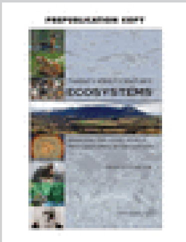

Twenty-First Century Ecosystems: Managing the Living World Two Centuries After Darwin

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TWENTY-FIRST CENTURY
ECOSYSTEMS

MANAGING THE LIVING WORLD TWO CENTURIES AFTER DARWIN

REPORT OF A SYMPOSIUM

Committee for Biodiversity and Ecosystem Services: A Symposium

U.S. National Committee for DIVERSITAS

Board on International Scientific Organizations

Policy and Global Affairs

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STEPHEN SCHNEIDER (1945–2010)

Stephen Schneider was an extraordinarily talented scientist who dedicated his professional life to understanding the complexities of the earth's climate system and to urging action to avoid the most dangerous consequences of anthropogenic climate change. Along with his wife, Terry Root, he was also a tireless voice elucidating the consequences of climatic change for the Earth's biodiversity. He commanded the attention of international leaders in science, policy, and business, and used that attention to transform both climate science and the science-policy dialogue. His was a formidable intellect, a "few in a generation" talent, but his heart was larger—the size of the planet he worked so hard to save.

It is interesting to contemplate a tangled bank, clothed with many plants of many kinds, with birds singing on the bushes, with various insects flitting about, and with worms crawling through the damp earth, and to reflect that these elaborately constructed forms, *so different from each other, and dependent upon each other in so complex a manner*, have all been produced by laws acting around us.

Charles Darwin, Origin of Species, 1859; emphasis added

Preface and Acknowledgments

The two hundredth anniversary of the birth of Charles Darwin, February 12, 2009, occurred at a critical time for the United States and the world. A global financial crisis had demonstrated the extent of interconnections among the world's economies, but also alarming instability in the economic systems on which the entire world depends. The analogy with ecological systems was both clear and troubling. Recognition of human-induced changes in global climate was also stimulating urgent discussion of priorities for mitigation and adaptation. Policies governing crucial systems for human well-being, such as energy, agriculture, and trade, were being rethought. A new presidential administration was also developing new approaches to respond to these complex, interconnected issues, and had indicated its desire to incorporate the best scientific guidance available.

In honor of Darwin's birthday, the National Research Council appointed a committee under the auspices of the U.S. National Committee (USNC) for DIVERSITAS to plan a Symposium on Twenty-first Century Ecosystems. The purpose of the symposium was to capture some of the current excitement and recent progress in scientific understanding of ecosystems, from the microbial to the global level, while also highlighting how improved understanding can be applied to important policy issues that have broad biodiversity and ecosystem effects. The meeting was an effort to bring together the academic community, the nongovernmental organization (NGO) community, and policy makers to share their perspectives on how biodiversity and ecosystems should be conserved and managed for the future. In selecting trade, energy, climate, and agriculture as the key issues for exploration at the symposium, the committee sought to highlight the economic, public health, and societal costs and benefits of policies that have ecological and biodiversity dimensions. The aim was to help inform new policy approaches that could satisfy human needs while also maintaining the integrity of the goods and services provided by biodiversity and ecosystems over both the short and the long terms.

The symposium, held on February 11–12, 2009, included presentations from 37 speakers from around the world (Appendix A). The auditorium at the American Association for the Advancement of Science was filled to capacity for most of both days of the symposium; there was a total of 400 registrants. The presentations were also available to a worldwide audience via simultaneous webcasting, and an estimated 2,000 or more people watched at least some portion of the webcast. The video was subsequently posted on the World Wide Web, with a link from the USNC DIVERSITAS Web site (http://www.nationalacademies.org/usnc-diversitas).

This report does not provide a session-by-session summary of the presentations at the symposium. Instead, the symposium steering committee identified eight key themes that emerged from the lectures, which were addressed in different contexts by different speakers. The focus here is on general principles rather than specifics. These eight themes provide a sharp focus on a few concepts that enable scientists, environmental NGOs, and policy makers to engage more effectively around issues of central importance for biodiversity and ecosystem management.

This report summarizes the views expressed by symposium participants. The symposium committee is responsible for the overall quality and accuracy of the report as a record of what transpired at the symposium, but the views contained in the report are not necessarily those of the symposium committee, the USNC for DIVERSITAS, nor the National Academies.

The U.S. National Committee for DIVERSITAS and the symposium committee gratefully acknowledge the contributions of the many people and organizations that made this symposium a success. We especially thank the speakers, who contributed their time and expertise for both their presentations and the accompanying discussions. We also thank the hundreds of scientists, policy makers, and interested individuals who attended, and whose questions and comments enlivened the discussion.

The organization of the symposium was accomplished with the cooperation of three lead partners: the American Association for the Advancement of Science, which hosted the meeting in its auditorium and provided invaluable logistical support; the Smithsonian Institution National Museum of Natural History, which hosted the speakers' dinner in the Sant Ocean Hall; and DIVERSITAS, which offered advice and expertise throughout the organizing process. DIVERSITAS also contributed the global expertise of its Scientific Committee (SC) by coordinating its annual SC meeting with the Twenty-first Century Ecosystems Symposium.

We are grateful for the financial support provided by the National Science Foundation through its grant supporting the U.S. National Committee for DIVERSITAS, and by three federal agencies that awarded generous grants to support the symposium: the National Oceanographic and Atmospheric Administration, the U.S. Geological Survey, and the U.S. Forest Service. We are also grateful for the support of Defenders of Wildlife and the International Union for Conservation of Nature.

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Academies' Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for quality and objectivity. The review comments and draft manuscript remain confidential to protect the integrity of the process.

We wish to thank the following individuals for their review of this report: David Blockstein, Senior Scientist, National Council for Science and the Environment; Frank Casey, Director, Conservation Economics Program, Defenders of Wildlife; Christopher Field, Director, Department of Global Ecology, Carnegie Institution for Science; John M. Fitzgerald, J.D., Policy Director, Society for Conservation Biology; Falk Huettmann, Institute of Arctic Biology, University of Alaska, Fairbanks; Calestous Juma, Professor of the Practice of International Development, Harvard University Kennedy School of Government.

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the content of the report, nor did they see the final draft before its release. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

Peter R. Crane
Chair, Committee for Biodiversity and
Ecosystem Services: A Symposium

Contents

1

Introduction

Our destiny lies in understanding that humility leads to enlightenment and hubris leads to extinction.

Paul Falkowski, February 12, 2009

The publication of the report *Biodiversity* by the National Academy of Sciences/Smithsonian Institution in 1988 helped reframe the concept of biological diversity as a "global resource, to be indexed, used, and above all, preserved,"[1] and captured the attention of the public and policy makers. Earlier concerns about biological extinction had led to the passage of the U.S. Endangered Species Act of 1973, but the 1986 National Academy of Sciences forum, on which the *Biodiversity* report was based, placed contemporary biological extinctions in a broader ecological, economic, and global development context. In subsequent decades, studies of biodiversity broadened still further to encompass diversity at the genetic and ecosystem levels. Concepts of ecosystem services and natural capital also emerged as a means of illuminating and capturing the value of biodiversity and ecosystems to human well-being. The imperative of an international approach to the conservation of biological resources resulted in the introduction of the Convention on Biological Diversity at the United Nations Conference on Environment and Development in Rio de Janeiro in 1992 and its subsequent ratification by almost all of the countries of the world. It positioned the conservation and sustainable utilization of biological resources as two sides of the same coin, while also enshrining the principle of national sovereignty over biological resources and the requirement of fair and equitable

[1] Wilson, E. O., ed. 1988. P. 3 in *Biodiversity*. Washington, DC: National Academies Press.

sharing of the benefits from their conservation and sustainable use. Since then, a series of studies, assessments, and monographs from the National Research Council, the United Nations, and the academic community have sought to provide direction and impetus to further action on these issues. A sampling offered by James P. Collins included seven titles from the "bookshelf of reports in my office."[2] In 2005 the *Millennium Ecosystem Assessment*[3]—a massive effort involving more than 2,000 scientists from 77 countries conducted over the preceding 5 years and authorized under four international conventions[4]—attempted a comprehensive overview of the changing state of the ecological services that underpin human well-being.

By 2009 the biodiversity issue had developed new and far-reaching breadth and complexity. Scientific advances in microbial biology and molecular genetics had opened new possibilities for understanding fundamental aspects of the natural world that had previously been beyond our grasp. New instrumentation had made it increasingly possible to gather and analyze data over large geographic areas based on remote sensing from satellites, as well as land- and ocean-based sensors. Rapid advances in information management offered new opportunities for the synthesis and analysis of biological data. Yet, at the same time, the scientific community was increasingly aware of the limitations of current knowledge about many aspects of biodiversity, including the rapidity with which the different dimensions of biodiversity were being modified, eroded, or even disappearing entirely. Dr. Collins quoted estimates placing the number of species on Earth at 10–12 million, and stated that, at present rates of describing new species, just knowing what is out there will take 160 years. He also noted that by some estimates, 10–37 percent of remaining species could become extinct by 2050.[5] As a result, many thousands of species will be lost before

[2] In addition to the 1988 NAS/Smithsonian *Biodiversity*, his list included the following publications: NRC, 1992, *Conserving Biodiversity: A Research Agenda for Development Agencies;* UNEP, 1996, *Global Biodiversity Assessment*; NRC, 1999, *Perspectives on Biodiversity: Valuing Its Role in an Everchanging World*; F. S. Chapin, O. E. Sala, and E. Huber-Sannwald, eds., 2001, *Global Biodiversity in a Changing Environment: Scenarios for the 21st Century*; CBD Secretariat, 2006, *Global Biodiversity Outlook 2*; NRC, 2008, *In Light of Evolution, Vol. II: Biodiversity and Extinction.*

[3] Millennium Ecosystem Assessment. 2005. *Ecosystems and Human Well-being: Synthesis.* Washington, DC: World Resources Institute.

[4] The Millennium Ecosystem Assessment was authorized under the Convention on Biological Diversity, the United Nations Convention to Combat Desertification, the Ramsar Convention on Wetlands, and the Convention on Migratory Species.

[5] Thomas, C. D. et al. 2004. *Nature* 427, 145–148.

we learn of their existence, understand the role that they play in ecosystem functioning, and therefore comprehend what that loss might mean. The services that these species and ecosystems provide to human societies are, therefore, increasingly uncertain.

Global economic development and the implementation of new technologies have greatly improved many aspects of human well-being, but they have also extended the reach of human activity further into the natural world than ever before and have greatly increased its influence. Human mobility now connects ecological systems that have evolved in relative isolation over millions of years while technology facilitates the unsustainable exploitation of resources that accumulated over vast timescales. Human-induced environmental change is occurring across a very broad front and at unprecedented rates, with profound ramifications for atmospheric and oceanic chemistry, as well as species distributions and the process of evolution itself. These human interventions have global consequences, of which changing climates are only one manifestation. They also affect the landscapes and fisheries that underpin the global food supply, even as those resources will be required to support a human population at least 50 percent greater than exists today and three times as large as existed just 50 years ago.[6] Measures proposed to feed and supply energy to the rising human population, while simultaneously mitigating climate-changing emissions (e.g., biofuels and intensive farming in the developing world), imply the large-scale modification of much of the world's remaining habitat that supports wildlife. Ongoing alterations to global landscapes are amplified by increased ease of air and sea transport, which together with the widening and deepening of international travel and trade have succeeded in globalizing not only business and production but also diseases and natural pests on a scale never seen before.

The increasing capacity for humans to modify ecological systems and evolutionary and geological processes at a global scale poses challenges for understanding and managing ecosystems for human well-being, now and into the future. One hundred and fifty years after Darwin offered a framework for comprehending the origin of diversity in the natural world, and despite progress in understanding the processes by which ecosystems function and are sustained (see Figure 1-1), humankind is undertaking a

[6] Lutz, W., W. Sanderson, and S. Scherbov. *2007 Update of Probabilistic World Population Projections*. IIASA World Population Program Online Data Base of Results 2008, http://www.iiasa.ac.at/Research/POP/proj07/index.html?sb=5. Accessed July 2009.

