Earth Systems Science Partnership (ESSP)

**Description:** a partnership of four global change research programs (DIVERSITAS, IGBP, IHDP, and WCRP) for the integrated study of the Earth System, the changes that are occurring to the System and the implications of these changes for global sustainability.

**Research mission:**
The ESSP undertakes five types of activities:

1. Earth System analysis and modeling, via collaboration among existing projects/activities of the four constituent programs.
2. Joint projects on issues of global sustainability, designed to address the global change aspects of a small number of critical issues for human well-being; carbon cycle/energy systems; food systems, water resources, and human health.
3. Regional activities, including capacity building, networking, and integrated regional studies.
4. Global Change Open Science Conferences, the first of which was Challenges of a Changing Earth, held in Amsterdam in July 2001. The second Open Science Conference is scheduled for 2006.
5. Communication activities, currently under development. These include an ESSP website, a report series, a common design profile for the joint projects and a proposed biannual newsletter.

**Research priorities:**
Joint Projects:

**Global Carbon Project (GCP)**
*Contact:* Pep Canadell, Executive Officer
*E-mail:* Pep.Canadell@csiro.au

**Global Environmental Change and Food Systems (GECAFS)**
*Contact:* John Ingram, GECAFS Officer
*E-mail:* jsii@ceh.ac.uk

**Global Water System Project (GWSP)**
*Contact:* Holger Hoff, Interim Executive Officer
*E-mail:* hhoff@pik-potsdam.de
*Website:* [http://www.gwsp.org](http://www.gwsp.org)

**Earth System analysis and modeling**

**Regional Activities**

**Science Themes:**

**Patterns and Variability:** What are the current geographical and temporal distributions of the major pools and fluxes in the global carbon cycle?
Processes and Interactions: What are the control and feedback mechanisms - both anthropogenic and nonanthropogenic - that determine the dynamics of the carbon cycle?

Carbon Management: What are the likely dynamics of the carbon-climate-human system into the future, and what points of intervention and windows of opportunity exist for human societies to manage this system?

Website: http://www.ess-p.org/
Website: http://www.globalcarbonproject.org/

---

**DIVERSITAS**

**Description:** an international global environmental change research program.

**Research Priorities:** To promote integrative biodiversity science, linking biological, ecological and social disciplines in an effort to produce socially relevant new knowledge. To provide the scientific basis for an understanding of biodiversity loss, and to draw out the implications for the policies for conservation and sustainable use of biodiversity. 

http://www.diversitas-international.org/

---

**International Geosphere/Biosphere Program (IGBP)**

**Description:** IGBP Projects and Framework Activities-- The current IGBP structure is based on six IGBP Projects and two framework activities. The IGBP Projects study major components or processes within the Earth System and the framework activities undertake integrative or supporting work across the program.

**Research mission:** IGBP’s mission is to deliver scientific knowledge to help human societies develop in harmony with Earth’s environment. Our scientific objective is to describe and understand the interactive physical, chemical and biological processes that regulate the total Earth System, the unique environment that it provides for life, the changes that are occurring in this system, and the manner in which they are influenced by human actions.

**Research priorities:** IGBP is an international scientific research program built on interdisciplinarity, networking and integration. It addresses scientific questions where an international approach is the best or the only way to provide an answer. We add value to a large number of individual, national and regional research projects through integrating activities to achieve enhanced scientific understanding.
IGBP's integrating activities add value by:

- Developing common international frameworks for collaborative research based on agreed agendas.
- Forming research networks to tackle focused scientific questions.
- Promoting standardized methodologies.
- Guiding and facilitating construction of global databases.
- Undertaking model intercomparisons and comparisons with data.
- Facilitating efficient patterns of resource allocation.
- Undertaking analysis, synthesis and integration activities on broad Earth System themes.

**GAIM - Global Analysis, Integration and Modeling**

The goal of GAIM is to improve our understanding of how the Earth functions as a system using both data and models as tools. GAIM works closely with all Core Projects of IGBP, and is building increasing linkages with the World Climate Research Program (WCRP) and the International Human Dimensions Program on Global Environmental Change (IHDP) on the development and analysis of integrated data sets and linked models. The Task Force has traditionally focused its efforts on global biogeochemical cycles and their links to the hydrologic cycle and to the physical climate system, for natural systems as well as in the context of anthropogenic influences. The challenge to GAIM and its colleagues throughout IGBP, and in the WCRP and IHDP is to develop and apply a suite of Earth System models spanning a range of complexity that integrates the roles and interactions of physical climate, ecological systems, and human systems.

Contact:
Global Analysis, Integration and Modeling (GAIM)
Scientific Committee Chair: John Schellnhuber
**GAIM Scientific Steering Committee**
Executive Officer: Dork Sahagian
GAIM Task Force Office
Institute for the Study of Earth, Oceans & Space (EOS)
University of New Hampshire
Morse Hall, 39 College Road
Durham, NH 03824-3525 USA
Tel: (1-603) 862 3875
Fax: (1-603) 862 3874
E-mail: gaim@unh.edu
URL: gaim.unh.edu

**IGAC - International Global Atmospheric Chemistry**
The atmosphere is chemically complex and dynamic, interacting internally between troposphere and stratosphere, and externally with oceans, land, and biota. Although atmospheric composition varies naturally over time, it is now being markedly impacted by human activities. Concentrations of radiatively active ‘greenhouse’ gases and aerosols have risen sharply, the stratospheric ozone layer has thinned significantly over the poles, and rapid changes in a suite of other gases is potentially changing the role of the atmosphere in the Earth System. The goals of IGAC are to develop a fundamental understanding of the processes that determine atmospheric composition; understand the interactions between atmospheric chemical composition and physical, biospheric and climatic processes; and predict the impact of natural and anthropogenic forcings on the atmosphere’s chemical composition.

IGAC is co-sponsored by the Commission of Atmospheric Chemistry and Global Pollution (CACGP)

Contact:

International Global Atmospheric Chemistry (IGAC)

The IGAC Seattle Core Project Office (CPO)

Scientific Committee Co-Chairs: Tim Bates, Sandro Fuzzi, Shaw C. Liu
IGAC Scientific Steering Committee

Executive Officer: Sarah Masonis
IGAC International Project Office
NOAA Pacific Marine Environmental Laboratory
7600 Sandpoint Way NE
Seattle, WA 98115-6349
USA
Tel: (1-206) 543-6674
Fax: (1-206) 543-0308
E-mail: IGAC@noaa.gov
URL: http://www.igac.noaa.gov/

The IGAC Taipei Core Project Office (CPO)

Doris Chen
Institute of Earth Science
Academia Sinica
128 Academia Road
P.O. Box 1-55, Nankang
Taipei, Taiwan, 11529 ROC CHINA
Tel: +886 83 9910 ext 280
Fax: +886 227 88 0332
Email: igac.taipei@earth.sinica.edu.tw
SOLAS - Surface Ocean-Lower Atmosphere Study

SOLAS (Surface Ocean-Lower Atmosphere Study) is a new international research initiative sponsored by IGBP, the Commission on Atmospheric Chemistry and Global Pollution (CACGP) of the International Association of Meteorology and Atmospheric Sciences (IAMAS), and the Scientific Committee on Oceanic Research (SCOR) and the World Climate Research Program (WCRP), to carry out research at the interface between the oceans and the atmosphere. It became an IGBP Project in February 2001. It has as its goal:

To achieve quantitative understanding of the key biogeochemical-physical interactions and feedbacks between the ocean and the atmosphere, and how this coupled system affects and is affected by climate and environmental change.

SOLAS is focused on processes at the air-sea interface and includes a natural emphasis on the atmospheric and upper ocean boundary layers, while recognizing that some of the processes to be studied will, of necessity, be linked to significantly greater depth scales.

A fundamental characteristic of SOLAS is that the research is not only interdisciplinary (involving biogeochemistry, physics, mathematical modeling, etc.) but also involves closely coupled studies requiring marine and atmospheric scientists to work together, in line with the Earth System approach of IGBP Phase II.

SOLAS deals with the following issues or Foci.

Focus 1. Biogeochemical Interactions and Feedbacks Between Ocean and Atmosphere
The objective is to quantify feedback mechanisms involving biogeochemical coupling across the air-sea interface which can only be achieved by studying the ocean and atmosphere in concert. These couplings include emissions of trace gases of importance in atmospheric chemistry and climate, deposition of nutrients that control marine biological activity and carbon uptake, and the production of chemically-active particles by bubble bursting.

Focus 2. Exchange Processes at the Air-Sea Interface and the Role of Transport
and Transformation in the Atmospheric and Oceanic Boundary Layers
The objective is to develop a quantitative understanding of processes responsible for air-sea exchange of mass, momentum and energy to permit accurate calculation of regional and global fluxes. This requires establishing the dependence of these interfacial transfer mechanisms on physical, biological, and chemical factors within the boundary layers and the horizontal and vertical transport and transformation processes that determine these exchanges.

Focus 3 - Air-Sea Flux of CO2 and Other Long-Lived Radiatively Active Gases
The objective is to develop a quantitative understanding of the upper ocean mechanisms which create the regional, seasonal and interannual structure and variation of these fluxes in order to assess their sensitivity to variations in environmental forcing. The air-sea CO2 flux is a key inter-reservoir exchange within the global carbon cycle. Experimental, observational and modeling studies linking biological uptake, respiration, marine calcification and mixed-layer physics with upper ocean CO2 are necessary to predict changes in oceanic carbon uptake over the next century. The ocean also plays a key role in the global budgets of other long-lived radiatively gases including N2O and to some extent CH4.

There are several Common Issues to SOLAS, which includes modeling, remote sensing, time series, coastal zones, and paleo research.

The SOLAS science plan and other information are available on the SOLAS home page.

Contact:

Peter Liss, SOLAS Scientific Steering Committee Chair
School of Environmental Sciences,
University of East Anglia
Norwich NR4 7TJ
United Kingdom
Tel: +44 1603 592563
Fax: +44 1603 507714
Email: p.liss@uea.ac.uk
URL: http://www.solas-int.org

GCTE - Global Change and Terrestrial Ecosystems
GCTE studies the effects of changes in climate, atmospheric composition, and land use on the structure and functioning of terrestrial ecosystems, and how these effects lead to feedbacks to the atmosphere and the physical climate system. GCTE has four main focal areas: (i) the terrestrial carbon cycle with an emphasis on underlying drivers and processes of contemporary and future carbon quantities (fluxes and pools); (ii) vegetation dynamics and the processes that control them at the local and global scales, with an emphasis on landscape processes and patterns that dominate vegetation dynamics; (iii) impacts of global change on food production systems including the major
species that provide the bulk of food to humanity (e.g., wheat, rice) with the associated pests and diseases and biogeochemical consequences; (iv) the links between ecosystem functioning and biodiversity, and associated ecosystem stability, resilience, and buffering capacity to natural and human perturbations.

Contact:

Global Change and Terrestrial Ecosystems (GCTE)

Scientific Committee Chair: Louis F. Pitelka
GCTE Scientific Steering Committee

Executive Officer: Josep Canadell
GCTE International Project Office
CSIRO Land & Water
Pye Laboratory
PO Box 1666
Canberra ACT 2601
AUSTRALIA
Tel: (61-2) 6246 5630
Fax: (61-2) 6246 5560
E-mail: Rowena.Foster@csiro.au
URL: www.gcte.org

Focus 1: Ecosystem Physiology and Global Change
URL: gcte-focus1.org

Focus 2: Change in Ecosystem Structure
URL: www.gcte.org/focus2.htm

Focus 3 in the UK: Glocal Change Impact on Agriculture, Forestry and Soils
URL: mwnta.nmw.ac.uk/GCTEFocus3

Focus 4 in France: Global Change and Ecological Complexity
URL: www.gcte.org/gcte/focus4/

LUCC - Land-Use and Land-Cover Change (also see below)
The pace, magnitude and spatial reach of human alterations of the Earth's land surface are unprecedented. Among the most important are changes in land cover - biophysical attributes of the Earth's surface - as related to land use - human purpose or intent applied to these attributes. Land use and land cover change directly impacts biotic diversity worldwide, contributes to climate change, is the primary source of soil degradation, and, by altering ecosystem services, affects the ability of biological systems to support human needs. Such changes also determine, in part, the vulnerability of places and people to climatic, economic or socio-political perturbations. LUCC research addresses the problem of land use dynamics through comparative case
study analysis, addresses land cover dynamics through empirical observations and diagnostic models, and extends the understanding of cause-use-cover dynamics through integrated regional and global modeling.

Contact:

Land-Use and Land-Cover Change (LUCC)

Scientific Committee Chair: Eric F. Lambin
LUCC Scientific Steering Committee

Executive Officer: Helmut Geist
LUCC International Project Office
University of Louvain
place L. Pasteur 3
1348 Louvain-la-Neuve
BELGIUM
Tel: (32-10) 472 870
Fax: (32-10) 472 877
E-mail: geist@geog.ucl.ac.be
URL: http://www.geo.ucl.ac.be/LUCC

Focus 1
URL: http://www.indiana.edu/~act/focus1/
E-mail: focus1@indiana.edu

Focus 2
URL: http://shiba.iis.u-tokyo.ac.jp/LUCC/
E-mail: focus2@skl.iis.u-tokyo.ac.jp, shiba@skl.iis.u-tokyo.ac.jp

Focus 3
URL: http://www.lucc.nl/
Email: tom.veldkamp@geomin.beng.wau.nl

LOICZ - Land-Ocean Interactions in the Coastal Zone
LOICZ studies biogeochemical processes and changes in the fluxes of materials from within the river catchments to the coastal shelf boundaries, the influence of human activities on these changes, and the impact of flux changes on human welfare. The project has two major thrusts. The first is the development of horizontal and, to a lesser extent, vertical material flux models (or budgets) from continental basins through regional seas to continental ocean margins, based on our understanding of biogeochemical processes and data for coastal ecosystems and habitats and the human dimension. Here, the influence of human activities on these changes and the impact of flux changes on human welfare is a vital area of work. The second addresses the scaling of the material flux models at spatial scales from local to global levels and to
a lesser extent across temporal scales. LOICZ also provides science information to the global community, especially decision-makers and coastal zone managers.

Contact:

Land-Ocean Interactions in the Coastal Zone (LOICZ)

Scientific Committee Chair: Han J. Lindeboom
LOICZ Scientific Steering Committee

Executive Officer: Chris Crossland
LOICZ International Project Office
Netherlands Institute for Sea Research (NIOZ)
PO Box 59
NL-1790 AB Den Burg-Texel
NETHERLANDS
Tel: (31-222) 369 404
Fax: (31-222) 369 430
E-mail: mailto:loicz@nioz.nl
URL: www.noiz.nl/loicz

JGOFS - Joint Global Ocean Flux Study
The oceans contain about 50 times as much CO2 as the atmosphere, and small changes in the ocean carbon cycle can have large atmospheric consequences. Both physico-chemical and biological processes influence the exchange of CO2 between the ocean and the atmosphere, with biological feedbacks, in particular, having the potential to amplify the chemical and physical effects. At present oceans absorb about one-third of the CO2 emitted to the atmosphere by human activities, but the future behavior of the ocean carbon system remains uncertain and could have a critical effect on the rate of build-up of CO2 in the atmosphere. The goal of JGOFS is to improve our knowledge of the processes that control carbon exchanges between the atmosphere, surface ocean, ocean interior and its continental margins, and the sensitivity of these fluxes to climate change.

Contact:

Joint Global Ocean Flux Study (JGOFS)

Scientific Committee Chair: Hugh Ducklow
JGOFS Scientific Steering Committee

Executive Officer: Roger B. Hanson
JGOFS International Project Office
Center for Studies of Environment and Resources
University of Bergen
High Technology Centre
GLOBEC - Global Ocean Ecosystem Dynamics
Natural variability, occurring over a variety of time scales, dominates the health of complex marine ecosystems, regardless of fishing or other environment pressures. GLOBEC’s goal is to advance our understanding of the structure and functioning of the global ocean ecosystem, its major subsystems and it’s response to physical forcing, especially natural variability. The project focuses on zooplankton, the primary carnivores that prey on them and their role in the functioning of marine ecosystems. Both groups play a critical role in determining the productivity of marine ecosystems and the fisheries that depend upon them. In addition, zooplankton form an important route for the transport of carbon through marine ecosystems by passing photosynthetically produced organic matter both up the food chain as the building blocks for higher trophic levels and down through the water column as waste products. Enhanced understanding of arine ecosystem dynamics will help us to forecast the interaction of this system with global change, and hence to manage global marine living resources, such as fisheries, during a period of increased human impact on the marine ecosystem, both in terms of climate change and our increasing dependence on these resources.

Contact:

Global Ocean Ecosystem Dynamics (GLOBEC)

Scientific Committee Chair: Roger Harris
GLOBEC Scientific Steering Committee

Executive Officer: Manuel Barange
GLOBEC International Project Office
Plymouth Marine Laboratory
Prospect Place
Plymouth PL1 3DH
UK
Tel: (44-1752) 633 160
Fax: (44-1752) 633 160
E-mail: m.barange@pml.ac.uk
URL: www.pml.ac.uk/globec

START - Global Change System for Analysis, Research and Training
START (Global Change SysTem for Analysis, Research and Training) was founded in 1992, as part of the IGBP. Now jointly sponsored by the IGBP, the International Human Dimensions Program on Global Environmental Change (IHDP), and the Climate
Research Program (WCRP), START fosters a regional approach to interdisciplinary global change research. START's objective is to build, through regional research and training activities, indigenous capacity, especially in developing countries, to address scientific and policy aspects of environmental changes and sustainable development. A global network of environmental change researchers is organized by region. START regional offices in East Asia, South Asia, Southeast Asia, Oceania, Africa, and the Mediterranean foster global change research within each region and facilitate collaborative partnerships between scientists of the region and those of the developed world. Overall program management is provided by the International START Secretariat.

Contact:

Global Change system for Analysis, Research (START)

Scientific Committee Co-Chairs: Sulochana Gadgil, Graeme Pearman
START Scientific Steering Committee

Executive Officer: Roland Fuchs
START Secretariat
2000 Florida Ave, N.W., Suite 200
Washington DC, 20009
USA
Tel: (1-202) 462 2213
Fax: (1-202) 457 5859
E-mail: start@agu.org
URL: www.start.org

World Climate Research Program (WCRP)

Description: The WCRP was established in 1980, under the joint sponsorship of International Council for Science (ICSU) and the World Meteorological Organization (WMO), and has also been sponsored by the Intergovernmental Oceanographic Commission (IOC) of UNESCO since 1993.

