

# Belfer Center for Science & International Affairs

---

## Sustainability Science

Robert W. Kates, William C. Clark, Robert Corell, J. Michael Hall, Carlo C. Jaeger, Ian Lowe, James J. McCarthy, Hans Joachim Schellnhuber, Bert Bolin, Nancy M. Dickson, Sylvie Faucheux, Gilberto C. Gallopin, Arnulf Gruebler, Brian Huntley, Jill Jäger, Narpal S. Jodha, Roger E. Kasperson, Akin Mabogunje, Pamela Matson, Harold Mooney, Berrien Moore III, Timothy O’Riordan, Uno Svedin

2000-33

December 2000

**Research and Assessment Systems for Sustainability**  
Environment and Natural Resources Program





## CITATION, CONTEXT, AND PROGRAM ACKNOWLEDGEMENTS

This paper may be cited as: Kates, Robert W., William C. Clark, Robert Corell, J. Michael Hall, Carlo C. Jaeger, Ian Lowe, James J. McCarthy, Hans Joachim Schellnhuber, Bert Bolin, Nancy M. Dickson, Sylvie Faucheux, Gilberto C. Gallopin, Arnulf Gruebler, Brian Huntley, Jill Jäger, Narpat S. Jodha, Roger E. Kasperson, Akin Mabogunje, Pamela Matson, Harold Mooney, Berrien Moore III, Timothy O’Riordan, and Uno Svedin. 2000. “Sustainability Science.” Research and Assessment Systems for Sustainability Program Discussion Paper 2000-33. Cambridge, MA: Environment and Natural Resources Program, Belfer Center for Science and International Affairs, Kennedy School of Government, Harvard University. Also published as Kennedy School of Government Faculty Research Working Paper RWP00-018, and submitted to *Science*, December 2000. Available at <http://sust.harvard.edu>. Comments are welcome and may be directed to William Clark at the Belfer Center for Science and International Affairs, John F. Kennedy School of Government, Harvard University, 79 John F. Kennedy Street, Cambridge, MA 02138; Email: [William\\_Clark@harvard.edu](mailto:William_Clark@harvard.edu).

Robert Kates is an Independent Scholar in Trenton, ME; William Clark and Nancy Dickson are at the Kennedy School of Government, Harvard University; Robert Corell is with the Atmospheric Policy Program, American Meteorological Society and Harvard University; Carlo Jaeger and Hans Joachim Schellnhuber are at the Potsdam Institute for Climate Impact Research in Germany; J. Michael Hall is at the Office of Global Programs at the National Oceanic and Atmospheric Administration; Ian Lowe is at the School of Science at Griffith University in Australia; James J. McCarthy is at the Departments of Earth and Planetary Sciences and Organismic and Evolutionary Biology at Harvard University; Bert Bolin is at the Department of Meteorology, Stockholm University; Sylvie Faucheux is at the Centre d’Economie et d’éthique pour l’Environnement et le Développement, Université de Versailles; Gilberto C. Gallopin is with the Division of Environment and Human Settlements of the Economic Commission for Latin America and the Caribbean in Chile; Arnulf Gruebler is at the International Institute for Applied Systems Analysis in Austria; Brian Huntley is at the National Botanical Institute in South Africa; Jill Jäger is at the International Human Dimension Programme on Global Environmental Change in Germany; Narpat S. Jodha is at the International Centre for Integrated Mountain Development in Nepal; Roger E. Kasperson is at the Stockholm Environment Institute; Akin Mabogunje is at the Development Policy Centre in Nigeria; Pamela Matson is at the Department of Geological and Environmental Sciences, Stanford University; Harold Mooney is at the Department of Biological Sciences, Stanford University; Berrien Moore III is at the Institute for the Study of Earth, Oceans, and Space at the University of New Hampshire; Timothy O’Riordan is at the Centre for Social and Economic Research on the Global Environment, University of East Anglia; Uno Svedin is with the Swedish Council for Planning and Coordination of Research (FRN).

The Research and Assessment Systems for Sustainability Program seeks to foster the design and evaluation of strategies with which the next generation of national and international global environmental change programs might more effectively integrate and support its research, assessment and decision-support activities. In particular, we intend to catalyze and contribute to three interrelated lines of work: 1) broadening the science-defined agenda for studying global environmental change to engage more explicitly the socially defined agenda for sustainable development; 2) deepening a place-based, integrated understanding of social and ecological vulnerability to global change; and 3) exploring the design and management of systems that can better integrate research, assessment and decision support activities on problems of global change and sustainability. The program seeks to contribute to the evolution of strategies for pursuing these goals through collaboration among a small, international set of leading scholars and program managers involved in the production, assessment, and application of knowledge relating to global environmental change.

The Research and Assessment Systems for Sustainability Program is supported by a core grant from the National Science Foundation (NSF) (award BCS-0004236) with contributions from the National Oceanic and Atmospheric Administration's Office of Global Programs. The views expressed in this paper are those of the authors and do not imply endorsement by any of the supporting institutions.

Publications of the Research and Assessment Systems for Sustainability Program can be found on the SUST web site at <http://sust.harvard.edu>. Further information on the SUST Program can be obtained from the program's Executive Director: Nancy Dickson, Belfer Center for Science and International Affairs, Kennedy School of Government, Harvard University, 79 JFK Street, Cambridge, MA 02138, telephone (617) 496-9469, telefax (617) 495-8963, Email [nancy\\_dickson@harvard.edu](mailto:nancy_dickson@harvard.edu).

## **ABSTRACT**

The world's present development path is not sustainable. Efforts to meet the needs of a growing population in an interconnected but unequal and human-dominated world are undermining the Earth's essential life-support systems. Meeting fundamental human needs while preserving the life support systems of planet Earth will require a world-wide acceleration of today's halting progress in a transition toward sustainability. A significant response to this challenge has begun to emerge as a new field of sustainability science. This paper, written by a group of leading natural scientists, social scientists, and policy analysts from around the world, outlines the core questions of the field, the extensions of existing research strategies that will be required to address those questions successfully, and the institutional innovations that will be needed to develop an integrated system of research, assessment and decision support adequate for the task at hand.