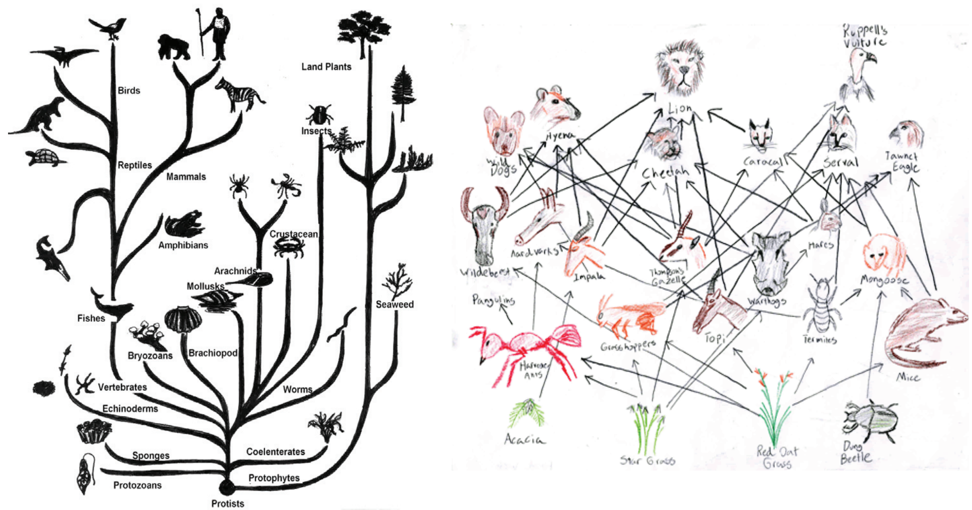

FIGURE 1-1 The tree of life and the web of life.
SOURCE: Michael Donoghue presentation. Tree of Life (left-hand figure) adapted from: Hotton III, Nicholas. A Simplified Family Tree of Life in *The Evidence of Evolution.* Smithsonian, 1968.

Darwin and Hutchinson were responsible for solidifying the two great metaphors that orient our understanding of biology—the notion of the tree of life and the notion of the web of life. Each, in his own way, managed quite comfortably, even seamlessly, to interdigitate the two. Today, my sense is that this, unfortunately, is a rather rare ability, and sadly the two have become quite separated from one another in the ways that we teach and carry out biological research. In my view, one of the greatest challenges before us, as scientists, is to work out the ways in which to connect the tree of life with the web life ~~to~~ truly reintegrate ecology and evolutionary biology.

Michael Donoghue, February 11, 2009

vast, uncontrolled global experiment in the reorganization of natural systems, the full consequences of which will be played out over millennia. The Symposium on Twenty-first Century Ecosystems was organized to highlight the ecological dimensions of critical challenges facing the world and our nation. The report highlights the complexity and interrelatedness of these issues, drawing on the overlapping themes that emerged from speakers' presentations. It includes suggestions that could help mitigate the current and intensifying problems confronting the living world, while also offering improved approaches to environmental management based on developments in science, technology, and economics.

This report is not organized as a session-by-session summary of the presentations of the symposium. Instead, it focuses on eight key themes that emerged from the speakers' presentations, all of which are linked by the imperative of a systems-based approach to both research and decision making about twenty-first century ecosystems.

THEME 1: LEARNING WHAT WE HAVE

Successful management of biodiversity is founded on knowledge of the variety of life, the processes by which it is sustained, and the ways in which it functions within ecosystems. Speakers in several sessions highlighted significant deficiencies in human knowledge of biological diversity and the processes through which species interact, but they also described new technologies, approaches, information systems, and analytical tools that have the potential to realize a step-change in the ways that information about species and how they are changing is acquired, maintained, and used. Some speakers emphasized the need to accelerate the acquisition of knowledge about the components of the natural world in the face of large-scale habitat modification and destruction and the accompanying eradication of species.

THEME 2: LEARNING HOW ECOSYSTEMS WORK AND ARE CHANGING

Ecosystems are now subject to a broad range of challenges that are unprecedented in their magnitude, rate, and diversity. Speakers described challenges that flow directly or indirectly from human activity related to land use, food production, economic development, and trade. They enumerated changes in ecosystems that are occurring at all scales, from global to highly local, with implications for ecosystem degradation, rapid evolutionary changes, and the spread of microbes and other species that are ecologically disruptive and affect the health of animals, people, and plants. Many speakers noted that these problems appear to be exacerbated by climate change. Our understanding of the functioning of ecosystems has grown rapidly since the 1980s, but with that understanding has come increased insight into the complexity of such systems and the difficulty of fully comprehending the consequences of human-induced changes and the attendant functioning and effects on ecosystem health. The difficulty of accurately predicting the consequences of future changes is considerable, and several speakers emphasized the importance of a precautionary approach that can be adapted to respond to ongoing observations and analysis.

THEME 3: SAVING WHAT WE CAN

Saving biodiversity and sustaining ecosystem functioning will require an array of strategies, founded on the best possible understanding of what biodiversity exists, how organisms interact to create functioning ecosystems, and how these organisms and systems are changing. A variety of strategies were presented to address the ongoing erosion of biological diversity and ecosystem function, although numerous speakers emphasized that successful interventions require a systems approach and a broad understanding of the goods and services provided by species in ecosystems. Some speakers also asserted that successful conservation and management interventions inevitably depend on enhanced levels of public engagement, awareness, and support.

THEME 4: MANAGING ECOSYSTEM SERVICES AS COMPLEX ADAPTIVE SYSTEMS

A recurring theme of the sessions was that decisions to conserve, manage, and use biodiversity and ecosystems for human benefit should be based on the best available information on the full suite of services that ecosystems provide, and awareness of the trade-offs among ecosystem services (see Figure 1-2). Some speakers observed that much research on and management of ecosystems has been approached in a fragmented way, in large part because of the difficulties of integrating different academic fields and administrative jurisdictions. A central theme of several presentations was the increased imperative for further integration both in science and in policy. Broader approaches, those speakers contended, are necessary to

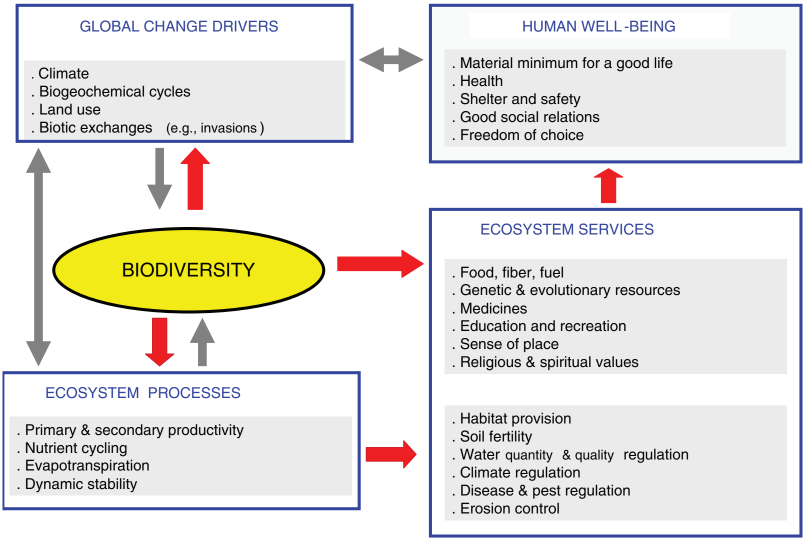

FIGURE 1-2 The relationship of biodiversity to ecosystem services and global change. SOURCE: Sandra Díaz presentation, adapted from Millennium Ecosystem Assessment. 2005. *Ecosystems and Human Well-Being. Biodiversity Synthesis.* Washington, DC: World Resources Institute.

> *The conceptual model shows how global change drivers affect human well-being both directly and indirectly. Similarly, biodiversity in the broad sense affects the provision of ecosystem services both directly and through ecosystem processes. It may also alter the drivers of global change themselves.*
>
> Sandra Díaz, February 12, 2009

avoid unintended and often cascading consequences. Examples they cited included the effects of policies related to biofuels and carbon on agriculture, water resources, and biodiversity; of approaches to fisheries management on marine ecosystems; and of trade policies on the global dispersal of pests and pathogens. Understanding and managing such complex systems, several speakers noted, requires ongoing adaptive cooperation and collaboration among disciplines and across jurisdictions, both public and private, as knowledge continues to evolve.

THEME 5: INCREASING CAPACITY TO INFORM POLICY THROUGH INTEGRATED SCIENCE

Incorporating biodiversity and ecosystem science into policy decisions is not straightforward. Several symposium speakers described how the ecosystem services framework has helped demonstrate and quantify links between ecosystem functioning and the economy, as well as other aspects of human well-being. Economics and social science, they contended, must be integrated with scientific approaches to biodiversity and ecosystem management to support the development of effective public policy. Appropriate information must be made comprehensible and available to decision makers at all levels, both public and private. Some speakers emphasized that scientific input should be informed by awareness of both the strengths and limitations of research results and the complexities of policy making, and that effective policy advice should also take into account the need for public support of particular policy approaches.

THEME 6: INCREASING SOCIETAL CAPACITY TO MANAGE AND ADAPT TO ENVIRONMENTAL CHANGE

Environmental changes, from climate change to introduced pests and pathogens, can threaten both ecosystem functioning and the services that human beings derive from ecosystems. Some speakers detailed challenges to ecosystem services that are crucial to human well-being, such as food production, clean water, and regulation of atmospheric chemistry. They argued that both scientific progress and public education will be necessary to develop and implement well-formulated strategies for mitigation and adaptation. Climate shifts and other human-induced environmental changes that are already ongoing, and likely to intensify, some speakers contended, demand attention at every scale, from global to local, in all parts of the world.

THEME 7: STRENGTHENING INTERNATIONAL INSTITUTIONS AND U.S. ENGAGEMENT AND LEADERSHIP

Numerous speakers pointed out that threats to biodiversity and ecosystem services that are global in scope require effective international coordination and cooperation if they are to be managed successfully. They characterized existing international cooperative efforts as insufficient to meet the scale and scope of current and future challenges, and emphasized the opportunity—and urgency—for U.S. leadership in taking domestic action and bringing nations together. Two opportunities that several speakers mentioned specifically as vehicles for international cooperation were enhanced trade regulation and the nascent Intergovernmental Platform for Biodiversity and Ecosystem Services (IPBES).[7]

THEME 8: ACCOUNTING FOR THE VALUE OF NATURE

Some speakers contended that ecosystems and biodiversity will continue to suffer as long as economic incentives and associated social pressures fail to incorporate nonmarket externalities and to favor short-term exploitation and damage without regard to long-term sustainable management. Ecosystem services, they said, are frequently ignored because they are outside the market and so are unpriced, or because they involve services that are "public goods" that are open to all—this despite the fact that many ecosystem services, such as the provision of fresh water, are of fundamental importance, and degradation of such services has broad consequences. Proposals were made in some presentations to expand the system of national accounts to include changes in nonmarketed ecosystem services, and to record changes in the value of ecosystems (natural capital), to support public environmental decision making and encourage the design of policies that promote more sustainable economic growth that assures the long-term availability of vital ecosystem services.

Drawing on the eight themes that emerged from the speakers' presentations at the symposium may help those scientists, nongovernmental organizations, and policy makers who are attempting to work more effectively together toward improving the future management of biodiversity and ecosystems, as well as the goods and services on which we all depend.

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[7] IPBES.net, accessed May 2011.

2

Eight Themes for Managing the Living World

THEME 1: LEARNING WHAT WE HAVE

We are the first generation of scientists with the tools to address the dimensions of biodiversity on Earth… and ironically we may be the last generation with the opportunity to discover and understand Earth's biodiversity before it is irrevocably changed or lost.

James Collins, February 13, 2009

The availability of solid baseline knowledge of the full dimensions of biodiversity on Earth, from genes to species, communities, and ecosystems, is fundamental to the successful management of both the variety of life and the ecosystems that they comprise. Despite centuries of progress with documenting biological diversity, speaker after speaker demonstrated how, for many groups of organisms and many aspects of their diversity, knowledge remains grossly incomplete. Life is vast, and scientific exploration is nascent. Speakers described how, as a result, humankind remains unprepared to recognize and respond to many of the changes in biodiversity being brought about through a range of direct and indirect human influences on the environment.

During the symposium, some speakers observed that knowledge is especially incomplete for certain groups of organisms and in certain geographic regions and environments. Understanding of microbial diversity (including bacteria, archaea, fungi, and so on) and its role in ecological processes is still in its infancy, despite the evident importance of these small and ubiquitous organisms in many of the key biogeochemical processes that are important for sustaining life. Modern technology (primarily in genomics) is making possible the study of previously inaccessible aspects of microbial diversity and microbial systems for the first time. It is also highlighting the limitations of past understanding, based as it was on only the very small fraction of microbes that had been cultured and studied.

Numerous speakers addressed the implications of these scientific developments. Paul Falkowski explained recent developments in the study of marine microbial diversity that show how their biochemical and physiological diversity underpins the functioning of the entire biosphere. Michael Donoghue demonstrated that microorganisms may provide the basis for transformational technological innovations, offering examples of microbial fungi that show promise as new antibiotics and even alternative energy sources. Rodney Brown and Philip Robertson cited research in microbial systems directed toward improvements in agriculture that may be necessary to feed burgeoning human populations while also limiting environmental impacts. Dr. Donoghue argued strongly for policies to support the discovery of biodiversity as central to the development of new technologies.

For macroscopic plants and animals, some of the most biodiverse terrestrial ecosystems remain among the least well inventoried. The tropical forest ecosystems of the Amazon described by Yadvinder Malhi and the cloud forests discussed by Christian Körner are both especially vulnerable to climate and other changes, but their biodiversity is especially poorly known.