Research mission:
The objectives of the program are to develop the fundamental scientific understanding of the physical climate system and climate processes needed to determine to what extent climate can be predicted and the extent of human influence on climate. The program encompasses studies of the global atmosphere, oceans, sea and land ice, and the land surface which together constitute the Earth's physical climate system. WCRP studies are specifically directed to provide scientifically founded quantitative answers to the questions being raised on climate and the range of natural climate variability, as well as to establish the basis for predictions of global and regional climatic variations and of changes in the frequency and severity of extreme events.
Research priorities: WCRP has formulated a broad-based multi-disciplinary science strategy offering the widest possible scope for investigation of all physical aspects of climate and climate change. This multi-disciplinary strategy is reflected in the ongoing WCRP core-projects. All projects are led by scientific steering or working groups normally meeting once a year:

The Arctic Climate System Study (ACSYS), a regional project studying climate of the Arctic region including its atmosphere, ocean, sea ice, and hydrological regime, is being expanded into a global project Climate and Cryosphere ( CliC) investigating the role of the entire cryosphere in global climate

Climate Variability and Predictability ( CLIVAR) is the main focus in WCRP for studies of climate variability, extending effective predictions of climate variation and refining the estimates of anthropogenic climate change. CLIVAR is attempting particularly to exploit the "memory" in the slowly changing oceans and to develop understanding of the coupled behavior of the rapidly changing atmosphere and slowly varying land surface, oceans and ice masses as they respond to natural processes, human influences and changes in the Earth's chemistry and biota. CLIVAR will advance the findings of the successfully completed Tropical Ocean and Global Atmosphere (TOGA) project, and will expand on work now underway in WCRP's World Ocean Circulation Experiment.

The Global Energy and Water Cycle Experiment ( GEWEX) is the scientific focus in WCRP for studies of atmospheric and thermodynamic processes that determine the Global hydrological cycle and water budget and their adjustment to global changes such as the increase in greenhouse gases. One of the main thrusts of GEWEX is the implementation of a series of atmospheric/hydrological regional process studies such as the GEWEX Continental-scale International Project (GCIP) embracing the whole Mississippi river basin, the GEWEX Asian Monsoon Experiment (GAME), or the Baltic Sea Experiment ( BALTEX). Observational projects in order to satisfy specific and evolving scientific needs include the International Satellite Cloud Climatology Project ( ISCCP), the International Satellite Land-Surface Climatology Project ( ISLSCP), Global Water Vapour Project ( GVaP), and the Global Precipitation Climatology Project ( GPCP). Progress has also been made in the GEWEX Cloud System Study ( GCSS) aiming to develop improved parameterizations and models of cloud systems used in climate and numerical weather prediction studies.

Another WCRP research activity playing an important role in better understanding the climate system is the Stratospheric Processes And their Role in Climate (SPARC) study, concentrating on the interaction of dynamical, radiative and chemical processes. Activities organized by SPARC include the construction of a stratospheric reference climatology and the improvement of understanding of trends in temperature, ozone and water vapour in the stratosphere. Gravity wave processes, their role in stratospheric dynamics and how these may be parameterized in models is another topic taken up.
The **World Ocean Circulation Experiment (WOCE)** is a fundamental element of the WCRP scientific strategy to understand and predict changes in the world ocean circulation, volume and heat storage, which would result from changes in atmospheric climate and net radiation, by means of a combination of in situ oceanographic measurements, observations from space and global ocean modeling.

**WCRP Modeling activities:**
The development of global climate models is an important unifying component of WCRP, building on scientific and technical advances in the more discipline-oriented activities. These models are the fundamental tool for understanding and predicting natural climate variations and providing reliable estimates of anthropogenic climate change. Models also provide the essential means of exploiting and synthesizing in a synergistic manner all relevant atmospheric, oceanographic, cryospheric and land-surface data collected in WCRP and other programs. The **Working Group on Numerical Experimentation (WGNE)**, jointly sponsored by the JSC of WCRP and the WMO Commission for Atmospheric Sciences (CAS), leads the development of atmospheric circulation models for both climate studies and numerical weather prediction, but also each project has a numerical experimentation group, that supports the respective WCRP components.

In addition, the **Working Group on Coupled Modeling (WGCM)**, jointly sponsored by JSC and CLIVAR, leads the development of coupled ocean/atmosphere/land models used for climate studies on longer time-scales. WGCM is also WCRP’s link to the earth system modeling in **IGBP’s Global Analysis Integration and Modeling (GAIM)** and to the **Intergovernmental Panel on Climate Change (IPCC)**. Activities in this area concentrate on the identification of errors in model climate simulations and exploring the means for their reduction by organizing coordinated model experiments under standard conditions. Under the auspices of WCRP, the **Atmospheric Model Intercomparison Project (AMIP)** has been set up in which the ten-year period 1979-1988 has been simulated by thirty different atmospheric models under specified conditions. The comparison of the results with observations has shown the capability of many models to represent adequately mean seasonal states and large-scale interannual variability for several basic climate parameters. A similar **Coupled Model Intercomparison Project (CMIP)** is also now being organized.

---

**International Human Dimensions Program (IDHP)**

**Description:** The International Human Dimensions Program on Global Environmental Change (IHDP) was initially launched in 1990 by the International Social Science Council (ISSC) as the Human Dimensions Program (HDP). In February 1996, the International Council for Science (ICSU) joined ISSC as co-sponsor of the Program. At this time, the name of the Program was changed to IHDP, and the Secretariat was moved to Bonn, Germany, through a generous grant from the German government.
IHDP is an international, interdisciplinary, non-governmental science program dedicated to promoting and co-ordinating research. Its aims are to describe, analyze and understand the human dimensions of global environmental change. IHDP's program is designed around its three main objectives of research, capacity building and networking. Increasingly these activities are carried out in collaboration with the international partner programs on global environmental change: the International Geosphere-Biosphere Program (IGBP), the World Climate Research Program (WCRP), and the International Program on Biodiversity (DIVERSITAS). IHDP is also a scientific sponsor of the Global Change System for Analysis, Research and Training (START) and collaborates with intergovernmental bodies, such as the Asia-Pacific Network for Global Change Research (APN) and the Inter-American Institute for Global Change Research (IAI).

**Research mission:** IHDP's science projects address key issues of concern to human dimensions of global environmental change research. They are key mechanisms used to generate new IHDP research activities in priority areas. Such projects evolve when the Scientific Committee of IHDP identifies priority themes, or when one or more National Committees and/or other groups of scientists make proposals directly to IHDP. All IHDP research activities are guided by four overarching questions:

1. **Vulnerability/Resilience**
   What factors determine the capacity of coupled systems to endure and produce sustainable outcomes in the face of social and biophysical change?

2. **Thresholds/Transitions**
   How can we recognize long-term trends in forcing functions and ensure orderly transitions when thresholds are passed?

3. **Governance**
   How can we steer tightly coupled systems towards desired goals or away from undesired outcomes?

4. **Learning/Adaptation**
   How can we stimulate social learning in the interest of managing the dynamics of tightly coupled systems?

**Research priorities:**

IHDP presently has four Core Science Projects:

1. **Global Environmental Change and Human Security (GECHS)**

What are the relationships between global environmental change and human security? This is the primary research question posed by the GECHS project. Answering this question involves the need to focus on issues of perception, adaptation, vulnerability, interaction, response, and thresholds. Research areas include conceptual and theoretical issues, resource use such as conflicts around water, and how population issues relate to both global environmental change and human security. One objective is to encourage the collaboration of scholars internationally, another to facilitate improved
communication and cooperation between the policy community, user groups and the research community. To the latter end, a regular policy bulletin, AVISO, is published and spread broadly.

Three key issues facing humankind as we prepare to enter the 21st century are environmental degradation, impoverishment, and the insecurity that can result from either of these two. Over the past decade, a considerable literature has arisen on the links between these three issues, and between environmental degradation and insecurity in particular. The Science Plan for the GECHS project focuses on developing a better understanding of these links, based on providing a new and different perspective than exists in previous research. In particular, we argue for a more interdisciplinary and integrative perspective on these issues.

Three key premises inform the development of this Science Plan. First, we recognize that human perceptions of the natural environment, and the way we use the environment, are socially constructed. Second, we accept that environmental problems must be addressed from a broader perspective that includes issues of impoverishment and issues of (in)equity. And third, we recognize that "space matters." In the context of our work, it is important to consider the various spatial levels at which both environment and security concerns can be addressed. A review of environment and security work indicates that there is an ongoing need for conceptual and theoretical discussions on the nature of the relationship between environment and security. It is also important to build upon early empirical work that focused on environment and conflict and to provide additional empirical studies on environmental change and its relationship to a broader conception of security. At the same time expanded research networks and improved communication among researchers, policy makers, and NGOs are required in order to develop integrated research projects on environmental change and human security. It is believed that these needs can be best met through an international research program that focuses both on guiding future research and assisting in policy development (at all levels).

**Key Issues and the GECHS Project**

Six key issues will form the backdrop for GECHS research activities. There needs to be continued theoretical and conceptual development of the links between environmental change, impoverishment, and insecurity. The GECHS project will focus on theoretical and conceptual development, using empirical studies to guide their development as well as for the validation of theory and conceptual frameworks. We recognize this needs to be integrated into all GECHS activities.

Focus Area 1 of the GECHS Science Plan (see below) addresses this issue. There is a strong need for empirical studies focusing on the elements of environmental change that actually threaten human security, and on the role various processes (e.g., economic, social) play. GECHS research will concentrate on integrated regional studies about the relationship between environmental change and human security.
This issue is represented in Focus Areas 2 and 3 of the Science Plan under the topics of “Environmental Change, Resource Use, and Human Security” and “Population, Environment, and Human Security.” Researchers, NGOs, and policy makers must be encouraged to be actively involved in future environment and security activities of the GECHS project. The GECHS project will endeavor to actively engage NGOs and the policy community in all its activities. These activities include research, publications, education, and workshops. In addition, joint projects will be initiated with other IHDP and IGBP core projects (in all cases, this has already begun). Research needs to focus on why some communities and organizations have been able to adapt to environmental change, while others appear to have been more vulnerable. GECHS research will examine the differential aspects of vulnerabilities and adaptations; for example, how the same set of circumstances—some aspect of global environmental change—might lead to war in one case, refugee movements in another case, famine in another, and adaptive responses in a fourth. This implies not only discerning between biophysical risk and social vulnerability, but also acknowledging the spatial variations in each. Issues of inequality and impoverishment must be incorporated into the analysis of environment and security links.

Focus Area 2 of the GECHS Science Plan addresses the interrelationships between population, environment, and security. These include issues of environmental justice, unequal access to resources, and distributional aspects of resources and environmental services. Research may also include studies of the underlying social, political, and economic processes contributing to injustices and inequalities with respect to the environment and access to resources. There is a need to develop methods for the early warning of environmental change and its potential impacts, to identify regions of potential insecurity, and to determine why some groups or communities are more vulnerable than others, given the same level of biophysical risk. Researchers are already investigating issues of data and indicators of environmental change and human security. Focus Area 4 of the Science Plan, entitled “Indicators of Environmental Stress and Human Vulnerability,” provides a framework to expand this work.

Research Questions
The overall research question addressed by the GECHS project is, “What is the relationship between global environmental change and human security?” From this general question, additional research questions have been identified. These questions can be placed into three categories: context, response options, and analysis.

Research Foci for GECHS
The five key research foci for the GECHS project, along with two activities that will be integrated throughout the project, are as follows:

- **FOCUS 1 Conceptual and Theoretical Issues in Environment and Human Security** – Why some regions and societies are more vulnerable than others; the relationship between environment and conflict; how environmental change threatens human security.
- **FOCUS 2 Environmental Change, Resource Use, and Human Security**—Water and human security; food security; energy security; atmospheric change and
human security; land use change and human security (linkage project with LUCC); environment and conflict/cooperation.

- **FOCUS 3 Population, Environment, and Human Security**—Environment, migration, and human security; urbanization and human security; population, impoverishment, and human security; health, the environment, and human security; environmental change and indigenous people; women, environment, and human security.

- **FOCUS 4 Modeling Regions of Environmental Stress and Human Vulnerability**—Developing indicators of environmental change and human security; modeling environmental stress and human vulnerability; critical zones (linkage project with the IGU).

- **FOCUS 5 Institutions and Policy Development in Environmental Security**—The framework of global governance (linkage project with IDGEC); environment, conflict, and democracy; environmental change, adaptation, and human security; private vs. public investment and human security; technological innovation and transfer.

---

### 2. Institutional Dimensions of Global Environmental Change (IDGEC)

**Description:** Institutions are systems of rules, decision-making processes and programs that give rise to social practices, assign roles to the participants and guide their initial interactions. IDGEC's research agenda centers on the examination of the role of social institutions in causing, exacerbating and solving large-scale environmental problems. The analysis looks particularly closely at concepts of institutional fit, interplay, and issues of scale. The core activities of IDGEC circle around three themes: ocean governance, forest use and carbon management; the circumpolar North and Southeast Asia are regional foci.

**Research Mission:** The following constitutes the Science Plan for the project on the Institutional Dimensions of Global Environmental Change (IDGEC), which in turn is part of a larger science planning enterprise taking place under the auspices of the International Human Dimensions Program on Global Environmental Change (IHDP).

The core of the IDGEC project is an analysis of the roles that social institutions play as determinants of the course of human/environment interactions. Institutions are systems of rules, decision-making procedures, and programs that give rise to social practices, assign roles to participants in these practices, and guide interactions among the occupants of the relevant roles. Unlike organizations, which are material entities that typically figure as actors in social practices, institutions may be thought of as the rules of the game that determine the character of these practices.

Institutions loom large as causes of large-scale environmental problems that are both systemic (e.g., climate change, ozone layer depletion) and cumulative (e.g., loss of biological diversity) in nature. Faulty structures of property rights, for example, can lead to severe depletions of stocks of living resources or to excessive uses of ecosystems for
the disposal of airborne and waterborne pollutants. Conversely, institutions often figure prominently in efforts to solve or manage environmental problems. The establishment of limited-entry arrangements to prevent the ravages of overfishing and of regulatory regimes to control emissions of ozone-depleting substances or greenhouse gases are examples of obvious relevance to global environmental change.

**Four sets of priorities** define the scope of the IDGEC project and give it a distinct identity within the family of projects addressing issues of global environmental change. These priorities encompass: (1) research foci, (2) analytic themes, (3) regional applications, and (4) programmatic partnerships.

Research Foci - The research foci spelled out in the IDGEC Science Plan all involve the roles that social institutions play in causing and confronting global environmental changes. They single out for particular attention the roles of environmental and resource regimes, defined as institutional arrangements concerned explicitly with human/environment relations. Taken together, the IDGEC research foci form a hierarchical sequence that moves from broadly theoretical to applied concerns by addressing matters of (1) causality (how much of the variance in collective outcomes is attributable to institutions?), (2) performance (why are some institutional responses to environmental problems more successful than others?), and (3) design (how can we structure institutions to maximize their performance?).

1. **Research Focus 1.** What roles do institutions play in causing and confronting global environmental changes? This focus encompasses three more specific themes: (1) what is the role of environmental and resource regimes in global environmental change? (2) what is the role of other institutions (e.g., trade and investment regimes) in global environmental change? and (3) what factors determine the resilience of institutions in the face of global environmental change? As a group, these themes address the fundamental causal connections linking institutions to collective outcomes in the realm of human/environment relations.

2. **Research Focus 2.** Why are some institutional responses to global environmental changes more successful than others? This focus directs attention to a more circumscribed set of issues in order to deepen our understanding of factors that determine the results arising from human efforts to solve or manage environmental problems through institutional responses. It, too, includes three specific themes: (1) are there common features or elements of (un)successful institutional responses? (2) what factors threaten the development or the survival of institutional responses? and (3) what unintended consequences do institutional responses produce?

3. **Research Focus 3.** What are the prospects for (re)designing institutions to confront environmental challenges? The goal of this most applied focus is to derive policy-relevant conclusions from the study of the institutional dimensions of global environmental change. This effort involves four specific themes: (1) what are the (dis)advantages of creating new institutions in contrast to reforming existing institutions? (2) how can we incorporate flexibility, self-correcting procedures, and social learning processes into environmental and resource
regimes? (3) what are the relative merits of a range of institutional attributes, including formal arrangements versus informal social practices, hard-law versus soft-law arrangements, different types of decision rules, and alternative funding mechanisms in conjunction with environmental and resource regimes? and (4) can we integrate environmental and resource regimes with other institutional arrangements, especially economic arrangements, at different stages of national development?

Analytic Themes - Running through these substantive concerns are several analytic threads dealing with factors that determine the performance of institutions governing human/environment relations that are poorly understood at present. They constitute analytic priorities for research carried out under the auspices of the IDGEC project. Two clusters of factors arise repeatedly in efforts to understand variations in the performance of specific institutional arrangements. One cluster—referred to in the IDGEC project as the problem of fit—centers on issues pertaining to the match between institutional arrangements and biogeophysical systems; it directs particular attention to sources of institutional mismatches. The second cluster—known in the project as the problem of interplay—draws attention to linkages among distinct institutional arrangements both at the same level of social organization and across levels of social organization. It has become clear as well that studies of the effectiveness of institutional arrangements at different levels of social organization raise questions about the extent to which the causal mechanisms through which institutions affect behavior are generalizable from one level to another. Known to the IDGEC project as the problem of scale, this cluster of concerns parallels a topic well-known to students of biogeophysical systems.

Regional Applications - Some institutional arrangements, such as the regimes dealing with the protection of stratospheric ozone and the control of greenhouse gases, are global in scope. They call for research efforts to deal with issues arising in international society and global civil society. Yet many institutions relevant to systemic as well as cumulative environmental changes operate at lower levels of social organization, so that a large fraction of the research required to understand the institutional dimensions of global change will need to focus on processes at work at the regional, national, and even local levels. Only after we understand these processes will it be possible to aggregate and synthesize the results in the interests of arriving at broader conclusions that parallel and complement the findings of natural scientists concerned with changes in biogeophysical systems that are global in scope.

The IDGEC project will operate on an inclusive basis. An explicit effort will be made to incorporate research conducted in all parts of the world that addresses the substantive and analytical concerns of the project. At the same time, the IDGEC Science Plan identifies two major regions of the world as priority areas for research on the institutional dimensions of global environmental change.

- Southeast Asia - This region encompassing eleven countries and half a billion people contains a large portion of the Earth’s moist tropical forests and generates the largest land-to-ocean sediment flows in the world. Heavily influenced by international economic institutions, debates regarding alternative paths to
economic development, and domestic political turmoil, Southeast Asia offers an appropriate setting for analyses of many of the institutional forces that impact human/environment relations in the world today.

- Circumpolar North - This region covers parts of eight countries, including both Russia and the United States. The Russian taiga contains approximately as much carbon as the rain forests of the Amazon Basin, and the Circumpolar North as a whole is undergoing a transition from sink to source of greenhouse gases. Because global environmental changes are already occurring in this region and are expected to impact the high latitudes with particular force, the Far North offers exceptional opportunities to analyze both the impacts of large-scale environmental changes and institutional responses to these impacts.
  - Despite their obvious differences, the two regions share a number of attributes that are particularly relevant to the institutional dimensions of global change. The most significant of these involve the roles of large marine ecosystems, forest ecosystems, indigenous peoples, and the interplay of external and internal forces.