## TABLE OF CONTENTS

|  |          |
|--|----------|
| <b>SUSTAINABILITY SCIENCE</b> .....                    | <b>1</b> |
| <b>CORE QUESTIONS FOR SUSTAINABILITY SCIENCE</b> ..... | <b>1</b> |
| <b>RESEARCH STRATEGIES</b> .....                       | <b>2</b> |
| <b>INSTITUTIONS AND INFRASTRUCTURE</b> .....           | <b>3</b> |
| <b>NEXT STEPS</b> .....                                | <b>4</b> |
| <b>FIGURES</b> .....                                   | <b>5</b> |
| <b>ENDNOTES</b> .....                                  | <b>7</b> |

## SUSTAINABILITY SCIENCE

The world's present development path is not sustainable. Efforts to meet the needs of a growing population in an interconnected but unequal and human-dominated world are undermining the Earth's essential life-support systems.<sup>1</sup> The extraordinary complexity of the challenges that lie ahead is suggested by today's emerging interactions among global environmental changes and the profound transformations underway in social and economic life. These include such diverse alterations of the earth as climate warming, land transformation, and loss of biological diversity, together with social transitions including a population that is growing more slowly, while aging and urbanizing; an economy that is globalizing while increasing both wealth and inequality in the face of persisting poverty; and a system of resource utilization that in the energy, manufacturing and agricultural sectors is making more with less even as it increases its overall demands on the earth to unprecedented levels.<sup>2</sup>

Meeting fundamental human needs while preserving the life support systems of planet Earth will require a world-wide acceleration of today's halting progress in a transition toward sustainability. A significant response to this challenge from the scientific community has begun to emerge from various global and regional programs of environmental research,<sup>3</sup> from the World's Scientific Academies (including individual reports from the African, Brazilian, and United States academies),<sup>4</sup> from independent networks of scholars and scientists,<sup>5</sup> and from the recent Friibergh workshop on sustainability science.<sup>6</sup> Above all, a response has begun to emerge from science itself and the growing recognition across many disciplines of the need for synthesis and integration – needs that are being reflected in many new multidisciplinary research efforts and institutions.<sup>7</sup> These various scientific efforts to promote the goals of a sustainability transition – meeting human needs while preserving the life support systems of the earth<sup>8</sup> – are leading to the emergence of a new field of sustainability science.

## CORE QUESTIONS FOR SUSTAINABILITY SCIENCE

Sustainability science focuses on the dynamic interactions between nature and society. Substantial understanding of those interactions has been gained in recent decades through work in environmental science that includes human action on the environment and environmental impacts on humans, work in social and development studies that seeks to account for environmental influences, and a small but growing body of interdisciplinary research.<sup>9</sup> But we urgently need to move beyond these beginnings to shape a better general understanding of the rapidly growing interdependence of the nature-society system.

A growing body of evidence and experience suggests that the needed understanding must encompass the interaction of global processes with the ecological and social characteristics of particular places and sectors.<sup>10</sup> The regional character of much of what sustainability science is trying to explain means that relevant research will have to learn how to integrate the effects of key processes across the full range of scales from local to global.<sup>11</sup> It will also require fundamental advances in our ability to address such issues as the behavior of complex self-organizing systems, the responses, some irreversible, of the nature-society system to multiple and interacting stresses, and the options for combining different ways of knowing and learning so that social actors with different agendas can act in concert under conditions of uncertainty and limited information.

With a view toward promoting the research necessary to achieve such advances, we propose in Box 1 an initial set of core questions for sustainability science. These are meant to complement the core questions of existing global change programs by focusing research attention on both the fundamental character of *interactions* between nature and society and on society's capacity to guide those interactions along more sustainable trajectories.



---

### Box 1: Core Questions of Sustainability Science

1. How can the dynamic interactions between nature and society – including lags and inertia – be better incorporated in emerging models and conceptualizations that integrate the Earth system, human development, and sustainability?<sup>12</sup>
2. How are long-term trends in environment and development, including consumption and population, reshaping nature-society interactions in ways relevant to sustainability?<sup>13</sup>
3. What determines the vulnerability or resilience of the nature-society system in particular kinds of places and for particular types of ecosystems and human livelihoods?<sup>14</sup>
4. Can scientifically meaningful “limits” or “boundaries” be defined that would provide effective warning of conditions beyond which the nature-society systems incur a significantly increased risk of serious degradation?<sup>15</sup>
5. What systems of incentive structures – including markets, rules, norms and scientific information – can most effectively improve social capacity to guide interactions between nature and society toward more sustainable trajectories?<sup>16</sup>
6. How can today’s operational systems for monitoring and reporting on environmental and social conditions be integrated or extended to provide more useful guidance for efforts to navigate a transition toward sustainability?<sup>17</sup>
7. How can today’s relatively independent activities of research planning, monitoring, assessment, and decision support be better integrated into systems for adaptive management and societal learning?<sup>18</sup>

### RESEARCH STRATEGIES

The sustainability science that is necessary to address these questions differs to a considerable degree in structure, methods and content, from science as we know it. In particular, sustainability science will need to (i) span the range of spatial scales between such diverse phenomena as economic globalization and local farming practices; (ii) account for both the temporal inertia and urgency of processes like ozone depletion; (iii) deal with functional complexity such as is evident in recent analyses of environmental degradation resulting from multiple stresses; and (iv) recognize the wide range of outlooks regarding what makes usable knowledge within both science and society. Given the magnitude of these challenges, it is clear that incomplete knowledge, and limitations in our ability to utilize it, will permanently challenge sustainability science as it tries to link research to action and to reconcile scientific excellence with social relevance.

What does this mean for the organization of the scientific fabric? It means, in particular, that sustainability science research must be created through processes of co-production in which scholars and stakeholders interact to define important questions, relevant evidence, and convincing forms of argument. The pertinent actions are not ordered linearly in the familiar sequence of scientific inquiry, where action lies outside the research domain. Rather, these are combined in entangled patterns relating to the problem to be tackled and the practical constraints of inquiry. The climate change issue illustrates this entanglement. In it, all stages of scientific exploration and practical application (e.g., predictive models *and* preventive action, scenario exploration of the future *and* impacts analysis of the past, government review of science *and* scientists commenting on policy) are occurring simultaneously and influencing each other.<sup>19</sup>

In each single stage of sustainability science research, novel schemes and techniques have to be used, extended or invented. Spanning the large range of spatial scales involved may require the construction of “macro-scopes” that blend remote sensing with ground-truth in conceptually rigorous ways.<sup>20</sup> The problem of mismatch between the time scales of action and those of classic scientific hypothesis testing, publication, and international assessment or review might be reduced by systematic use of networks to organize expert judgment.<sup>21</sup> The challenge of complex outcomes from multiple stresses may be addressed by integrated place-based models that employ semi-qualitative representations of entire classes of dynamical behavior rather than seeking to predict exact trajectories into the future.<sup>22</sup> Inverse approaches that start from outcomes to be avoided and work backwards to identify relatively safe corridors could eventually circumvent many difficulties in standard environmental assessment and cost-benefit accounting.<sup>23</sup> Finally, new methodological approaches for decisions under a wide range of uncertainties in natural and socio-economic systems and their inertia are becoming available.<sup>24</sup>

The new quality of sustainability science makes explicit the character of social learning that was implicit in the scientific enterprise since its beginnings.<sup>25</sup> In a world put at risk by the unintended consequences of scientific progress, social trust in scientific knowledge claims and institutions cannot be taken for granted. Participatory procedures involving scientists, stakeholders, advocates, active citizens and users of knowledge are needed to transform knowledge claims into trustworthy, socially-robust, usable knowledge about the realities which matter in social and environmental change and in the transition to sustainability.<sup>26</sup> In addition, scientists will need to be increasingly sensitive to shifts in patterns of governance that could assist their endeavors.

