SCIENCE AND TECHNOLOGY, FEDERAL ENERGY RESEARCH AND DEVELOPMENT FOR THE CHALLENGES OF THE 21ST CENTURY (1997).

[47] *See* NATIONAL ACADEMY OF ENGINEERING, THE GREENING OF INDUSTRIAL ECOSYSTEMS (1994).

[48] *See*, *e.g.*, COMMITTEE ON GLOBAL CHANGE RESEARCH, NATIONAL RESEARCH COUNCIL, *supra* note 27; European Union, *The Fifth Framework Programme, 1998 to 2002*, *available at* http://www.cordis.lu/fp5/home.html (containing the program text and archived additional reports); INTERNATIONAL HUMAN DIMENSIONS PROGRAM ON GLOBAL ENVIRONMENTAL CHANGE, INDUSTRIAL TRANSFORMATION SCIENCE PLAN (2000), *available at* http://www.uni-bonn.de/ihdp/ITSciencePlan/index.htm.

[49] COMMITTEE ON GLOBAL CHANGE RESEARCH, NATIONAL RESEARCH COUNCIL, *supra* note 25; UNITED NATIONS ENVIRONMENT PROGRAMME ET AL., PROTECTING OUR PLANET, SECURING OUR FUTURE (1998).

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, ecological, social, and technological. The same can be said for sectoral distinctions 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 distinction between global and local perspectives. Finally, it will need to bridge the gulf that separates the detached practice of scholarship from the engaged practices of engineering and management.

Fortunately, integrative approaches in research addressing environment and development issues at the ecosystem scale are not wholly new.[50] Today, for example, forest management strives to encompass social systems and natural resources in an inclusive and interacting systems framework.[51] In addition, integrated approaches are forming a new paradigm in water management. Researchers now seek to understand the interactions of urban, agricultural, industrial, and natural ecosystem requirements for water resources and the policy implications for water management.[52] In agriculture, especially in systems designed for high-yields, successful production is more likely when crop selection, pest management, irrigation systems, as well as local culture, are considered. On a broader scale, the international global change research programs have made tremendous progress in the task of integrating previously separate disciplines. For example, fifteen years ago, atmospheric chemists and biologists had not combined their knowledge in order to study atmospheric change, despite the fact that biological processes significantly effect atmospheric composition. Furthermore, neither discipline was well integrated into atmospheric physics, oceanography, and 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.[53]

Although the first steps towards an integrative science of sustainability have been taken, the journey has only just begun. 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. A similar lack of progress is evident in efforts to incorporate biodiversity considerations into contemporary global climate change studies. As a result, we now know much about what emissions cause various global environmental changes, but less about what drives those emissions, what impacts they will have on people and other species, and what to do about them. Likewise, though integrated forest ecosystem management programs have progressed to the point of

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[50] *See*, *e.g.*, BARRIERS AND BRIDGES TO THE RENEWAL OF ECOSYSTEMS AND INSTITUTIONS (Lance H. Gunderson et al. eds. 1995)[hereinafter, BARRIERS AND BRIDGES]; COMMITTEE ON PROTECTION AND MANAGEMENT OF PACIFIC NORTHWEST ANADROMOUS SALMONIDS, NATIONAL RESEARCH COUNCIL, UPSTREAM: SALMON AND SOCIETY IN THE PACIFIC NORTHWEST (1996).

[51] *See*, *e.g.*, USDA Forest Service National Headquarters, *available at* http://www.usfs.gov.

[52] *See*, *e.g.*, COMMITTEE ON WATERSHED MANAGEMENT, NATIONAL RESEARCH COUNCIL, NEW STRATEGIES FOR AMERICA'S WATERSHEDS (1998) [hereinafter, COMMITTEE ON WATERSHED MANAGEMENT] .

[53] COMMITTEE ON GLOBAL CHANGE RESEARCH, NATIONAL RESEARCH COUNCIL, *supra* note 27.

including people in the ecosystem at a local scale, there has been much less progress in regional level planning and assessment. 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 programs remains problematic. 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? One response to this dilemma that seems especially worth pursuing involves integrating research for sustainability not around particular disciplines or sectors, but rather around the study of interactions between development and environment in particular places.

3.1.3 Place-based science

I summarized earlier the Board's finding that critical threats to sustainability are likely to emerge in specific regions with distinctive social and ecological attributes and that a successful transition will need to be based in such regions. Fortunately, "place" also provides a conceptual and operational framework within which progress in "integrative" understanding and management are possible (see Figure 1B). Not surprisingly, the Board found some of the best examples of analytic and policy progress towards sustainability in studies on particular geographic locations.

To argue that the basic research challenges of 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. Understanding the linkages between macroscale and microscale phenomena is clearly one of the great challenges of our age for a wide array of sciences.[54] The pursuit of such understanding should 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 challenge of understanding the "kinds" of pressures and stresses that occur at those scales. While any classification is necessarily somewhat arbitrary and will lump together places exhibiting differences, without one we are left with the dismal prospect of approaching each "place" as though it were altogether unique. One intermediate approach to this dilemma in the context of sustainability science is the concept of recurrent "degradation syndromes."[55] The potential contribution to a "place-based" framework for such science seems substantial and merits further exploration.

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[54] *E.g.*, Clark Gibson et al., *Scaling Issues in the Social Sciences* (1998), *available at* http://www.uni-bonn.de/ihdp/WP01.htm; Terry L. Root & Stephen H. Schneider, *Ecology and Climate: Research Strategies and Implications*, 269 SCI. 334 (1995); Thomas J. Wilbanks & Robert W. Kates, *Global Change in Local Places: How Scale Matters*, 43 CLIMATIC CHANGE 601 (1999); David W. Cash & Susanne C. Moser, *Information and Decision Making Systems for the Effective Management of Cross-Scale Environmental Problems: A Theoretical Concept Paper* (1998), *available at* http://environment.harvard.edu/gea/pubs/jan98ws_concept.html; William C. Clark, *Scales of Climate Impacts*, 7 CLIMATIC CHANGE 5 (1985).

[55] *See* GERMAN ADVISORY COUNCIL ON GLOBAL CHANGE, WORLD IN TRANSITION: THE RESEARCH CHALLENGE (1997), *available at* http://www/awi-bremmerhaven.de/WGBU.

However defined, sustainability science as a place-based science will benefit from the many ongoing efforts to regionalize environment-development relationships. Since its inception, the START (SysTem for Analysis, Research and Training) initiative of the International Geosphere-Biosphere Program, the World Climate Research Program, and the International Human Dimensions Program on Global Environmental Change has focused on the regional dimensions of global change.[56] It now addresses issues ranging from determinants of land use change to industrial transformation to implications of environmental change for national security.[57] The flagship international scientific assessment of climate change produced an addendum of 10 regions to its second assessment and based its third assessment on such regional analyses.[58] The recommendations of the German Advisory Council on Global Change have already been noted.[59] In the United States, the first assessment of climate change and impacts observes the problem on a scale of approximately twenty regions.[60] Analogous efforts are underway in the European Union, Canada, and a number of other countries.[61] Implicit in many of these efforts is a search for parsimony—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 financial resources. Common to all of 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.