Some speakers noted that aquatic biodiversity is also inadequately understood. Mary Glackin showed that most knowledge about the world's oceans is based on information gathered in the upper 100 meters of the water column, though the mean depth of the ocean is 4,000 meters. She emphasized the need for active exploration to better characterize ocean biodiversity, noting that the number of known marine fish species has increased to nearly 28,000, more than a threefold growth from the 8,000 identified in Darwin's time. In the same 200 years, Boris Worm estimated a 7 percent rate of extinction and 36 percent rate of species collapse for coastal species, principally as a result of overfishing.[1] Both also warned that changes in global climate, together with associated increases in ocean acidification and decreases in sea ice, may pose threats to the abundance and diversity of sea life.

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[1] Worm, B. et al. 2006. *Science* 314:787-790.

New tools are available for the inventory of biodiversity, but further innovation and application could assist synthesis, manipulation, and analysis, and might help assess response to environmental change. Several speakers described the burgeoning capacity to secure vast amounts of data, especially on genetic diversity, as well as opportunities to place data of all kinds in a spatial context through the use of new kinds of instrumentation for global and regional scale remote sensing in combination with geographic information systems (GIS). James P. Collins described how new genomics technologies and cyber-enabled observatories, which he termed "game changers," are leading to new programs for understanding biodiversity and ecosystems, including the National Science Foundation's National Ecological Observatory Network, as well as global initiatives such as the Group on Earth Observations Biodiversity Observation Network, and the biodiversity component of the Global Earth Observation System of Systems (see Box 2-1).

The explosion of new data at multiple levels and across many scales calls for new approaches to process and make information available and to achieve more effective integration. Cristián Samper urged the development of cutting-edge information systems that would provide broad access to the research community and to policy makers, as well as for education and outreach activities at all levels. He and other speakers referred to the Encyclopedia of Life (EOL), the Global Biodiversity Information Facility (GBIF), the National Institutes of Health genetic sequence database GenBank, and the Consortium for the Barcode of Life (CBOL) as examples of the many databases developed by specific communities and individual institutions that are using new technologies to organize biological data for broad access. Dr. Samper emphasized, however, that these efforts need to be sustained, intensified, and coordinated if they are to realize their full potential. Furthermore, he noted that these effects are complementary to, but not a replacement for, traditional methods of archiving natural history data in other ways, such as through reference and voucher specimens in museum collections.

Increasingly, data on species distributions are being combined with other knowledge (e.g., phylogenetic trees) or models (e.g., climate-change scenarios) to provide improved predictions and new kinds of insights. Using GIS approaches, they are also increasingly integrated with other data to model species distributions and their associated environmental parameters. José Sarukhán described how the Mexican National Commission on Biodiversity (CONABIO; Box 2-2) uses such tools to synthesize and analyze data and make them broadly accessible to citizens and decision makers.

BOX 2-1
Pathways to Understanding the Dimensions of Biodiversity

Next Steps

Within a decade: What are the dimensions of biodiversity?
Inventory of the Biosphere

Within a career: What are the consequences of species loss?
The Biology of Extinction

Within a generation: What information is needed to represent ecosystem services accurately in national accounts?
The Dynamics of Coupled Natural and Human Systems

Adaptations Required of the Scientific Community

- Academic Community:
  —Value research that is discovery based as well as research with a strong theoretical-conceptual basis
  —Reward "team driven" as well as individual research achievement
- Biodiversity Research Community:
  —Adopt open-source biodiversity information and rapid posting of new data
  —Develop and adopt new technologies for biodiversity assessment

SOURCE: James P. Collins presentation

> *What might next steps look like? We need an inventory of the biosphere within 10 years to get a better summary of what's out there, and this could entail using new technologies. Then, over the course of a career, some individuals have to think about what a 'biology of extinction' might entail. We need better models to predict how ecosystems come apart, one or a few species at a time. . . . Within a generation, we need to have a much better understanding of the dynamics of coupled natural and human systems. Natural scientists and physical scientists have to do a lot more work with social scientists in terms of theories, concepts, and methods. What information is needed to represent ecosystem services accurately in national accounts? We need to have that dialogue more aggressively and more creatively.*
>
> James P. Collins, February 13, 2009

BOX 2-2
CONABIO

Comisión Nacional para el Conocimiento y Uso de la Biodiversidad (National Commission for the Knowledge and Use of Biodiversity)

Conceived as a

- demand-driven research organization,
- promoter of basic (systematic, ecological, socioeconomic) research,
- compiler of existing national and international biodiversity information on Mexico,
- generator of human capacity in the area of informatics for biodiversity,
- an open resource of information to all society.

CONABIO implements and operates the National Information System on Biodiversity, providing place-specific, electronic data on the species that can be found in each geographical location in Mexico. CONABIO's users include national, state, and local officials; researchers, consultants, and nongovernmental organizations (NGOs); and farmers, foresters, and peasant communities. The database has guided national-scale conservation and sustainable use of biodiversity in Mexico, such as establishment of protected areas and biodiversity corridors, as well as contributing to understanding of Mexico's ecosystems, genetic diversity, and natural landscapes. It is also used to inform local infrastructure and land-use decisions, such as the location of rural water treatment facilities.

SOURCE: José Sarukhán presentation

> *CONABIO, developed under the auspices of the government of Mexico, is a world-leading authority in the collection, synthesis, and utilization of biodiversity information in support of policy at all levels, from local to national.*
>
> José Sarukhán, February 11, 2009

Such projects, which have been replicated in other countries (e.g., Brazil's Biota-FAPESP, the Biodiversity Virtual Institute of the São Paulo State Foundation for Research Support), reflect the increasing need for national governments to harness reliable data for both the planning and the implementation of policy decisions. Such data also provide the opportunity to monitor environmental change, through careful observation of changes in the biosphere itself, and to use those data to implement new interventions that serve the global public good.

THEME 2: LEARNING HOW ECOSYSTEMS ARE WORKING AND CHANGING

> *Tropical forests face a number of challenges from climate change. These include rising temperatures, associated increases in water use, and in some regions a decrease in dry season rainfall. How tropical forests respond to these changes depends critically on the interactions with climate change.*
>
> Yadvinder Malhi, February 12, 2009

It is now widely understood that by-products of the fossil fuels that have underpinned industrial growth in the last two centuries are transforming the chemistry of the atmosphere and the oceans with far-reaching effects on biodiversity. Several symposium speakers observed that climate change is only one among many anthropogenic drivers of biodiversity and ecosystem change. Closer integration of the world economic system has led both to the homogenization of farmlands, grasslands, and forests around the world and to the widespread dispersal of species, including harmful pests and pathogens. Some speakers also described important changes in the way in which people access and use terrestrial and marine resources. On land, habitats have been destroyed, transformed, and fragmented; water has been diverted to human use, altering hydrological flows; the chemical composition of soils has been changed; and wild species have been depleted. In the oceans the changes are less easily visible but equally profound, and Boris Worm described how direct harvest of natural fisheries is transforming marine ecosystems through the depletion of the largest predator species and the preferential harvest of the largest specimens of commercial favorites. New understanding of these processes is demonstrating the transformative and irreversible nature of some of these changes, leading several speakers to call for effective mitigation.

Climates have changed throughout earth history, but many symposium participants noted that current rates of change are extraordinary and take us outside the boundaries of previous natural and human experience. Yadvinder Malhi described the challenges from climate change to tropical ecosystems that have already been greatly affected by human encroachment. Climate changes in coming decades are projected to equal those that, in the past, have occurred over millennia. Likewise, although organisms have an inherent capacity for dispersal, sometimes across great distances, and sometimes in waves, previous levels of dispersal are quite unlike the global movements of species that have been brought about by human travel and trade. As with the effects of climate change, these species introductions, described by Charles Perrings, often occur in habitats already disturbed and fragmented by human settlement and agriculture, and that are vulnerable to invasion. Moreover, Dr. Perrings contended, under climate change, species moving between broadly bioclimatically similar regions may be less likely to encounter predators and competitors capable of keeping them in check, since climate change itself alters the "natural" range of species, and species respond individualistically.

The effect of anthropogenic modification on biodiversity and ecosystems depends on the capacity of the affected species to adapt to changes in their environment. As noted by several participants during the symposium, species unable to adapt will decline in abundance and potentially face local extirpation, or potentially whole-scale extinction of endemics. Species better able to adapt may exploit new conditions opportunistically, or may undergo rapid evolution, including the evolution of new traits resulting from changes in the nature and extent of selection pressure. Several symposium attendees observed that, in general, scientists, managers, and policy makers lack knowledge of how such changes and other new circumstances will affect ecosystem function, and how both species and systems may respond to change. In turn, this limits the ability to predict the outcome of management interventions, and to formulate appropriate policy responses.

Several speakers described the environmental consequences of closer integration in the global economy and the consequent widening and deepening of international trade. Especially significant is the dispersal of pest species in general, and pathogens in particular. For example, Ann Marie Kimball described how the rate at which novel zoonotic diseases are emerging and being transmitted through markets is rapidly accelerating (e.g., avian flu) ~~as~~ is the rate at which diseases are being spread through changes in the range of their vectors (e.g., West Nile virus).

The economic costs of some of these ecological changes, such as those resulting from the spread of nonnative species, can be high. David Lodge described how the rapid spread of zebra mussels in American freshwater systems since 1988 has caused massive damage to native species and has clogged industrial intake pipes. The estimated annual economic costs are greater than $200 million. Ann Bartuska cited a study that identified the accumulation in the United States over the past century of more than 200 "economically significant" invasive forest insects and diseases (see Figure 2-1).[2] Some of these may have entered the country with other species introduced intentionally, for example, for use in gardens or aquaria. Others may have entered entirely accidentally, for example, through packing material or fodder.

Further economic costs can be incurred for agricultural systems through changes in the broader ecosystems of which they are part, such as loss of pollinators and predators. Alison Power explored both how agricultural practices can be threatened through broader environmental changes and how agriculture itself affects habitats, nutrient and water supplies, and soil health. Rodney Brown similarly emphasized the necessity of taking a complete systems approach in understanding "the inescapable interconnectedness of agriculture's different roles and functions."

The potential for rapid evolutionary changes, both reversible and irreversible, was demonstrated by Michael Donoghue and Andrew Hendry, who described recent results documenting the subtle effects of invasive species, and overexploitation. [3] For example, introduced, nonnative weed species of *Persicaria* have hybridized with native species in South America to create invasive "superweeds";[4] and hunting pressure for trophies has resulted in the evolution of bighorn sheep that have smaller horns (Figure 2-2). Such shifts, which are rapid in the context of background rates of evolutionary change, have now been documented in a variety of vertebrates (fish, frogs, lizards, birds, mammals), as well as in plants, but may be even more rapid

[2] Holmes, T., J. Aukema, B. Von Holle, A. M. Liebhold, E. Sills. 2009. Economic impacts of invasive species in forests: Past, present, and future. In *The Year in Ecology and Conservation Biology*, Ostfeld and Schlesinger, eds. New York: New York Academy of Sciences.

[3] Hendry, A. et al. 2008. Human influences on rates of phenotypic change in wild animal populations. *Molecular Ecology* 17:20–29.

[4] Kim, S-T., S. E. Sultan, and M. J. Donoghue. 2008. Allopolyploid speciation. In *Persicaria* (Polygonaceae): Insights from a low-copy nuclear marker. *Proceedings of the National Academy of Sciences USA,* 105: 12370–12375.

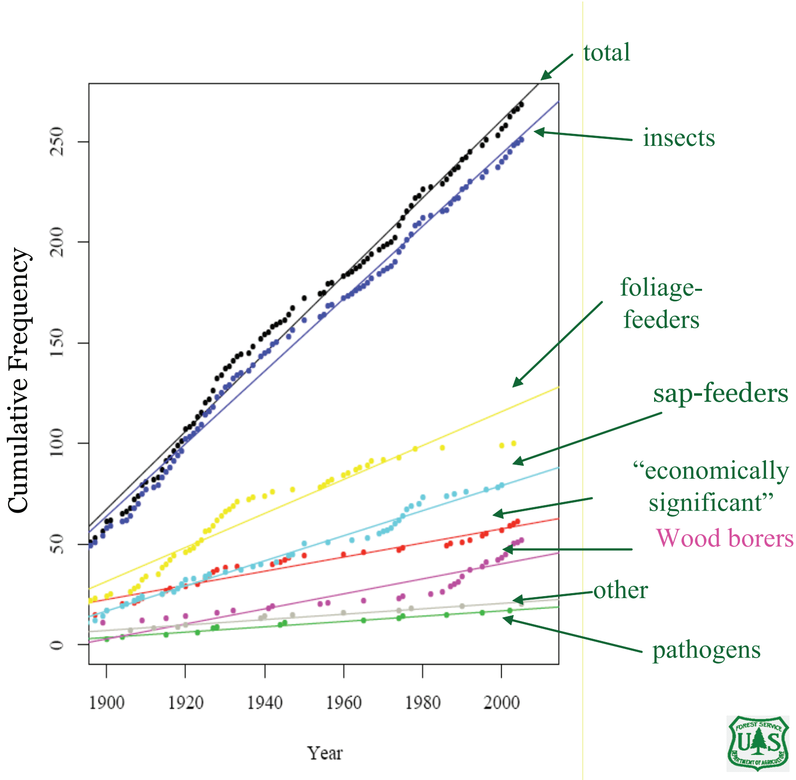

FIGURE 2-1 Increases in invasive forest insects and diseases.
SOURCE: Ann Bartuska presentation, from U.S. Forest Service, Department of Agriculture

As part of an analysis by the National Center for Ecological Analysis and Synthesis of the economic impacts of invasive forest insects and diseases, 396 invasive species were listed, and their dates of introduction were plotted as cumulative introductions over time by feeding guild. The average overall is 2 per year, showing that improvements in regulation, detection, and eradication are just keeping up with increases in trade. "Economically significant" pests were defined as those causing damage greater than $25,000. Note that the increase in wood borers since 1980 may result from an upsurge in container shipping, which pathway uses a lot of wood-packing material.