## **INSTITUTIONS AND INFRASTRUCTURE**

The scientific infrastructure needed to effect a transition to sustainability must build upon and evolve in concert with existing institutions that have served the scientific community during this recent quarter century of remarkable progress. However, major inadequacies and institutional barriers in these existing systems will require innovative means to ensure that urgent research questions relating to interactions of nature and society are addressed. Progress in sustainability science will require the fostering of problem-driven, interdisciplinary research; building capacity for this research, particularly in developing countries; creating coherent systems of research planning, operational monitoring, assessment and application; and providing reliable financial support for all of these endeavors over the long term. These institutions for sustainability science must foster the development of capacities ranging from rapid appraisal of knowledge and know-how needs in specific field situations, through global operational observation and reporting systems, to long-term integrated research on nature-society interactions in key places and regions of the world.

Generating adequate scientific capacity and institutional support in developing countries is particularly urgent in order to enhance resilience in regions that are most vulnerable to the multiple stresses that arise from rapid, simultaneous changes in social and environmental systems. Existing and novel funding mechanisms involving philanthropic foundations, businesses, and governmental and intergovernmental bodies should be explored to support these endeavors.

Efforts to increase scientific capacity will take place within a context of very different funding patterns, environmental concerns, and research orientations, aggravated by a deepening digital divide (see Figure 1). But the opportunity to rapidly bridge this information gap, and to share knowledge and new technologies and their benefits to even the most remote and disadvantaged communities, is a real possibility for the early decades of this century. Some of the new infrastructure needs can be met with internet-oriented systems that link interdisciplinary research teams across regions and users of scientific

information with the scientists who provide it. A few institutions with wide ranging global capabilities are needed as well. But a comprehensive approach to capacity building will have to nurture in tandem with these global institutions many locally focused, trusted, and stable institutions that can integrate work situated in particular places and grounded in particular cultural traditions with the global knowledge system. Examples of such arrangements are few, but our experience includes such diverse examples as: mountain development in the Himalayas,<sup>27</sup> global ENSO forecasting and decision support systems in Africa,<sup>28</sup> scientific support for the Convention on Long-Range Transboundary Air Pollution in Europe,<sup>29</sup> the Yaqui Valley study of land-use change in Mexico,<sup>30</sup> and the Sustainable Cities Ph.D. program with its focus on Los Angeles.<sup>31</sup>

## **NEXT STEPS**

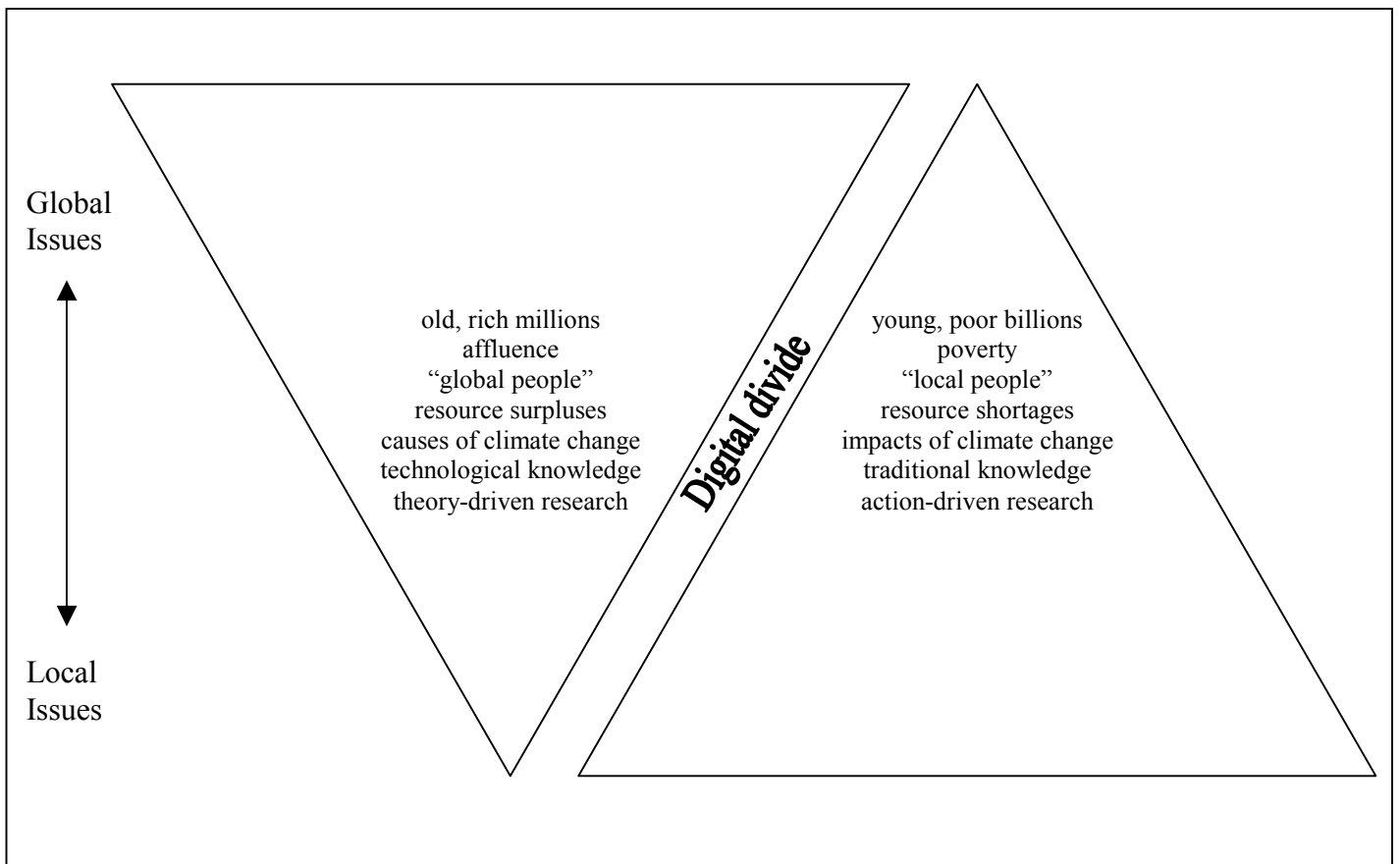
In the coming years, sustainability science needs to move forward along three pathways. First, there should be wide discussion within the scientific community, North and South, of the particular novelty of the approach, its key questions, appropriate methodologies and institutional needs. Meetings of scientific academies and scholarly communities need to advance discussions of content, systems of inquiry, and infrastructure support for sustainability science. International environmental research programs and many regional and national affiliates are undertaking reviews, planning exercises and institutional experiments to consider refocusing or broadening their programs. The World Academies of Science have made a commitment to generate, share, and disseminate science in support of a transition towards sustainability. Consultations in Africa, Asia, Europe, Latin America, and North America will consider the place of sustainability science in regional centers and local research efforts. Following such an extended period of consideration and reflection on the substance and strategy of sustainability science, attention should be given to required institutional innovations and ways of achieving them.<sup>32</sup>

A second pathway is to reconnect science to the political agenda for sustainable development, using in particular the forthcoming “Rio + 10” conference.<sup>33</sup> The idea of sustainable development emerged in the early 1980’s from scientific perspectives on the relationship between nature and society. Over the last 15 years, however, with few exceptions, science and technology have not been active partners in the societal and political process of sustainable development. Scientists helped construct an agenda for science but had little impact on subsequent action.<sup>34</sup> Ten years later the emergence of sustainability science offers a more pertinent opportunity to help guide nature-society interactions along sustainable trajectories throughout the globe.