3.2 Focused Research Programs on Critical Issues

The Board determined that it would be premature to suggest a comprehensive research agenda for a still-nascent sustainability science.[62] 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 UNCED.[63] The chapter on "Science for Sustainable Development" in Rio's "Agenda 21" carried forward this broad conception of research needs, and has served

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[56] International Geosphere-Biosphere Programme, *Global Change System for Analysis, Research and Training* (START), *available at* http://www.igbp.kva.se/start.html.
[57] *Id.*
[58] *See* THE REGIONAL IMPACTS OF CLIMATE CHANGE: AN ASSESSMENT OF VULNERABILITY (Robert T. Watson et al. eds. 1998).
[59] *See supra* note 18.
[60] U.S. Global Change Research Program, *U.S. National Assessment —The Potential Consequences of Climate Variability and Change, at http://www.nacc.usgcrp.gov/.*
[61] *E.g.*, European Union, *supra* note 40; Canadian Tri-Council Eco-Research Program home page, *at* http://www.sdri.ubc.ca/GBFP/sum_tri.html; Inter-American Institute for Global Change Research home page, http://www.iai.int/; United Nations Commission on Sustainable Development home page, http://www.un.org/esa/sustdev/csd.htm (providing a broad overview of other initiatives).
[62] *But see* Robert W. Kates et al., *Sustainability Science*, 292 SCI. 641 (2001) *and additional materials in the* SUSTAINABILITY SCIENCE FORUM <http://www.sustainabilityscience.org> *for illustrations of the momentum subsequently built for such an agenda*.
[63] AN AGENDA OF SCIENCE FOR ENVIRONMENT AND DEVELOPMENT INTO THE 21ST CENTURY (James C. I. Dooge et al. eds. 1992).

as a template for subsequent progress reports by the UN Commission on Sustainable Development.[64] Those reports and others show that several research programs relevant to sustainability have indeed grown over the last decade, especially within the central branches of scholarship described in the preceding section. Much research in what might be termed the "sustainability science" agenda is clearly moving along well. It remains true, however, that the very breadth of the research that could contribute to understanding long term, large scale interactions between environment and society carries the risk that the overall research program actually carried out will remain relatively diffuse, under-funded and unproductive. Evidence presented at the UN General Assembly's Rio+5 review bore out this expectation. Several opportunities for international efforts to address these issues and reinvigorate an agenda of science for environment and development have been conducted or scheduled around events marking the turn of the century. These include the World Conference on Science hosted by UNESCO and ICSU for Budapest in 1999[65] and the Conference on the Transition to Sustainability in the 21st Century hosted by the InterAcademy Panel on International Issues in 2000 in Japan.[66]

In hopes of contributing to such efforts, the Board followed the thrust of recent National Research Council 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."[67] In particular, it specified several areas of inquiry that are central to the challenges of a sustainability transition and amenable to research, but are understudied in existing research programs. The causes for such neglect vary. They include cases where the science is just now maturing, where the questions seem to fall between disciplines, and where the urgency in the context of the sustainability transition is only recent. Independent of the reasons for current neglect, the Board set these issues forward as candidates for focused research programs in sustainability science. I summarize several of the candidates below, but I refer the reader to the Board's report, and to subsequent international studies that have followed from it, for a full listing and elaboration.[68]

3.2.1 Critical loads and carrying capacities

To pursue a 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 sometimes separate normal and radically transformed states of life support systems.[69]

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[64] *See* http://www.un.org/esa/sustdev/science.htm
[65] *See* http://www.unesco.org/science/wcs/.
[66] *See* http://interacademies.net/intracad/tokyo2000.nsf/all/home (containing the statement of the academies issued at the conference)
[67] BOARD ON SUSTAINABLE DEVELOPMENT, NATIONAL RESEARCH COUNCIL, *supra* note 1, at 18.
[68] *See supra* note 62.
[69] C.S. Holling, *The Resilience of Terrestrial Ecosystems: Local Surprise and Global Change, in* SUSTAINABLE DEVELOPMENT OF THE BIOSPHERE 292 (William C. Clark & R. E. Munn eds. 1986); William C. Clark, *Visions of the 21st Century: Conventional Wisdom and Other Surprises in the Global Interactions of*

Moreover, we know that the abrupt changes associated with the crossing of such boundaries provide special windows of opportunity for mobilizing political action and institutional reform.[70] Finally, indicator systems lose much of their attraction if they provide no signal of the approach to a "dangerous threshold" or to a 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 longstanding and widespread. While many of these efforts to specify safety limits for human pressures on the biosphere have been helpful, the underlying concepts have proven to be contentious, ambiguous, and frustrating. Carrying capacities turn out to be dependent on available technologies and consumption practices.[71] Efforts to specify actual critical loads or safety levels are undermined by the heterogeneity of the environment and populations at risk. Thresholds turn out to be more relative than absolute. 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— including, but not limited to such single-valued characteristics.

The Board encountered all these difficulties in its sustainability study, failing to develop criteria that could provide a "bright line" test for significant degradation of regional ecosystems and their life-support functions. 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" or "carrying capacities" 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.

3.2.2 Understanding and monitoring the transitions

The persistent trends in environment and development discussed earlier in this paper can, if properly understood, serve as important guides to a sustainability transition. 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.[72]

Population, Technology, and Environment, in PERSPECTIVE 2000: PROCEEDINGS OF A CONFERENCE SPONSORED BY THE ECONOMIC COUNCIL OF CANADA, DECEMBER 1998 7 (K. Newton et al. eds. 1988).

[70] *See* JOHN W. KINGDON, AGENDAS, ALTERNATIVES AND PUBLIC POLICIES (1984); FRANK R. BAUMGARTNER & BRYAN D. JONES, AGENDAS AND INSTABILITY IN AMERICAN POLITICS (1993); IAN BURTON ET AL., THE ENVIRONMENT AS HAZARD (2d ed. 1993); BARRIERS AND BRIDGES, *supra* note 48.

[71] JOEL COHEN, HOW MANY PEOPLE CAN THE EARTH SUPPORT? (1995).

[72] *E.g.*, DAVID S. LANDES, THE WEALTH AND POVERTY OF NATIONS: WHY SOME ARE SO POOR AND SOME SO RICH (1998); ARNULF A. GRUBLER, TECHNOLOGY AND GLOBAL CHANGE (1998); THE EARTH AS TRANSFORMED BY HUMAN ACTION: GLOBAL AND REGIONAL CHANGES IN THE BIOSPHERE OVER THE PAST 300 YEARS (B. L. Turner et al. eds. 1990).

The search for fundamental *transitions*—or breaks in trends—concerning the relationships between society and environment has been more challenging. The Board identified one powerful transition that is both credible and interesting: the change in population regimes from ones of high birth and death rates to ones 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; in agricultural productivity, the transition from increases in production deriving from additions to the amount of land farmed to increases arising from additions to local yields. Other possible transitions were previously noted—for example, the globalization of the economy, changes in consumption patterns, energy intensity and pollution per unit value produced by the economy, and modifications in 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. Improved documentation and understanding, especially for those transitions that transcend the normal disciplinary boundaries of scholarship, should be a priority for sustainability science.