Programmatic Partnerships - From the perspective of global environmental change, institutions constitute a crosscutting theme, emerging as an important dimension of an array of substantive concerns ranging from changes in patterns of land use to shifts in human activities in the coastal zone and the transformation of industrial systems. Taking advantage of this aspect of the project, the IDGEC implementation strategy features the establishment of partnerships with other projects as a means to foster strong institutional components in the work programs guiding the activities of these projects.

The production of insights flowing from these partnerships and dealing with matters such as the institutional drivers of changes in land-use practices and institutional responses to coastal zone problems will constitute one important measure of the value added as a result of research sponsored by the IDGEC project.

Fruitful exchanges have occurred already with scientists participating in other global change projects, especially Global Change and Terrestrial Ecosystems (GCTE), Land-Ocean Interactions in the Coastal Zone (LOICZ), and Land-Use and Land-Cover Change (LUCC). The IDGEC project has forged cooperative links with regional partners as well, including the Southeast Asian Regional Committee for START (SARCS) and the International Arctic Science Committee (IASC). Somewhat similar links are expected to develop with some national global change research programs and with the leaders of a variety of other projects dealing with large-scale environmental issues.

In addition, IDGEC seeks to produce results that are directly relevant to the concerns of members of the policy community seeking to understand issues such as the causes of unsustainable uses of living resources or to design regulatory systems capable of controlling problems like the emission of ozone-depleting substances or greenhouse gases. In this connection, the leaders of the IDGEC project will seek to stimulate mutually beneficial dialogues with key individuals associated with policy-making bodies (e.g., UNEP, UNDP, FAO, the GEF) responsible for devising and implementing
responses to large-scale environmental problems. The success of these dialogues will constitute another measure of the performance of the IDGEC project.

3. **Industrial Transformation (IT)**

**Description:** The IT Project is an international, multi-disciplinary research initiative aimed at understanding complex society-environment interactions; identifying driving forces for change; and exploring development trajectories that have a significantly smaller burden on the environment on a global scale. IT research is based on the assumption that important changes in production and consumption systems will be required in order to meet the needs and aspirations of a growing world population while using environmental resources in a sustainable manner.

**Research Mission:** Through its five key research foci on energy and material flows, food, cities, information and communication, and governance and transformation processes, IT research aims at building on the foundations of different disciplinary research approaches in the social, technical and natural sciences.

**Research Priorities:** This Science Plan on Industrial Transformation research is one of the four international science projects co-ordinated by the International Human Dimensions Program (IHDP) on Global Environmental Change (The other IHDP science projects are: Land-Use and Land-Cover Change (LUCC), co-sponsored by IGBP; Global Environmental Change and Human Security (GECHS); and Institutional Dimensions of Global Environmental Change (IDGEC) (see IGBP and HDP 1995; IHDP, 1999a; and IHDP, 1999b)). IHDP is initiated and co-ordinated by the international research community and provides a unique forum and institutional setting for its science projects.

Industrial Transformation research seeks to understand complex society-environment interactions, identify driving forces for change, and explore development trajectories that have a significantly smaller burden on the environment. It is based on the assumption that important changes in production and consumption systems will be required in order to meet the needs and aspirations of a growing world population while using environmental resources in a sustainable manner. Appendix I outlines some of the activities and priorities of production and consumption research in other organizations worldwide.

The focus on systems and systems change research makes this project unique and different from the present mainstream of environmental research. To set certain limitations as to what would qualify as Industrial Transformation research, four general characteristics are defined:

1. Industrial Transformation research deals with the relationship between societal, technological, and environmental change;
2. Industrial Transformation focuses on systems and system changes that are relevant in view of the global environment (such as the energy system, the food system, and the urban system);
3. Industrial Transformation research relates producer and consumer perspectives, including the incentives and institutions that help in shaping these perspectives; and
4. Industrial Transformation research is international in scope.

Multi-Disciplinary Co-operation in a Systems Approach

The definitions and approaches described above imply that Industrial Transformation research is multi-disciplinary in character. It builds on the foundations of a range of social science disciplines including economics, sociology, psychology, human ecology, anthropology, political science, geography, and history, as well as on the foundations of natural sciences such as physics, chemistry, biology, and technological sciences.

To provide a framework for the co-operation required between various disciplines, a matrix was developed (Figure 1). The rows reflect the disciplinary research fields that each have a certain tradition (outlined in Research Approaches to Support the Industrial Transformation Science Plan 1999), while the columns describe a set of human activities aimed at meeting specific human needs. Through this multi-disciplinary approach, the Industrial Transformation Project strives to build on existing pillars of research and draw from expert communities while developing new research topics and radical approaches.

Research Foci

It was clear that the energy system, in view of its environmental implications at global and local levels should be a major focus for research. During the elaboration of this focus it was decided to include the flow of materials because of the major links between Energy and Material Flows.

Food production and consumption were prioritized due to their relation to biodiversity issues and the major impact on the environment throughout the food production, processing, transport, consumption, and waste cycle. International interdependencies were another argument for including a focus on Food. Moreover, the potential connections between climate change and food production made this a priority topic.

Water and transport were two other topics raised in nearly all workshops. In view of the important spatial aspects of water and transport, it was ultimately decided to include these issues in the more generic focus of Cities.

A special focus added to the priorities of the Science Plan is Information and Communication. Developments in this field are considered to be one of the major driving forces in societal transformation and have important implications for the global environment. Since Information and Communication is a major driver for transformation, it can also be seen as a cross-cutting theme embedded in each of the research foci.
Finally, two research topics were raised in many of the workshops and the Open Science Meeting: transformation processes and governance. Both are cross-cutting themes that focus on generic aspects of Industrial Transformation. It was ultimately decided to combine the two in a single focus, *Governance and Transformation Processes*, with emphasis on analyzing and understanding the driving forces that are changing the way society relates to the environment.

It is not by accident that these foci directly reflect the natural sciences issues and concerns regarding the major global biogeochemical cycles such as the carbon - climate change - energy connection, and the nitrogen - biodiversity - food connection. Water and transport have been selected in the context of urban development (*Cities*) as these systems have geographically specific components.

Table 1: Key Research Questions for Industrial Transformation Research.

<table>
<thead>
<tr>
<th>Research Focus</th>
<th>Key Research Questions</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Energy and Material Flows</strong></td>
<td>From geographical, sectoral, and company levels, what are the strengths, and the nature, of the relations between energy and material use, technological change, and economic performance? How will international trade in energy, investments in energy infrastructure (production and distribution), and the related flows of energy and materials be affected by international treaty regimes, for example the Framework Convention on Climate Change and related protocols, and the WTO? What are the technical, economic, and social driving forces for the private energy sector towards the development of low carbon technologies and markets? What is driving and/or pulling consumer needs and preferences in the field of energy and material use, and what institutional, socio-psychological, and technical arrangements would influence purchasing, investment, and lifestyle towards a significantly lower level of environmental effects?</td>
</tr>
<tr>
<td><strong>Food</strong></td>
<td>What is the feasibility of „de-linking“: is it possible to meet growing needs and changing preferences while simultaneously reducing environmental impacts? What are the regional differences in sustainability of different FCPSs (food consumption and production systems), and what role do FCPSs play in regional development? What are the global trends and what solutions can be envisaged? Which measurement tools can be used/developed to measure progress in the sustainability of the FCPS? How do regional policies affect the contribution of FCPSs to global environmental change and how could they be redesigned?</td>
</tr>
<tr>
<td><strong>Cities (focus on)</strong></td>
<td>What are the opportunities and constraints to de-couple transport from the carbon cycle?</td>
</tr>
<tr>
<td><strong>Transport and Water</strong></td>
<td>Why is the transport/carbon budget different from one city to another? How can systems be redesigned to minimize negative effects both locally and remotely, seen from technological, spatial, and institutional perspectives? How can the need for water be de-coupled from effects on the hydrological cycle? Why do these effects differ from city to city? How can technological, spatial, and institutional redesign help to reduce the negative effects of water use?</td>
</tr>
<tr>
<td><strong>Information and Communication</strong></td>
<td>What is the role of global environmental change in the strategic decisions of leading companies in the electronics, information, and communication technology sector? In what ways can the new technologies alter the overall system of production and consumption to raise standards of living while contributing to materials efficiency and reducing burdens on the global environment? How will information and communications technology influence society and lifestyle and through this alter the way environmental resources are used? To what extent do changes in information and communication enable the development of an international civil society supporting international and local discourses about global environmental change among and in society, the scientific community, and policy and decision-makers?</td>
</tr>
<tr>
<td><strong>Governance and Transformation Processes</strong></td>
<td>How does systemic change in society-environment relations occur and what processes shape the relation between socio-economic activity and the natural environment, both historically and in the contemporary period? What contemporary transformation processes might be harnessed to the goal of systemic change in society-environment relations? What are the most powerful supra-national and non-state driving agents for global environmental change? What is the role of the state in a globalised context in promoting global environmental change? What are successful models of policy intervention, with special attention paid to the societal context?</td>
</tr>
</tbody>
</table>

**Programmatic Links**
The Industrial Transformation Project is linked to, and should be viewed in the context of, the four international programs addressing global environmental change issues (IHDP, the World Climate Research Program (WCRP), the International Geosphere-Biosphere Program (IGBP), and the International Program of Biodiversity Science (DIVERSITAS)). There are several links between the issues addressed in the IHDP science projects: the Land-Use and Land-Cover Change (LUCC) Project has direct links with the Food focus, the Institutional Dimensions of Global Environmental Change
(IDGEC) Project provides insight for all of the Industrial Transformation research foci, and the Cities focus is related to the Global Environmental Change and Human Security (GECHS) Project. The four IHDP science projects are interacting with the more natural sciences focused programs such as WCRP, IGBP, and DIVERSITAS. Through combined international conferences, and where possible, local research co-operation, the links between the primarily social sciences program (IHDP) and the primarily natural sciences programs on global environmental change will be maintained.

4. **Land-Use and Land-Cover Change (LUCC, co-sponsored with IGBP)**

**Description**: LUCC is a joint project of IHDP and the International Geosphere-Biosphere Program (IGBP). The project aims to improve understanding of the dynamics of land-use and land-cover change and their relationship with global environmental change.

**Research Mission**: LUCC's interdisciplinary research agenda is implemented through case studies, development of models and integrative analyses. Climate change, food production, health, urbanization, coastal zone management, transboundary migration, and availability and quality of water are addressed in LUCC's research, and their impacts on the quality of human life are investigated. LUCC studies and documents temporal and geographical dynamics of land-use and land-cover. Links are defined between sustainability and various land uses. The project aims to understand the interrelationship between LUCC, biogeochemistry and climate.

At a global scale, land-use changes are cumulatively transforming land cover at an accelerating pace (Turner et al., 1994; Houghton, 1994). These changes in terrestrial ecosystems are closely linked with the issue of the sustainability of socio-economic development since they affect essential parts of our natural capital such as climate, soils, vegetation, water resources and biodiversity (Mather and Sdasyuk, 1991). Today, there is increased recognition that land-use change is a major driver of global change, through its interaction with climate, ecosystem processes, biogeochemical cycles, biodiversity and – even more importantly - human activities.

**Research Priorities**: LUCC is an interdisciplinary project designed to improve the understanding and projections of the dynamics of land-use and land-cover change. The LUCC community of scientists aims for new integrated and regional models, informed by empirical assessments of the patterns of land use and case studies that explain the processes underpinning such configurations of land-use and land-cover change over varying spatial and temporal scales. The following key themes outline the broader research agenda of LUCC (Figure 1, page 17):

- patterns of land-cover change,
- processes of land-use change,
- human responses to land-use/land-cover change,
- integrated global and regional models,
development of databases on land surface, biophysical processes and their drivers.

Land-use/land-cover change is central to the interests of the science of global environmental change. It is a significant agent of change which influences, and is affected by, climate change, loss of biodiversity, and the sustainability of human-environment interactions. Land-use/land-cover change is a significant cause, or forcing function, of global change, and the medium through which many human responses to global change will occur. It is clearly an essential component in all considerations of sustainability. LUCC is building a bridge between social and natural sciences. It is a pathfinder project for a “science of sustainability”. We refer the reader to the LUCC Science/Research Plan (IGBP/HDP, 1995) for a more thorough description of the role of land-use/land-cover change as a critical issue for global change research, and as «bridging program» between the natural and social sciences.

The overall objectives of LUCC

The ultimate and broad objective of LUCC is to improve understanding of, and gain new knowledge on regionally based, interactive changes between land uses and covers, especially as manifested in modeling approaches. A more specific goal is the development of improved means for projecting and backcasting land uses and land covers. The leitmotif of the science may be described as “from natural to human, from global to regional,” with LUCC science involving an integrative synthesis of the natural and social sciences. Research that is cross-cutting and regional is important because some of the effects accompanying global change will be most significant at the regional level. A region is defined as a continuous portion of the earth’s surface, characterized by a rough match between a distinct physical environment and a system or set of systems of human use.

The region offers a middle level for land-use/land-cover change studies between the local and global poles. At the regional level we can gain an understanding of the nature of human decisions that alter land-use/cover, and it is usually at this level that policy interventions are both possible and effective. Dealing with the regional approach as an intermediate level between the global and the local requires a good understanding of methodologies for up- and down-scaling. The LUCC research agenda is based to a large extend on the development of comparable research designs in different regions to address a similar set of questions. This research orientation reflects recent shifts within the broader IGBP and IHDP communities toward integrating the natural and social sciences, and focusing on the regional perspective of global environmental change.

To meet these objectives, LUCC has defined several science questions which are central to the project. These have been enumerated in the Science/Research Plan as:

1. How has land cover been changed by human use over the last 300 years?
2. What are the major human causes of land-cover change in different geographical and historical contexts?
3. How will changes in land use affect land cover in the next 50-100 years?
4. How do immediate human and biophysical dynamics affect the sustainability of specific types of land uses?
5. How might changes in climate and global biogeochemistry affect both land use and land cover?
6. How do land uses and land covers affect the vulnerability of land-users in the face of change and how do land-cover changes in turn impinge upon and enhance vulnerable and at-risk or critical regions?

Toward Integrated Environmental Decision-Making
EPA Science Advisory Board
2002 SAB Report (EPA-SAB-EC-00-011).

In the Summer 2000, the EPA Science Advisory Board (SAB) released its report, Toward Integrated Environmental Decision-making. Marking the culmination of an extensive effort of interdisciplinary teams of scientists, engineers, and economists, the report explores the scientific and technical analyses that can and should inform environmental decisions, the strengths and limitations of current science and analytical techniques, the import of other inputs, and areas for future development. Among the findings and conclusions made by the Steering Committee were the following:

1. Scientists have important and unique contributions to make in protecting public health and the environment.
2. While scientists can help to characterize environmental risks, they are not solely qualified to set priorities among them and broader deliberation is essential.
3. Integrated environmental decision-making requires a process within which the decision-maker can meld the results of science and the goals of the people served.
4. Deliberative processes play an important role in eliciting values of people and in obtaining stakeholder participation in decision-making.
5. Integrated decision-making requires explicit consideration of the trade-offs involved in pursuing multiple goals.
6. Integrated decision-making should combine risks into logical groupings, for example, those with a common source or pathway, in order to identify risk reduction opportunities across stressors.
7. "Environmental Report Cards" are needed to measure and document performance and outcomes of risk reduction activities. An environmental results reporting system should include a mix of processes, stressors, exposures, and outcome measures.

Based on these findings and conclusions, the Board's report proposes a Framework for Integrated Environmental Decision-making that stresses integration—of information and techniques from multiple disciplines and points of view, and of multiple stressors, exposure routes, and effects. The report calls for an evolution in environmental decision-making that builds on, rather than replaces, existing regulatory processes and requirements. This evolution is characterized by a decision-making process that is a)
transparent and well-documented; b) makes the best use of both analytical and deliberative processes; c) draws on the interdisciplinary expertise of scientists, managers, and members of the public; and d) looks at environmental problems in a whole and complete way in order to maximize the reduction of aggregate risk to populations or ecological systems.

The report also contains 10 recommendations intended to foster the evolution to Integrated Environmental Decision-making:

1. EPA should continue development of integrated, outcomes-based environmental protection, while maintaining the safeguards afforded by the current system.
2. Because science plays a critical role in protecting the environment, EPA should commit the resources necessary to expand the scientific foundation for integrated decision-making and outcomes-based environmental management.
3. EPA should apply and encourage the broader use of risk comparison methodologies that clearly identify how scientific information and judgment are incorporated into risk comparisons.
4. EPA should explore a broader range of risk reduction options in combination to manage environmental risks.
5. When evaluating risk reduction options, EPA should strive to weigh the full range of advantages and disadvantages, both those measured in dollars as costs and benefits and those for which there may not be a comprehensive dollar measure, such as sustainability and equity.
6. EPA should seek and develop methods to characterize public values and incorporate those values into goal-setting and decision-making.
7. EPA, by itself and in concert with others, should identify, collect, and disseminate scientifically-based environmental metrics organized in new ways to support a more integrated approach to managing environmental risk.
8. EPA, by itself and in concert with others, should develop a system of "report cards" to organize and disseminate information on the status of ecological and human health and the quality of life in order to assess the effectiveness of its environmental decisions and to guide future environmental management.
9. EPA should expand and develop new collaborative working relationships with other federal and non-federal governmental agencies and others who also will be involved in integrated environmental decision-making.
10. EPA should explore options for reducing risks from significant stressors that currently are addressed inadequately by the nation’s environmental institutions.
The Global Carbon Project is a project of the Earth System Science Partnership of the International Geosphere Biosphere Programme (IGBP) World Climate Research Programme (WCRP) and the International Human Dimensions Programme (IHDP)

The growing realization that anthropogenic climate change is a reality has focused the attention of the scientific community, policymakers and the general public on the rising concentration of greenhouse gases, especially carbon dioxide (CO$_2$) in the atmosphere, and on the carbon cycle in general. Initial attempts, through the United Nations Framework Convention on Climate Change and its Kyoto Protocol, are underway to slow the rate of increase of greenhouse gases in the atmosphere. These societal actions require a scientific understanding of the carbon cycle, and are placing increasing demands on the international science community to establish a common, mutually agreed knowledge base to support policy debate and action.

The newly formed Global Carbon Project is responding to this challenge through a shared partnership between the International Geosphere-Biosphere Program (IGBP), the International Human Dimensions Program on Global Environmental Change (IHDP), and the World Climate Research Program (WCRP).

The scientific goals of the Global Carbon Project are to develop a complete picture of the global carbon cycle, including both its biophysical and human dimensions together with the interactions and feedbacks between them. This will be:

- Patterns and Variability: the current geographical and temporal distributions of the major stores and fluxes in the global carbon cycle;
- Processes, Controls and Interactions: the underlying mechanisms and feedbacks that control the dynamics of the global carbon cycle, including interactions with human activities;
- Future Dynamics of the Carbon Cycle: the range of plausible trajectories for the dynamics of the global carbon cycle into the future.