A third is research itself, currently underway across the continents, in groups small and large, on the character of nature-society interactions, on improving our ability to guide those interactions along sustainable trajectories, and on ways of promoting the social learning that will be necessary to navigate the transition to sustainability. It is along this pathway – in the field, in the simulation laboratory, in the users’ meeting, and in the quiet study – that sustainability science will flourish.

## FIGURES

**Figure 1.** Sustainability Science within a Divided World. A cartoon-like view of the sharp contrast in both perceptions and realities of resource distribution between countries of the “North” and “South.” The research of the “North” is global in orientation, theory-driven, and draws upon technological knowledge. The much smaller research effort of the “South” is local in orientation, action-driven, and draws upon traditional knowledge. The socio-economic, environmental, and knowledge dichotomies are exacerbated by the deepening “digital divide.”





## ENDNOTES

---

<sup>1</sup> Kofi Annan, *We, the Peoples: The Role of the United Nations in the 21<sup>st</sup> Century* (United Nations, New York, 2000), <http://www.un.org/millennium/sg/report/full.htm>; National Research Council, Board on Sustainable Development, *Our Common Journey: A Transition Toward Sustainability* (National Academy Press, Washington, D.C., 1999), <http://www.nap.edu/catalog/9690.html>; Robert Watson, John A. Dixon, Steven P. Hamburg, Anthony C. Janetos, Richard H. Moss, *Protecting Our Planet, Securing Our Future* (UN Environment Programme, Nairobi, 1998), <http://www-esd.worldbank.org/planet/>; President's Committee of Advisers on Science and Technology (PCAST), Panel on Biodiversity and Ecosystems, *Teaming with Life: Investing in Science to Understand and Use America's Living Capital* (The White House, Washington, D.C., March 1998), <http://www.whitehouse.gov/WH/EOP/OSTP/Environment/html/teamingcover.html>; Peter M. Vitousek et al., "Human domination of the Earth's ecosystems," *Science* 277: 494-499 (1997).

<sup>2</sup> United Nations Environment Programme (UNEP), *Global Environmental Outlook 2000* (Earthscan, London, 2000), <http://grid.cr.usgs.gov/geo2000/>; J. R. McNeill, *Something New Under the Sun: An Environmental History of the 20<sup>th</sup> Century World* (Norton, New York, 2000); United Nations Development Programme (UNDP), *Human Development Report 1998: Human Development to Eradicate Poverty* (United Nations, New York, 1997), <http://www.undp.org/hdro/97.htm>; B. L. Turner II et al., eds., *The Earth as Transformed by Human Action: Global and Regional Changes in the Biosphere over the Past 300 Years* (Cambridge University Press, Cambridge, New York, 1990).

<sup>3</sup> These include the scientific programs advanced by the United Nations Economic and Social Council (UNESCO), *Science for the 21<sup>st</sup> Century: A New Commitment* (statement of the World Conference on Science held in Budapest in 1999), [http://www.unesco.org/science/wcs/eng/intro\\_framework.htm](http://www.unesco.org/science/wcs/eng/intro_framework.htm); the International Geosphere Biosphere Programme (IGBP), <http://www.igbp.kva.se/index.html>; the International Human Dimensions Programme on Global Environmental Change (IHDP), <http://www.uni-bonn.de/ihdp/>; the World Climate Research Programme (WCRP), <http://www.wmo.ch/web/wcrp/wcrp-home.html>; DIVERSITAS (the international programme of biodiversity science), <http://www.icsu.org/DIVERSITAS/>; START (the global change SysTem for Analysis, Research and Training), <http://www.start.org/>; the European Commission's *Fifth Framework Programme: Putting Research at the Service of the Citizen*, <http://www.cordis.lu/fp5/src/over.htm>; the United Nations Conference on Environment and Development (UNCED) *Agenda 21: The United Nations Programme of Action from Rio* (United Nations, New York, 1993), <http://www.un.org/esa/sustdev/agenda21.htm>; J. C. I. Dooge et al., eds., *An Agenda of Science for Environment and Development into the 21st Century* (Cambridge University Press, Cambridge, 1992).

<sup>4</sup> See the World's Scientific Academies' *Transition to Sustainability in the 21<sup>st</sup> Century* (Tokyo Summit of May 2000), [http://interacademies.net/intracad/tokyo2000.nsf/all/sustainability\\_statement](http://interacademies.net/intracad/tokyo2000.nsf/all/sustainability_statement); C. E. Rocha-Miranda, ed., "Transition to Global Sustainability: The Contributions of Brazilian Science" (Academia Brasileira de Ciências, Rio de Janeiro, 2000), [http://www.abc.org.br/eventos/trabsim99\\_en.htm](http://www.abc.org.br/eventos/trabsim99_en.htm); the African Academy of Sciences' Tunis Declaration: Millennial Perspective on Science, Technology and Development in Africa and its Possible Directions for the Twenty-first Century (Fifth General Conference of the African Academy of Sciences, Hammamet, Tunisia, 23-27 April 1999), [http://www.unesco.org/general/eng/programmes/science/wcs/meetings/afr\\_hammamet\\_99.htm](http://www.unesco.org/general/eng/programmes/science/wcs/meetings/afr_hammamet_99.htm); the United States National Research Council, Board on Sustainable Development, *Our Common Journey: A Transition Toward Sustainability* (National Academy Press, Washington, D.C., 1999), <http://www.nap.edu/catalog/9690.html>. To these reports from Academies of Science should also be added a remarkable series of *Annual Reports* by the German Advisory Council on Global Change (WGBU), [http://www.wbgu.de/wbgu\\_publications.html](http://www.wbgu.de/wbgu_publications.html).