3.2.3 Consumption patterns: determinants and alternatives

One of the biggest obstacles to a successful sustainability transition is that humans continue to desire lifestyles requiring ever-larger flows of energy and materials. Yet despite the increasing attention paid to changes in the efficiency with which "final" consumer goods and services are delivered, relatively little research has addressed the factors determining changes in the consumption of ultimate resources: energy and materials. For example, although much work has been done on documenting trends of dematerialization and decarbonization, an explanatory theory to account for variations in rates of decreasing mass per unit of service has not yet been developed.[73] Methodology is also needed distinguish resource-depleting or environmental-damaging consumption from general consumption and to substitute modes of consumption that deplete less energy and materials for the highly consumptive approaches that currently exist. Further, although little-studied of late, the systematic potential for substituting information for materials and energy (for example, through the substitution of local area thermostats for one-size fits all temperature control of buildings) could be particularly important in activities as diverse as agriculture and space-conditioning.

Turning to the demand-side of consumption, advertising and culture remain remarkably effective in encouraging the emulation of high consumption lifestyles. Nonetheless, the human behavior driving consumption is still poorly understood,

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[73] *E.g.*, Robert S. Herman et al., *Dematerialization*, *in* TECHNOLOGY AND ENVIRONMENT 50 (Jesse H. Ausubel & Hedy E. Sladovich eds. 1989); Nebojsa Nakicenovic, *Freeing Energy from Carbon*, DAEDALUS, June 22, 1996, at 95; Iddo K. Wernick, *Consuming Materials the American Way*, 53 TECHNOLOGICAL FORECASTING AND SOCIAL CHANGE 111 (1996); GRUBLER, TECHNOLOGY AND GLOBAL CHANGE, *supra* note 69.

especially in the potential for alternative consumption patterns and the value systems that would support them.[74] 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.[75] A rigorous, comparative research program is needed to investigate how the values underlying alternative consumption patterns are formed, stabilized and undermined in contemporary societies.[76]

3.2.4 Incentives for technical innovation

Incentives for the creation of 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. Markets, however, do not always produce environmentally desirable products and processes or the desirable solutions to social allocation problems. The conditions associated with such market failure include unpriced externalities and public goods, and insecure or uncertain property rights. Standard remedies are equally well known, generally involving governmental regulation of externalities, provision of public goods, and enforcement of property rights.

More systematic applications of existing remedies for market failure would surely help to align incentives for technical innovation with the need to transition toward sustainability, such as 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 "large and long" character 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 most needed for navigating a transition toward sustainability poses extraordinary challenges for dealing with intellectual property rights, as can be seen in recent debates over appropriate biotechnology. In addition, a global trend to commercialize data is manifested in emerging national legislation (proposed in the United States; ratified in the Europe as European Database Directive) and international agreements (for example, 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 permanent and exclusive rights

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[74] *See* COMMITTEE ON THE HUMAN DIMENSIONS OF GLOBAL CHANGE, NATIONAL RESEARCH COUNCIL, *supra* note 36; Policy Research Project on Sustainable Development, LYNDON B. JOHNSON SCHOOL OF PUBLIC AFFAIRS, THE ROAD TO SUSTAINABLE DEVELOPMENT: A GUIDE FOR NONGOVERNMENTAL ORGANIZATIONS (1998); Robert W. Kates, *Population and Consumption: What We Know, What We Need to Know,* ENV'T, April 2000, at 10.

[75] *E.g.*, WILLETT KEMPTON ET AL., ENVIRONMENTAL VALUES IN AMERICAN CULTURE (1995); MERCK FAMILY FUND, YEARNING FOR BALANCE: VIEWS OF AMERICA ON CONSUMPTION, MATERIALISM AND THE ENVIRONMENT (1995).

[76] UNITED NATIONS DEVELOPMENT PROGRAMME, HUMAN DEVELOPMENT REPORT 1998: CONSUMPTION FOR HUMAN DEVELOPMENT (1998).

to the contents of their databases without regard to fair use exceptions such as research and education.[77] The Board concluded that a concerted research program is surely worth pursuing to determine the kinds of incentives—market and otherwise—needed to promote technological innovations for a sustainability transition, to develop means for providing such incentives in a highly uncertain, multi-actor, globalizing world, and to analyze the actual performance of incentives in that world.

3.2.5 Indicator systems

The Board argued in its report that an informed dialogue on goals for the transition toward sustainability is necessary if we as a society are to take some measure of responsibility for where we ought to be headed, rather than merely acquiescing in where the currents of demographic, economic, and environmental transformation are taking us. 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. Treated in this manner, indicators become part of an information feedback system through which societies can assess progress, adjust directions, and signal warnings of unsustainability.

The Board 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, to 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 by the Board 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.[78] The Board believes that a research effort focused on bridging this gap between practice-driven and theory-driven indicator systems for sustainability could reap significant benefits.

3.2.6 Assessment tools

The Board assessed the need for methods and processes to perform "what-if" explorations of possible trends, transitions and policy options. It presented examples of how scenarios, integrated assessment models, 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 were identified that could help to remedy this.[79]

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[77] *See* COMMITTEE ON ISSUES IN THE TRANSBORDER FLOW OF SCIENTIFIC DATA, NATIONAL RESEARCH COUNCIL, BITS OF POWER: ISSUES IN GLOBAL ACCESS TO SCIENTIFIC DATA (1997).
[78] BOARD ON SUSTAINABLE DEVELOPMENT, NATIONAL RESEARCH COUNCIL, *supra* note 1, at Chapter 5.
[79] BOARD ON SUSTAINABLE DEVELOPMENT, NATIONAL RESEARCH COUNCIL, *supra* note 1, at Chapter 4.

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 more specific case of stratospheric ozone depletion. Such scenario efforts should focus on the interactions between the needs of future generations and the impacts upon life-support systems of efforts to meet those needs as shaped by technologies and institutions of the future.

A second assessment initiative recommended by the Board stems from the growing realization that the effectiveness of international science-based assessments (for example, the IPCC assessment of climate change) and their use by individual countries is strongly influenced by decisions about who participates in those assessments.[80] This lesson has been repeatedly learned at national and local levels, and is a central issue for ongoing U.S. efforts to conduct regions-based assessments of global change. Critical experimentation with a variety of methods for achieving legitimacy-enhancing participation without undue cost to scientific credibility is badly needed.[81]

We must also develop integrative methods that bring a variety of disciplinary perspectives into the formulation of assessment questions and strategies. Fortunately, there is substantial activity on this front, with truly integrative approaches replacing earlier models that merely used the social sciences to supplement assessments framed primarily by the natural sciences.[82]

Finally, much of the knowledge and decision making necessary for navigating a transition toward sustainability is 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, there has been progress in efforts to bring global sustainability perspectives to bear on practical problems of ecosystem, watershed, and community management.[83] Some of these, such as recent efforts to deal with sustainable futures for the Columbia Basin and Alpine regions of Europe, have become quite sophisticated in their ability to integrate global modeling with local stakeholder perspectives, knowledge bases

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[80] GLOBAL ENVIRONMENTAL ASSESSMENT PROJECT, A CRITICAL EVALUATION OF GLOBAL ENVIRONMENTAL ASSESSMENTS: THE CLIMATE EXPERIENCE (1997), *available at* http://environment.harvard.edu/gea/pubs/97swr.html; JAN-STEPHAN FRITZ, REPORT ON INTERNATIONAL SCIENTIFIC ADVISORY PROCESSES ON THE ENVIRONMENT AND SUSTAINABLE DEVELOPMENT (1998), *available at* http://www.unep.ch/earthw/sciadv.htm.