Ann Bartuska, February 11, 2009

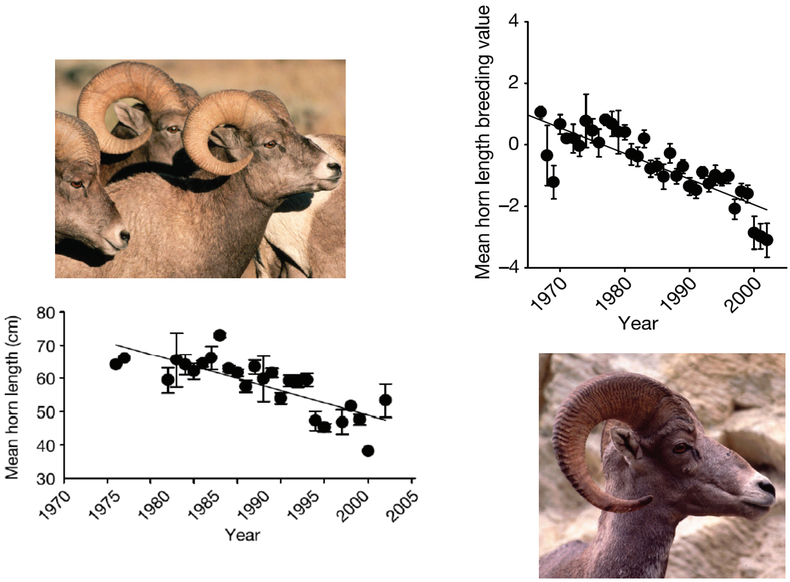

FIGURE 2-2 The effect of trophy hunting of bighorn rams on heritable characteristics. SOURCE: Andrew Hendry presentation; adapted from Coltman, D. W. et al. 2003. Undesirable evolutionary consequences of trophy hunting. *Nature* 426:655–658.

> *Humans do things specifically to populations that drive their evolutionary change. The best example is harvesting of populations, whether it be fish, or other animals, or snow lotuses. This is an example from Ram Mountain in Alberta, where there is a small population of bighorn sheep that are targeted by trophy hunters. They are only allowed to kill sheep with a horn size that passes a certain point. Over 30 years, the mean horn length is going down quite substantially. The same thing has been happening with harvested fish populations.*
>
> Andrew Hendry, February 11, 2009

and profound in smaller organisms with rapid life cycles (bacteria, fungi, planktonic organisms, and so on).

Current models of environmental change frequently assume little or no evolutionary change or adaptation. Several speakers noted that better understanding of the evolutionary responses of organisms as conditions change and populations or species respond through evolution, migration, or extinction may offer insights for predicting ecosystem change, particularly when integrated with knowledge from deeper history of past patterns of migration, evolution, and extinction. For example, the discovery of specific responses to changing environmental parameters, such as the ability or inability to shift flowering time in response to climate changes, can help in assessing the vulnerabilities of species and ecosystems as the world changes around them.

Regarding microbial systems, where analytical abilities have been especially limited until recently, new insights from new methods have implications at all levels, from global engineering to public health. Paul Falkowski, in his presentation entitled "Don't Touch Those Dials!," enjoined scientists and policy makers to be cautious in proposing large-scale tinkering with the fundamentals of microbial systems that have evolved over billions of years and perform vital global biogeochemical regulatory functions through poorly understood biogeochemical systems. At a completely different scale, Ann Marie Kimball showed how rapid evolution facilitates the spread of disease-causing microbes, which can move rapidly as they adapt to new environments and also respond quickly to disease-prevention measures (e.g., resistance to antibiotics). Rapid evolution at the level of microbes and microbial systems, according to Scott Barrett, can pose special challenges, for example, in requiring coordinated international efforts to eradicate diseases.

These observations highlight opportunities for productive research, to understand both the new evolutionary and ecological circumstances of our modern world and the possible evolutionary and ecological consequences. James P. Collins emphasized that the rapid changes and evolving pressures on ecosystems required a new, cyber-enabled observing system, one that includes hybrid operational and research platforms and standardized infrastructure, procedures, and quality control. Long-term measurements, he said, could allow tracking of changes. Open data policies would allow for research that could vastly increase understanding of ecosystems, and lead to the development of effective decision support tools. The need for such tools was also emphasized by Ann Bartuska, who underlined the importance of understanding and predicting ecosystem change to underpin policy, to justify regulation or interventions, and to help develop effective mitigation measures.

Many symposium participants called for improved systems thinking in learning about how ecosystems work and are changing. Without such a systems approach, subtle and dynamic changes and interconnections will often be overlooked. In those cases, the full implications of proposed management interventions will be incompletely considered, and unforeseen consequences may be difficult to alter.

THEME 3: SAVING WHAT WE CAN

> *We do have to realize that in many parts of the world where we today find the greatest diversity of life, also some of the largest protected areas and parts of our landscape that are set aside specifically for biodiversity conservation, involve developing countries.*
>
> Achim Steiner, February 11, 2009

The U.S. Endangered Species Act of 1973 was predicated on the principle that endangered species should be saved at any cost. Nonetheless, even in the face of such a broad and unlimited commitment and many successful instances of species and ecosystem conservation that have been implemented over many decades, the extinction of species in our nation and globally remains an urgent problem.

Though extinctions are increasingly well documented, and while many experts acknowledge that the intensity of extinction will increase, many speakers offered compelling arguments that it is in human self-interest to preserve as much as possible. Different ecosystem services, argued Sandra Díaz, depend on different characteristics of the organisms present in the ecosystem—and many are not well understood. Speakers offered many examples of the importance of biodiversity in maintaining key ecosystem services, from the provision of stable water supplies to the stabilization of local climate. Several speakers also noted that some of these services have been degraded or carelessly destroyed in the process of human settlement and development, and that often they can be re-created only at great cost. Christian Körner showed one subtle example of an apparently nondescript species of grass that, nonetheless, engineers the edge of soil banks and thereby significantly influences erosion and hydrology in the Alpine landscapes of Switzerland. Adaptation strategies that maintain ecosystem services in the face of climate change and increasing population pressures, he said, will likely draw on different species in different combinations than they occur today. Ensuring that a broad spectrum of biodiversity resources remain available as a basis for both natural and human adaptation argues for developing strategies to preserve as much as possible.

Many symposium attendees called for various mitigation and adaptation strategies as climate and other environmental changes intensify, emphasizing that such strategies should be founded on the best possible scientific understanding of the different dimensions of biodiversity, the functioning of ecosystems, and the rate and scope of changes in both. A variety of strategies, implemented at appropriate scales, could engage stakeholders locally while also leveraging support at national and international levels.

A long-standing approach has been to preserve biodiversity in protected areas that have been chosen based on a great range of criteria. However, both José Sarukhán and Rodger Schlickeisen emphasized that most biodiversity will nonetheless lie outside protected areas, often in human-dominated landscapes, and in these circumstances will require different kinds of approaches to conservation. Some of the species found in managed landscapes are domesticates or species that thrive in proximity to people and the kinds of environments they create. However, many others are among the wild species currently most at risk from anthropogenic stresses. Several speakers emphasized that these nonpristine reservoirs of biological diversity should not be neglected. Dr. Sarukhán described how building community awareness and encouraging local action have served as important complements to improved data and bioinformatics, as well as reserves, in greatly enhancing biodiversity protection within Mexico.

Many speakers observed that some protected areas will be compromised by changes in climate or other environmental parameters, such as habitat fragmentation or degradation related to development. In these changing circumstances, current protected areas may no longer be suitable for particular species. To avoid the destruction of the population or species, wildlife corridors, such as those deployed in the Amazon and described by Yadvinder Malhi, can allow migration and support survival, though they also require careful planning to avoid facilitating the penetration of invasive species (see Box 2-3). In other cases, Stephen Schneider and Christian Körner suggested, direct human intervention might be needed, for example, when a warming climate results in particular conditions shifting upward in altitude. In different cases, Dr. Körner suggested that the mountains may represent "refugia, traps, or a survival opportunity" for threatened species. Some species may survive by moving up slope in response to changing climate,[5] but others may have no appropriate habitat available at higher levels. Schneider noted that transporting such "trapped" species to a com-

[5] Lenoir, J. et al. 2008. A Significant Upward Shift in Plant Species Optimum Elevation During the 20th Century. *Science* 320:1768–1771; Raxworthy, C. J. et al. 2008. Extinction vulnerability of tropical montane endemism from warming and upslope displacement: A

BOX 2-3
Maintaining Tropical Forest Area Is a Strategy for Mitigating and Adapting to Climate Change

- Minimize contact points between forest fragments and fire zones
- Lower surface temperatures because of evaporative cooling of near-surface area
- Maintain shade habitats
- Maintain dry season rainfall
- Maintain connectivity for species migration to highland refugia

SOURCE: Yadvinder Malhi presentation

Maintaining large areas of intact forest in eastern Amazonia is a strategy for not only conserving biodiversity and mitigating the rate of global change but also increasing the resilience of the region to local climate change, through maintaining regional rainfall, lowering surface temperatures, and providing migration corridors for species.

Yadvinder Malhi, February 12, 2009

patible environment may sometimes be effective for conservation, but at the same time raises ethical issues, and opens the possibility of unintended ecological consequences.

Ex situ conservation offers an additional insurance policy, especially in our current time of rapid change and when future patterns of land use, climate, or other key variables are uncertain. Peter Crane cited the critical role of the ex situ conservation efforts carried out by seed banks, botanical gardens, and zoos as both "insurance" and "last chance" repositories of genetic resources.[6] Dr. Crane also emphasized the importance of more fully engaging the expertise and information residing in botanic gardens and

preliminary appraisal for the highest massif in Madagascar. *Global Change Biology* 14:8, 1703–1720.

[6] The Millennium Seed Bank Project—coordinated by the Royal Botanic Gardens, Kew—and the Svalbard Global Seed Vault are high-profile examples of two such conservation initiatives since the 1990s. Together, hundreds of millions of stored seeds already preserve the genetic diversity of tens of thousands of plant species and millions of accessions of key crops.

natural history museums to understand the full dimensions of biological diversity.

> *There are some simple things that we can do to buy us time. Seed banking is extremely important for the world's crop species, and surely also for the world's wild plant species. We shouldn't wait until extinction is at the door before we undertake that kind of action.*
>
> Peter Crane, February 12, 2009

Rodger Schlickeisen called for cooperation between public and private entities, and between scientists and advocates, to develop and realize appropriate strategies for biodiversity and ecosystem protection. He joined Cristián Samper in arguing that broadening public engagement and awareness is crucial, on the basis that policy makers will act only in response to the public's awareness of biodiversity loss as a problem. The loss of biodiversity and the rapid transformation of landscapes is often most apparent between generations, as parents consider the environment that they remember compared to the world they are passing on to their children. Several participants called for enhanced awareness of the rapidity of such changes in the broader context of nature. Dr. Schlickeisen, the final speaker, echoed the opening remarks of Peter Raven, and many other speakers, by calling on scientists to raise the issue of biodiversity loss in every relevant forum, to broaden awareness of the evidence connecting biodiversity and ecosystems to well-being. He emphasized the need to ensure that the ongoing transformation of the biological world, which is driven by human activity, receives the same attention as the transformation of the climate and the economy. These systems, which are all crucial for sustaining and improving human well-being, are inextricably linked.

> *We need as a people to speak up. . . . We need to reinvent wildlife conservation in America and in the world. The old way of doing things is not working. We're just scratching the surface of how we address climate change in the face of all these other threats to wildlife. We ought to be looking not in the rearview mirror but out of the windshield, using models, to plan for floods and wildlife preservation.*
>
> Larry Schweiger, February 12, 2009

THEME 4: MANAGING ECOSYSTEM SERVICES AS COMPLEX ADAPTIVE SYSTEMS

Policy makers, assessment groups, agencies, and commissions, among others, need to be better coordinated to take into account the interactions among the drivers of global change, and their separate and synergistic impacts.