<sup>5</sup> For example, the program of The Resilience Alliance, <http://www.resalliance.org/index.html> (2000); G. C. Gallopín, S. Funtowicz, M. O'Connor, J. Ravetz, "Science for the 21st century: From social contract to the scientific core," *International Journal of Social Science* 168 (In Press); Arnulf Grubler, "Managing the global environment," *Environmental Science and Technology* 34: 184A-187A (2000); Berrien Moore III, "Sustaining Earth's life support systems – The challenge for the next decade and beyond," *Global Change Newsletter* 41: 1-2 (2000); Timothy O'Riordan, "Environmental science on the move," in *Environmental Science for Environmental Management*, Timothy O'Riordan, ed. (Prentice Hall, Harlow, 2000), pp. 1-27; D. Yencken, D. Wilkinson, *Resetting the Compass: Australia's Journey Towards Sustainability* (CSIRO Publishing, Collingwood, 2000); S. Funtowicz,

---

M. O'Connor, eds., "Science for sustainable development," special issue of *International Journal of Sustainable Development* 2: 3 (1999); Jane Lubchenco, "Entering the century of the environment: A new social contract for science," *Science* 279: 491-497 (1998); P. Raskin, G. Gallopin, P. Gutman, A. Hammond, R. Swart, *Bending the Curve: Toward Global Sustainability*, A report of the Global Scenario Group, Stockholm Environment Institute PoleStar Series Report No. 8 (Stockholm Environment Institute, Stockholm, 1998), <http://www.gsg.org/gsgpub.html>; H. J. Schellnhuber, V. Wenzel, eds., *Earth System Analysis: Integrating Science for Sustainability* (Springer-Verlag, Berlin, 1998); Robert W. Kates, "Sustaining life on the earth," *Scientific American* 271(4): 114 (1994); German Advisory Council on Global Change (WBGU), *Conservation and Sustainable Use of the Biosphere* (Earthscan, London, 2001), [http://www.wbgu.de/wbgu\\_jg1999\\_engl.html](http://www.wbgu.de/wbgu_jg1999_engl.html).

<sup>6</sup> The Sustainability Science Workshop took place on October 10-14, 2000 at Friibergh Manor, Örsundsbro, Sweden. All of the authors of this article were workshop participants. It was hosted by the Swedish Council for Planning and Coordination of Research and made possible by financial contributions from the Swedish Council, the David and Lucile Packard Foundation, the Office of Global Programs, U.S. National Oceanic and Atmospheric Administration and other U.S. Global Change Agencies, and the U.S. National Science Foundation. The Organizing Committee included William C. Clark, Robert Corell, Bert Bolin, Robert Kates, Jane Lubchenco, John Schellnhuber and Uno Svedin. Further information on the workshop and its follow-up are tracked in the Sustainability Science Forum, <http://sustainabilityscience.org>.

<sup>7</sup> See, for example, the following essays from the *Global Change Newsletter* No. 38 (1999): Berrien Moore III, "Meeting tomorrow's challenges," p. 2; Coleen Vogel, "Facing the challenges of the new millennium," pp. 3-4; Jill Jaeger, "The IGBP Congress from an IHDP perspective," pp. 5-6; German Advisory Council on Global Change (WBGU), *Conservation and Sustainable Use of the Biosphere* (Earthscan, London, 2001), [http://www.wbgu.de/wbgu\\_jg1999\\_engl.html](http://www.wbgu.de/wbgu_jg1999_engl.html); National Science Board, *Environmental Science and Engineering for the 21st Century: The Role of the National Science Foundation* (National Science Board, Arlington, VA, 2000) <http://www.nsf.gov/pubs/2000/nsb0022/start.htm>; the European Commission's *Fifth Framework Programme: Putting Research at the Service of the Citizen*, <http://www.cordis.lu/fp5/src/over.htm>; Synthesis and integration of the sciences of sustainability are a major focus of the Global Change Open Science Conference (Amsterdam, July 2001), <http://www.sciconf.igbp.kva.se/fr.html>.

<sup>8</sup> The major documents addressing a sustainability transition employ a variety of conceptualizations, but nearly all define the transition in terms of these two major goals. See the analysis in National Research Council, Board on Sustainable Development, "Our common journey," in *Our Common Journey: A Transition Toward Sustainability* (National Academy Press, Washington, D.C., 1999), pp. 21-58, <http://www.nap.edu/catalog/9690.html>.

<sup>9</sup> A sampling of the kinds of interdisciplinary perspectives on which sustainability science is building includes Thomas E. Graedel, "The evolution of industrial ecology," *Environmental Science and Technology* 34(1): 28A-31A (2000); Timothy O'Riordan, Chris Church, "Synthesis and context," in *Globalism, Localism and Identity: Fresh Perspectives on the Transition to Sustainability in Europe* (Earthscan, London, 2000); Jeffrey D. Sachs, "A new map of the world," *The Economist* 355: 81-83 (June 24, 2000); Anders Wijkman, "Sustainable development requires integrated approaches," *Policy Sciences* 32(4): 345-350 (1999); Fikret Berkes, Carl Folke, eds., *Linking Social and Ecological Systems: Management Practices and Social Mechanisms for Building Resilience* (Cambridge University Press, Cambridge, 1998); Narpal S. Johda, "Reviving the social system—ecosystem links in the Himalayas," in *Linking Social and Ecological Systems*, Fikret Berkes, Carl Folke, eds. (Cambridge University Press, Cambridge, 1988), pp. 285-310; Peter Cebon, Urs Dahinden, Huw Davies, Dieter Imboden, Carlo G. Jaeger, eds., *Views from the Alps: Regional Perspectives on Climate Change* (MIT Press, Cambridge, 1998); Gretchen Daily, Partha Dasgupta, Bert Bolin, Pierre Crosson, et al., "Food production, population growth, and the environment," *Science* 281:1291-1292 (1998); Pamela A. Matson, Rosamond Naylor, Ivan Ortiz-Monasterio, "Integration of environmental, agronomic, and economic aspects of fertilizer management," *Science* 280: 112-115 (1998); Steve Rayner, E. L. Malone, eds., *Human Choice and Climate Change* (Batelle Press, Columbus, Ohio, 1998); Jared M. Diamond, *Guns, Germs, and Steel: The Fates of Human Societies* (W. W. Norton and Company, New York, 1997); S. Faucheux, M. O'Connor, J. van der Straaten, eds., *Sustainable Development: Concepts Rationalities and Strategies* (Kluwer, Dordrecht, 1997); Keith Pezzoli, "Sustainable development: A transdisciplinary overview of the literature," *Journal of Environmental Planning and Management* 40(5): 549-574 (1997); J. Kasperson, R. E. Kasperson, B. L. Turner II, eds., *Regions at Risk: Comparisons of Threatened Environments* (United Nations University Press, Tokyo, 1995);



---

W. C. Clark, R. E. Munn, eds., *Sustainable Development of the Biosphere* (Cambridge University Press, Cambridge, 1986); R. W. Kates, J. H. Ausubel, M. Berberian, eds., *Climate Impact Assessment: Studies of the Interaction of Climate and Society*, ICSU/SCOPE Report No. 27 (John Wiley, Chichester, 1985).

<sup>10</sup> National Research Council, Committee on Global Change Research, *Global Environmental Change: Research Pathways for the Next Decade* (National Academy Press, Washington, D.C., 1999), p. 533, <http://www.nap.edu/catalog/5992.html>. National Research Council, Board on Sustainable Development, *Our Common Journey: A Transition Toward Sustainability* (National Academy Press, Washington, D.C., 1999), p. 8, <http://www.nap.edu/catalog/9690.html>; C. S. Holling, "Regional responses to global change," *Conservation Ecology* 1(2): 3 (1997), <http://www.consecol.org/vol1/iss2/art3>; German Advisory Council on Global Change (WBGU), *World in Transition: The Research Challenge*, Annual Report 1996 (Springer-Verlag, Berlin, 1997), [http://www.wbgu.de/wbgu\\_publications.html](http://www.wbgu.de/wbgu_publications.html).