[81] *E.g.*, Report of a workshop sponsored by the ESRC Global Environmental Change Programme (UK) and the Social Sciences and Humanities Research Council (Canada), Interactive social science: Environmental research (1998), *available at* http://www.sdri.ubc.ca/GBFP/brighton.html.

[82] *E.g.*, Hadi Dowlatabadi & M.Granger Morgan, *A Model Framework for Integrated Assessment of the Climate Problem*, 21 ENERGY POLICY 209 (1993); Jan Rotmans & Hadi Dowlatabadi, *Integrated Assessment Modeling, in* HUMAN CHOICE AND CLIMATE CHANGE, ch. 5 (Steven Rayner & Elizabeth Malone eds. 1998).

[83] *See* BARRIERS AND BRIDGES, *supra* note 48; PRESIDENT'S COUNCIL ON SUSTAINABLE DEVELOPMENT, TOWARDS A SUSTAINABLE AMERICA: ADVANCING PROSPERITY, OPPORTUNITY AND A HEALTHY ENVIRONMENT FOR THE 21ST CENTURY (1999); United Nations Division for Sustainable Development, *Sustainable Development Success Stories*, *available at* http://www.un.org/esa/sustdev/success.htm .

and decisionmaking needs.[84] Such experiences need to be codified so that they can be critiqued, adapted and learned from in capacity-building efforts throughout the world.

3.3 Policy as Experiment: Learning by Doing

A third strand of the Board's strategy for navigating a sustainability transition involves efforts to "learn by doing" through policy experimentation in specific issue areas identified by the Brundtland Commission. For some issues, such as population, the Board felt that enough was known to recommend specific measures that would both promote sustainability goals and constitute a policy experiment from which additional valuable knowledge could be gleaned. For other issues, such as urban development, our present understanding is inadequate to support more than guesses about what policy interventions might best promote a sustainability transition. As a result, developing an initial strategy for designing and implementing multiple small policy experiments therefore seemed more appropriate. In all cases, the Board advocated an iterative, adaptive approach in which science both informs action and learns as much as possible from those actions. The Board realized that activities related to many of its action priorities are already underway around the world, though with generally inadequate levels of support. The Board hoped, not to compete with such initiatives, but to help focus attention on a few issues in which learning through experimental policy implementation and evaluation seemed especially warranted. Once again, I summarize here the Board's conclusions while referring the reader to the full report for supporting details and argumentation.

3.3.1 Human Population

The Board concluded that an achievable population goal is to accelerate current trends in fertility reduction. After reviewing the continuing reduction in fertility and the potential for accelerated reductions, it determined that achieving a 10% reduction in the population now projected for 2050 is a desirable and potentially attainable goal.[85] A billion less people would ease the transition toward sustainability.

We know that desired family size diminishes with increased incomes, child survival, educational and employment opportunities for women, and access to birth control.[86] All of these factors 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 changes, cultural changes, and aggressive, coordinated action by governments, international organizations and other institutions, as well as by

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[84] *E.g.,* VIEWS FROM THE ALPS: REGIONAL PERSPECTIVES ON CLIMATE CHANGE (Peter Cebon et al. eds. 1998); Edward L. Miles, *Integrated Assessment of Climate Variability, Impacts, and Policy Response in the Pacific Northwest,* US GLOBEC NEWS, Nov., 1995, at 4-5, 14-15; COMMITTEE ON PROTECTION AND MANAGEMENT OF PACIFIC NORTHWEST ANADROMOUS SALMONIDS, NATIONAL RESEARCH COUNCIL, *supra* note 50.

[85] BOARD ON SUSTAINABLE DEVELOPMENT, NATIONAL RESEARCH COUNCIL, *supra* note 1, at 304.

[86] *Id.*

individuals. While additional research to clarify these relationships is surely needed, the Board determined that focused policy initiatives could both augment the knowledge base and promote increases in the rate of fertility reduction.

Over the short-term, the most obvious strategy for fertility reduction is to meet the unsatisfied demand for contraception by increasing knowledge about and availability of existing technologies to those who might want to use them. Over the medium term, strategies are needed to reduce family size through enhancing the status of women, particularly by developing incentive structures for educating girls and women. Education is a reasonably well-known and tested intervention, but accelerating the education of women requires new and sustained efforts. Finally, looking to the longer term, the most promising effect will be achieved by delaying the onset and spacing of childbearing. Extending the age of marriage and addressing such difficult issues as adolescent sexuality have the potential to slow population momentum. Here too, educational and employment opportunities for women are imperative. But more specific strategies—such as the novel program in Hyderbad India that provides dowries to empower young women to stay in school and postpone marriage—are also needed. All of 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.

3.3.2 Cities

The Board judged that it should be possible to accommodate a tripling of the urban infrastructure over the next two generations in a habitable, efficient and environmentally friendly manner. By making use of 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.

We are in the midst of a transition from a world with two billion people in cities to a world with six billion in cities, mostly in developing countries. Over the next two generations, the equivalent of 1000 great cities will be built in and about existing cities—an average of 20 per year. The challenge facing urban areas and high density population areas is achieving settlement patterns that make efficient use of land and infrastructure and reduce burdens on material and energy use while providing satisfactory levels of living. This 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 moving 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 obtain the necessary knowledge for addressing this still dimly recognized enormous challenge and opportunity.

3.3.3 Agricultural production

The Board concluded that reversing declining trends in agricultural production in Africa while sustaining historic production trends elsewhere is an achievable goal. 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.

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 difficulty of managing agricultural soil resources, the constraints resulting from traditional land tenure institutions, limited agricultural capacity, urban bias in agricultural and food policy, and lack of stability in economic governance and political institutions. But the weight that should be given to these factors and the nature of 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, and non-governmental organizations will be needed to address the underlying causes and actions needed for the countries of Sub-Saharan Africa to acquire the capacity to implement the technical and institutional changes necessary to reverse the decline in production, get agriculture moving, and build the agriculturally based development needed for an African transition toward sustainability.

3.3.4 Industry and energy

An achievable goal, in the view of the Board, is to accelerate efficiency improvements in the use of energy and materials, perhaps doubling the historic rate of 1-2% per year.[87] This conceptualization does not distinguish among resources which have varying environmental effects. It does, however, point generally in the right direction, leave freedom for experimentation with varying methods, and convey a simple message.

Strategies for pursuing this goal require an integrated approach with both short- and long-term components. In the short term, there must be enhanced efforts to promote more rapid adoption of existing in-use efficiency technology and practices worldwide. We need to disseminate efficient, available technologies to places around the world where such technologies could be enhance the transition process. In the medium term, we need to move beyond simply using what we have to promoting experimental use of the efficient technologies that are currently in a demonstration phase. Renewable energy sources seem to show enough promise to rate some special nurturing in this category. For the longer term, we need to commit to fostering a broad-based, collaborative program of basic energy research and development. This program should be collaborative in the sense that it involves the public and the private sectors in ways that deregulation and multiple scale developments allow. These individual research initiatives would benefit from one another,

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[87] BOARD ON SUSTAINABLE DEVELOPMENT, NATIONAL RESEARCH COUNCIL, *supra* note 1, at 310.

and thus can usefully be viewed as a portfolio within which technology choices for the future can be based.