For further information, please see the Carbon Challenge Brochure (pdf, 0.7Mb), Overview complete (ppt, 7.45Mb), Overview slides 1-6 (ppt, 3.45Mb) & Overview slides 7-23 (ppt,1.73Mb) and the Science Framework (pdf, 2.17Mb).

Other strategy and research priorities:

- To develop a research framework for integration of the biogeochemical, biophysical and human components of the global carbon cycle, including the development of data-model fusion schemes, and design of cost effective observational and research networks.
- To synthesize current understanding of the global C cycle and provide rapid feedback to the research and policy communities, and general public.
- To develop tools and conceptual frameworks to couple the biophysical and human dimensions of the carbon cycle.
To provide a global coordinating platform for regional/national carbon programs to improve observation network design, data standards, information and tools transfer, and timing of campaigns and process-based experiments.

To strengthen the broad carbon research programs of nations and regions, and those of more disciplinary projects in IGBP, IHDP, WCRP, and IGCO through better coordination, articulation of goals, and development of conceptual frameworks.

To develop a small number of new research initiatives that are feasible within a 3-5 year time framework on difficult and highly interdisciplinary problems of the carbon cycle.

To foster new carbon research in regions (e.g., tropical Asia) that will provide better constrains of continental and global carbon budgets through promoting partnerships between institutions and exchange visits.

---

Complex Environmental Systems: Synthesis for Earth, Life, and Society in the 21st Century: A 10-Year Outlook for the National Science Foundation (NSF)

National Science Foundation (NSF)
Summary report (PDF)
Full report (PDF)

Executive Summary
As the global footprint of human activity continues to expand, environmental science and engineering problems will provide great challenges and opportunities in the next decade. Because of the complex relationships among people, ecosystems, and the biosphere, human health and well-being are closely linked to the integrity of local, regional, and global ecosystems. Therefore, environmental research and education are central elements of local, national, and global security, health, and prosperity. New instrumentation, data-handling, and methodological capabilities have expanded the horizons of what we can study and understand about the environment. These advances create the demand for collaborative teams of engineers and natural and social scientists that go beyond current disciplinary research and educational frameworks. Imagination, diversity, and the capacity to adapt quickly have become essential qualities for both institutions and individuals, not only to facilitate research, but also to ensure the immediate and broad-based application of research results related to the environment.

To meet these complex challenges as well as urgent human needs, we need to develop environmental synthesis to frame integrated interdisciplinary research questions and activities and to merge data, approaches, and ideas across spatial, temporal, and societal scales. An essential part of this process is the effective communication of scientific information, models, and conclusions to and among researchers, educators, students, resource and industrial managers, policy makers, and the public.
To advance the fundamental knowledge necessary to address critical environmental challenges, the Advisory Committee for Environmental Research and Education recommends increased focus on three interrelated areas:

(A) coupled human and natural systems,  
(B) coupled biological and physical systems,  
(C) people and technology.

Research in these areas is important, timely, feasible, and likely to lead to significant scientific and practical outcomes in the next decade.

**Coupled human and natural systems research** explores the complex web of environmental relationships and feedbacks at diverse temporal and spatial scales. Research challenges include:

1. land, resources, and the built environment,  
2. human health and the environment,  
3. freshwater resources, estuaries, and coastal environments,  
4. environmental services and valuation.

**Coupled biological and physical systems research** focuses on understanding the systems, processes and dynamics that shape the physical, chemical, and biological environment from the molecular to the planetary scale. 

Research areas include:

1. biogeochemical cycles,  
2. climate variability and change,  
3. biodiversity and ecosystem dynamics.

**People and technology research** seeks to discover new technologies that protect and improve the environment and also to understand how individuals and institutions interact with the environment, and how they use resources and respond to change.

Research areas include:

1. materials and process development,  
2. decision making and uncertainty,  
3. institutions and environmental systems.

To fulfill this research Outlook and to support a new generation of environmental professionals, the Advisory Committee recommends major investments in environmental education, training, infrastructure, and technical capacity. Scientists, engineers, technicians, resource managers, and educators must be prepared to cross disciplines, integrate diverse information, and collaborate to solve environmental problems. Long-term, dynamic partnerships that cross national and regional jurisdictions and international boundaries can be the most effective means of addressing multi-scale challenges.

**Environmental education** should be used as an integrating concept in pre-school, elementary, and secondary education, particularly when enhanced with teacher
education and professional training programs. At two and four year colleges and research institutions, academic institutional structures and incentives should facilitate interdisciplinary environmental research, increased diversity in the environmental workforce, and productive interactions with policy makers and the community. Informal education about the environment through parks, museums, zoos, media, and citizen-scientist partnerships is also a critical component of enhancing public understanding of complex environmental information and decisions.

**Infrastructure and technical capacity** must also be expanded and strengthened to address the environmental challenges of the coming decade. As sensors, instruments, and observing systems continue to improve, and the quantity and quality of environmental data grow rapidly, cyberinfrastructure must evolve quickly in order to archive, integrate, interpret, and communicate environmental information. Interdisciplinary research also necessarily relies on experiments, models, and their interactions to understand environmental systems at multiple scales and to develop scenarios and projections that are relevant to policy and practice. As our technological and research capacity increases, we face both the promise of understanding the environment and our relationship to it, and the responsibility of making wise decisions about managing the complex relationships among people, ecosystems and planetary processes.

---

**Sustainability Science**  
**Forum on Science and Technology for Sustainability**

The Forum is a project of the international Initiative on Science and Technology for Sustainability (ISTS) seeks to enhance the contribution of knowledge to environmentally sustainable human development around the world. The Initiative is based on an evolving vision of "science and technology for sustainability" that is:

- **anchored in concerns for the human condition**, seeking knowledge and know-how that will help feed, nurture, house, educate and employ the world’s slowing but still growing human population while conserving its basic life support systems and biodiversity;
- **essentially integrative**, bridging efforts across the natural, social and engineering sciences, the environment and development communities, multiple sectors of human activity, geographic and temporal scales and, more generally, the worlds of knowledge and action;
- **regional and place-based**, focusing at intermediate scales where multiple stresses intersect, where complexity is comprehensible, where integration is possible, where innovation and management happen, and where significant transitions toward sustainability have begun; and
- **fundamental in character**, addressing the unity of the nature-society system, asking how that interactive system is evolving and can be consciously, if
imperfectly, steered through the reflective mobilization and application of appropriate knowledge and know-how.

The Initiative aims to make significant progress toward three broad and interrelated goals:

- **expanding and deepening the research and development agenda** of science and technology for sustainability;
- **strengthening the infrastructure and capacity** for conducting and applying science and technology for sustainability; and
- **connecting science and policy** more effectively in pursuit of a transition toward sustainability.

The Initiative is an open-ended network. Policy is set by an international Steering Group, coordinated by two Co-Conveners (Robert Kates and Akin Mabogunje). The tasks of the Secretariat of the Initiative are shared between Harvard University (Cambridge, Massachusetts, United States) and the Third World Academy of Sciences (TWAS) (Trieste, Italy). To date, major funding has come from the David and Lucile Packard Foundation, the U.S. National Oceanic and Atmospheric Administration’s Office of Global Programs, and numerous regional institutions.

The Initiative’s web-based Forum on Science and Technology for Sustainability facilitates information exchange and engagement with the larger community involved with science and technology for sustainability. It provides access to the Network for Science and Technology for Sustainability, the Initiative’s effort to help build a virtual community linking disparate scholars, managers, and decision makers, and to promote the sharing of knowledge, ideas, and goals among a community working on science and technology for sustainability.

**Core Questions of Science and Technology for Sustainability**

**Core Questions Home**

**Introduction**

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. 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. 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...
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, an initial set of core questions for sustainability science has begun to emerge. 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. The questions as posed at the Fribergh Workshop on Sustainability Science are summarized below. The Editors of the Forum invite comments on and additions to this list, and will use subsequent "editions" of the Forum as a means of promoting a dialogue on the questions. Contributions should be submitted to the Managing Editor.

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?  
2. How are long-term trends in environment and development, including consumption and population, reshaping nature-society interactions in ways relevant to sustainability?  
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?  
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?  
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?  
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?  
7. How can today’s relatively independent activities of research planning, observation, assessment, and decision support be better integrated into systems for adaptive management and societal learning?

Our Common Journey: A Transition Toward Sustainability  
US National Research Council  
Washington DC: National Academy Press, 1999
Executive Summary

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

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

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

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

GOALS FOR THE TRANSITION TO SUSTAINABILITY
In the Board’s judgment, the primary goals of a transition toward sustainability over the next two generations should be to meet the needs of a much larger but stabilizing human population, to sustain the life support systems of the planet, and to substantially reduce hunger and poverty. For each of these dimensions of a successful sustainability transition, international conventions and agreements reflect a broad consensus about minimal goals and targets, though there is seldom analysis of these goals’ implications, their potential interactions with one another, or their competing claims on scarce resources. Our analysis documents these goals and the uneven progress that has been made in meeting them. In particular, in the area of human needs, internationally agreed-on targets exist for providing food and nutrition, nurturing children, finding shelter, and providing an education, but not for finding employment. There is an implicit hierarchy of needs that favors children and people in disasters and that favors feeding and nurturing first, followed by education, housing, and employment.

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

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

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

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

Integrated assessment models seek to link in a consistent fashion formal models of the environment and society. The accumulating experience suggests that the models can make a difference in society’s ability to address complex interactions between environment and development by providing analytic insight through problem redefinition and by directly informing policy making through supporting international environmental negotiations (e.g., whaling and stratospheric ozone depletion). Models can also be useful probes of uncertainties and their significance in exploring the possible future implications of current decisions. Deliberate simplification of such complex models can be an important part of strategies for exploring the future. But the art of providing useful simplifications remains demanding and underdeveloped.
Long-range development scenarios are summary stories of how the world might unfold. They are useful for organizing scientific insight, gauging emerging risks, and challenging the imagination. Scenarios are told in the language of words as well as numbers, because some critical dimensions—assumptions about culture, values, lifestyles, and social institutions—require qualitative description. Scenarios do not predict the future; they provide insight into the present. Experience suggests that scenarios to support the study of global futures and the requirements for a transition to sustainability should be rigorous, reflecting the insights of science and modeling. But scenario building must also recognize that the story of the future is not a mere projection of current trends and understanding. The spectrum of scenarios to consider should contrast long-range visions that reflect the uncertainty about how the global system might unfold, the possibility of surprise, and a range of pathways to a sustainable future.

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

Although the future is unknowable, based on our analysis of persistent trends and plausible futures, the Board believes that a successful transition toward sustainability is possible over the next two generations. This transition could be achieved without miraculous technologies or drastic transformations of human societies. What will be required, however, are significant advances in basic knowledge, in the social capacity and technological capabilities to utilize it, and in the political will to turn this knowledge and know-how into action. There is ample evidence from attitudinal surveys and grassroots activities that the public supports and demands such progress.

ENVIRONMENTAL THREATS AND OPPORTUNITIES
Knowledge about the most significant potential obstacles to sustainability is needed along with an awareness of the opportunities for deflecting, adapting to, or mitigating the threats. The most serious threats are those that affect the ability of multiple sectors of society to move ahead toward the normative goals for sustainability; have cumulative or delayed consequences, with effects felt over a long time; are irreversible or difficult to change; or have a notable potential to interact with each other to damage earth’s life support systems.

The Board attempted several approaches to identify significant environmental threats, including
(1) a review of comparative rankings of the severity of environmental hazards for particular times and places;
(2) expert assessment of the challenges and opportunities of human activities in several developmental sectors that the Brundtland Commission identified as critical (human population and well-being, urban systems, agricultural production, industry, energy, and living resources);
(3) evaluation of how these threats and opportunities may change when multiple activities from different sectors interact with complex environmental systems (e.g. freshwater systems, atmosphere and climate, and species and ecosystems).

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

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

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

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

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

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

To characterize the effectiveness of actions undertaken to reach the goals, at least four approaches seem promising and deserving of further study:

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

INTEGRATING KNOWLEDGE AND ACTION

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

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

Priorities for Research: Sustainability Science

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

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

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

- **Promote better utilization of existing tools and processes for linking knowledge to action in pursuit of a transition to sustainability.** A great deal of knowledge, know-how, and capacity for learning about sustainable development is already assembled in various observational systems, laboratories, and management regimes around the world—but these resources are not widely known or used. The successful production and use of the knowledge needed for a sustainability transition will require significant strengthening of institutional capacity in at least four areas:
  1. the linking of long-term research programs to societal goals;
  2. coupling global, national, and local institutions into effective research systems;
  3. linking academia, government, and the private sector in collaborative research partnerships;
  4. integrating disciplinary knowledge in place-based, problem-driven research efforts.

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

Priorities for action include the following:

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

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

- **Reverse declining trends in agricultural production in Africa; sustain historic trends elsewhere.** The most critical near-term aspect of this goal is to reverse the decline in agricultural production capability in Sub-Saharan Africa, the only region where population growth has outpaced growth in agricultural production. A collaborative effort involving African governments, the African
scientific community, African farmers, and nongovernmental organizations will be needed to address the causes and the responsive actions to achieve the technical capacity and implementation needed. At the same time, over the two generations to come, meeting the challenge of feeding the burgeoning world population as a whole and reducing hunger while sustaining life support systems will require a dramatic overall advance in food production, distribution, and access. Sustainable increases in output per hectare of two to three times present levels will be required by 2050. Productivity must be increased on robust areas and restored to degraded lands, while damage to fragile land areas is reduced. New biology-based technologies and implementation will be needed to meet these challenges, renewing yield increases and diminishing negative environmental and social consequences.

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

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

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

There is no precedent for the ambitious enterprise of mobilizing science and technology to ensure a transition to sustainability. Nevertheless, the United States has a special obligation to join and help guide the journey. In addition to having a robust scientific and technological capacity, the United States is a major consumer of global resources. Moreover, sustainable communities have not been realized across the U.S. landscape. Carrying out this enterprise successfully will require collaborative efforts across many dimensions of science and society. Implementation of the recommendations in this report will be a task not only for the National Research Council and its U.S. partners in science, but also for the international science community, governments, foundations, voluntary organizations, and the private sector working together through innovative knowledge-action collaboratives. Our goal here has not been to preempt any broader endeavors involving these national and international partners, but rather to encourage them and to suggest some initial directions for our common journey toward sustainability.

---

**Linking Science and Technology to Society’s Environmental Goals.**
National Research Council

A report based on National Research Council National Forums on Science and Technology Goals

**Executive Summary**
Six subjects of environmental goals from the report:
1. Economics and risk assessment
2. Environmental monitoring and ecology
3. Chemicals in the environment
4. The energy system
5. Industrial ecology
6. Population

1) Social Science (Economics) and Risk Assessment

Summary:
The need to better understand the relationship between the magnitude of risks and the number of people potentially affected. Also the need to identify the importance of incentive-based environmental regulation over command-and-control approaches. This would be identified using quantitative risk assessment and cost-benefit analysis methods to aid decision-makers.

Recommendations:
1. Research to improve the analytical tools available to decision-makers should be expanded.
2. Research should be increased and demonstration projects launched to expand the application of incentive-based approaches to environmental protection.
3. Social science research on comparative risk assessment can be helpful at all levels of government to help to establish regulatory and legislative priorities.

2) Environmental Monitoring and Ecology

Summary:
Current ecological data and understanding are inadequate in regard to the following:
1. Detecting, monitoring and characterizing environmental changes
2. Evaluating the consequences of human activities
3. Providing an information base for sustainable management of both natural and ecological human-designed systems

Recommendations:
1. White House Office of Science and Technology Policy should review and evaluate the quality of existing measurement and monitoring systems for relevance to and usefulness in meeting environmental goals.
2. US Congress should assign an existing or new federal research organization the mission of working with the scientific community to identify key subject areas for ecological research and ensuring that his research is being pursued adequately somewhere in the overall environmental research.
3. Research should aim at identifying and developing reliable indicators of the health and sustainability of the environment and ecosystems.
4. New systems of monitoring that meet society’s decision-making needs should be identified and implemented.
5. The nation’s existing monitoring system needs to be reviewed and evaluated for its relevance to indicators of environmental progress and identification of emerging issues.

3) **Chemicals in the Environment**

**Summary:**
Need to understand the basic knowledge and procedures evaluating the potential impacts of chemicals, compound mixtures, or artificial concentrations of natural substances that have an adverse effect on human health and environment.

**Recommendations:**
1. Better test methods should be developed to evaluate, model, and monitor the potential long-term environmental impacts of single compounds emitted as a result of new products or processes.
2. Better test methods should be developed to define and ultimately to model and predict the byproducts and degradation products associated with production and use of materials.
3. Basic studies of biochemical effects and of the impact of various chemicals and other adverse effects on the biochemistry of sensitive plant and animals species should be strongly supported.
4. Strong support should be given to innovative ideas for modeling and tests on lower-order surrogate species that help to reduce the cost of tests for potential adverse environmental health effects on humans or shorten the response time needed to obtain that information.
5. International standardization of testing and international sharing of testing responsibilities should be promoted to reduce costs and speed the availability of reliable and reproducible assessments.
6. The emerging concept of developing experimental “miniecosystems” –focused on controlled-exposure environments for testing and for developing mathematical simulations of ecosystem impact based on limited, specific tests—should be supported.

4) **The Energy System**

**Summary:**
Energy production and use underlie the growth of modern industrial society, but production and use are often replete with environmental problems. Of particular concern is the use of fossil fuels that lead to environmental problems, such as urban air pollution, acid rain, resource extraction, and global warming.

**Recommendations:**
Sustained research and development that will lead to more options for energy generation and use, less emission of carbon into the atmosphere and more-efficient use of natural resources. In particular, the following topics should be explored:

- Electricity
Renewable energy sources
- Coal
- Nuclear fission
- Nuclear fusion
- Hydrogen
- Transportation
US should continue to address the ways of making energy use more efficient, including pollution reduction.

5) Industrial Ecology

Summary:
A key component of industrial ecology is analyzing the environment effects of all materials in manufacture, use and disposal. This approach should avoid the "end-of-pipe" treatment since this treatment is less cost-effective and less desirable than other means of pollution control.

Recommendations:
1. Design products and processes for environmental compatibility should make use of such mechanisms as life-cycle analysis, alternative manufacturing processes, and efficient technologies.
2. Products and processes should be designed to accommodate recycling and reuse more readily.
3. Regulations introduced for other purposes often create barriers to the use of economic incentives for promoting the adopting of the principles of industrial ecology.
4. The use of industrial ecology approaches should be expanded to many industries through dialogue among ever-widening circle of corporations, governments, academic institutions, and environmental and citizen organizations.
5. Research should be conducted to develop methods for chemical species-specific separations that yield streams that are economically recoverable or dischargeable to the environment.
6. Research on new or improved catalytic systems that offer improved yields and improved specificity from more-benign chemicals should be promoted.