<sup>11</sup> David W. Cash, Susanne C. Moser, "Linking global and local scales: Designing dynamic assessment and management processes," *Global Environmental Change* 10(2): 109-120 (2000); Clark Gibson, Elinor Ostrom, Toh-Kyeong Ahn, "The concept of scale and the human dimensions of global change: A survey," *Ecological Economics* 32(2): 217-239 (2000); Thomas J. Wilbanks, Robert W. Kates, "Global change in local places: How scale matters," *Climatic Change* 43(3): 601-628 (1998); G. Peterson, C. R. Allen, C. S. Holling, "Ecological resilience, biodiversity, and scale," *Ecosystems* 1(1): 6-18 (1998); Thomas Rosswal, Robert G. Woodmansee, Paul G. Risser, *Scales and Global Change: Spatial and Temporal Variability in Biospheric and Geospheric Processes* (John Wiley and Sons, New York, 1988); William C. Clark, "Scales of climate impacts," *Climatic Change* 7: 5-27 (1985).

<sup>12</sup> For discussions of existing work on, and possible approaches to, this question see International Geosphere Biosphere Programme, "global analysis, integration and modeling," <http://gaim.unh.edu/> (2000); H. J. Schellnhuber, "Earth system analysis and the second Copernican revolution," *Nature* 402: C19-23 (1999); National Research Council, Committee on Global Change Research, *Global Environmental Change: Research Pathways for the Next Decade* (National Academy Press, Washington, D.C., 1999), p. 531ff, <http://www.nap.edu/catalog/5992.html>; National Research Council, Board on Sustainable Development, "Exploring the future," in *Our Common Journey: A Transition Toward Sustainability* (National Academy Press, Washington, D.C., 1999), pp. 133-184, <http://www.nap.edu/catalog/9690.html>.

<sup>13</sup> For a critical discussion of contemporary thinking on trends shaping a sustainability transition, see National Research Council, Board on Sustainable Development, "Trends and transitions," in *Our Common Journey: A Transition Toward Sustainability* (National Academy Press, Washington, D.C., 1999), pp. 59-132, <http://www.nap.edu/catalog/9690.html>; Arnulf Grübler, *Technology and Global Change* (Cambridge University Press, Cambridge, 1998); D. S. Landes, *The Wealth and Poverty of Nations: Why Some are so Poor and Some so Rich* (W. W. Norton and Co., New York, 1998); United Nations, *Critical Trends: Global Change and Sustainable Development* (United Nations, New York, 1997); M. Gell-Mann, *The Quark and the Jaguar: Adventures in the Simple and Complex* (W. H. Freeman, New York, 1994); J. G. Speth, "The transition to a sustainable society," *Proceedings of the National Academy of Sciences* 89: 870-872 (1992); William C. Clark, "Visions of the 21<sup>st</sup> century: Conventional wisdom and other surprises in the global interactions of population, technology and environment," in *Perspective 2000: Proceedings of a conference sponsored by the Economic Council of Canada*, K. Newton, T. Schweitzer, J. P. Voyer, eds. (Economic Council of Canada, Ottawa, 1988), pp. 7-32.

<sup>14</sup> An overview of current thinking on vulnerability is given in W. C. Clark et al., "Assessing Vulnerability to Global Environmental Risks," Report of the Workshop on Vulnerability to Global Environmental Change, 22-25 May 2000, Airlie House, Warrenton, Virginia. Research and Assessment Systems for Sustainability Program Discussion Paper 2000-12 (Environment and Natural Resources Program, Belfer Center for Science and International Affairs, Kennedy School of Government, Harvard University, Cambridge, MA, 2000), <http://ksgnotes1.harvard.edu/BCSIA/sust.nsf/pubs/pub1>; and Thomas E. Downing, "Toward a vulnerability science," *IHDP Update* 2000 (3) <http://www.uni-bonn.de/ihdp/IHDPUpdate0003/contents.htm>. Representative research is reported in Thomas E. Downing et al., *Climate Change Vulnerability: Toward a Framework for Understanding Adaptability to Climate Change* (Environmental Change Unit, University of Oxford, Oxford, 2000); S. C. Lonergan, ed., *Environmental Change, Adaptation, and Security* (Kluwer, Dordrecht, 1999); Roger E. Kasperson, Jeanne X. Kasperson, B.L. Turner II, "Risk and criticality: Trajectories of regional environmental



---

degradation,” *Ambio* 28(6): 562-68 (1999); Coleen Vogel, *LUCC Newsletter* 3, 15 (1999), <http://www.uni-bonn.de/iudp/lucc/publications/luccnews/news3/coleen.html>; George E. Clark et al., “Assessing the vulnerability of coastal communities to extreme storms: The case of Revere, MA., USA.,” *Mitigation and Adaptation Strategies for Global Change* 3: 59-82 (1998); Coleen Vogel, “Vulnerability and global environmental change,” *LUCC Newsletter* 3: 1-13 (1998); Susan L. Cutter, “Vulnerability to environmental hazards,” *Progress in Human Geography* 20(4): 529-539 (1996); Jesse C. Ribot, Antonio Rocha Magalhaes, Stahis Panagides, eds., *Climate Variability, Climate Change and Social Vulnerability in the Semi-Arid Tropics* (Cambridge University Press, Cambridge, 1996).

The current state of the debate on system resilience can be sampled in G. D. Peterson, “Scaling ecological dynamics: Self-organization, hierarchical structure, and ecological resilience,” *Climatic Change* 44(3): 291-309 (2000); L. Gunderson, “Resilience, flexibility and adaptive management—antidotes for spurious certitude?” *Conservation Ecology* 3(1): 7 (1999), <http://www.consecol.org/vol3/iss1/art7>; C. S. Holling, “Engineering resilience vs. ecological resilience,” in *Engineering within Ecological Constraints*, P. C. Schulze, ed. (National Academy Press, Washington, D.C., 1996), pp. 31-43; D. Tilman, J. A. Downing, “Biodiversity and stability in grasslands,” *Nature* 367: 363-365 (1994).

<sup>15</sup> The problematical nature of contemporary concepts of carrying capacity, critical loads, irreversibility and thresholds are reviewed in M. S. Cresser, “The critical loads concept: Milestone or millstone for the new millennium?” *Science of the Total Environment* 249(1-3): 51-62 (2000); R. A. Skeffington, “The use of critical loads in environmental policy making: A critical appraisal,” *Environmental Science and Technology* 33(11): 245A-252A (1999); S. R. Carpenter, D. Ludwig, W. A. Brock, “Management of eutrophication for lakes subject to potentially irreversible change,” *Ecological Applications* 9(3): 751-771 (1999); K. Arrow, B. Bolin, R. Costanza, P. Dasgupta, C. Folke, C. S. Holling, B. O. Jansson, S. Levin, K. G. Maler, C. Perrings, D. Pimentel, “Economic growth, carrying capacity, and the environment,” *Ecological Applications* 6(1): 13-15 (1996); G. C. Daily, P. R. Ehrlich, “Socioeconomic equity, sustainability, and Earth's carrying capacity,” *Ecological Applications* 6(4): 991-1001 (1996); J. E. Cohen, “Population growth and earth's human carrying capacity,” *Science* 269: 341-346 (1995); C. S. Holling, “The resilience of terrestrial ecosystems: Local surprise and global change,” in *Sustainable Development of the Biosphere*, W. C. Clark, R. E. Munn, eds. (Cambridge University Press, Cambridge, 1986).