3.3.5 Living Resources

The Board focused on a goal of restoring degraded systems while conserving diversity elsewhere. For the human dominated ecosystems undergoing degradation from multiple demands and stresses, the goal should be to work towards 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; some of these pristine systems represent the last reserves of Earth’s biological diversity, providing a treasure for future generations as storehouses of biodiversity and aesthetic jewels. 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.

A variety of “manipulation” experiments are underway to evaluate the applications of ecology to restoring degraded systems: the management of forests, agriculture, and oceans while retaining ecosystem services; the effects of species re-introductions (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 decreased incentives to engage in forestry, irrigation, and fisheries in ways that encourage land degradation or over-exploitation of living resources, would help restore degraded systems, encourage sustainable use of renewable resources, and build natural capital for future generations.

Biodiversity can be protected, in part, by setting aside designated areas. Unfortunately, many existing protected sites were established because of convenience, threat of overuse, or aesthetic reasons, not because of biodiversity.[88] Many programs are now underway to evaluate important areas for protecting species diversity (for example, identification of “hot spots” or areas of high biodiversity with greatest threat from disturbance, wilderness areas, or intact ecosystems), to engage local communities in conservation efforts (for example, UNESCO’s Biosphere Reserves), and to establish buffer zones around protected areas as transition zones.[89] 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.

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[88] *Id.* at 316.
[89] *Id.*

3.3.6 Interactions

As noted above, the Board identified effective integrated, place-based ecosystem management as one of the fundamental goals that would have to be attained in the course of a transition toward sustainability. This is an area in which we have little experience, and our immediate action must be to learn by doing and re-doing. There are several dimensions to this action agenda. First, we must ask in rigorous and careful ways about the determinants of success or failure in our on-going experiments in integrative research (for example, see previous discussion of research on degraded ecosystems), a point made earlier with respect to social learning and adaptive management. Second, 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 disciplinary information, fewer agencies have been willing to invest in studies that are interdisciplinary and integrative from their inception, and therefore, have a better chance of developing the conceptual underpinnings of integrative science. Third, new frameworks for interactions among industry, academia, foundations, and other non-governmental organizations must be developed in which all partners contribute to the analysis of sustainability on local and regional scales.

4 Institutions for a sustainability transition

I close with a summary of the Board's conclusions on some of the institutional innovations that will be needed to implement the learning strategy described in Section 3, above.

4.1 Which institutions, for what purposes?

If institutions are the norms, expectations, and rules through which societies figure out what to do and organize themselves to get things done, then the institutions with which society will navigate the transition toward sustainability may be quite different from those with which we have the most experience to date. Those institutions will likely be less government-centered than in the past, involving substantial roles for a variety of private sector and non-profit actors.[90] Moreover, they could well be less centered at the level of nation states, spanning instead scales from the local to the global.[91] Finally, they will almost certainly be substantially more information-intensive than the institutions of the past, with increasing tasks of monitoring, assessment and reporting.[92] Within these emerging institutions, initiatives are less likely to be pushed by the individual actors with which we are familiar—a UN agency, a national government, or a single firm or

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[90] *See* Jessica T. Mathews, *Power Shift*, FOREIGN AFFAIRS, Jan. 1997, at 50; GOVERNANCE IN A GLOBALIZING WORLD, (Joseph S. Nye, Jr. & John D. Donahue eds. 2000)
[91] *See* RONNIE D. LIPSCHUTZ WITH JUDITH MAYER, GLOBAL CIVIL SOCIETY & GLOBAL ENVIRONMENTAL GOVERNANCE: THE POLITICS OF NATURE FROM PLACE TO PLANET (1996).
[92] *See* Joseph S. Nye Jr. & Robert O. Keohane, *Power and Interdependence in the Information Age*, FOREIGN AFFAIRS, Sept. 1998, at 81.

sector—than by ad-hoc networks of advocates temporarily united around a shared purpose.[93]

Today, we have a very limited understanding of what these emergent institutions might look like.. We know even less about the factors determining their effectiveness in promoting a sustainability transition, though issues of participation, credibility, capacity and linkage seem significant. Nonetheless, recent work has begun to sketch the outlines of what might be included in a long-term research program to improve our understanding of institutions for a sustainability transition.[94] Central to this emerging agenda is the need to better understand the institutional arrangements through which enlightened self-interest can provide sufficient grounds for state and non-state actors to engage in behaviors promoting a sustainability transition, when various forms of collective action are also necessary.[95]

More broadly, institutions are needed that can promote the integration of knowledge and action that is central to the learning strategies for sustainable development sketched earlier in this paper. 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, little of this is currently utilized in even a fraction of the situations where it could make a contribution to successful navigation of the transition toward sustainability.[96] As the science and technology community pursues new research and development endeavors of the sort described in earlier sections of this paper, it faces the additional challenge of promoting better use of what is already known and what is being learned.

In general, the need is for two-way, dynamic processes that transform 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" efforts, the model that characterized earlier efforts in information diffusion and technology transfer.[97] Newly emerging information technologies almost certainly play a role in making such collaborations both effective and global in reach. Much, however, remains to be understood about the potential risks and opportunities posed by these new technologies, and about the social and technological infrastructures needed to assure their effective and

[93] *E.g.,* Margaret E. Keck & Kathryn Sikkink, ACTIVISTS BEYOND BORDERS: ADVOCACY NETWORKS IN INTERNATIONAL POLITICS (1998).
[94] *E.g.*, ELINOR OSTROM, GOVERNING THE COMMONS: THE EVOLUTION OF INSTITUTIONS FOR COLLECTIVE ACTION (1990); INSTITUTIONS FOR THE EARTH: SOURCES OF EFFECTIVE INTERNATIONAL ENVIRONMENTAL PROTECTION (Peter M. Haas et al. eds. 1993); COMMITTEE ON THE HUMAN DIMENSIONS OF GLOBAL CHANGE, NATIONAL RESEARCH COUNCIL, *supra* note 39; HUMAN CHOICE AND CLIMATE CHANGE (Steve Rayner & Elizabeth L. Malone eds. 1998); International Human Dimensions Programme on Global Environmental Change, *About IHDP*, *available at* http://www.uni-bonn.de/ihdp/ABOUT.HTML.
[95] *See* TODD SANDLER, GLOBAL CHALLENGES: AN APPROACH TO ENVIRONMENTAL, POLITICAL, AND ECONOMIC PROBLEMS (1997).
[96] BOARD ON SUSTAINABLE DEVELOPMENT, NATIONAL RESEARCH COUNCIL, *supra* note 1, at 296.
[97] *Id.* at 297.

equitable use.[98] Effective two-way collaborations have emerged in engineering, agricultural development, and renewable resource management, as well as in research-intensive private sector activities.[99] There is a continuing need to advance our understanding of what underlies these effective collaborations in the process of moving knowledge into action, to make that understanding part of the normal training for professionals engaged in research, and to apply it systematically to promote better use of existing knowledge to effectuate a sustainability transition.