Stephen Schneider, February 12, 2009

The value of ecosystems for human well-being extends from meeting fundamental human utilitarian needs, such as shelter or medicine, to the more sublime human requirements for a sense of place, spiritual or aesthetic fulfillment, or a moral commitment to stewardship. Several symposium participants pointed out that human populations flourish only within a relatively narrow climatic range, and all human life depends on the food and clean water provided by biological systems. Human history is filled with examples of the unexpected and unwelcome consequences of human activities that are channeled to fill these or other needs while ignoring the complexity of the systems required to provide those goods and services over the long term. Paul Falkowski described how oceanic microbes drove the initial development of Earth's oxygen-rich atmosphere and continue to regulate its functioning in ways that are only just becoming clear, and he cautioned against tinkering with that system through geoengineering.

Even one of the most fundamental of all provisioning functions—food production—is both extraordinarily complex and surprisingly fragile. Industrial food systems are profoundly different from traditional, small-scale farming and livestock management, and insofar as they reflect a particular form of land use, a number of speakers described how that use involves trade-offs with other benefits that the land might provide, such as energy from biofuels or the maintenance of clean water systems by forests. Many speakers emphasized the complexity of the systems on which human well-being depends, and the importance of carefully considering the unintentional and often cascading negative effects of specific management decisions. Stephen Schneider illustrated this point in the climate context. He noted that local limitations on the capacity to adapt needed to be considered in parallel with the development of target concentrations of atmospheric carbon dioxide. He cited studies showing increases in California wildfires in years of early snowmelt runoff—an increasingly high-probability occurrence in a warming climate. He also noted the detrimental health effects of widespread wildfire smoke.

Several speakers also emphasized that many mitigation strategies that might be developed as responses to climate change depend heavily on ecosystem services. Harold Mooney pointed out that carbon markets and other economic incentives aimed at decreasing greenhouse gases in the atmosphere depend fundamentally, at present, on plant physiology. The detrimental effects of carbon markets on other ecosystem services are already being observed. Yadvinder Malhi noted the possibilities for perverse trade-offs in the Amazon, such as some proposed incentives for carbon governance that maximize carbon storage without considering the many other ecosystem services of forests, which have the potential to damage, rather than preserve, tropical forest functioning. Moreover, Philip Robertson pointed out that the U.S. Energy Policy Act of 2007, which stipulates that ethanol must make up 22 percent of transportation fuel by 2022, requires that grain-based ethanol production more than double between 2007 and 2022 (from 6.4 to 15 billion gallons per year). The act also requires even larger cellulosic ethanol production (16–21 billion gallons per year) from technologies that are not yet commercially viable. Several speakers observed that potentially well-intentioned goals such as these are likely to have serious ramifications for land and water use. The development of policies to guide the law's implementation calls for an understanding of the complex biological, biochemical, and biophysical systems that are affected and a more expansive view of the systemic risks inherent in managing complex ecological systems for a narrow suite of outputs.

Agricultural systems, whether used for food, fiber, or fuel, should likewise be considered within a broader context of the complex landscape-scale ecological systems in which they are embedded. Alison Power described how agricultural systems both use and produce ecosystem services (Figure 2-3). They are dependent upon, and influence, soil structure, nutrient cycling, water provision, and genetic diversity. They are intimately connected to a range of ecological services such as water supply, soil conservation, climate change mitigation, and wildlife habitat that are not currently captured in a comprehensive way either by the market or by appropriate policy and regulatory systems. As several speakers noted, agricultural policies that do not consider the systemic effects and risks of the practices that they encour-

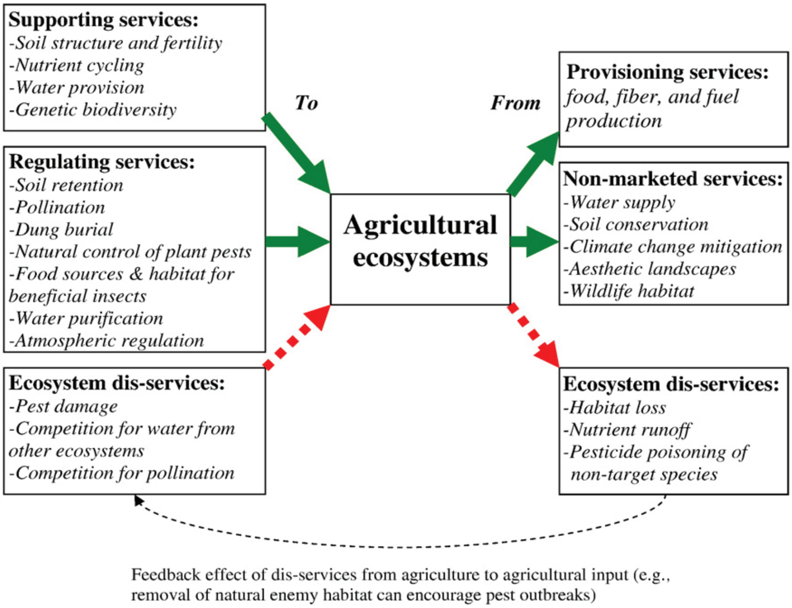

FIGURE 2-3 Ecosystem services and agriculture.
SOURCE: Alison Power presentation, adapted from Zhang, W., Ricketts, T. H., Kremen, C., Carney, K. & Swinton, S. M. 2007. Ecosystem services and dis-services to agriculture. *Ecological Economics* 64:253-260.

> *Agricultural systems both rely on and provide ecosystem services. If you are mindful of these kinds of aspects of services when you design agriculture, you can mitigate these disservices. What is important to understand is that the arrows should be going both ways. Agriculture can either support these services in the landscape or detract from these services. It should be a two-way system between agricultural ecosystems and the supporting and regulating services.*
>
> Alison Power, February 12, 2009

age can have undesirable consequences. David Tilman's prepared remarks[7] warned how biofuel strategies could conflict with projections of new crop and pastureland requirements of 1 to 1.5 billion hectares to meet food de-

[7] David Tilman was unable to attend the symposium, but a summary of his presentation was given by the session chair.

mand over the next 50 years. He stated that the combined effects on other ecosystem services could be devastating without equally important parallel strategies of increasing agricultural yields, especially in developing countries; reforming meat production systems; and carefully targeting biofuels programs to already-cleared or degraded lands.

Globalization of the agricultural system also means that it is affected by the global trade system, which, as Ann Marie Kimball pointed out, leads to difficulties in containing hazards that, in the past, would have had effects only locally. Changes in practices and increasing trade in foodstuffs mean that both dangerous products (such as tainted meats and vegetables) and pathogens (such as antibiotic-resistant microbes) can be transmitted around the world very rapidly.

Direct harvesting of food from the sea, several participants said, is also threatened by systems of utilization and management that are not sufficiently cognizant of the ecosystem context from which fish are extracted. Marine wild fisheries are changing rapidly, both in response to increasingly efficient capture technologies and as a result of changing global climate. Boris Worm described the challenges confronting contemporary fisheries management, where wild fisheries output is decreasing and the number of commercial stocks that are threatened is increasing; species-specific regulation has not effectively controlled the decline in fisheries. Mary Glackin added a list of broad threats to marine biodiversity, including ocean acidification, sea-level rise, loss of sea ice, and changes in marine species distributions, adding that other issues such as shipping, marine sonar, and energy exploration and development also have ecosystem consequences that are not yet fully addressed by appropriate policies (see Box 2-4). Both Ms. Glackin and Dr. Worm highlighted opportunities to improve fisheries conservation through better governance, elimination of harmful subsidies, and establishment of protected areas. They expressed hope that ecosystem-based management approaches presently being enacted could make a difference. These two speakers noted that the complexity of the systems, along with the uncertainty surrounding climate effects and ocean acidification, requires that, even as new management systems are instituted, they be carefully monitored and adjusted to ensure their efficacy.

Rebecca Goldburg provided a complementary look at aquaculture production, which has grown exponentially since the 1980s, often with demonstrably adverse environmental consequences. In large part, that growth has depended on the provision of cheap fish-meal feed, which has a variety of associated problems. She said that making aquaculture sustainable will

BOX 2-4
Changes in the Marine Environment and Associated Ecosystem Consequences

Climate Change

- Ocean acidification
- Sea-level rise
- Changes in freshwater in coastal areas
- Loss of sea ice (at both poles)
- Ocean warming and changes in circulation

Marine Sound and Vessel Traffic

- Sonar
- Shipping
- Construction
- Oil and gas exploration

Pollution

- Plastics
- Endocrine disruptors
- Marine debris

Coastal Habitat Loss and Nutrient Enrichment

- Harmful algal blooms
- Hypoxia
- Loss of sea grasses

SOURCE: Mary Glackin presentation

> *NOAA [National Oceanographic and Atmospheric Administration] is engaged in the study and management of numerous emerging threats to marine biodiversity. Climate change impacts are an umbrella for several threats, such as ocean acidification, sea-level rise, changes in freshwater, and loss of sea ice. Marine sound and vessel traffic become more widespread as problems as more areas of the ocean become navigable, raising the potential for additional impacts on biodiversity, particularly from energy exploration. The general issue of pollution includes marine debris that can be ingested or entangle animals, but also the introduction of certain chemicals. In coastal regions, dead zones caused by nutrient enrichment can cause loss of habitat (e.g., sea-grass beds) because of the anoxic environment they create, and harmful algal blooms can cause economic and ecosystem problems.*
>
> Mary Glackin, February 11, 2009

require resolving environmental issues related to the placement of fish farms as well as addressing the sources of fish-farm feeds. Again, systems thinking, and development of appropriate strategies to improve technical and other issues, were called for by the speaker.

> *Ecosystem services must be part of the national debate, and among those services is the power of nature to inspire awe and wonder.*
>
> Larry Schweiger, February 12, 2009

The complexity and interconnectedness of all these systems drove many speakers to urge policy makers to take into account the fullest possible suite of ecosystem services in their management decisions. They repeatedly emphasized the systemic risks inherent in basing policy and management on simplistic views of inherently complex systems. Achim Steiner also reminded the group that no consideration of ecosystem services can neglect the need to alleviate poverty, and Peter Raven further noted that "science cannot prescribe solutions that circumscribe human aspirations for a better life for themselves and their families." In other words, while every decision, ultimately, will respond to human needs and aspirations, many of which are conflicting, only improved awareness of the full ecological ramifications of different policy approaches offers a chance to satisfy those aspirations without further endangering the long-term health of the planet.

THEME 5: INCREASING CAPACITY TO INFORM POLICY THROUGH INTEGRATED SCIENCE

> *Transformative action in our economies to deal with climate change, and to ultimately stop global warming and reverse it, is inextricably linked to the biodiversity and ecosystem sphere. Indeed, global warming has most of its impact in the context of our biosphere.*
>
> Achim Steiner, February 11, 2009

A major contribution of the Millennium Ecosystem Assessment (MA) was to develop a conceptual framework for understanding the benefits that people derive from functioning ecosystems. Provisioning services comprise the largely consumptive use of managed ecosystems to produce foods, fuels, fibers, pharmaceuticals, and other materials. Cultural services comprise the largely nonconsumptive use of ecosystems—often in a more "natural" state—for recreational, aesthetic, spiritual, scientific, or cultural purposes. Regulating services refer to the role of ecosystems in moderating the variability in the supply of both the cultural and provisioning services, and include such crucial processes as soil retention and pollination. The last set of services identified by the MA, supporting services, are the ecosystem processes that underpin the production of all other services. [8]

The definition of these services offers a framework for incorporating ecosystem science more effectively into policy, not only in the environmental realm but also in agriculture, public health, and disaster management. As noted under Theme 1, CONABIO has worked to bridge the gap between academia, civil society, and decision makers in a country that is highly diverse both ecologically and culturally. Jose Sarukhán described how CONABIO has synthesized, promoted, and supported studies on the biodiversity of Mexico, and has converted basic taxonomic, biogeographic, and ecological data into information that is useful for Mexican decision makers from local to national levels. While national in concept, this approach has also provided benefits at the community level, where much of the nation's natural capital is owned and managed. At the same time, it has also helped policy makers to formulate national approaches that address conservation and resource management problems based on sound science.

> *From India comes a fascinating example where the GDP [gross domestic product] of the poor is estimated to be 57 percent dependent on nature and ecosystem services. . . .We need to look at the equity and the dependence, particularly of poorer communities ~~in~~ how much their ability to rise out of poverty and to develop rural economies will depend on the degree to which national and international policy making make biodiversity conservation and ecosystem services an explicit part of [international] agreements.*
>
> Achim Steiner, February 11, 2009

In the United States, agencies that have long relied on scientific input to guide their decisions in areas as different as fisheries and land management are likewise adapting the MA framework to broaden their approach and to attempt to consider a wider suite of the services provided by ecosystems. Mary Glackin described how fisheries managers are extending and

[8] Millennium Ecosystem Assessment. 2005. *Ecosystems and Human Well-being: Synthesis.* Washington, DC: World Resources Institute.

supplanting their species-by-species fisheries management with broader approaches based on integrated, ecosystem-based assessments. She stressed the importance of enforceable legal instruments, such as those governing marine fisheries, marine mammals, and endangered species, all of which clearly enunciate the critical role of sustainable ecosystem management. Ms. Glackin went on to note that achieving such goals requires thorough understanding of adaptation and change in marine ecosystems in response to modifications of both physical and biological systems and the ways that they are managed. She emphasized that "the United States and its international partners need to implement agreements and provide the resources to support them" through sustained investment and cooperation in observing systems, ecosystem analysis, and ongoing adaptive management in response to new understanding.