6) Population

Summary:
The current and potential threats to environmental quality are the results of the character and magnitude of today’s economic activity and human population growth.

Recommendations:
1. US, in its efforts to cooperate with the world community, should recognize the linkages between birth rates, child survival, economic development, education, and the economic and social status of women in its environmental research efforts.
2. Researchers should focus on ways to improve the potential for universal access to effective family planning information, contraceptives, and health care.

3. US policies need to support, through partnerships with developing countries, for the scientific and technological research needed by international population programs.

4. Interdisciplinary research should be conducted on the future environmental consequences of population growth. Research should incorporate human biology, human behavior, epidemiology, and ecology to acquire a better understanding of all aspects of the population-environment interface.

U.S. National Research Council
Grand Challenges In Environmental Sciences

Executive Summary

Scientists have long worked to understand the environment and humanity’s place in it. The search for this knowledge grows in importance as rapid increases in human populations and economic development intensify the stresses human beings place on the biosphere and ecosystems. People want to be warned of major environmental changes and, if the environment is under threat, want to know how to respond. Fortunately, rapid increases in scientific capability—such as recent advances in computing power and molecular biology and new techniques for sensing biological, physical, and chemical phenomena below, on, and above the Earth’s surface—together with the rediscovery that the human-environment relationship is a critical topic for the human sciences, are making it possible for science to provide much of this knowledge. The scientific excitement and challenge of understanding the complex environmental systems humans depend on make the environmental sciences centrally important as humankind attempts a transition to a more sustainable relationship with the Earth and its natural resources.

This report was written in response to a request from the National Science Foundation (NSF) that the National Research Council (NRC), drawing on expertise from across the environmental sciences, offer a judgment regarding the most important environmental research challenges of the next generation—the areas most likely to yield results of major scientific and practical importance if pursued vigorously now. In formulating this judgment, the committee established by the NRC confronted the problem of the unity of the environment—the fact that every aspect of the environment is connected to every other in some way.

Consequently, no branch of environmental science can progress very far without drawing on knowledge from other branches. The committee sought to identify a small number of grand challenges in the environmental sciences—major scientific tasks that are compelling for both intellectual and practical reasons, that offer potential for major breakthroughs on the basis of recent developments in science and technology, and that
are feasible given current capabilities and a serious infusion of resources. After
soliciting input as broadly as possible and considering more than 200 nominations from
the scientific community, the committee selected the eight grand challenges described
below. The committee’s selection criteria included probability of significant scientific and
practical payoff, large scope, relevance to important environmental issues, feasibility,
timeliness, and requirement for multidisciplinary collaboration.

Attaining the needed environmental knowledge for the next generation will depend on
the active pursuit of all eight grand challenges. However, the committee was asked to
identify an even more focused list of activities to be pursued in the near term by NSF,
either alone or in collaboration with other research funders. Therefore, the committee
selected four areas, derived from the grand challenges, to recommend for immediate
research investment by NSF and others. In addition to the criteria used to choose the
eight grand challenges, the committee considered whether the activities are currently
underfunded, i.e., stand to benefit from an infusion of financial and human resources;
the committee also applied the criteria of scientific importance, urgency, and scope. The
committee did not rank-order the grand challenges, as we consider them all to be
broadly and deeply important, nor did we rank-order the immediate research
investments for the same reason. Both are therefore presented below in alphabetical
order.

The Grand Challenges

1. Biogeochemical Cycles
The challenge is to further our understanding of the Earth’s major biogeochemical
cycles, evaluate how they are being perturbed by human activities, and determine how
they might better be stabilized. Important research areas include quantifying the
sources and sinks of the nutrient elements and gaining a better understanding of the
biological, chemical, and physical factors regulating transformations among them;
improving understanding of the interactions among the various biogeochemical cycles;
assessing anthropogenic perturbations of biogeochemical cycles and their impacts on
ecosystem functioning, atmospheric chemistry, and human activities, and developing a
scientific basis for societal decisions about managing these cycles; and exploring
technical and institutional approaches to managing anthropogenic perturbations.

2. Biological Diversity and Ecosystem Functioning
The challenge is to improve understanding of the factors affecting biological diversity
and ecosystem structure and functioning, including the role of human activity. Important
research areas include improving tools for rapid assessment of diversity at all scales;
producing a quantitative, process-based theory of biological diversity at the largest
possible variety of spatial and temporal scales; elucidating the relationship between
diversity and ecosystem functioning; and developing and testing techniques for
modifying, creating, and managing habitats that can sustain biological diversity, as well
as people and their activities.

3. Climate Variability
The challenge is to increase our ability to predict climate variations, from extreme events to decadal time scales; to understand how this variability may change in the future; and to assess realistically the resulting impacts. Important research areas include improving observational capability, extending the record of observations back into the Earth’s history, improving diagnostic process studies, developing increasingly comprehensive models, and conducting integrated impact assessments that take human responses and impacts into account.

4. Hydrologic Forecasting
The challenge is to develop an improved understanding of and ability to predict changes in freshwater resources and the environment caused by floods, droughts, sedimentation, and contamination. Important research areas include improving understanding of hydrologic responses to precipitation, surface water generation and transport, environmental stresses on aquatic ecosystems, the relationships between landscape changes and sediment fluxes, and subsurface transport, as well as mapping groundwater recharge and discharge vulnerability.

5. Infectious Disease and the Environment
The challenge is to understand ecological and evolutionary aspects of infectious diseases; develop an understanding of the interactions among pathogens, hosts/receptors, and the environment; and thus make it possible to prevent changes in the infectivity and virulence of organisms that threaten plant, animal, and human health at the population level. Important research areas include examining the effects of environmental changes as selection agents on pathogen virulence and host resistance; exploring the impacts of environmental change on disease etiology, vectors, and toxic organisms; developing new approaches to surveillance and monitoring; and improving theoretical models of host-pathogen ecology.

6. Institutions and Resource Use
The challenge is to understand how human use of natural resources is shaped by institutions such as markets, governments, international treaties, and formal and informal sets of rules that are established to govern resource extraction, waste disposal, and other environmentally important activities. Important research areas include documenting the institutions governing critical lands, resources, and environments; identifying the performance attributes of the full range of institutions governing resources and environments worldwide, from local to global levels; improving understanding of change in resource institutions; and conceptualizing and assessing the effects of institutions for managing global commons.

7. Land-Use Dynamics
The challenge is to develop a systematic understanding of changes in land uses and land covers that are critical to ecosystem functioning and services and human welfare. Important areas for research include developing long-term, regional databases for land uses, land covers, and related social information; developing spatially explicit and multisectoral land-change theory; linking land change theory to space-based imagery; and developing innovative applications of dynamic spatial simulation techniques.
8. Reinventing the Use of Materials
The challenge is to develop a quantitative understanding of the global budgets and cycles of materials widely used by humanity and of how the life cycles of these materials (their history from the raw-material stage through recycling or disposal) may be modified. Important research areas include developing spatially explicit budgets for selected key materials; developing methods for more complete cycling of technological materials; determining how best to utilize materials that have uniquely useful industrial applications but are potentially hazardous to the environment; developing an understanding of the patterns and driving forces of human consumption of resources; and developing models for possible global scenarios of future industrial development and associated environmental implications.

RECOMMENDED IMMEDIATE RESEARCH INVESTMENTS
The committee recommends that immediate investments be made in four priority research areas related to the grand challenges:

1. Biological Diversity and Ecosystem Functioning
   - Recommendation: Develop a comprehensive understanding of the relationship between ecosystem structure and functioning and biological diversity. This initiative would include experiments, observations, and theory, and should have two interrelated foci: (a) developing the scientific knowledge needed to enable the design and management of habitats that can support both human uses and native biota; and (b) developing a detailed understanding of the effects of habitat alteration and loss on biological diversity, especially those species and ecosystems whose disappearance would likely do disproportionate harm to the ability of ecosystems to meet human needs or set in motion the extinction of many other species.

1. Hydrologic Forecasting
   - Recommendation: Establish the capacity for detailed, comprehensive hydrologic forecasting, including the ecological consequences of changing water regimes, in each of the primary U.S. climatological and hydrologic regions. Important specific research areas include all those described under Grand Challenge 4.

2. Infectious Disease and the Environment
   - Recommendation: Develop a comprehensive ecological and evolutionary understanding of infectious diseases affecting human, plant, and animal health.

5. Land-Use Dynamics
   - Recommendation: Develop a spatially explicit understanding of changes in land uses and land covers and their consequences.
IMPLEMENTATION ISSUES
The identification of grand challenges in environmental sciences and priorities for immediate research investment is only a prelude. The key then becomes implementation. In the committee’s view, several critical implementation issues cut across all of the research areas identified. These issues include such matters as whether to proceed by establishing regional research centers, how best to support interdisciplinary research, and how to make environmental science useful to decision makers and managers and the public.

Recommendation: NSF, together with other agencies as appropriate, should conduct workshops that include research scientists in academia, the relevant agencies, and the private sector, as well as potential users of the research results, to discuss and plan research agendas and address implementation issues.

Under the Weather: Climate, Ecosystems, and Infectious Disease
US National Research Council

Executive Summary
Health and climate have been linked since antiquity. In the fifth century B.C., Hippocrates observed that epidemics were associated with natural phenomena rather than deities or demons. In modern times, our increasing capabilities to detect and predict climate variations such as the El Niño/Southern Oscillation (ENSO) cycle, coupled with mounting evidence for global climate change, have fueled a growing interest in understanding the impacts of climate on human health, particularly the emergence and transmission of infectious disease agents. Simple logic suggests that climate can affect infectious disease patterns because disease agents (viruses, bacteria, and other parasites) and their vectors (such as insects or rodents) are clearly sensitive to temperature, moisture, and other ambient environmental conditions. The best evidence for this sensitivity is the characteristic geographic distribution and seasonal variation of many infectious diseases. Weather and climate affect different diseases in different ways. For example, mosquito-borne diseases such as dengue, malaria, and yellow fever are associated with warm weather; influenza becomes epidemic primarily during cool weather; meningitis is associated with dry environments; and cryptosporidiosis outbreaks are associated with heavy rainfall. Other diseases, particularly those transmitted by direct interpersonal contact such as HIV/AIDS, show no clear relationship to climate. By carefully studying these associations and their underlying mechanisms, we hope to gain insights into the factors that drive the emergence and seasonal/interannual variations in contemporary epidemic diseases and, possibly, to understand the potential future disease impacts of long-term climate change.
The U.S. federal agencies entrusted with guarding the nation’s health and the environment, along with other concerned institutions, requested the formation of a National Research Council committee to evaluate this issue.

Specifically, the committee was asked to undertake the following three tasks:

1. **Conduct an in-depth, critical review of the linkages between temporal and spatial variations of climate and the transmission of infectious disease agents;**
2. **Examine the potential for establishing useful health-oriented climate early-warning and surveillance systems, and for developing effective societal responses to any such early warnings;**
3. **Identify future research activities that could further clarify and quantify possible connections between climate variability, ecosystems, and the transmission of infectious disease agents, and their consequences for human health.**

There are many substantial research challenges associated with studying linkages among climate, ecosystems, and infectious diseases. For instance, climate-related impacts must be understood in the context of numerous other forces that drive infectious disease dynamics, such as rapid evolution of drug- and pesticide-resistant pathogens, swift global dissemination of microbes and vectors through expanding transportation networks, and deterioration of public health programs in some regions. Also, the ecology and transmission dynamics of different infectious diseases vary widely from one context to the next, thus making it difficult to draw general conclusions or compare results from individual studies. Finally, the highly interdisciplinary nature of this issue necessitates sustained collaboration among disciplines that normally share few underlying scientific principles and research methods, and among scientists that may have little understanding of the capabilities and limitations of each other’s fields. In light of these challenges, the scientific community is only beginning to develop the solid scientific base needed to answer many important questions, and accordingly, in this report the committee did not attempt to make specific predictions about the likelihood or magnitude of future disease threats. Instead, the focus is on elucidating the current state of our understanding and the factors that, at present, may limit the feasibility of predictive models and effective early warning systems. The following is a summary of the committee’s key findings and recommendations:

**KEY FINDINGS: LINKAGES BETWEEN CLIMATE AND INFECTIOUS DISEASES**

Weather fluctuations and seasonal-to-interannual climate variability influence many infectious diseases. The characteristic geographic distributions and seasonal variations of many infectious diseases are *prima facie* evidence of linkages with weather and climate. Studies have shown that factors such as temperature, precipitation, and humidity affect the lifecycle of many disease pathogens and vectors (both directly, and indirectly through ecological changes) and thus can potentially affect the timing and intensity of disease outbreaks. However, disease incidence is also affected by factors
such as sanitation and public health services, population density and demographics, land use changes, and travel patterns. The importance of climate relative to these other variables must be evaluated in the context of each situation.

Observational and modeling studies must be interpreted cautiously. There have been numerous studies showing an association between climatic variations and disease incidence, but such studies are not able to fully account for the complex web of causation that underlies disease dynamics and thus may not be reliable indicators of future changes. Likewise, a variety of models have been developed to simulate the effects of climatic changes on incidence of diseases such as malaria, dengue, and cholera. These models are useful heuristic tools for testing hypotheses and carrying out sensitivity analyses, but they are not necessarily intended to serve as predictive tools, and often do not include processes such as physical/biological feedbacks and human adaptation. Caution must be exercised then in using these models to create scenarios of future disease incidence, and to provide a basis for early warnings and policy decisions.

The potential disease impacts of global climate change remain highly uncertain. Changes in regional climate patterns caused by long-term global warming could affect the potential geographic range of many infectious diseases. However, if the climate of some regions becomes more suitable for transmission of disease agents, human behavioral adaptations and public health interventions could serve to mitigate many adverse impacts. Basic public health protections such as adequate housing and sanitation, as well as new vaccines and drugs, may limit the future distribution and impact of some infectious diseases, regardless of climate-associated changes. These protections, however, depend upon maintaining strong public health programs and assuring vaccine and drug access in the poorer countries of the world.

Climate change may affect the evolution and emergence of infectious diseases. Another important but highly uncertain risk of climate change are the potential impacts on the evolution and emergence of infectious disease agents. Ecosystem instabilities brought about by climate change and concurrent stresses such as land use changes, species dislocation, and increasing global travel could potentially influence the genetics of pathogenic microbes through mutation and horizontal gene transfer, and could give rise to new interactions among hosts and disease agents. Such changes may foster the emergence of new infectious disease threats.

There are potential pitfalls in extrapolating climate and disease relationships from one spatial/temporal scale to another. The relationships between climate and infectious disease are often highly dependent upon local-scale parameters, and it is not always possible to extrapolate these relationships meaningfully to broader spatial scales. Likewise, disease impacts of seasonal to interannual climate variability may not always provide a useful analog for the impacts of long-term climate change. Ecological responses on the timescale of an El Niño event, for example, may be significantly different from the ecological responses and social adaptations expected under long-
term climate change. Also, long-term climate change may influence regional climate variability patterns, hence limiting the predictive power of current observations.

Recent technological advances will aid efforts to improve modeling of infectious disease epidemiology. Rapid advances being made in several disparate scientific disciplines may spawn radically new techniques for modeling of infectious disease epidemiology. These include advances in sequencing of microbial genes, satellite-based remote sensing of ecological conditions, the development of Geographic Information System (GIS) analytical techniques, and increases in inexpensive computational power. Such technologies will make it possible to analyze the evolution and distribution of microbes and their relationship to different ecological niches, and may dramatically improve our abilities to quantify the disease impacts of climatic and ecological changes.

**KEY FINDINGS: THE POTENTIAL FOR DISEASE EARLY WARNING SYSTEMS**

As our understanding of climate/disease linkages is strengthened, epidemic control strategies should aim towards complementing “surveillance and response” with “prediction and prevention.” Current strategies for controlling infectious disease epidemics depend largely on surveillance for new outbreaks followed by a rapid response to control the epidemic. In some contexts, however, climate forecasts and environmental observations could potentially be used to identify areas at high risk for disease outbreaks and thus aid efforts to limit the extent of epidemics or even prevent them from occurring. Operational disease early warning systems are not yet generally feasible, due to our limited understanding of most climate/disease relationships and limited climate forecasting capabilities. But establishing this goal will help foster the needed analytical, observational, and computational developments.

The potential effectiveness of disease early warning systems will depend upon the context in which they are used. In cases where there are relatively simple, low-cost strategies available for mitigating risk of epidemics, it may be feasible to establish early warning systems based only on a general understanding of climate/disease associations. But in cases where the costs of mitigation actions are significant, a precise and accurate prediction may be necessary, requiring a more thorough mechanistic understanding of underlying climate/disease relationships. Also, the accuracy and value of climate forecasts will vary significantly depending on the disease agent and the locale. For instance, it will be possible to issue sufficiently reliable ENSO-related disease warnings only in regions where there are clear, consistent ENSO-related climate anomalies. Finally, investment in sophisticated warning systems will be an effective use of resources only if a country has the capacity to take meaningful actions in response to such warnings, and if the population is significantly vulnerable to the hazards being forecast.

Disease early warning systems cannot be based on climate forecasts alone. Climate forecasts must be complemented by an appropriate suite of indicators from ongoing meteorological, ecological, and epidemiological surveillance systems. Together, this information could be used to issue a “watch” for regions at risk and subsequent
“warnings” as surveillance data confirm earlier projections. Development of disease early warning systems should also include vulnerability and risk analysis, feasible response plans, and strategies for effective public communication. Climate-based early warning systems being developed for other applications, such as agricultural planning and famine prevention, provide many useful lessons for the development of disease early warning systems.

Development of early warning systems should involve active participation of the system’s end users. The input of stakeholders such as public health officials and local policymakers is needed in the development of disease early warning systems, to help ensure that forecast information is provided in a useful manner and that effective response measures are developed. The probabilistic nature of climate forecasts must be clearly explained to the communities using these forecasts, so that response plans can be developed with realistic expectations for the range of possible outcomes.

RECOMMENDATIONS FOR FUTURE RESEARCH AND SURVEILLANCE

Research on the linkages between climate and infectious diseases must be strengthened. In most cases, these linkages are poorly understood and research to understand the causal relationships is in its infancy. Methodologically rigorous studies and analyses will likely improve our nascent understanding of these linkages and provide a stronger scientific foundation for predicting future changes. This can best be accomplished with investigations that utilize a variety of analytical methods (including analysis of observational data, experimental manipulation studies, and computational modeling), and that examine the consistency of climate/disease relationships in different societal contexts and across a variety of temporal and spatial scales. Progress in defining climate and infectious disease linkages can be greatly aided by focused efforts to apply recent technological advances such as remote sensing of ecological changes, high-speed computational modeling, and molecular techniques to track the geographic distribution and transport of specific pathogens.