Indeed, one implication of the emerging "collaborative" view of knowledge and technology dissemination is already clear. Making knowledge more usable means enhancing the capacity of groups around the world not only to use it, but also to critique and adapt it to their own place-specific contexts. This is as true for contemporary challenges of shaping useful assessments of climate change as it has been for the classical challenges 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. Nonetheless, programs that implement this realization remain largely inadequate.[100]

The Board concluded that 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: (1) linking long-term research programs to societal goals; (2) coupling global, national and local institutions into effective research systems; (3) integrating disciplinary knowledge in place-based, problem-driven research efforts; and (4) linking academia, government and the private sector in collaborative research partnerships. None of these needs is unique to sustainability science; strengthening our institutional capacity to address them will provide broad societal benefits. The requisite institutional forms and processes will be a function of the particular problems and places involved. Nonetheless, several general needs for the development of institutional capacity seem clear and are addressed below.

4.2 Linking research programs to societal goals

The Board's report repeatedly emphasized that some of the knowledge and know-how needed to navigate the transition toward sustainability will be produced without need for strategic design or priority setting by governments or international bodies. Given adequate support for curiosity-driven research, incentives for private sector research, and

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[98] *See* KNOWLEDGE SOCIETIES: INFORMATION TECHNOLOGY FOR SUSTAINABLE DEVELOPMENT (Robin Mansell & Uta Wehn eds. 1998) (prepared for the United Nations Commission on Science and Technology for Development).

[99] BOARD ON SUSTAINABLE DEVELOPMENT, NATIONAL RESEARCH COUNCIL, *supra* note 1, at 297.

[100] *See* UNITED NATIONS COMMISSION ON SUSTAINABLE DEVELOPMENT, OVERALL PROGRESS ACHIEVED SINCE THE UNITED NATIONS CONFERENCE ON ENVIRONMENT AND DEVELOPMENT (1997).

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, in meeting the goals of a transition toward sustainability that is unlikely to be produced through such channels. This knowledge includes most extensive monitoring data, much "public good" understanding on the interactions of social and environmental systems, and certain know-how lacking near term prospects for generating competitive returns on investment. To create and disseminate such knowledge, society needs to enhance its institutional capacity to design and sustain long-term research programs directly linked to sustainability goals.

In the United States, as in most other countries, the lack of such capacity is generally acknowledged.[101] 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, prioritizing 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 United States in certain areas of the space program (for example, Apollo), defense (for example, the Atlas rocket development) and health (for example, polio). Submissions to the UN Division of Sustainable Development show that a number of countries have made substantial progress towards the articulation of goals relevant to sustainability.[102] In addition, the European Union's 5th Framework Program for research and development (1998-2002) explicitly recognizes the link between sustainability goals and priority research programs.[103]

Forging similar long-term linkages in the U.S. political context will be particularly difficult given the government's fragmented approach to domestic and international policymaking.[104] In 1992, the Carnegie Commission advanced a number of general recommendations for enhancing the nation's capacity to link science and technology to societal goals; a number of follow up efforts are now in play. 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.[105] A focused effort is now needed to adapt these general recommendations to the challenges of designing long-term research programs in support of sustainability goals.

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[101] *See, e.g.*, CARNEGIE COMMISSION ON SCIENCE, TECHNOLOGY AND GOVERNMENT: ENVIRONMENTAL RESEARCH AND DEVELOPMENT: STRENGTHENING THE FEDERAL INFRASTRUCTURE (1992); CARNEGIE COMMISSION ON SCIENCE, TECHNOLOGY AND GOVERNMENT, INTERNATIONAL ENVIRONMENTAL RESEARCH AND ASSESSMENT: PROPOSALS FOR BETTER ORGANIZATION AND DECISION MAKING (1992) [hereinafter, CARNEGIE COMMISSION].

[102] *See* United Nations Division for Sustainable Development, *Sustainable Development Success Stories*, *available at* http://www.un.org/esa/sustdev/success.htm..

[103] *See* European Union, *The Fifth Framework Programme, 1998 to 2002, available at* http://www.cordis.lu/fp5/home.html.

[104] *See* ROGER B. PORTER & RAYMOND VERNON, FOREIGN ECONOMIC POLICYMAKING IN THE UNITED STATES (1989).

[105] BOARD ON SUSTAINABLE DEVELOPMENT, NATIONAL RESEARCH COUNCIL, *supra* note 1, at 299.

4.3 Building research systems

The knowledge base to support a transition toward 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 occurring at regional or even global scales. The Board concluded that we need better arrangements to unite local end-users—the corporations, the farmers, the households, the land use planning commissions, the regional research centers—with the international science and technology community in a global research system.[106] This system needs to link local use and the best that international science has to offer in a manner providing 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.[107] The design of an integrated research system of sustainability science must evolve independently. 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 Consultative Group on International Agricultural Research (CGIAR) of the World Bank, the United Nation's Food and Agricultural Organization (FAO), the United Nations Development Programme (UNDP), and the United Nations Environment Programme (UNEP)—with centers located in regions reflecting major sustainability challenges. As noted above, the Carnegie Commission on Science, Technology and Government has recommended one such CGIAR-derived approach.[108] The new efforts could well be based in or affiliated with the START centers of the IGBP and IHDP, or related institutions such as the Inter-American Institute for Global Change Research. Mandates for each institute should include research responsibility for one or more sustainability science issues of particular relevance to the region in which it is located, plus 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 research and development, and assess progress in energy, agriculture, environment and other priority areas as outlined in this paper. National capacity is also important in producing the knowledge and analysis necessary to

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[106] *Id.*

[107] In 1992, The Carnegie Commission suggested establishing a Consultative Group for Research on the Environment (CGREEN), patterned after the CGIAR. CARNEGIE COMMISSION, *supra* note 99, at 22. *See generally* AGRICULTURE, ENVIRONMENT AND HEALTH: SUSTAINABLE DEVELOPMENT IN THE 21ST CENTURY (Vernon W. Ruttan ed. 1994); THE INTERNATIONAL RESEARCH PARTNERSHIP FOR FOOD SECURITY AND AGRICULTURE, THE THIRD SYSTEM REVIEW OF THE CONSULTATIVE GROUP ON INTERNATIONAL AGRICULTURAL RESEARCH (CGIAR) (1998).

[108] *Id.*

enable national governments and national constituencies to make decisions about research priorities, technology development and investment, and to establish policies and programs advancing the sustainability transition. In the United States, a national mechanism should be developed to promote research and development on critical issues falling outside 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.[109]

In addition to national capacity, all countries except for the very smallest will need decentralized research, education, and training capacity at regional, local and firm levels. With appropriate incentives, decentralized systems can make important contributions to the generation, transfer and communication of locally relevant knowledge.[110] The network should be organized and funded in a manner providing incentives for it to contribute to local level concerns for a sustainability transition (for example, eutrophication of lakes or contamination of ground water) and to do what has been termed "routine science" (for example, monitoring or operational research) and technology development.

4.4 Supporting place-based research programs

Sustainability science requires making progress in institutional designs that foster integration of research planning and support across disciplines to address system interactions in particular regions and locales.[111] 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, plants, hydrology, or soils of a watershed than of their interactions. And we are far more likely to see studies assessing the implications of energy use on one region and land use change on another, than an integrated study examining how multiple human activities jointly affect a particular landscape. Within the U.S. science policy structure, the government has attempted to address these issues by using a variety of arrangements involving Presidential initiatives, lead agencies, multi-agency coordinating committees and task forces, and other mechanisms. None of these mechanisms have been uniformly successful..