Several symposium participants called for improved science and analysis during discussions on invasive species, where explosive increases in trade and other cross-border exchanges have led to increased opportunities for nonindigenous species to damage crops, ecosystems, and health. Ann Bartuska explained the barriers to control of potentially harmful organisms. The U.S. Fish and Wildlife Service bans importation of "injurious wildlife," and horticultural plants can be blacklisted if they are known to be noxious weeds or if they may carry pests. Success, however, is only partial, and most invaders remain unrecognized until they are already well established. There is, she said, "usually someone who wants to import without restriction: The nursery industry wants free rein to explore remote regions and import new exotics, and can achieve considerable cost savings by producing plants for retail sale overseas. It is not reasonable to restrict these rights without technical justification." However, she explained, establishing such justification in every case is time consuming, costly, and fraught with uncertainty. Similarly, precautionary interventions that she described against incidental importation of pests, such as ballast water exchange or fumigation of logs and packing materials, impose significant costs on importers.

Christopher Costello noted that control of invasions after they are detected carries less political risk, since it is impossible to prove that you have prevented a harmful and costly invasion. However, proactive measures to prevent invasions are generally more cost effective. He also cited studies showing that "nonindigenous invasive species risk varies across trade partner, product, time, and delivery mechanism." Dr. Costello suggested that relatively "blunt instruments," such as fumigation or ballast water exchange, could be made even more effective and less costly by the development of more nuanced regulatory regimes based on understanding ecosystems and analyzing the history of invasions.[9]

To meet these challenges, David Lodge described advances in risk modeling that allow the prediction of the risk to ecosystems from the import of living organisms, and suggested ways of incorporating those analyses rated into effective policy design. Crucial elements include assessment of the relative costs of prevention versus control, combined with empirical research that includes historical patterns and biogeographic-climatic similarities among trading partners.

Some speakers described a comparable need for a precautionary and adaptive approach to climate change. Andrew Revkin noted that the *Intergovernmental Panel on Climate Change* (IPCC) has evolved from being dominated by atmospheric science and energy emissions scenarios to incorporating much more biological, social, and biogeochemical science, in large part because of new emphasis on the specific issues of atmospheric carbon dioxide mitigation, adaptation to climate change effects, and biofuels (as a special case of carbon dioxide mitigation). As Harold Mooney noted, the only proven, large-scale carbon capture and storage mechanisms rely on biological processes. Several speakers described how enhancing such carbon sequestration requires a thorough understanding of how ecosystems work, from microbial mechanisms in forest soils and oceanic plankton that absorb and store carbon, to the complex interactions among species that sustain tropical forests. Climate shifts and land-use changes can select for species with particular combinations of life history characteristics and, as Sandra Díaz explained, the provision of ecosystem services can be affected in unforeseen ways.

> *Different ecosystem services depend on different characteristics of the organisms present in the ecosystem. Some depend on the dominant characteristic; some, on the variety of characteristics. Some ecosystem services need vast tracts of land; others, only tiny pockets. Not all ecosystem services can be simultaneously maintained in the same place. Different people value different aspects, and that can cause human conflicts.*
>
> Sandra Díaz, February 12, 2009

[9] Costello, C., M. Springborn, C. McAusland, and A. Solow. 2007. Unintended biological invasions: Does risk vary by trading partner? *Journal of Environmental Economics and Management*, 54(3):262–276.

Meeting global food demand in the face of a growing and more affluent global population, several speakers noted, while at the same time increasing the use of biofuels and adapting to climate change in other ways, will create new requirements for crop and pasture land and offer new challenges for maintaining ecosystem services. Allison Power described research into modified agricultural practices that minimize damage to ecosystem services, while Philip Robertson explored the possibilities for new agricultural landscapes, developed to support a cellulosic biofuels industry and maximize carbon accumulation, as well as sustain food production and rural communities.

Numerous speakers described the obstacles to broadening the use of ecosystem science in policy, which will require that policy makers and the public understand both the economic value and the intangible value of ecosystem services. Some economists, as highlighted in the presentation by Steve Polasky, are building on the analyses of the MA to develop approaches for valuing nature in monetary terms. By integrating ecology and economics, they aim to provide unambiguous economic signals regarding the consequences of particular actions or policy choices, including influences on ecosystems and biodiversity, as well as effects on private-sector actors. These challenges for economic research and policy are discussed in more detail under Theme 8.

> *Scientists have to figure out ways to translate the complexities of systems science for nonscientists, especially policy makers. Because we are committed to being rational actors, we know that there are generalizations that we can identify and principles that we can use to organize ideas and communicate them more effectively than we've ever done before. As scientists interested in biodiversity trying to communicate with policy makers, our first job (to paraphrase the mission of the Dumbarton Oaks Library) is "to clarify an ever-changing present," and then try to "inform the future with [just a little bit of] wisdom" that we've learned from our studies.*
>
> James P. Collins, February 12, 2009

A key barrier to successful use of science by policy makers is less-than-effective communication and translation of scientific advice. Policy makers need scientific information that is readily understood and tailored to the particular issues and questions that are being addressed. Speakers charged the scientific community with supplying the necessary information in an appropriate form, and placing it in an appropriate context. For ecosystem management, the challenge is heightened by the inherent complexity of ecological systems and the interconnectedness of the biological, economic, and regulatory systems involved, at a variety of spatial scales from local and regional to national and international.

> *If scientists are not thinking more creatively about how to convey their own story—and I emphasize "story"—then we are in trouble. People need to understand that science is not just a set of facts, that the trajectory of science is based on argument. . . . It is important, as journalists and scientists, to focus people on trajectory as the story develops."*
>
> Andrew Revkin, February 12, 2009

Some of the impediments to integrating scientific advice more closely with policy development are inherent in the scientific culture. Bruce Babbitt enjoined scientists to expand their efforts to explore the policy ramifications of their scientific results. He emphasized that the fear of appearing to be "advocates" if they stray too far from the specifics of their results in their policy discussions can be overdone and can be counterproductive to expanding the influence of scientific research. A related issue, identified by James P. Collins, is that devoting time and energy to the policy applications of scientific work does not necessarily result in professional advancement. In some instances, he said, scientists may even be penalized if such work detracts from their other professional efforts or if it is taken on too early in their careers, before their position is fully secure. Dr. Collins proposed that funders and administrators, as well as tenure and promotion committees, develop new approaches and systems of rewards to encourage more policy interaction and team-driven, as well as individual-driven, research. Andrew Revkin further suggested that every scientist should be thinking of ways to make his or her research understandable by the public. All three speakers emphasized the need to foster a community of science-policy professionals who are respected within the scientific community and who can also serve as conduits for effective scientific advice to policy makers.

One avenue for developing such a community, the American Association for the Advancement of Science (AAAS) Congressional Fellowships Program, has injected hundreds of scientists into the policy process, and the alumni of those fellowships are found throughout the government and in science policy support positions, from the halls of Congress to senior agency staff, to the National Academy of Sciences, to NGOs. The importance of the program, which has been in existence since the 1970s, is coming into clearer focus as the science and technology elements of critical issues facing the nation and the world have grown in complexity and importance. Many symposium attendees noted with regret that the AAAS Science and Technology Policy Fellowship Program has no fellows who are sponsored by societies in the fields of ecology and organismal biology.

Incorporating science into environmental decision making within developing countries presents a particular and significant challenge, as numerous speakers pointed out, because much of the planet's biodiversity is located in the world's least developed nations. CONABIO (Box 2-1) offers a valuable model, and Mary Glackin cited the "critical need for capacity building for marine biodiversity protection in developing countries." Unfortunately, the capacity of many national governments both to monitor environmental change and to take domestic measures that serve both the national and the global public good (e.g., control of infectious diseases, sanitary and phytosanitary measures, greenhouse gas mitigation) is currently limited. Continuing and intensifying efforts to build capacity in developing countries will generate benefits not just to the citizens of those countries but to developed countries as well.

THEME 6: INCREASING SOCIETAL CAPACITY TO MANAGE AND ADAPT TO ENVIRONMENTAL CHANGE

> *Prepare for an uncertain future: a world of rapid changes in climate and vegetation, a world of increasing extreme events, a world of regime shifts, a world of weeds and diseases.*
>
> Harold Mooney, February 11, 2009

In his opening remarks to the symposium, Harold Mooney offered the prospect of significant and ongoing changes to the biosphere as a result of economic development, population growth, and climate change. He emphasized that we face the increasing prospect of a world of rapid change; a world of rising seas and acidifying oceans; a world that has been "diced and replumbed," with increasing nitrogen and phosphorus redistribution; a world of venture capital moving quickly among nations to places of investment "opportunity" and often environmental sensitivity.

The presentations that followed in the next two days reiterated and expanded upon many of these themes, with a dual emphasis on strategies for mitigating the impacts of massive environmental change and pathways toward adaptation, so that ecosystem services are maintained despite unavoidable changes. Stephen Schneider introduced the discussion of climate with an emphatic call for treating adaptation and mitigation "as complements, not trade-offs, since both biogeophysical and social systems have inertia on the order of decades." Schneider forcefully advocated the development of technologies and strategies that will take us quickly past an emissions peak and into a phase of decline, as soon as possible. Equally important, he called for adaptation strategies based on place- and system-based studies that examine regional, sectoral, and group vulnerabilities to environmental change. These local studies could be integrated with global and regional climate change predictions to provide guidance for policy makers.

Many speakers emphasized the contribution that science can make to understanding such substantial environmental change and its causes, as well as the opportunity to use that understanding to increase societal resilience. Others examined the barriers to the application of these scientific findings, some resulting from broader societal and political resistance, others due to difficulties in engaging and communicating with the public. Journalist Andrew Revkin described the challenges of "growing population, growing complexity, and growing consumptive impact on this earth," and cited studies indicating that "even a well-educated person tends to go out into the media environment and find the information that reinforces what they already believe." He contended that no story that he will write, and no study that scientists will produce, will show people "in a crystal-clear, simple way, that this is the problem, this is the solution." However, as Defenders of Wildlife President Rodger Schlickeisen stated, "politicians won't save biodiversity until it's popular enough to put on a t-shirt." Increasing societal capacity to grasp the magnitude of current environmental disruptions and to adapt to environmental change resides in both scientific progress and improved public engagement.

Speaker presentations returned again and again to the close connections between human and natural systems. Human travel and trade have offered openings to pests and pathogens; overfishing has generated changes in marine ecosystems that are undermining the livelihoods of coastal peoples; intensive agriculture has transformed landscapes over much of the world; and climate change is testing the adaptive capacities of both organisms and ecosystems. In every case cited, new technologies are key drivers that have created opportunities to improve important aspects of human well-being, while at the same time creating new challenges and threats, the cumulative effect of which is vast.

The many cases of invasive species documented around the world offer graphic and well-understood instances of the need to maintain the resilience of local ecosystems to introduced species and the difficulties of doing so. Justin Ward summarized the threats to ecosystems posed by increasing economic globalization in his introduction to the session on trade, pests, and pathogens. The session's speakers described the scientific research and monitoring and economic studies needed to guide more effective policy. The goal of the proposed policies would be to maximize the resilience of ecosystem services in the face of increased threats of invasion (see Box 2-5).

The food provisioning services offer another example of the importance of equipping society to deal more effectively with ecosystem change. Rodney Brown cited the role that technology has played in an approximately fourfold increase in agricultural productivity of major commodity crops since 1950. To address the food needs of populations that might increase by 50 percent by 2050, that trend will need to continue, and both Dr. Brown and Allison Power agreed that genomics offers an important tool in reaching that goal. However, during that same period, the effects of agricultural systems on other ecosystem services have become increasingly evident. Dr. Brown described an evolution in agricultural studies from a state of what a colleague had termed "natural enmity" with natural sciences to the present,

BOX 2-5
Successful Early Detection and Rapid Response (EDRR) Systems

- Agile organizations
- Readily available funding
- Cadre of volunteers and partners
- Effective detection, identification, and control technology
- Technology developed before arrival

The characteristics of a successful EDRR policy for mitigating the damage from invasive species, presented by Ann Bartuska, February 11, 2009.

in which biologists and agronomists increasingly cooperate to understand the full suite of ecosystem services of which food production is a part.