<sup>16</sup> An excellent review of the problem of incentives from a multi-problem perspective is T. Sandler, *Global Challenges: An Approach to Environmental, Political, and Economic Problems* (Cambridge University Press, Cambridge, 1997). A sampling of additional perspectives is provided by L. H. Goulder, I. W. H. Parry, R. C. Williams et al., “The cost-effectiveness of alternative instruments for environmental protection in a second-best setting,” *Journal of Public Economics* 72(3): 329-360 (1999); F. Schneider, J. Volkert, “No chance for incentive-oriented environmental policies in representative democracies? A public choice analysis,” *Ecological Economics* 31(1): 123-138 (1999); J. B. Wiener, “Global environmental regulation: Instrument choice in legal context,” *Yale Law Journal* 108(4): 677-800 (1999); B. Gustafsson, “Scope and limits of the market mechanism in environmental management,” *Ecological Economics* 24(2-3): 259-274 (1998); N. O. Keohane, R. L. Revesz, R. N. Stavins, “The choice of regulatory instruments in environmental policy,” *Harvard Environmental Law* 22(2): 313-367 (1998); E. Gawel, “Mixed instrument strategy in environmental policy: Economic considerations on a new policy approach,” *Jahrbuch Sozialwissenschaft* 43 (2): 267-286 (1992).

<sup>17</sup> An especially insightful discussion of the role of indicator and information systems is provided in Donella Meadows, *Indicator and Information Systems for Sustainable Development: A Report to the Balaton Group* (The Sustainability Institute, Hartland Four Corners, VT, 1998), [http://iisd1.iisd.ca/pdf/s\\_ind\\_2.pdf](http://iisd1.iisd.ca/pdf/s_ind_2.pdf); and Kai N. Lee, *Compass and Gyroscope* (Island Press, Washington, D.C., 1993). A review of challenges currently facing the field are given in National Research Council, Board on Sustainable Development, “Reporting on the transition,” *Our Common Journey: A Transition Toward Sustainability* (National Academy Press, Washington, D.C., 1999), pp. 233-274, <http://www.nap.edu/catalog/9690.html>.

<sup>18</sup> An overview of the historical performance of such systems is given in D. E. Bell, W. C. Clark, V. W. Ruttan. “Global research systems for sustainable development: agriculture, health and environment,” in *Agriculture, Environment and Health: Sustainable Development in the 21st Century*, V.W. Ruttan, ed. (University of Minnesota Press, Minneapolis, 1994), pp. 358-379. More recent developments are outlined in David W. Cash, “Distributed assessment systems: An emerging paradigm of research, assessment and decision making for environmental

---

change,” *Global Environmental Change* 10(4): 241-244 (2000); David H. Guston, William Clark, Terry Keating, David Cash, Susanne Moser, Clark Miller, Charles Powers, “Report of the Workshop on Boundary Organizations in Environmental Policy and Science,” 9-10 December 1999, Bloustein School of Planning and Public Policy, Rutgers University, Belfer Center for Science and International Affairs (BCSIA) Discussion Paper 2000-32 (Environmental and Occupational Health Sciences Institute at Rutgers University and UMDNJ-RWJMS, New Brunswick, NJ; Global Environmental Assessment Project, Environment and Natural Resources Program, Kennedy School of Government, Harvard University, Cambridge, MA, 2000), <http://environment.harvard.edu/gea/pubs/huru1.html>; B. L. Johnson, “Introduction to the special feature: Adaptive management - scientifically sound, socially challenged?” *Conservation Ecology* 3(1): 10 (1999), <http://www.consecol.org/vol3/iss1/art10>; L. Gunderson, “Resilience, flexibility and adaptive management - - antidotes for spurious certitude?” *Conservation Ecology* 3(1): 7 (1999), <http://www.consecol.org/vol3/iss1/art7>; Thomas M. Parris, C. A. Zracket, W. C. Clark, “Usable Knowledge for Managing Responses to Global Environmental Change: Recommendations to Promote Collaborative Assessments and Information Systems,” Belfer Center for Science and International Affairs (BCSIA) Discussion Paper E-98-26 (Environment and Natural Resources Program, Kennedy School of Government, Harvard University, Cambridge, MA, 1998), <http://environment.harvard.edu/gea/pubs/e-98-26.html>; C. Walters, “Challenges in adaptive management of riparian and coastal ecosystems,” *Conservation Ecology* 1(2):1 (1997), <http://www.consecol.org/vol1/iss2/art1>.

<sup>19</sup> Bert Bolin, The Intergovernmental Panel on Climate Change (IPCC). Prepared for the *UNEP Encyclopedia on the Global Environment* (forthcoming).

<sup>20</sup> See, for example, the program of The Center for the Study of Institutions, Population, and Environmental Change (CIPEC), <http://www.cipec.org/foundations/> (2000); proposals by H. J. Schellnhuber, “‘Earth system’ analysis and the second Copernican revolution,” *Nature* 402: C19-23 (1999); and the review by the National Research Council, Committee on the Human Dimensions of Global Change, *People and Pixels: Linking Remote Sensing and Social Science* (National Academy Press, Washington, D.C., 1998), <http://books.nap.edu/catalog/5963.html>.

<sup>21</sup> There is the buoyant field of so-called belief networks which formalize the process of causal hind-casting through expert judgment gradually improved by new pieces of information. See, for example, O. Varis, “A belief network approach to optimization and parameter estimation: Application to resource and environmental management,” *Artificial Intelligence* 101: 135-163 (1998); S. Kuikka, O. Varis, “Uncertainties of climatic change impacts in Finnish watersheds: A Bayesian network analysis of expert knowledge,” *Boreal Env. Res.* 2: 109-128 (1997); Olli Varis, “BeNe-EIA: A Bayesian approach to expert judgment elicitation with case studies on climate change impacts on surface waters,” *Climatic Change* 37(3): 539-564 (1997); Dave Upendra, “Probabilistic reasoning and Bayesian belief networks,” *Journal of the Operational Research Society* 47(5): 721-722 (1996); Bruce Abramson, “The design of belief network-based systems for price forecasting,” *Computers and Electrical Engineering* 20(2): 163-180 (1994); J. Pearl, *Probabilistic Reasoning in Intelligent Systems* (Morgan Kaufmann Pub., San Mateo, California, 1988).