That said, over the last decade, substantial progress has been made in bridging disciplinary and even, occasionally, sectoral perspectives to address problems of global

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[109] The Advanced Research Projects Agency (ARPA), later named the Defense Advanced Research Projects Agency, was established by the Department of Defense in 1958 to foster and fund cutting-edge research related to defense needs. The ARPA-supported work in universities let to the development of the internet and optical communications, among other accomplishments. For an account of ARPA's workings in supporting development of what became the internet, see THOMAS P. HUGHES, RESCUING PROMETHEUS (1998).
[110] *See* David W. Cash & Suzanne C. Moser, *Linking Global and Local Scales: Designing Dynamic Assessment and Management Processes*, 10 GLOBAL ENVIRONMENTAL CHANGE: HUMAN & POLICY DIMENSIONS 109 (2000).
[111] *See* NATIONAL SCIENCE BOARD, ENVIRONMENTAL SCIENCE AND ENGINEERING FOR THE 21ST CENTURY: THE ROLE OF THE NATIONAL SCIENCE FOUNDATION (2000).

environmental change.[112] Even this limited progress, however, has proven tenuous and enormously difficult to sustain.[113] 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 science and technology policy system that puts control of more research funds in the hands of place-based institutions with missions to promote 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 research and development.[114] Internationally, institutions such as the START system could – if properly supported –provide the testing ground for such integrative, place-based efforts.

4.5 Collaborative partnerships

Finally, the Board concluded that linkages that facilitate collaboration among academics, governmental and private sectors, and non-governmental actors in research partnerships are also needed to promote the sustainability transition. By now, it is 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.[115] 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.[116] We will need to enhance these collaborative efforts in order to maximize opportunities to harness science and technology to the sustainability transition.

Multi-sector research and development partnerships need not be formally codified. Indeed, 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.[117] While

[112] *See, e.g.,* UNITED STATES GLOBAL CHANGE RESEARCH PROGRAM, OUR CHANGING PLANET: THE FY 1999 US GLOBAL CHANGE RESEARCH PROGRAM: A REPORT BY THE SUBCOMMITTEE ON GLOBAL CHANGE RESEARCH (1998); COMMITTEE ON WATERSHED MANAGEMENT, *supra* note 50.

[113] NATIONAL RESEARCH COUNCIL, COMMITTEE ON GLOBAL CHANGE RESEARCH, *supra* note 33.

[114] BOARD ON SUSTAINABLE DEVELOPMENT, NATIONAL RESEARCH COUNCIL, *supra* note 1, at 302.

[115] *See* THE INTERNATIONAL RESEARCH PARTNERSHIP FOR FOOD SECURITY AND AGRICULTURE, *supra* note 104; *Global Research Systems for Sustainable Development: Agriculture, Health and Environment*, in AGRICULTURE, ENVIRONMENT AND HEALTH: SUSTAINABLE DEVELOPMENT IN THE 21ST CENTURY 358 (David E. Bell et al. eds. 1994).

[116] *See, e.g.*, Vicki Norberg-Bohm, *Stimulating 'Green' Technological Innovation: An Analysis of Alternative Policy Mechanisms*, 32 POL'Y SCIENCES 13 (1999).

[117] *See Defining successful partnerships and collaborations in scientific research: Hearing before the House Science Comm.* (March 11, 1998), *available at* 1998 WL 8993067 (statement of Lewis Branscomb, Aetna Professor, Emeritus, in Public Policy and Corporate Management, John F. Kennedy School of Government, Harvard University).

these exchanges often work reasonably well within nations mechanisms promoting two-way exchanges of scientists and engineers across national as well as sectoral boundaries must be strengthened.

Successful informal partnerships of the sort noted above may exist, however, there still remains a need to foster more structured cross-sectoral partnerships in order 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 sub-national level where organizational arrangements can be more readily tailored to specific needs and opportunities.[118]

This emphasis on cross-scale issues in institutional design reemphasizes the point made earlier regarding the importance of nurturing 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.

5 Conclusion

The challenge of mobilizing science and technology for a transition toward sustainability is daunting. This paper has summarized conclusions of the recent study on the subject by the Board on Sustainable Development of the National Research Council, published late in 1999 under the title *Our Common Journey: A transition toward sustainability*. The Board concluded that meeting the challenge of a sustainability transition will require that research and policy efforts move beyond their present focus on individual problems and impacts to address the interacting stresses and responses that are increasingly characterizing interactions between society and environment. Doing this will require that relevant knowledge 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 through 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, non-state 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 Board noted that we have no precedent for conducting such an enterprise in our national history. The role of science and technology in the agricultural, defense and health complexes may provide partial and instructive analogies. Each of these complexes involved collaboration among an extended community of universities, businesses and

[118] *See* HOUSE COMMITTEE ON SCIENCE, UNLOCKING OUR FUTURE: TOWARD A NEW NATIONAL SCIENCE POLICY (1998); David Guston, *Critical Appraisal in Science and Technology Policy Analysis: The Example of 'Science, the Endless Frontier'*, 30 POL'Y SCI. 233 (1997).

government agencies to address a specific set of social problems. Each also involved the development of mission-oriented laboratories and experiment "stations." These latter institutions were essential in promoting 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 we believe is increasingly needed.[119] 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 the Board's 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. It is past time to start thinking about developing the institutional capacity to fund and promote sustainability science in terms that are commensurate with the magnitude of the task ahead.

[119] I am indebted to Harvey Brooks of Harvard University for helping to clarify my thinking on the potential analogies discussed here.

6 Figure captions

Figure 1: (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. Some of the greatest, but least addressed, challenges and opportunities exist a midrange scales. (Source: OUR COMMON JOURNEY, *supra* note 1, at 286.)

Figure 2: Assessments of the importance of environmental hazards. (Source: OUR COMMON JOURNEY, *supra* note 1, at 190.)

Figure 3: Four interlinked, research-based components of sustainability science. (Source: OUR COMMON JOURNEY, *supra* note 1, at 281.)