Alison Power described research that could help farmers and agribusiness deal with changes in pest control requirements, or adapt agricultural landscapes to better facilitate wildlife preservation. However, to transform the management of agricultural systems in ways that consider the full range of ecosystem services, these and similar research results will have to reach the farmers and agricultural business executives who make the production decisions. Research will also need to be bolstered by regulatory interventions and incentives to provide these services, Dr. Power said. She emphasized the potentially positive role that the system of land grant colleges and agricultural extension services could play in encouraging the adoption of new approaches. While the traditional role of these institutions in advising farming communities has emphasized maximizing production in the context of local, national, and international policies and markets, these extension offices are now especially well positioned to assist in the engagement and outreach needed to adjust current systems toward a more sustainable approach while also adjusting to the realities of climate change and the need to sustain ecosystem services.

> *We need to take a new look at biodiversity, and develop a new and much more positive outlook. Instead of seeing the preservation of biodiversity as a heinous, expensive task without reward, view biodiversity correctly as the source of innovations for the coming century and the solutions to many of the problems facing humanity. Our lives depend on knowing about it and taking advantage of it.*
>
> Michael Donoghue, February 11, 2009

Improved decision making is required for human society to adapt to these and other changes, and this will depend on enhancing the capacity to predict the consequences of current actions, and to understand the ways in which the future will differ from the past. Sandra Díaz described the need for conservation of sufficient levels of functional diversity to provide critical ecosystem services over a wide range of environmental conditions. She asserted that there is sufficient evidence of the mechanistic links between biodiversity in the broad sense and ecosystem processes and services to justify the protection of the biotic integrity of ecosystems. However, the role of different aspects of biodiversity in specific types of ecosystem functioning is still not well understood. New models of biodiversity change are needed, Dr. Díaz said, that extend our understanding of the interaction among global economics, biodiversity, and climate change; and adaptation strategies must be able to respond to evolution in knowledge. Larry Schweiger joined Andrew Revkin and Christian Körner in enjoining scientists to help communicate to the public the breadth of systemic risks faced by twenty-first century ecosystems, so that integrated thinking about the services that ecosystems provide becomes an integral part of the national debate on climate, development, and consumption.

THEME 7: STRENGTHENING INTERNATIONAL INSTITUTIONS AND U.S. ENGAGEMENT AND LEADERSHIP

> *States have, in accordance with the Charter of the United Nations and the principles of international law, the sovereign right to exploit their own resources pursuant to their own environmental policies, and the responsibility to ensure that activities within their jurisdiction or control do not cause damage to the environment of other States or of areas beyond the limits of national jurisdiction.* Convention on Biological Diversity, Article 3
>
> Cited by Harold Mooney, February. 11, 2009

In every session, one or more of the talks cited the need for coordinated multistakeholder and multijurisdictional action for the effective management of biodiversity and ecosystems. For policy to be effective in preserving biodiversity and its associated ecosystem services, they said, cooperation is needed across multiple sectors and jurisdictions, from the local to the international, and with diverse stakeholders, from local communities and small landholders to national governments and international agencies. In the opening session, which posed the challenges of the twenty-first century and examined emerging research and approaches to deal with them, José Sarukhán cited the work of CONABIO that uses informatics approaches to inform conservation and land use decisions from the local to the national levels in Mexico. During the discussion on invasive species and trade, Ann Bartuska and Ann Marie Kimball highlighted the need for regulatory action spanning the local to international levels in controlling invasive species, whether the threats they pose are to agriculture and forests or to public health. The diversity of the issues emphasized that every sector must play a part in an inclusive strategy to manage the living world in the face of the challenges posed by human activities.

United Nations Environment Program (UNEP) Executive Director Achim Steiner noted the complexity of the current international regime, where more than 500 international environmental agreements address a myriad of issues with environmental dimensions, including trade; human, plant, and animal health; conservation; and specific biomes, habitats, resources, and species. This complexity, he noted, is a significant challenge. Leadership is necessary to improve the functioning of these agreements and to introduce greater coherence to the disparate goals of different sectoral approaches. Very often the interconnections among the issues covered by distinct agreements are poorly articulated or neglected entirely.

Leadership is also needed, others noted, to implement actions that will make existing international agreements function better within their own spheres of responsibility. Some speakers contended that these agreements critically need U.S. engagement and leadership, noting that the United States has not ratified several key agreements, including the United Nations Convention on the Law of the Sea and the Convention for Biological Diversity (CBD). These agreements include many of the goals and strategies addressed by the speakers, but implementation is often inadequate. Moreover, several speakers charged that these and other UN mechanisms or organizations with a mandate to address international environmental issues, including UNEP, are severely underfunded, and are hampered by the lack of enforcement authority.[10] Mechanisms mandated to make investments in global environmental public goods, most notably the Global Environmental Facility, are likewise insufficiently funded. Many speakers called for the United States to play a leadership role, both in securing greater global commitment to these bodies and in enhancing their effectiveness. Achim Steiner was one of the speakers who called for U.S. action, noting, "We need leadership in recognizing that developing countries need scientific support. It is no secret that the resources of the U.S. National Academy of Sciences, the scientific community, the universities, and the NGOs are extraordinary in comparison with what we will find in many countries across Africa."

Beyond the existing agreements and institutions, Mr. Steiner and others emphasized that the ecosystem and biodiversity challenges that are

[10] The CBD leaves specific decisions on implementation of the agreement to the parties and, like most treaties, has a dispute-resolution article, which could be invoked by any party that feels that another party has injured it by not implementing the CBD. However, that enforcement mechanism has never been used.

the principal focus of this symposium—understanding, anticipating, monitoring, and responding to changes in the global environment—urgently require international cooperation. Scott Barrett addressed some of the characteristics of successful international agreements related to the environment that drew heavily on scientific input. The successful cases that he cited, including limitations on hunting of fur seals, eradication of smallpox, and mitigation of the ozone hole, had specific characteristics on which negotiators capitalized in designing and executing the agreements. In all cases, there were strong incentives for buy-in by all relevant parties and an accepted distribution of costs. Dr. Barrett presented the similarities and differences of fisheries regulation, polio eradication, and climate change, respectively. He suggested that successful international cooperation on these issues requires high, if not universal, participation; near or total compliance; and actions that will effectively deal with the problem. Regarding the Kyoto protocol, he said that a better approach might be to negotiate separate agreements for individual sectors as well as for research and development of new technologies to help address the problems of both mitigation and adaptation.

An Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES) has been established to offer advice to governments on biodiversity and ecosystem issues, in a manner analogous to the IPCC's role in climate science.[11] Given its existing expertise in environmental science, including at the local level, several speakers, including Harold Mooney and Stephen Schneider, called on the United States to play a leadership role in building this mechanism.

The role of trade in the accelerated spread of invasive species offers a complementary set of challenges and opportunities for international cooperation, and Charles Perrings asserted that U.S. leadership in this area is crucial. The World Trade Organization (WTO) has broad powers related to trade, and Mark Lonsdale explained that the WTO can be of value in controlling invasive species. Australia, for example, uses measures stipulated in the Agreement on the Application of Sanitary and Phytosanitary Measures (SPS Agreement) to implement robust biosecurity controls. The

[11] On December 20, 2010, the United Nations 65th General Assembly agreed to establish an IPBES with the following remit: (a) to identify and prioritize key scientific information needed for policy makers; (b) to perform regular and timely assessments of knowledge on biodiversity and ecosystem services; (c) to support policy formulation and implementation by identifying policy-relevant tools and methodologies; and (d) to prioritize key capacity-building needs to improve the science-policy interface. UNEP is charged with convening the first plenary of the new body in 2011. See http://IPBES.net.

idiosyncratic attributes of invasive species, as described by Dr. Lonsdale, require both risk-averse and adaptive approaches. International cooperation that includes analyses of risk, careful inspections of cargo, and effective observation systems will be necessary to control and combat invasions. Dr. Lonsdale suggested that the WTO try to evolve from an adversarial approach, grounded in jurisprudence, to a biosecurity management system that is more adaptive, cooperative, precautionary, and responsive to new information. He also noted that a key element in the acceptance of trade regulations is that they are applied domestically, as well as on imports.

> *Policy makers, assessment groups, agencies, commissions, et cetera, need to be better coordinated to take into account the interactions among the drivers of global change, and their separate and synergistic impacts. This would include international-level conventions, secretariats, et cetera.*
>
> Stephen Schneider, February 12, 2009

Ann Marie Kimball noted that the WTO Environment Committee needed to be strengthened to deal with biosecurity issues and that a WTO Health Committee should be established to address the diverse microbial invasions that cause both pandemics and agricultural crises. Charles Perrings suggested the establishment and funding of an international mechanism to coordinate the actions of international bodies with responsibilities for different aspects of the invasive species problem, including (in addition to the WTO) UN-related agencies with responsibility for human, animal, and plant health, such as the World Health Organization (WHO), the World Organization for Animal Health (OIE), and the International Plant Protection Convention (IPPC) (see Box 2-6).

THEME 8: ACCOUNTING FOR THE VALUE OF NATURE

> *The economy is a wholly owned subsidiary of the environment.*
>
> Peter Raven, February 11, 2009
> (quoting ecological economist Herman Daly)

Ecosystems and biodiversity will continue to suffer as long as economic incentives promote short-term exploitation without regard for its effect on ecological externalities and for the potential long-term damage

BOX 2-6
Policies and Partnerships for Curtailing Invasive Species

Nationally

- Enhance border surveillance against imports and exports of invasive harmful species.
- Establish and fund an interagency center to coordinate federal, state, and local efforts to prevent the export or import of invasive species, and control the spread of established species.

Internationally

- Use the CBD, WTO, WHO, OIE, and IPPC to strengthen sanitary and phytosanitary requirements on exporters; the United States should take a leadership role in this effort.
- Establish an international mechanism a bit like the U.S. Centers for Disease Control to provide countries with the information needed to protect themselves and their trading partners against risks associated with contaminated products, as set forth in the General Agreement on Tariffs and Trade (GATT) and SPS Agreement.
- Establish and fund an international mechanism to coordinate the actions of international bodies with responsibilities for particular aspects of the invasive species problem.

SOURCE: Charles Perrings presentation

The problem of invasive species is global, and needs to be addressed at a global level by strengthening relevant Multilateral Environmental Agreements, enhancing monitoring and information, and coordinating international responses.

Charles Perrings, February 11, 2009

caused. Of the ecosystem services identified by the Millennium Ecosystem Assessment, only the provisioning services are allocated through reasonably well-functioning markets that offer the private sector incentives to consider ecosystem services when they are making decisions. Even the provisioning services do not capture all the ecosystem effects of market transactions. Indeed, several speakers noted that many of the most important drivers of biodiversity degradation and loss are externalities of markets for foods, fuels, and fibers. The cultural services, these speakers contended, are less well served by markets, and there are fewer markets still for the regulating services.

Although the CBD calls for monetizing the value of biodiversity in the context of providing access and sharing benefits, the treaty's influence in this area has so far been limited. Insurance markets address some of the risks associated with the provisioning and cultural services, but the role of biodiversity in moderating variability in the supply of such services is rarely priced in the market. Bruce Babbitt contended that economic globalization, governed by the economic systems put into place after World War II, had been the "primary driver of environmental destruction."

> *It is not unfair to say that the world trade system, and the world financial systems, are the primary drivers, now, of much of the destruction of biodiversity. . . . Since Bretton Woods at the end of World War II, we have created (first through GATT, now the WTO) a finely tuned, international economic system, that has clear, enforceable rules and regulations devoted to what? Devoted to maximizing the consumption of resources with complete disregard for the externalities and the unsustainable resource costs. We have created a global trading system in which any discussion of environmental externalities is absolutely unavailable. . . . It is a sort of nineteenth-century concept of a closed economic system, administered by a world group of trade mandarins who have made it simply a sacrosanct system. That must change.*
>
> Bruce Babbitt, February 12, 2009

Numerous speakers offered examples of ways in which the failure of markets to appropriately price environmental resources has resulted in ecological damage. Jerome Ringo also observed that "people of color and poor people are disproportionately impacted by environmental damage." He joined Larry Schweiger in advocating for the development of new technologies that are more efficient and that will not only help to mitigate climate change and increase national energy security but also help to stimulate the economy and, Mr. Ringo said, "create jobs that are beneficial to all societal levels."

Biodiversity in our global community of nations is increasingly a question of equity.

Achim Steiner, February 11, 2009

Where markets have failed to reflect the environmental consequences of resource use, those consequences have most often been ignored. Speakers offered several potential mechanisms for correcting market failures and ensuring that the true value of ecosystem services is taken into account. Among those mentioned by various speakers were (a) regulation of activities that lead to the pollution or the degradation of ecosystems, (b) assignment of property rights to resource users, (c) development of systems of governance for common ecological services, and (d) use of market-based instruments, such as environmental taxes, subsidies, charges, user fees, and payments for ecosystem services. A key step forward in providing policy makers with more useful information, several speakers noted, might be to reform the system of national accounts to reflect changes in the stocks of ecological assets by amending overly simplistic and incomplete measures of GDP to incorporate elements of natural and social capital.