Further development of disease transmission models is needed to assess the risks posed by climatic and ecological changes. The most appropriate modeling tools for studying climate/disease linkages depend upon the scientific information available. In cases where there is limited understanding of the ecology and transmission biology of a particular disease, but sufficient historical data on disease incidence and related factors, statistical-empirical models may be most useful. In cases where there are insufficient surveillance data, “first principle” mechanistic models that can integrate existing knowledge about climate/disease linkages may have the most heuristic value. Models that have useful predictive value will likely need to incorporate elements of both these approaches. Integrated assessment models can be especially useful for studying the relationships among the multiple variables that contribute to disease outbreaks, for looking at long-term trends, and for identifying gaps in our understanding.

Epidemiological surveillance programs should be strengthened. The lack of high-quality epidemiological data for most diseases is a serious obstacle to improving our
understanding of climate and disease linkages. These data are necessary to establish an empirical basis for assessing climate influences, for establishing a baseline against which one can detect anomalous changes, and for developing and validating models. A concerted effort, in the United States and internationally, should be made to collect long-term, spatially resolved disease surveillance data, along with the appropriate suite of meteorological and ecological observations. Centralized, electronic databases should be developed to facilitate rapid, standardized reporting and sharing of epidemiological data among researchers.

Observational, experimental, and modeling activities are all highly interdependent and must progress in a coordinated fashion. Experimental and observational studies provide data necessary for the development and testing of models; and in turn, models can provide guidance on what types of data are most needed to further our understanding. The committee encourages the establishment of research centers dedicated to fostering meaningful interaction among the scientists involved in these different research activities through long-term collaborative studies, short-term information-sharing projects, and interdisciplinary training programs. The National Center for Ecological Analysis and Synthesis provides a good model for the type of institution that would be most useful in this context.

Research on climate and infectious disease linkages inherently requires interdisciplinary collaboration. Studies that consider the disease host, the disease agent, the environment, and society as an interactive system will require more interdisciplinary collaboration among climate modelers, meteorologists, ecologists, social scientists, and a wide array of medical and public health professionals. Encouraging such efforts requires strengthening the infrastructure within universities and funding agencies for supporting interdisciplinary research and scientific training. In addition, educational programs in the medical and public health fields need to include interdisciplinary programs that explore the environmental and socioeconomic factors underlying the incidence of infectious diseases.

Numerous U.S. federal agencies have important roles to play in furthering our understanding of the linkages among climate, ecosystems, and infectious disease. There have been a few programs established in recent years to foster interdisciplinary work in applying remote sensing and GIS technologies to epidemiological investigations. The committee applauds these efforts and encourages all of the relevant federal agencies to support interdisciplinary research programs on climate and infectious disease, along with an interagency working group to help ensure effective coordination among these different programs. The U.S. Global Change Research Program (USGCRP) may provide an appropriate forum for this type of coordinating body. This will require, however, that organizations such as the Centers for Disease Control and Prevention, and the National Institute of Allergy and Infectious Diseases become actively involved with the USGCRP.

Finally, the committee wishes to emphasize that even if we are able to develop a strong understanding of the linkages among climate, ecosystems, and infectious diseases, and
in turn, are able to create effective disease early warning systems, there will always be some element of unpredictability in climate variations and infectious disease outbreaks. Therefore, a prudent strategy is to set a high priority on reducing people’s overall vulnerability to infectious disease through strong public health measures such as vector control efforts, water treatment systems, and vaccination programs.

“Public Access to Environmental Information”

PATRICK D. EAGAN, LYNDA M. WIESE, and DAVID S. LIEBL


Access to relevant environmental information can help to improve the ecology of industry. Imagine geographic databases that allow cross correlation of municipal and industrial discharges in various media (air, water, land). Envision the siting of industrial facilities on the basis of environmental carrying capacity of a geographic location. Think of the capability to determine the environmental profile of common industrial products. Technically, these capabilities exist. The ecology of industry can be improved by aggregating, evaluating, and increasing access to environmental information using information technology. Indeed, there are several reasons to step up the aggregation and dissemination of information:

- There is increasing pressure to deliver public services more economically and effectively.
- Public agencies benefit by making issues public and engaging the public in decision-making.
- Public-interest groups are demanding aggregated environmental information to monitor company performance and influence public policy.
- The demand for facility-based environmental information is increasing.
- Access to environmental information, such as the Toxics Release Inventory (TRI), has been shown to be effective in raising awareness about and reducing toxic chemicals.
- There is increasing demand in the private sector for facility-based environmental information for supply-chain management.
- Cross-media, aggregated environmental information will support better environmental decision-making.
- The technology exists to deliver aggregated, spatially connected environmental information.

Public environmental protection agency administrators and industrial environmental managers, however, face fundamental questions about the availability of and, indeed, whether the collection of various types of environmental information will contribute to better environmental decisions in the agency or business. The public administrator’s concern about accessibility and perceived value may revolve around whether greater public access to aggregated environmental information will lead to improved public
policy, whereas the industrial manager may question whether access to aggregated environmental information will increase the ability to control risk from a supply chain, gather life-cycle environmental information for design purposes, or allow unwanted access to competitive engineering processes.

This paper discusses the value of aggregated environmental information to Environmental Protection Agency administrators and industrial environmental managers. It also presents the challenges in providing public access to this type of information, using the case study of an environmental information system called Fact, which is being implemented by the Wisconsin Department of Natural Resources (WDNR).

**AVAILABILITY OF ENVIRONMENTAL INFORMATION**

Environmental regulatory agencies are mandated to protect the environment. As part of this mandate, federal and state environmental protection agencies collect large amounts of permit discharge and ambient monitoring data to assess regional and local environmental conditions, to determine compliance, and to charge fees. Industrial entities similarly collect vast amounts of environmental information related to their operations. Companies that implement environmental management systems under the International Organization for Standardization 14001, and adopt the goals of organizations such as the Coalition of Environmentally Responsible Economies or the Global Environmental Management Initiative, collect and publicly disclose much more information than is required by regulation. Each entity—industrial or governmental—collects environmental information to meet specific needs. The information, therefore, is available, but this information alone may not be what is needed to answer a specific environmental question or issue.

**VALUE OF COLLECTING ENVIRONMENTAL INFORMATION**

State agencies have partnered with other stakeholders to collect, aggregate, and analyze data. The WDNR (1996) report, *Acid Deposition Monitoring and Evaluation Program*, demonstrates the value of collaborating and coordinating efforts to meet data needs. In the case of acid deposition, the report states: Wisconsin’s Acid Deposition Monitoring and Evaluation Program, as developed by the Acid Deposition Research Council, began its efforts during 1985 when the Acid Rain Law, Wisconsin Act 296, was enacted. In addition to its significant contribution in the area of acid rain research, the Acid Deposition Research Council model brought together diverse interest groups and then maximized the use of pooled resources to accomplish a common goal—to assess the threat of acid rain to Wisconsin’s resources. Using the consensus approach, the Council has been able to reach agreement on complex issues like research objectives, priorities, and funding levels. Under Council leadership, the once acrimonious acid rain debate was transformed into an objective evaluation of facts. Industrial environmental data also has proved to be especially useful for strategic planning by regulatory agencies and providers of state manufacturing assistance. For example, state agency personnel have correlated industrial emissions information from the TRI2 with manufacturing processes. The TRI requires that companies report releases of toxins to the air, land, and water. Using the emissions data correlation, decision makers then set
statewide priorities for reducing emissions at the source (Liebl, 1991, 1992). Community
groups have similarly used aggregated environmental information to create
demographic maps with toxic emission overlays as a basis for promoting environmental
justice and to stimulate citizen activism to pressure industry to reduce the use of toxins
(Dorr et al., 1993). There are industrial and regulatory agency benefits to aggregated
reporting of environmental information. The development of the Integrated Toxics
Reporting System (ITRS) in Wisconsin allows for the identification and correction of
data errors relating to hazardous waste generated by specific companies. The ITRS
reports are reviewed by companies and cross checked against internal records for
verification of data accuracy. The data from the ITRS also have been used by
companies to develop full facility profiles as a first step to understanding the scope of
hazardous waste generation and toxic emissions. These profiles offer managers
incentives and justification to reduce toxins (WDNR, 1995).

GOVERNMENT DEMAND FOR ENVIRONMENTAL INFORMATION
In addition to the needs of public agencies for specific environmental data and
information, there are several forces driving state agencies and the private sector to
increase public access to environmental information. These include the need for greater
administrative efficiency, the increased public demand for information, and the potential
for improving environmental protection.

Administrative Efficiency
Public agencies have been under mounting pressure to decrease costs and increase
productivity in monitoring industrial environmental performance; state agencies collect
information (some of which is publicly available) from companies. This information is
used to fulfill requests for paper copies of reports and permits or to provide notices of
violations relating to specific companies. An environmental information system being
implemented by the WDNR is expected to decrease the costs of copying, searching,
and integrating relevant information; to speed delivery of information; and to ease
records retention problems at the agency. A new data reporting protocol being tested
would allow companies using the American National Standards Institute (ANSI) X-12
data standards to access the WDNR computing systems directly and submit the
required data online. In fact, the future may bring direct links with company data
systems such that the state agencies would not require annual reporting. Rather, state
regulators might be provided with direct access to specific company environmental
performance data sets that the company would routinely update for regulators. The
costs of maintaining and retrieving publicly requested information, however, can be
substantial, even if done electronically. When facilities submit paper reports to state
agencies, data from the report are entered into the database. Then it is stored and
manipulated for billing and reports. Data entry operations cost time and money. Quality
assurance for accurate data adds to the costs. For example, data comparisons with
previous years’ submittals are made to flag wide variations in data points so that agency
engineers can investigate reasons for the
wide discrepancies. Electronic submittal of facility reports entails entering the data onto
a computer diskette that is sent back to the state agency. As with paper-based reporting
systems, resources are needed to support an electronic reporting system. For example,
resources are needed to help first-time users with installing necessary programs as well as uploading and downloading information specific to each facility onto diskettes. In addition, technical staff is still needed to undertake quality assurance checks. However, responsibility for data entry errors rests with the company, not the state agency.

**INCREASED PUBLIC DEMAND FOR INFORMATION**
The mere existence of technology to increase public accessibility to environmental information has increased demand for information collected by state bureaucracies. Customers of state agencies (the public) are demanding that compliance and permit data be made available in electronic formats and be accessible on the World Wide Web (WWW). The spread of digital technology also has increased the demand for real-time information. Geographic information systems (GISs), which enable the collation, manipulation, and integration of spatial environmental information in ways not envisioned before, are being demanded by industry, government, and the public. This type of information can be used to show people the impact of releases from a facility or group of facilities. The GIS enables a visual map of an affected area to be overlain with a street map of the immediate area to give the public information about public risk.

**Improved Environmental Protection**
The reduction in emissions from industrial sources attributed to the TRI program has demonstrated the value of having a variety of environmental data compiled in one report and made widely available. The TRI requires certain facilities over a specified threshold to report releases of contaminants to the air, land, and water. This information is gathered annually and published for the public to review. Carol M. Browner, former administrator of the U.S. Environmental Protection Agency (EPA), observed that arming the public with basic information about toxic chemicals in their communities is among the most effective, common sense steps to protect the health of families and children from the threats posed by pollution. She pointed out that since the inception of the Community Right-to-Know program (under which TRI was implemented), reported releases of pollution into the community have declined by 46 percent (Kearns, 1997). State agencies also have found TRI data particularly valuable in validating reports of various pollutants. For example, Wisconsin’s air management staff have used their ITRS to identify the failure to report air emissions to the state’s annual air emissions inventory, even though those emissions were reported under TRI. In the same way, Wisconsin also has begun using the ITRS at industrial facilities to ensure the quality of their own multiple reporting requirements and to ensure that all reporting is done accurately. Here the challenge is to use the data being collected to integrate single-media (air, land, or water) pollution reports, so that cross-media analysis can be done to help state agencies target companies that need assistance to minimize transfers of pollutants from one media to another.

**INDUSTRY DEMAND FOR ENVIRONMENTAL INFORMATION**
Aggregating environmental data enables more sophisticated analysis of environmental impacts of products and services and better environmental management and reduced risk. Progressive industry is interested in both product assessment and supply-chain environmental compliance performance. Product or service assessments are based on
the systematic, environmental review of the life-cycle steps associated with the product’s component materials and manufacturing processes. Comprehensive analyses are called life-cycle assessments (LCAs). LCA has been used generally on products comprising few materials (Ehrenfeld, 1997; Owens, 1997). Aggregation of data across the product life cycle of energy and materials is a major feature of an LCA. However, there is a limit to the level of aggregation that is meaningful. Accumulating emissions from many different sites can lead to inappropriate conclusions if not integrated with other assessment techniques (Owens, 1997). Less-data-intensive, streamlined, or abridged analyses also are described in the literature. Several industries have effectively used streamlined matrix analyses on complex products (Graedel et al., 1995), processes (Eagan and Weinberg, 1999), and materials selection (Allenby, 1994). Companies are also increasingly interested in the environmental performance of companies in their supply chains. Because of the consolidation of suppliers and a growing interdependence on suppliers and manufacturers to produce products and deliver services, the shared risk from environmental noncompliance or safety problems within supplier chains has become an issue for companies. Companies are therefore auditing suppliers for environmental risk (Anderson and Choong, 1997). Environmental performance data gathered on a supplier’s compliance history and current status by state agency can be used by companies to estimate the quality of suppliers and judge the risks associated with those facilities.

CHALLENGES AND ISSUES RELATED TO IMPLEMENTING ENVIRONMENTAL INFORMATION SYSTEMS
Implementation of environmental information systems has not been easy despite the availability of technology. The implementation of WDNR’s Fact System (see Box 1) revealed issues related to administration, public accessibility, and the interpretation of information.

Administrative Issues
Many administrative issues are associated with implementing a state-run environmental information system. The most obvious relate to designating responsibility for managing and administering the system. In the case of WDNR’s Fact System, the small size of the databases envisioned suggests that it be run by the state even if some of the data are required for federal reporting. A problem that may arise from this approach occurs when the federal government or an industry wishes to integrate data from various states, but each state has a slightly different program with its own integration problems. With each state implementing its own system, data integration problems at the federal level are very likely to occur. An anecdotal example in which one of the authors was involved demonstrates the next level of responsibility that relates to the data. In 1997, an environmental group in Wisconsin accessed ENVIROFACTS, an EPA public information tool on the Internet, which contains information from environmental reports made by facilities to the EPA. The environmental group proceeded to make a Freedom of Information Act request for Discharge Monitoring Reporting System information for all pulp and paper facilities in central Wisconsin. The EPA complied with the request, indicating that reports of the past two quarters from one mill were not in the system. The environmental group proceeded with a press release criticizing the pulp and paper mill
and hinting at violations of the Clean Water Act for the missing submittal. In fact, the reports had been submitted to the state authority, but the EPA files had not been updated. This example raises the question of where responsibility lies to ensure that publicly accessible data are up to date, of good quality, and used responsibly. In addition to being concerned that the data accessed may not be current, businesses also are concerned about putting incomplete data in an easily disseminated digital form when they submit the data to the regulatory agency. The public expects publicly available information, whether digital or paper, to be accurate. One might expect that it is the responsibility of the data providers to ensure that the information is accurate, that data keepers will be responsible for how the information is compiled, and that the user is responsible for reasonable interpretation.

There is growing concern about the possibility that individuals who have outside access to important databases will tamper with the data. Two options often mentioned are: (1) using a redundant database exclusively for public access or (2) using a firewall to protect the data and allowing read-only privileges. The use of redundant databases may be subject to uncertain financial support and the data currency issue described above. Hence, the use of firewalls is becoming common practice. Finally, there can be data compatibility problems. Aggregating information from a number of different sources requires compatible data formats. For example, data on a single company that is derived from multiple regulatory reporting systems may be expressed in unrelated units of measure; denote toxins as elements, compounds, or mixtures; or list the facility by physical address or mailing address of a parent company. These inconsistencies must be reconciled prior to aggregating the data if reliable information is to be derived.

Public Accessibility Issues
Technical information traditionally has been delivered in writing or through personal contact. More recently, other alternatives have emerged to deliver technical information to as many people as possible using minimal resources. These methods include telephone conferencing, television broadcasts, videotape distribution, and automated faxing systems. The growth of the Internet has added electronic delivery of text through e-mail, file transfer protocols, gophers, and Web sites to the menu of options for transferring information. In addition, the use of e-mail list servers (where notices are sent to subscribers) and online database search engines has dramatically increased the availability of technical information to a wider audience. In the environmental protection field, this audience includes waste generators, regulatory agencies, technical assistance providers, and the public. Electronic sources of environmental information, like other information, come in a variety of configurations. There are manually distributed databases for use on personal computers, interactive online databases that lead a user through a series of decision trees to locate information, online engineering and environmental library catalogs, and electronic information exchanges, such as e-mail list servers. As states and the federal government move toward public access to electronic environmental data, questions arise about the technical capability of all citizens to access and interpret this information. While most public libraries provide access to the Web; finding and interpreting data can be a substantial barrier to the public. Public and private organizations are addressing this problem by indexing
sources of information, compiling summary information on complex issues, and providing interpretation of environmental information (though often with a slant toward their own agendas). The case for public access to environmental data is hard to dispute. No regulatory agency wants to say that their data cannot be made public; they are public agents empowered to enforce the laws. The debate over public accessibility revolves around how accessible the information is to the average citizen. Wisconsin has an open-records law. Basically, all records reported to the WDNR, including environmental information, are open unless they meet the exclusion statute as a trade secret. By statute, there are two tests for a trade secret: (1) Has the company taken reasonable precautions to keep this information confidential? and (2) Would the release of the information cause the company to be put at a competitive disadvantage? Companies can request that certain information reported to the WDNR be kept confidential. Process-specific data, chemical usage, and production levels are the most common types of information protected as confidential. Much of the information gathered in annual reporting for the Air Emission Inventory includes company reports of production levels from which emissions are calculated using a standard set of emission factors—EPA air pollutant emission factors (AP-42). This causes concerns for highly competitive industries. Now that this information is easily accessible in electronic format, competitors can more easily gain intelligence that may influence pricing and competitive bidding. Although environmental information always has been available in paper files or on microfiche, the authors are not aware of any evidence that an industry has taken the time to search through regulator’s files to gain information on competitors. However, as profit margins shrink and competitors become more electronically adept, industries may look for any easily accessible competitive edge, such as evaluations of waste streams to reveal production processes or efficiencies. Whenever the issue of public access to environmental data arises, an electronic data system is the first solution considered and the first funded. The public supports electronic data systems that are being designed by the government for the public’s use. However, the average person needs to have the tools and training to be able to take advantage of these electronic data systems. Little research to date has explored how to raise the capacity of the public to embrace these electronic systems.