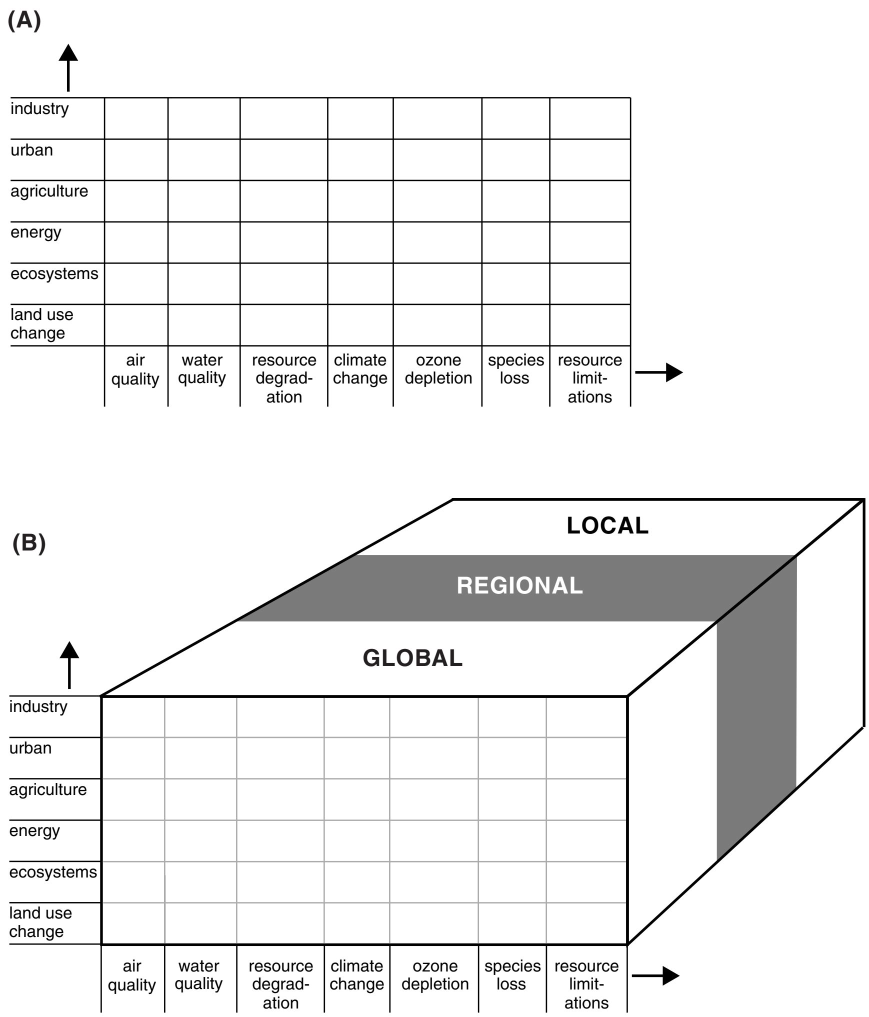
(A)
industry
urban
agriculture
energy
ecosystems
land use change
air quality
water quality
resource degrad-ation
climate change
ozone depletion
species loss
resource limit-ations
(B)
LOCAL
REGIONAL
GLOBAL
industry
urban
agriculture
energy
ecosystems
land use change
air quality
water quality
resource degrad-ation
climate change
ozone depletion
species loss
resource limit-ations

Fig. 6.2, A and B

Table 4.1
Left hand page

HAZARDS	Agenda 21	World Development Report	World Resources	The World Environment	A Moment on the Earth	The State of India's Environment	Global 2000	The Challenge of Man's Future
Freshwater—Biological Contamination								
Freshwater—Eutrophication								
Sedimentation								
Ocean Water								
Stratospheric Ozone Depletion								
Climate Change								
Acidification								
Ground Level Ozone Formation								
Metals and Toxics								
Toxic Air Pollution								
Indoor Air Pollutants—Radon								
Indoor Air Pollutants—Non-radon								
Radiation—Non-radon								
Chemicals in the Workplace								
Accidental Chemical Releases								
Food Contaminants								

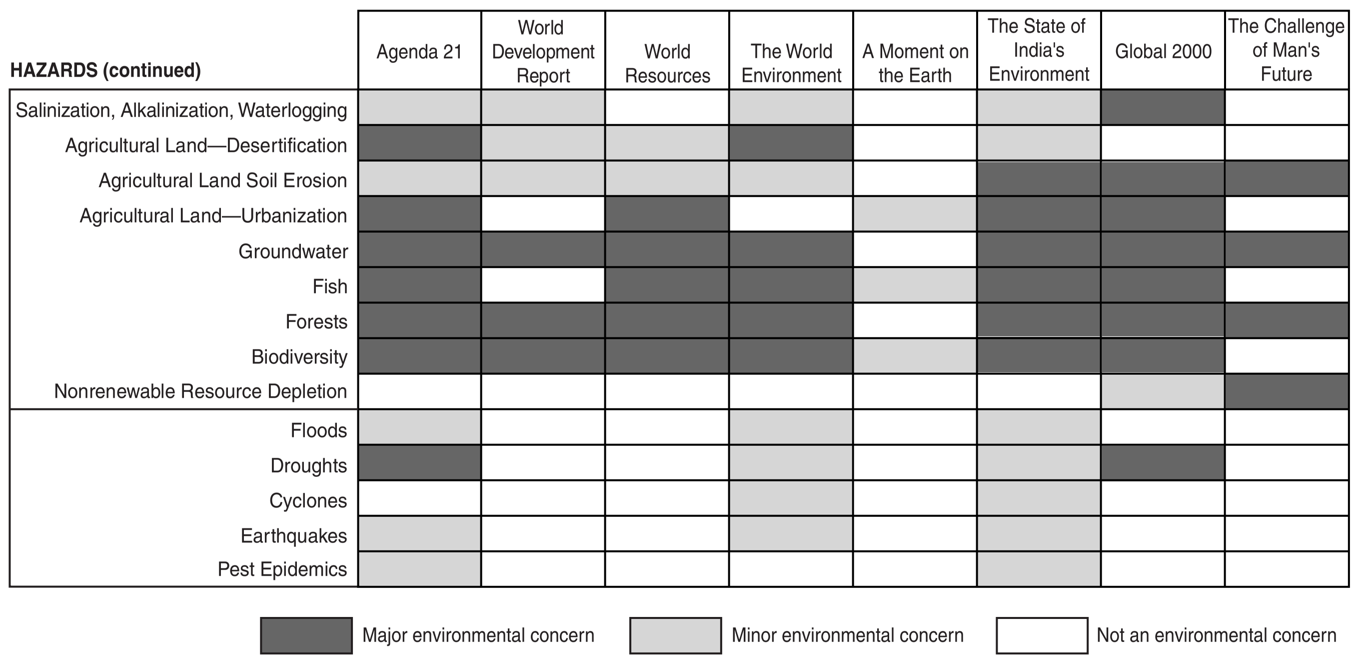

Table 4.1
right hand page

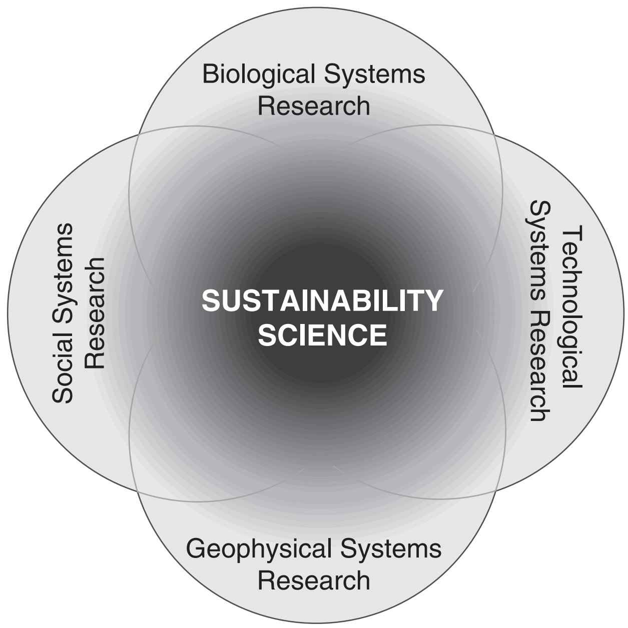
Biological Systems Research
Social Systems Research
SUSTAINABILITY SCIENCE
Technological Systems Research
Geophysical Systems Research

FIG 6.1