<sup>22</sup> See, for example, G. Petschel-Held, M. K. B. Lüdeke, “Integrating case studies on global change by means of qualitative differential equations,” *Integrated Assessment* (forthcoming); Gerhard Petschel-Held et al., “Syndromes of global change: A qualitative modeling approach to assist global environmental management,” *Environmental Modeling and Assessment*, 4: 295-314 (1999); G. Brajnik, M. Lines, “Qualitative modeling and simulation of socio-economic phenomena,” *Internet Journal of Artificial Societies and Social Simulation*, 1(1) (1998), <http://www.soc.surrey.ac.uk/JASSS/1/1/2.html>; H. J. Schellnhuber, A. Block, M. Cassel-Gintz, J. Kropp, G. Lammel, W. Lass, R. Lienenkamp, C. Loose, M. K. B. Lüdeke, O. Moldenhauer, G. Petschel-Held, M. Plöchl, F. Reusswig, “Syndromes of global change,” *GAIA* 6: 19-34 (1997); German Advisory Council on Global Change (WGBU), “Designing a syndrome-based research structure: A case study on the Sahel syndrome,” in *World in Transition: The Research Challenge* (Springer, Berlin, 1996), section C6, [http://www.wbgu.de/wbgu\\_jg1996\\_kurz\\_engl.html](http://www.wbgu.de/wbgu_jg1996_kurz_engl.html); U. Heller, P. Struss, “Qualitative model composition and transformation for improving environmental decision support,” *Umweltinformatik Aktuell* 10: 358-367 (1996).

<sup>23</sup> See, for example, G. Yohe, F. Toth, “Adaptation and the guardrail approach to tolerable climate change policy,” *Climate Change* 43, 103-128 (2000); H. Dowlatabadi, “Climate change thresholds and guardrails for emissions,” *Climatic Change* 41: 297-301 (1999); G. Petschel-Held, H.J. Schellnhuber, T. H. Bruckner, F. L. Toth, K.

---

Hasselmann, "The tolerable windows approach: Theoretical and methodological foundations," *Climatic Change* 41: 303-331 (1999); G. Yohe, "The tolerable windows approach: Lessons and limitation," *Climatic Change* 41: 283-295 (1999); R. Swart, M. Berk, M. Janssen, E. Kreileman, R. Leemans, "The safe landing approach: Risks and trade-offs in climate change," in *Global Change Scenarios of the 21<sup>st</sup> Century – Results from the IMAGE 2.1 Model*, J. Alcamo, R. Leemans, E. Kreileman, eds. (Pergamon, Oxford, 1998); J. Alcamo, E. Kreileman, "Emission scenarios and global climate protection," *Global Environmental Change* 6 (4): 305-334 (1996).

<sup>24</sup> Jill Jaeger, ed., "The EFIEA Workshop on Uncertainty," (European Forum on Integrated Environmental Assessment, Baden-bei-Wien, July 1999), [http://www.vu.nl/english/o\\_o/instituten/IVM/research/efiea/badenrep.pdf](http://www.vu.nl/english/o_o/instituten/IVM/research/efiea/badenrep.pdf); A. Gritsevskiy, N. Nakicenovic, "Modeling uncertainty of induced technological change," *Energy Policy* 28: 907-921 (2000); A. Grubler, N. Nakicenovic, D. G. Victor, "Modeling technological change: Implications for the global environment," *Annual Review of Energy and the Environment* 24: 545-569 (1999); M. Ha-Duong, M. J. Grubb, J. C. Hourcade, "Influence of socio-economic inertia and uncertainty on optimal CO<sub>2</sub> emission abatement," *Nature* 390: 270-273 (1997); R. J. Lempert, M. E. Schlesinger, S. C. Bankes, "When we don't know the costs or the benefits: Adaptive strategies for abating climate change," *Climatic Change* 33: 235-274 (1996).

<sup>25</sup> Edward A. Parson, William C. Clark, "Sustainable development as social learning," in *Barriers and Bridges to the Renewal of Ecosystems and Institutions*, Lance H. Gunderson, C. S. Holling, S. S. Light, eds. (Columbia University Press, New York, 1995), pp. 428-460; Robert Brandom, *Making it Explicit: Reasoning, Representing, and Discursive Commitment* (Harvard University Press, Cambridge, 1988).

<sup>26</sup> Sylvie Faucheux, C. Hue, "Politique environnementale et politique technologique: Vers une prospective concertative," *Natures Sciences Sociétés* 8(3): 31-44 (2000); Sylvie Faucheux, M. O'Connor, "Technosphère vs ecosphère—choix technologiques et menaces environnementales: Signaux faibles, controverses et décisions," *Futuribles* 25: 29-59 (2000); S. O. Funtowicz, J. Ravetz, M. O'Connor, "Challenges in the utilisation of science for sustainable development," *International Journal of Sustainable Development* 1(1): 99-108 (1998); Michael Gibbons, Helga Nowotny, Camille Limoges, Simon Schwartzman, Peter Scott, Martin Trow, *The New Production of Knowledge: The Dynamics of Science and Research in Contemporary Societies* (Sage, London, 1994).

<sup>27</sup> Narpat S. Johda, "Reviving the social system—ecosystem links in the Himalayas," in *Linking Social and Ecological Systems*, Fikret Berkes, Carl Folke, eds. (Cambridge University Press, Cambridge, 1998).

<sup>28</sup> Anthony Patt, "Communicating Probabilistic Forecasts to Decision Makers: A Case Study of Zimbabwe," Belfer Center for Science and International Affairs (BCSIA) Discussion Paper 2000-19 (Environment and Natural Resources Program, Kennedy School of Government, Harvard University, Cambridge, MA, 2000), <http://environment.harvard.edu/gea/pubs/2000-19.html>.

<sup>29</sup> Willemijn Tuinstra, Leen Hordijk, Markus Amann, "Using computer models in international negotiations," *Environment* 41(9): 32-42 (1999).

<sup>30</sup> Pamela Matson, R. Naylor, I. Ortiz-Monasterio, "Integration of environmental, agronomic and economic aspects of fertilizer management," *Science* 280: 112-116 (1998).

<sup>31</sup> Sustainable Cities Program, Environmental Sciences, Policy, and Engineering, University of Southern California, <http://www.usc.edu/dept/geography/ESPE/>.

<sup>32</sup> We have initiated an effort to track these rapidly developing discussions through the Sustainability Science Forum at [www.sustainabilityscience.org](http://www.sustainabilityscience.org).

<sup>33</sup> Developments in the planning of the Rio+10 review can be traced on the web page of the UN's Commission on Sustainable Development, <http://www.un.org/esa/sustdev/csd.htm>. The initial strategy document is United Nations General Assembly, "Ensuring effective preparations for the 10-year review of progress achieved in the Implementation of Agenda 21 and the Programme for the Further Implementation of Agenda 21: Report of the Secretary-General," UN General Assembly A/53/120 (United Nations, New York, 2000), <http://www.un.org/documents/ga/docs/55/a55120.pdf>.

---

<sup>34</sup> National Research Council, Board on Sustainable Development, “Our common journey,” in *Our Common Journey: A Transition Toward* (National Academy Press, Washington, D.C., 1999), pp. 21-58.