A fundamental problem with public access remains: Does the government collect environmental data that the public wants or can understand and meaningfully interpret? Local citizens want to know if they and their children can safely live near a manufacturing facility. Simply knowing that a manufacturing facility emitted 10 tons of permitted discharges into the air does not meet their need. Studies have shown that the American public is not well versed in environmental issues and may have limited knowledge to interpret the information (The Roper Organization, 1990). Although the government collects information for regulatory purposes, it may not know what information the public needs to make an informed contribution to the policy dialog. In all likelihood, the government has never asked. Another accessibility issue pertains to environmental justice. Citizens living in heavily industrialized areas may not have the educational background and technical skills needed to interpret environmental data. Governments need to understand the range of skills of their target audience and then
tailor information systems (electronic or otherwise) to them. Education to develop the interpretive capabilities of the public is also a possibility.

Interpretive Issues
Any attempt to aggregate and interpret environmental information must cope with the variety of waste types generated by a large industrial community and with the different reporting requirements and metrics of state and federal environmental agencies and programs. For example, in southeastern Wisconsin, nearly 5,000 companies generate 100 million pounds of hazardous waste and toxic emissions each year, comprising more than 300 chemical and waste types. These waste and emissions data are compiled by the following reporting systems: WDNR Resource Conservation and Recovery Act Annual Reports, EPA TRI Form R Reports, WDNR Air Emission Inventory, and WDNR NR101 Annual Water Discharge Summaries. The data are reported in the following units: total mass in pounds, mass in pounds of toxic constituent, or concentration in mass per volume of water or air. In most cases, the lack of comparability between the reporting metrics results in under- or overreporting of emissions when the data are aggregated for a single facility. Extensive analytical interpretation is required if meaningful information is to be derived (Liebl, 1992). In addition to providing an accurate summary of environmental information, regulatory agencies and others can provide further data interpretation for specific audiences. Individual companies may want to know how their level of emissions compare to an industrywide benchmark. Citizen groups may want to see maps that show air emission distributions over populated areas. Policy makers may want to track progress in environmental performance over time. Each of these special needs requires substantial data manipulation and interpretive configuration, and clearly will cost money.

CONCLUSIONS
As technology continues to advance, so also will the information handling and analytical capabilities of companies, citizens, and public agencies to deal with the important issues related to the environment. The importance of making linkages between the environmental conditions and human activities continues to grow. The benefits of aggregating environmental information to support private and public decision-making are certain. Making usable, environmental information accessible to the public while promoting the public’s capabilities to interpret the information is a complex problem. Because access to aggregated environmental information appears to be valuable, the administrative and implementation barriers that prevent society from taking advantage of this technology must be addressed.

NOTES
1. Issues such as property rights, described by Branscomb (1985) and Cohen and Martin (this volume), or other legal issues surrounding the submittal of electronic data or the confidentiality of personal information are beyond the scope of this paper.
2. The Environmental Protection Agency is authorized under the Superfund Amendments and Reauthorization Act Title 313 to collect and disseminate
information on the release of toxic chemicals to the environment. These data are compiled annually into the TRI.

3. A firewall is an approach to computer network security; it helps implement a larger security policy that defines the services and access to be permitted, and it is an implementation of that policy in terms of a network configuration, one or more host systems and routers, and other security measures such as advanced authentication in place of static passwords. A firewall system can be a router, a personal computer, a host, or a collection of hosts, set up specifically to shield a site from protocols and services that can be abused from hosts outside the site. The main purpose of a firewall system is to control access to or from a protected network. It implements a network access policy by forcing connections to pass through the firewall, where they can be examined and reevaluated.

REFERENCES


---

**Hydrologic Science Priorities for the U.S. Global Change Research Program: An Initial Assessment**

Committee on Hydrologic Science Water Science and Technology Board
Board on Atmospheric Sciences and Climate
Commission on Geosciences, Environment, and Resources
National Research Council
NATIONAL ACADEMY PRESS
Washington, DC (2000)

**Executive Summary**

The availability of water to sustain life and to fuel economies is perhaps the most important recurrent constraint in human history, and it will remain so for the foreseeable future. During the past decade, an in-depth understanding of the water cycle, especially at regional scales, has emerged as a major scientific challenge within the U.S. Global Change Research Program (USGCRP), a federal effort to enhance understanding of the global environment and assess its possible evolution. As water is a critical component of other systems, it has emerged as a crosscutting theme in the USGCRP.

The global water cycle, now one of USGCRP’s six fundamental program elements, offers two primary research challenges: (1) land-surface interactions and (2) atmospheric processes. Research in hydrologic science is primarily in the first area, an area that includes land surface-atmospheric coupling over a range of spatial and temporal scales and includes the role of the land surface state in climate variability and change. These challenges are important but limited. Broader challenges for hydrologic
sciences that address cross-disciplinary research and recognize the integrative nature of terrestrial hydrology could strengthen the USGCRP.

Terrestrial hydrologic processes, specifically the storage and movement of water on land and within the terrestrial biosphere, are important across all of the USGCRP elements and should serve as a unifying physical process within the USGCRP. To meet these additional challenges, this report identifies two broad science areas that augment the current hydrologic sciences content of the USGCRP: (1) predictability and variability of regional and global water cycles and (2) coupling of hydrologic systems and ecosystems through biogeochemical cycles.

Predictability directly addresses the USGCRP priority of identifying possible future environmental change. This report recognizes current plans within the climate variability element but recommends additional research topics that can strengthen the long-term research goals of USGCRP. These additional topics include enhanced understanding of linkages in variability of global and regional hydrologic systems as the basis for producing improved predictions. The emphasis on variability and predictability, particularly in regional hydrologic systems, is designed to link the understanding of the global water cycle with emerging regional and local water resources issues. Cross-disciplinary research involving hydrologic science is key to addressing challenges identified under both the USGCRP global carbon cycle and global water cycle elements. For example, terrestrial ecosystems exert a strong influence on the global water cycle through evaporation processes. Also ecosystem disturbances are likely to be a major pathway for any changes and shifts in water and chemical cycles resulting from human activity. The foundation for this research must be a better understanding of the water and chemical pathways and of hydrologic—ecosystem linkages and a new means of achieving this understanding. It is then possible to address the combined influences of climate change and land use change, which occur in the context of natural variability, on hydrologic systems and ecosystems.

The USGCRP should give high priority to developing effective measurement and data strategies specifically for the terrestrial component of the global water cycle. The strategies should address multiple needs, ranging from the detection of change to process studies to operational applications. Future planning for remote sensing and ground-based measurement networks should be integrated to give measurement strategies that are responsive to the priorities discussed above. This will require a high degree of interagency and international collaboration, and it will require new approaches to planning hydrologic measurements.

Considerable attention also needs to be given to recovering and archiving hydrologic data and making the data available through effective data and information systems. These strategies need to integrate remote sensing and ground-based data, and they must be sustained over the long term. Water issues are central to the USGCRP emphasis on global change and its impacts. Therefore water issues can help guide the evolution of new initiatives within the USGCRP. To yield effective results, concerted
efforts need to be made to improve connections between hydrologic research and its applications.

Setting Priorities

Study of the water cycle is a priority in global environmental research because this cycle is central to the working of the Earth system. Furthermore, the availability of unpolluted water to sustain life and fuel economies is perhaps the most important recurrent constraint in human history, and it will remain so for the foreseeable future. During this past decade, concomitant with consideration and implementation of several of the findings in *Opportunities in the Hydrologic Sciences* (NRC, 1991), an in-depth understanding of the water cycle, especially at regional scales, has emerged as a major scientific challenge. This is reflected in the research priorities highlighted in several National Research Council (NRC) reports dealing with global change, climate variability, environmental quality, and hazards mitigation (NRC, 1998b–e). Moreover, along with carbon, water is one of the two major themes in the NRC report *Global Environmental Change: Research Pathways for the Next Decade* (NRC, 1998a; the so-called Pathways report), and water now has been established as one of the key program elements of the U.S. Global Change Research Program (USGCRP, 1999). The NRC and USGCRP reports generally present water as a critical component of other systems. From this perspective, many but not all priorities for hydrologic sciences emerge as components in crosscutting programs such as the USGCRP. The Pathways report and the USGCRP implementation plan, *Our Changing Planet* (USGCRP, 1999), identify some key hydrologic science challenges, but there are also critical hydrologic issues that are not contained therein.

The USGCRP has progressed in its recognition of hydrology as a key issue. In the FY1999 edition of *Our Changing Planet* (USGCRP, 1998), hydrologic research and applications are discussed only in the context of climate variability and change research on seasonal-to-centennial time scales.

In the FY2000 edition (USGCRP, 1999), however, the hydrologic cycle is identified as one of USGCRP's six fundamental program elements:

1. understanding Earth's climate system
2. biology and biogeochemistry of ecosystems
3. composition and chemistry of the atmosphere
4. paleoenvironment/paleoclimate
5. human dimensions of global change
6. the global water cycle.

Terrestrial hydrologic processes, specifically the storage and movement of water on and within land and within the terrestrial biosphere, are important across all these elements and should serve as a unifying physical process of USGCRP activities.
The global water cycle element contains two primary research challenges. The first challenge relates to land surface interactions and the need to develop a better understanding of:

1. the coupling of land surface hydrologic processes to atmospheric processes over a range of spatial and temporal scales;
2. the role of the land surface in climate variability and climate extremes;
3. the role of the land surface in climate change and terrestrial productivity.

The second relates to atmospheric processes and the need to develop a better understanding of:

1. the role of clouds and their influence in the coupling of the atmospheric water and energy cycles
2. the vertical transport and mixing of water vapor on scales ranging from the local boundary layer to regional weather systems.

The global water cycle program element bridges the gap in the spatial-scale spectrum between large-scale atmospheric research and smaller-scale hydrologic research. Its proposed endeavors that are related to the "fast component" of the climate system should simultaneously draw upon and feed into international programs such as the Global Energy and Water Cycle Experiment (GEWEX) and the Biological Aspects of the Hydrologic Cycle (BAHC). This program element also addresses important "slow component" aspects of the climate system, therefore relating it strongly to the Program on Climate Variability and Predictability (CLIVAR) as well. These challenges are important, but limited. Broader challenges for hydrologic sciences that address cross-disciplinary research and recognize the integrative nature of terrestrial hydrology would strengthen the USGCRP.

Two strategic research areas are identified in this report:

1. predictability and variability of regional and global water cycles
2. coupling of hydrologic systems and ecosystems through biogeochemical cycles, including the characterization of water and chemical flow pathways at the surface-atmosphere and the surface-subsurface interfaces.

Within the first topic, predictability directly addresses the USGCRP priority of identifying possible future environmental changes and of defining the limits of prediction. The emphasis on variability, particularly in regional hydrologic systems, is designed to link understanding of the global water cycle with the emerging regional and local issues that are receiving increasing emphasis in USGCRP. Variability (and memory) in the global water cycle and regional hydrologic systems is due to both the cycling of water between reservoirs with various storage capacities (e.g., atmosphere, surface waters, near-surface soil moisture, and groundwater systems) and the development of feedback dynamics resulting from linkages among the reservoirs. Presently, for example, linkages to the groundwater
reservoir are not considered in the USGCRP. The ultimate aim is to use the enhanced understanding of linkages in the variability of global and regional systems as the basis for producing improved and useful hydrologic predictions.

The second topic addresses priorities identified in both Our Changing Planet (USGCRP, 1999) and the Pathways report and highlights the need to understand linkages between the cycles of water, energy, nutrients, and carbon through ecosystems. Terrestrial ecosystems exert a strong influence on the water cycle through evaporation processes. Evaporative flux linking the surface and atmospheric systems and the recharge flux linking the surface and subsurface systems are two key components of the hydrologic cycle that are poorly understood and are very poorly monitored. It is imperative that the characterization of these two fluxes be recognized as grand challenges for hydrologic science.

Finally, ecosystem disturbances are likely to be a major pathway for any changes and shifts in water and chemical cycles resulting from human activity. This cross-discipline research area is key to addressing challenges identified under both the USGCRP global carbon cycle (contained within the biology and biogeochemistry of ecosystems USGCRP program element) and the global water cycle element. The foundation for this research must be a better understanding of water and chemical pathway, and of hydrologic system-ecosystem linkage, and a new means of achieving that understanding. It will then be possible to address the combined influences of climate change and land use change, which occur both in the context of natural and human-induced variability, on hydrologic systems and ecosystems.
shortages, fires, and crop failure in Central and South America; fires in Southeast Asia; major storms in South America and California; tornadoes that killed more than 120 in the United States; and increased rainfall in the U.S. Southwest that fostered vegetation growth and increased the potential for serious wildfires and the threat of a hantavirus outbreak.

The improved ability to model ocean-atmosphere interactions and thereby to predict seasonal-to-interannual climatic variations across broad reaches of the planet has been a hallmark achievement of the first 10 years of the U.S. Global Change Research Program. Predictive skill has now increased to the point that the U.S. National Oceanic and Atmospheric Administration (NOAA) and weather services in other countries release forecasts of ENSO-related weather phenomena to the public in the expectation that these forecasts will allow individuals and organizations to prepare for climatic events and be better off as a result. It is clear that public awareness of El Niño has increased dramatically since early 1997. However, there is as yet no full accounting of how beneficial forecasts have been in reducing climate-related damage or in allowing people to benefit from climate-related opportunities. Even though the scientific capability to forecast seasonal-to-interannual climate variability remains imperfect, there is good reason to believe that much benefit can be gained by appropriately linking this capability to the practical needs of society.

To do this requires scientific understanding of social processes as well as climatic ones. How does society cope with seasonal-to-interannual climatic variations? How is the vulnerability to such variations distributed within and among societies? How have individuals and organizations used climate forecasts in the recent past? What kinds of forecast information are most useful to people whose well being is sensitive to climatic variations? Who is likely to benefit from the newly acquired forecast skill? How do the benefits depend on characteristics of the users, the information in the forecast, and the ways in which it is delivered? What is the nature of the potential benefits, and how can they be measured?

This volume responds to a request from NOAA to review the state of knowledge and to identify needed research on such questions. It identifies a set of scientific questions the pursuit of which is likely to yield knowledge that can make seasonal-to-interannual climate forecasts more useful. The scientific questions flow from our findings.

Here, we summarize the major findings and the scientific questions under three thematic categories: (1) the potential benefits of climate forecast information; (2) improved dissemination of forecast information; and (3) the consequences of climatic variations and climate forecasts.

Potential Benefits of Climate Forecast Information

Climate forecasts are inherently uncertain due to chaos in the atmospheric system; moreover, forecasting skill varies geographically, temporally, and by climate parameter. We expect forecasting skill to improve in regions and for climatic parameters for which limited skill now exists, thus increasing the potential usefulness of forecasts over time.
However, research addressed to questions framed by climate science is not necessarily useful to those whom climate affects. A climate forecast is useful to a recipient only if the outcome variables it skillfully predicts are relevant and the forecast is timely in relation to actions the recipient can take to improve outcomes. Useful forecasts are those that meet recipients' needs in terms of such attributes as timing, lead time, and currency; climate parameters; spatial and temporal resolution; and accuracy. The usefulness of climate forecast information also depends on the strategies recipients use for coping with climatic variability, which are often culturally, regionally, and sectorally specific. Although many coping strategies are widely available in principle, the ones available to any particular set of actors, and the relative costs of using them, can be known only by observation. Because the usefulness of forecasts is dependent on both their accuracy and their relationship to recipients' informational needs and coping strategies, we find that the utility of forecasts can be increased by systematic efforts to bring scientific outputs and users' needs together. These systematic efforts should focus on two scientific questions:

1. Which regions, sectors, and actors would benefit from improved forecast information, and which forecast information would potentially be of the greatest benefit?
2. Which regions, sectors, and actors can benefit most from current forecast skill?

Research on the first question would aim to set an agenda for climate science to make its outputs more useful to recipients: it would provide a voice of consumer demand to the climate science community. Research on the second would proceed from the viewpoint of climate science and would explore ways to get the most social benefit from currently available forecast information. For both kinds of research, two scientific strategies are appropriate and should be conducted in parallel. One uses models and other analytic techniques to identify and estimate the benefits that particular recipients could gain from optimal use of particular kinds of forecast information. The other relies on querying potential users of climate forecast information about their informational needs, either by using survey methodologies or via structured discussions involving the producers and consumers of forecasts. Some of the research on these questions should be directed at improving the effectiveness of participatory, structured discussion methods.

**Dissemination of Climate Forecast Information**

The limited evidence from past climate forecasts and a much larger body of evidence on the use of analogous kinds of information show that the effectiveness of forecast information depends strongly on the systems that distribute the information, the channels of distribution, recipients' modes of understanding and judgment about the information sources, and the ways in which the information is presented. This evidence suggests that information delivery systems will be most effective when organized to meet recipients' needs in terms of their coping strategies, cultural traits, and specific
situations; that participatory strategies are likely to be most useful in designing effective climate forecast information systems; that new organizations delivering climate forecast information will require a period of social learning to become fully effective; and that useful information is likely to flow first to the wealthiest and most educated in any target group.

Individual and organizational responses to climate forecasts are likely to conform to known generalities about responses to similar kinds of new information. For example, interpretations of forecast information are likely to be strongly affected by individuals' preexisting mental models and organizations' preexisting routines and role responsibilities. Knowledge about information processing suggests several specific hypotheses about the use of forecast information, such as that forecasts that turn out to be wrong have a strong negative influence on the future use of forecast information.

Research on five scientific questions can advance knowledge about how to improve the dissemination of climate forecast information:

3. **How do individuals conceptualize climate variability and react to climate forecasts?** What roles do their expectations of climate variability play in their acceptance and use of forecasts?
4. **How do organizations interpret climatic information and react to climate forecasts?** What are the roles of organizational routines, cultures, structures, and responsibilities in the use and acceptance of forecasts?
5. **How do recipients of forecasts deal with forecast uncertainty, the risk of forecast failure, and actual forecast failure?** What are the implications of these reactions for the design of forecast information?
6. **How are the effects of forecasts shaped by aspects of the systems that disseminate information (e.g., weather forecasting agencies, mass media) and of the forecast messages?** How do these effects interact with attributes of the forecast users?
7. **What are the ethical and legal issues created by the dissemination of skillful, but uncertain, climate forecasts?**

Research on these scientific questions can usefully begin with generalizations and hypotheses derived from existing knowledge, based largely on analogous situations of information dissemination. It should expand and refine this knowledge by studying responses to climate forecast information. Responses to past climate forecasts, including those for the 1997-1998 El Niño, are an essential source of information for addressing these scientific questions.

**Consequences of Climatic Variations and of Climate Forecasts**

Climatic events and forecasts have differing effects across regions, sectors, and actors (e.g., farmers, firms). Moreover, these effects are shaped by a complex mosaic of anticipatory (ex ante) strategies that individuals, organizations, and societies have developed for coping with climate variability, including risk sharing (e.g., insurance),
technological innovations (e.g., irrigation), and information delivery systems. Some coping strategies interact synergistically, some compete and offset one another, and some substitute for others. These coping strategies are neither universally available to nor used consistently by all actors at all times. To understand and estimate the consequences of climatic events and of skillful forecasts, it is necessary to take these coping strategies and differences in their use into account. It is also necessary to consider that social, environmental, and economic forces having little or nothing to do with climate variability will partly govern the sensitivity or vulnerability to climatic events and determine the types of information needed to respond. Building an improved capability to estimate the human consequences of climatic variation requires improved basic understanding of these nonclimatic phenomena and of how they interact with climatic ones.

Various quantitative and qualitative methods exist for estimating the consequences of climate variability and the value of forecasts. However, the methods now in use have important methodological and conceptual limitations, such as overreliance on simplifying assumptions; oversimplification of the dynamic relationships between climate and human consequences; imprecise definitions of key concepts such as adaptation, sensitivity, and vulnerability; lack of distinction between potential and actual value of climate forecasts; lack of attention to outcomes that are not easily measured; lack of explicit attention to the distribution of damages and benefits, especially the impacts of catastrophically large negative events on highly vulnerable activities or groups; and lack of reliable strategies for defining baseline conditions of actors, regions, sectors, and populations. Estimating consequences is also complicated by the fact that the resolution of data in space and time determines the ability to model and detect certain types of consequences. Many governments and other organizations collect potentially relevant data, but little or no meta-data exist describing the availability, quality, resolution, and other essential traits of these data.

Research on five scientific questions can improve the ability to estimate the consequences of climatic variations and the value of climate forecasts:

8. How are the human consequences of climate variability shaped by the conjunctions and dynamics of climatic events and social and other nonclimatic factors (e.g., technological and economic change, the availability of insurance, the adequacy of emergency warning and response systems)? How do seasonal forecasts interact with other factors and types of information in ways that affect the value of forecasts?

9. How are the effects of forecasts shaped by the coping systems available to affected groups and sectors? How might improved forecasts change coping mechanisms and how might changes in coping systems make climate forecasts more valuable?

10. Which methods should be used to estimate the effects of climate variation and climate forecasts?

11. How will the gains and losses from improved forecasts be distributed among those affected? To what extent might improved forecasting skill
exacerbate socioeconomic inequalities among individuals, sectors, and countries? How might the distribution of gains and losses be affected by policies specially aimed at bringing the benefits of forecasts to marginalized and vulnerable groups?

12. How adequate are existing data for addressing questions about the consequences of climate variability and the value and consequences of climate forecasts? To what extent are existing data sources under-exploited?

The Science of Regional and Global Change: Putting Knowledge to Work
Committee on Global Change Research
National Research Council
NATIONAL ACADEMY PRESS
Washington, D.C.

WHAT ARE THE CHALLENGES?

A central challenge facing the United States and other countries in the twenty-first century will be to enhance human well-being in a world where growing populations and the drive to improve living standards place potentially huge demands on natural resources and the environment. Whether we succeed or fail in meeting this challenge will be determined, in part, by how we respond to immediate demands to address human health and economic growth in the context of the wide range of crucial, environmentally related decisions made every day by insurance companies, water resource managers, agribusiness, households, city planners, public health officials, and countless others. Rising to this challenge will entail using natural resources as efficiently as possible, devising practical solutions that meet our immediate needs and also provide for long-run economic growth, while maintaining the environmental systems on which life depends.

To guide wise public policy decisions that continue to improve human and economic conditions and to clarify public debate, it is necessary to restructure the science and engineering framework addressing the biological, chemical, and physical integrity of our surroundings. Private-sector and governmental decisions will be made regarding air, water, and living systems that will fundamentally affect our nation's health and its economic and environmental vitality. Will the information that is necessary to adequately inform these decisions be available? The answer to this question is not consistently “yes” because of several limitations that are beyond the capacities of individual agencies, including the following:

- The observing “system” available today is a composite of observations that do not provide the information needed nor the continuity in the data to support decisions on many critical issues.
The United States today does not have the computational and modeling capabilities needed to serve society's information needs for reliable environmental predictions and projections.

The necessary partnerships do not exist between both the physical and social science research communities and the public and private decision makers that are required to address multiple interacting and changing environmental factors in specific geographic areas.

Reliable and consistent observations are a critical first step in providing the scientific information necessary for decisionmaking, and the federal government has a primary responsibility for providing them. The observations of the environment that are available today are useful but cannot provide the decisive information needed to make properly informed decisions on many crucial issues. Critical examples of these information gaps include the absence of a precise, sustained, and comprehensive climate observing system, inadequate coverage of carbon flux measurements that define sources and sinks, the inability to define ultraviolet dosage levels and the causes for midlatitude ozone erosion, and ineffective attempts at mapping sulfate–nitrate–organic–heavy-metal emissions on the urban-to-regional scale. To make vital, informed decisions on the basis of these and many other types of data, substantial improvements in observations of the atmosphere, surface and ground water, oceans, and ecosystems, as well as relevant economic and societal data, will be required. Individual researchers and research teams do not have the wherewithal to develop and maintain observing systems that can provide a comprehensive and consistent historical record in outcomes of interest. The federal government has been key to the success of past observing systems, whether the problem was measuring economic progress, demographic change, weather, or pollution levels. If critical chokepoints in our understanding of global environmental change are to be overcome, the federal government must make a substantial commitment to establishing and maintaining an observing system that is up to the job.

The nation's ability to create reliable short- and long-term environmental projections and analyses is promising but insufficient. Promising advances have been made in modeling and analysis in such fields as climate, hydrology, atmospheric chemistry, agronomy, and the economics underlying carbon dioxide emissions. But insufficient progress has been made in analyzing and modeling ecosystem and human responses to environmental change, as well as physical (e.g., climate, atmospheric and land surface chemistry) changes at the fine scales of human interest. The federal government should find a way to increase efforts in these areas of research to meet the needs of a diverse set of U.S. interests ranging from agriculture to fisheries, from environmental protection to energy production, and from commodity markets to public health. Improvements in the nation's observational and modeling capabilities will set the stage for dramatic new opportunities to reduce vulnerability and increase resilience to environmental change, maximize economic gains, protect the nation's natural resources, and better understand the sensitivity of our national security to the environment.
The previous decade of research on global environmental change reinforced the idea that, while understanding and predicting change requires a global perspective, solutions to these changes must work at the local and regional levels as well as the global level. This is true whether one is projecting long-term climate, transboundary air pollution, crop prices, or the effects of proposals to limit greenhouse gases on U.S. industrial competitiveness. Indeed, the effects of environmental change on societies and ecosystems can vary profoundly from place to place, due in part to the set of multiple stresses and conditions that are unique to each locality. As suggested above, the ability to provide regionally specific information pertaining to environmental change calls for an entirely new management philosophy for the environmental research enterprise. This approach must encompass several disciplines, include public- and private-sector participation, and must involve end users and stakeholders as well as researchers at all steps of the process from basic research to decision making. One of the challenges will be to embrace a new regionally specific approach while continuing to foster and even strengthen the global-scale environmental research enterprise, which produced remarkable advances in knowledge over the past decade.

In addition:

- The current situation in the federal government does not sufficiently promote delivery of resources to key research, observational, and technological endeavors that either cross or transcend formal agency responsibilities.
- There are many areas where science has advanced but where research funding has been inadequate to develop effective technologies and assess potential responses to take advantage of this knowledge. For instance, the application of advances in physical science knowledge is particularly hampered by lack of knowledge pertaining to human–environment interactions and their linkage to natural environmental changes.

Consequently, the committee concludes that the federal government’s research on earth sciences and the environment, including the U.S. Global Change Research Program and other environmental research that we now see as increasingly interconnected with global environmental change, needs to address these obstacles. Doing so will catalyze the study of global change and human–environment interactions, thereby providing the foundation for a healthy society, economy, and environment—all three of which are inextricably intertwined.

**KEY DECISIONS AT THE NATIONAL LEADERSHIP LEVEL**

The NRC’s Committee on Global Change Research recommends the establishment of an institutional arrangement positioned with sufficient authority to coordinate global and regional environmental research and decision making by ensuring adequate resources over the long term and directing them to the highest-priority issues. Decentralized research management has served U.S. research programs well in many areas and should remain a significant component of global change research. Decentralized research management is successful at creating
a diverse set of research activities, which is important when there are several competing hypotheses. However, a weakness of a decentralized approach in, for example, the U.S. Global Change Research Program, is that important areas may not have strong advocates in the existing agency structure and the needed observation systems are too costly for each agency to build its own. A high-level focus is thus needed to ensure that:

1. The federal government's resources can be directed into emerging and underfunded research areas that do not fall within the purview of a single agency. Success depends in part on appointments of agency directors and high-level staff who have the vision to support broad research with potential long-term benefits that may be difficult to defend under narrow interpretations of agency missions.

2. Organizational and resource obstacles to a sustained and flexible program of observations are removed. An integrated observing strategy must be established to effectively monitor climate, environmental chemistry, and ecosystems as well as concomitant socioeconomic factors.

3. Integrated multidisciplinary modeling and information systems on global, national, and regional levels are developed and sustained. These systems, which depend on strong disciplinary knowledge bases, should be designed in close cooperation with those whose decision making they are designed to support in both the public and private sectors.

4. Regionally focused environmental research and assessments are developed to complement global-scale research and transform its advances into usable information for decision making at all spatial scales. This will require building the necessary resource base, as well as new partnerships between the relevant sciences and the public and private sectors.

There are a number of institutional options that could ensure that these critical tasks are fulfilled. Several high-level approaches were considered by the committee, including the following:


2. Strengthening the existing interagency structure through the National Science and Technology Council.

3. Broadening the mandate of the Council on Environmental Quality to give it oversight of the relevant research.

Whatever approach is chosen, it must be able to cream a national framework that will encourage an intimate connection between research, operations, and the support of decision-making. Specific responsibility and resources must be assigned to the integration of multiple-agency programs. Only by recognizing the nature of the challenges that will be present during the next few years and by showing early and innovative leadership can the tremendous capacity of the research community, the operational mission agencies, state and local governments, and the private sector be brought together to serve society and the environment.
Preface

In the coming century, a human population perhaps twice as large as the population today will have to navigate a sustainable path through the ever-changing landscape of this small planet. Knowledge gleaned by science will be its best beacon and provide its soundest navigational chart. Science itself faces its own navigational challenges, as questions of growing complexity and richness abound, while financial resources are limited. Scientists confront not only these research obstacles, but also the urgent call from politicians and policy makers who seek guidance in reaching major decisions. As this report was being prepared, for example, representatives of many nations gathered in Kyoto to forge an agreement on goals to cut greenhouse gas emissions. Such agreements set environmental goals, which will clearly affect scientific priorities as well as economic paths in the coming decade.

Thus, science needs its own clear framework, through which to focus its energies. This intellectual framework is required to hone questions that need immediate attention, to separate the vital from the interesting, and to preserve basic research for discovery of the unexpected. In this Overview volume, the Committee on Global Change Research (CGCR) provides guidance on such a framework by clarifying especially promising pathways for the planning of future US research on global environmental change. This document summarizes the background and the findings and recommendations presented in the Committee's full report, which will be released in the coming months. The foundation of the report's recommendations includes the accumulated knowledge of worldwide scientific research over the past decade and especially that of the US Global Change Research Program (USGCRP).

The CGCR was charged with reviewing the current status of the USGCRP with a view toward defining the critical scientific questions in the Program's four areas of concentration (seasonal to interannual climate prediction, decadal to centennial climate change, atmospheric chemistry, and terrestrial and marine ecosystems) and with preparing a report that would (1) articulate the central scientific issues posed by global environmental change; (2) state the key scientific questions that must be addressed by the USGCRP; and (3) identify the scientific programs, observational efforts, modeling strategies, and synthesis activities needed to attack these scientific questions. This report traces the scientific roots and programmatic
development of the USGCRP, highlighting some of the lessons learned that help point
to the most appropriate pathways ahead. The Committee calls for a revitalization of the
USGCRP, recognizing the need for a more sharply focused scientific strategy and a
more coherent programmatic structure and stressing the importance of US leadership in
supporting global change research.

CGCR’s study was undertaken in the context of intense national and international
debate about the nature of global environmental change, particularly about the
characteristics and potential impacts of climate change. This context is sharpened in
several questions raised by the scientific community and the public at large:

➤ **The Science:**
  - In light of the US Administration policy and agreements at the Kyoto
    conference, are not the causes of global change sufficiently clear,
    and therefore should not the US Global Change Research Program
    now concentrate on the science related to mitigation measures?

➤ **The Strategy:**
  - What is the appropriate science strategy for resolving uncertainties
    about global environmental change? Are changes in the current
    strategy needed? If so, why (what has changed)? What are the
    crucial differences between any proposed new strategy and the
    existing strategy, and how do we make a transition from one to the
    other?

➤ **The Implementation:**
  - How can this strategy be implemented in terms of programs? Who
    will develop the priorities? When will this happen?

**THE SCIENCE**

It would be a misinterpretation of US Administration policy and agreements at the Kyoto
conference to conclude that the causes and characteristics of global change are
sufficiently clear that scientific inquiry in this area should be limited to mitigation
measures. The agreements at the Kyoto conference are based on a general
understanding of some causes and characteristics of global change; however, there
remain many scientific uncertainties about important aspects of climate change. If the
United States were to abandon or significantly reduce the current research programs,
the remaining scientific uncertainties would persist. In addition, it would be difficult to
have confidence that mitigation measures were addressing the underlying causes.

It is true that the forcing terms of global change are being more clearly resolved. For
example, the flux of greenhouse gases from industrial activities is reasonably well
established; the rates and geographical distributions of the mobilization of other
chemical compounds are also becoming clearer; and quantitative patterns of land-use
change are being elucidated. In addition, significant progress has been made in
understanding the lifetimes in the atmosphere of key chemical species such as greenhouse gases. We understand better the chemical and physical interactions that lead to the loss of ozone in the stratosphere and the production of ozone in the troposphere. We have begun to make considerable progress in characterizing patterns of climate variability, with one noted accomplishment being the successful prediction of the most recent El Niño event well in advance of its greatest impacts. And, although on a very limited basis, we have begun to investigate the possible impacts of various climate change scenarios on terrestrial systems by using global models of these systems.

However, a great deal more needs to be understood about global environmental change before we concentrate on "mitigation" science. We do not understand the climate system well enough to clarify the causes and likelihoods of rapid or abrupt climate changes. What does the record from the past reveal in detail about environmental changes? What will be the patterns and modes of human-forced climate changes? What will be the impacts of multiple stresses upon systems; in other words, what are the effects on terrestrial ecosystems of changes in the chemistry of the atmosphere, changes in the patterns and intensities of land use, and changes in temperature and rainfall patterns? How will the chemistry of the atmosphere be affected by continuing patterns of human-induced forcing, and how will these changes be affected by climate variability and change? What is the geographical distribution of the sources and sinks of greenhouse gases, and how might they change? How will institutions respond to climate and other environmental changes? These are the types of scientific unknowns that require clarification if we are to make sound policy decisions; they are also the questions that must be answered if we are to have a sound foundation for mitigation science.

THE STRATEGY

The current science strategy was developed in concert with the initial planning of the USGCRP and based on the view that what was most needed was a broad attack on understanding the Earth as a system. This has been a valuable and intellectually exciting goal, but it also has made the Program too diffuse and left it vulnerable. When budgets ceased to expand and began to contract, the Program was not well grounded or well integrated enough to scale back in a logical way. The concept of an Earth system science view of the Program simply could not weather the budget process that demanded greater specificity and accountability. Moreover, the need for prioritization—which should be one benefit derived from taking a systems viewpoint—has proved to be exceedingly difficult to achieve in practice. Finally, gains in understanding over the last 10 years and changes in the perceived requirements for research (i.e., results are now seen to be needed sooner rather than later, and key issues are now in need of resolution) must be recognized in a new strategy.

Therefore, it is time to shift course; we are no longer simply building a ship but steering it too. Given all that we know, these corrections in course are necessary to reach our destination, and they will require retrofits in the hardware and navigational aids to improve speed and efficiency.
Resources and time are again in finite supply. We must concentrate scientific talents, observational capabilities, and modeling teams. Achieving these goals calls for an alternative strategy: one focusing on answering specific, central scientific questions about global change. In fact, our current inability to answer these scientific questions is seriously blocking progress in critical policy development as well as hindering our development of a more systemic view of the planet. Thus, the Committee recommends shifting to a scientific strategy of greater focus and sets forth corresponding pathways for research, observations, data systems, and modeling.

**THE IMPLEMENTATION**

To implement a new strategy effectively, the USGCRP, working closely with the Office of Management and Budget (OMB) and the Office of Science and Technology Policy (OSTP), must develop initiatives based directly on the Research Imperatives, Scientific Questions, and crosscutting elements described in this Overview volume and its Appendix C and elaborated in detail in the full report. The recommendations in these documents regarding the observational strategy, technological development, data and information systems, and modeling should be explicitly addressed by the USGCRP and OSTP.

Establishing the necessary observational systems will be especially challenging. They are likely to be expensive; their components must serve the needs of several different communities and as a bridge between research and operational lines; and their design must be more robust in the face of changes in financial support. The National Aeronautics and Space Administration’s (NASA) Earth Observing System (EOS) polar platforms—initially, EOS AM-1, EOS-PM-1, and EOS CHEM-1—were conceived as broadly scoped data-gathering systems. This foundation will be central for needed future missions, and it will set the baseline for a long-term, operational environmental monitoring program that must be built on the operational weather and ozone-observing system of the National Oceanic and Atmospheric Administration, the Department of Defense, and their international partners.

To further the advances of the first three polar platforms, the Committee calls for restructuring NASA’s Earth Observing System to obtain data relevant to the Research Imperatives and unanswered Scientific Questions identified in this report, through smaller and more focused missions along the lines of the new Earth System Science Pathfinders. Moreover, some aspects of the observational systems must address three crosscutting scientific themes that are also fundamental to scientific understanding and policy: clarifying the Earth’s carbon and water cycles; characterizing climate change on temporal and spatial scales relevant to human activities; and elucidating the connections among radiation, dynamics, chemistry, and climate. These achievements will require good in-situ observational systems as well as space-based systems. The Committee also recommends maintaining existing critical global observations that could be threatened by budget reductions, while designing a more coherent and balanced data and observational strategy for the future to capitalize on technological innovation.
As in all science, the task is not complete. Given the recommendations provided in this report, the next task is to review and map the USGCRP activities against the set of Research Imperatives and unanswered Scientific Questions identified here, to help set optimal programmatic priorities. This step should be the next effort of the Committee, its partners in the National Research Council (NRC) complex, and USGCRP agencies.

The NRC parent board of this Committee, the Board on Sustainable Development (BSD), is seeking to develop its own sound scientific and intellectual strategy for the transition of our nation and indeed our global society to a sustainable future. This CGCR report will help to guide the Board's emerging agenda for research on the closely linked issues of energy, environment, and society, an agenda that will be needed to successfully navigate the transition to sustainability.