Steve Polasky stated the challenge as a three-point problem: (1) improve understanding of the likely consequences of human actions on ecosystems; (2) express the value of these changes in terms that are readily understood by policy makers and the general public; and (3) link an understanding of effects and values to incentives in order to "mainstream" ecosystem services into everyday decisions and longer-term policies. Dr. Polasky's description of the efforts of the Natural Capital Project to factor ecosystem services into decision making at the landscape scale highlighted promising approaches that are being developed. He emphasized that a more sustainable approach to biodiversity and ecosystem management requires that such principles be broadly accepted and widely applied. Harold Mooney endorsed these recent efforts to extend the system of national accounts to include the option value of nature, and long-term effects on ecosystem services.

Ecosystems are capital assets—part of national wealth, but loss of wealth associated with declining ecosystem services is not reflected in national accounts.

Harold Mooney, February 11, 2009

The urgency of making reforms was stated most clearly by Bruce Babbitt. "The problem and the opportunity," he said, "is to begin to appreciate that we have created a global economic system that does not take account of environmental or biodiversity considerations. The moment may be at hand to fundamentally transform this economic machine, which is so destructive to biodiversity."

CONCLUDING THOUGHTS

The eight themes that emerged from the symposium have been highlighted many times before, in many different fora, for scientists, for policy makers, and for the general public. The emphasis at the symposium, however, was not just on each theme individually but on ideas for action in all eight areas if there is to be continuing progress toward conserving and managing species and ecosystems that sustain human society and support its further development. The challenges described at the symposium are complex and daunting, but several speakers emphasized the need for multiple and coordinated actions across a broad front. In the more than 150 years since Darwin contemplated his "tangled bank," the complexity of ecosystems at all scales, and the extent to which they are affected by human activities, has become ever more clear.

Many symposium speakers expressed concern that human capacity for modification of the global environment has reached the magnitude of a geological force; the impacts have never been greater and continue to increase rapidly. Several speakers went on to say that the present trajectory is unsustainable and carries considerable systemic risks. And while the inherent complexity of coupled natural and human systems makes prediction difficult, the effects of continuing perturbations are likely to be profound.

Many speakers called for additional research to better understand the components of biological, physical, and sociocultural systems, as well as the interconnections within and among them, which will determine the nature and extent of future risks. While not disagreeing with the importance of research, other speakers reminded participants that much is already clear, and there is a strong basis for immediate action, including the development and implementation of national and international policies that are more firmly grounded in a systems approach. Technology has a role to play in mitigating these risks and increasing human capacity to adapt to changing environmental conditions, but it is no substitute for the fundamental realignment of our relationship to the natural world implicit in the themes discussed at the symposium and highlighted in this report.

Appendix A

Symposium Program

**TWENTY-FIRST CENTURY ECOSYSTEMS:
SYSTEMIC RISK AND THE PUBLIC GOOD**

**A National Academies Symposium
On the Science and Policy for Managing the Living World
Two Centuries after Darwin**

**Hosted and Cosponsored by the American Association for the Advancement of Science
Cosponsored by DIVERSITAS**

February 11-12, 2009

Introductory Remarks

Welcome and Introduction by the Session Chair
Peter Crane, John and Marion Sullivan University Professor, University of Chicago;[1] Chair, U.S. National Committee for DIVERSITAS, NAS

Biodiversity, Ecosystems, and the Global Decision Making
Harold Mooney, Paul S. Achilles Professor of Environmental Biology, Stanford University; Chair, DIVERSITAS Science Committee

Reflections on Biodiversity and Its Future
Peter Raven, Director, Missouri Botanical Garden

Biodiversity and Global Environmental Change
Achim Steiner, Director, United Nations Environment Program [via prerecorded video]

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[1] All affiliations reflect the speakers' positions at the time of the symposium.

SESSION 1 – Biodiversity and the Public Good

Charles Darwin Meets the Biodiversity Crisis: Advice for the New Administration
Michael Donoghue, Vice President and G. Evelyn Hutchinson Professor of Ecology and Evolutionary Biology, Yale University

Don't Touch Those Dials! Microbes Made This Planet Habitable for You
Paul Falkowski, Board of Governors' Professor of Marine and Geological Sciences, Rutgers University

Biodiversity Implications of Rapid Evolution
Andrew Hendry, Associate Professor of Biology, McGill University

Questions and Discussion

Bioinformatics: Inputs for the Sustainable Management of Natural Capital
José Sarukhán, Institute of Ecology, National Autonomous University of Mexico

Darwin's Fishes: Why Should We Care About Marine Biodiversity?
Mary Glackin, Deputy Under Secretary for Oceans and Atmosphere

Valuing Nature: Ecosystem Services and Biodiversity
Steve Polasky, Fesler-Lampert Professor of Ecological/Environmental Economics, University of Minnesota

Questions and Discussion

Concluding Remarks on the Morning Session
Cristián Samper, Director, National Museum for Natural History, Smithsonian Institution

SESSION 2 – Trade, Pests, and Pathogens in the 21st Century

Introductory Remarks by the Session Chair
Justin Ward, Vice President for Business Practices, Conservation International Center for Environmental Leadership in Business

Trade and Invasive Species: A Global Perspective
Charles Perrings, Professor of Environmental Economics, Arizona State University

Trade and the Spread of Animal and Human Pathogens
Ann Marie Kimball, Professor of Epidemiology and Health Services, University of Washington, and Director, Asia Pacific Economic Cooperation Emerging Infections Network

Risks of Invasive Species from International Trade
Christopher Costello, Associate Professor, Resource Economics, University of California, Santa Barbara

Questions and Discussion

Control of Invasive Species in Forests
Ann Bartuska, Deputy Chief, U.S. Forest Service Research and Development

Risk Assessment and Risk Management of Aquatic Invasive Species
David Lodge, Professor of Biology, University of Notre Dame

Trading Blows: Can We Control Invasive Species Through Trade Agreements?
Mark Lonsdale, Chief of Entomology, Commonwealth Scientific and Industrial Research Organization, Canberra, Australia

Questions and Discussion

The Color of Green: The Next Inconvenient Truth
Jerome Ringo, President, the Apollo Alliance

SESSION 3 - Climate Change, Energy, and 21st Century Ecosystems

Welcome and Introductions by the Session Chair
Ann Kinzig, Associate Professor of Life Sciences, Arizona State University

Preserving Biodiversity: Any Messages for Climate Policy Making?
Stephen Schneider, Professor of Biology and Codirector, Center for Environmental Science and Policy, Stanford University

Climate Change, Deforestation, and the Future of Tropical Forests
Yadvinder Malhi, Professor of Ecosystem Science, Oxford University Center for the Environment

Mountain Biota and Global Change
Christian Körner, University of Basel, Switzerland

Questions and Discussion

Functional Diversity, Ecosystem Services, and Global Change
Sandra Díaz, Senior Permanent Research Fellow, Argentine National Council of Scientific and Technical Research

The Biofuel, Food, and Environment Trilemma
David Tilman, Regents Professor and Distinguished McKnight University Professor, University of Minnesota [Professor Tilman was not able to attend the symposium; a summary of his talk was given by Ann Kinzig.]

Last Chance: Preserving Life on Earth
Larry Schweiger, President and Chief Executive Officer, National Wildlife Federation

Questions and Discussion

Reinventing the Global Economy to Protect Biodiversity—Trade, Infrastructure, and Carbon
Bruce Babbitt, Former Secretary of the Interior

SESSION 4 - Food, Agriculture, and 21st Century Ecosystems

Introductory Remarks by the Session Chair
Thomas Lovejoy, Biodiversity Chair, The H. John Heinz III Center for Science, Economics, and the Environment

Agricultural Systems and Ecosystem Services: Trade-offs or Synergies?
Alison Power, Professor of Ecology and Evolutionary Biology, Cornell University

Biofuels and Agricultural Sustainability
Philip Robertson, Professor of Ecosystem Science, Michigan State University

Marine Fisheries: Is the Glass Half Full or Half Empty?
Boris Worm, Assistant Professor in Marine Conservation Biology, Dalhousie University

Aquaculture and Marine Resources: Can There Be a Salmon in Every Pot?
Rebecca Goldburg, Director, Marine Science, Pew Environment Group, The Pew Charitable Trusts

Agriculture and Agricultural Landscapes in the Twenty-first Century
Rodney J. Brown, Dean, College of Biology and Agriculture, Brigham Young University

Questions and Discussion

SESSION 5 - Biodiversity: International Institutions, Science, and Policy

Introductory Remarks by the Session Chair
Thomas Lovejoy, Biodiversity Chair, The H. John Heinz III Center for Science, Economics, and the Environment

International Environmental Cooperation in the Twenty-first Century
Scott Barrett, Professor of Environmental Economics, Johns Hopkins University

The Daily Planet—An Exploration of How, on a Fast-Changing Earth, the Shrinking Media Can Continue to Cover Environmental Change and Help Build Informed Policy
Andrew Revkin, Environment Reporter, The New York Times

Ten Million Places at the Table: Translating Biodiversity Issues from Science to Policy
James P. Collins, Associate Director for Biological Sciences, National Science Foundation

Questions and Discussion

Concluding Comments on the Day: Advocacy and Policy
Rodger Schlickeisen, President and Chief Executive Officer, Defenders of Wildlife

Concluding Remarks and Thanks
Peter Crane, John and Marion Sullivan University Professor, University of Chicago; Chair, U.S. National Committee for DIVERSITAS, National Academy of Sciences

Appendix B

Selected Definitions

KEY TERMS[1]

adaptation – Societal strategies for managing ecosystems to maintain ecosystems and ecosystem services in the face of environmental change that cannot be avoided. (In this report, adaptation refers to societies' and ecosystems' ability to adapt to climate change and other environmental stressors, as opposed to the ecological meaning of the process of change established by natural selection, or a biological character that gives increased Darwinian fitness.) (EB, p. 17)

biodiversity/biological diversity – Species, genetic, and ecosystem diversity in an area, sometimes including associated abiotic components such as landscape features, drainage systems, and climate. (EB, p. 377)

complex adaptive systems – Systems made up of individual agents, whose interactions have macroscopic consequences that feed back to influence individual behaviors.[2] (Levin, 1998)

ecosystem functioning – The rate, level, or temporal dynamics of one or more ecosystem processes, such as primary production, total plant biomass, or nutrient gain, loss, or concentration. (EB, p. 109)

[1] Most definitions are from Levin, S., ed., 2001. *Encyclopedia of Biodiversity.* Academic Press: 4666 pages. Cited in definitions as "EB," with page number.

[2] Levin, S. 1998. *Ecosystems and the Biosphere as Complex Adaptive Systems. Ecosystems* 1(5):431–436.

ecosystem services – The wide array of conditions and processes through which ecosystems, and their biodiversity, confer benefits on humanity; these conditions and processes include the production of goods, life-support functions, life-fulfilling conditions, and preservation of options. (EB, p. 353)

evolution – The morphological or genetic change in species over time. Small changes that do not lead to reproductive isolation among members of a group are referred to as *microevolution*. Speciation, or the generation of new species, is generally referred to as *macroevolution*. (EB, p. 393)

ex situ – Literally, away from the site or location; in this context, referring to conservation efforts elsewhere than the natural habitat; for example, in botanical gardens. (EB, p. 645)

functional diversity – The range and value of the species and organismal traits that influence ecosystem functioning. (EB, p. 109)

invasive species – Introduced species that establish self-maintaining populations and spread, with and without human assistance, into new areas where they frustrate human intentions in production and natural landscapes. (EB, p. 501)

mitigation – The implementation of measures designed to avoid, reduce or eliminate the undesirable effects of a proposed action on the environment. (CEQ Regulations for Implementing the National Environmental Protection Act, Sec. 1508.20)

Appendix C

Biographies of Speakers[1]

Bruce Babbitt is a former U.S. secretary of the interior. He was governor of Arizona for nine years, 1978–1987, and attorney general of Arizona, 1975–1978. Mr. Babbitt, who was in the private practice of law when he was nominated to be interior secretary, also was national president of the nonpartisan, nonprofit League of Conservation Voters. In 1978 he served as a member of the President's Commission on the Accident at Three Mile Island. He was a founding member of the Democratic Leadership Council and served as chairman of the Democratic Governors Association in 1985. Mr. Babbitt has been a member of the Advisory Council on Intergovernmental Relations and was a member of the Council on Foreign Relations and the Grand Canyon Trust. Described by the *Almanac of American Politics* as one of America's most original governors, his advocacy led to passage of a nationally acclaimed state water management code in 1980, and in 1986 of a water quality act described by the *Los Angeles Times* as perhaps "the nation's toughest law to protect underground water." Mr. Babbitt received a master's degree in geophysics from the University of Newcastle in England, which he attended as a Marshall Scholar. He graduated from Harvard Law School in 1965.

Scott Barrett is the Lenfest-Earth Institute Professor of Natural Resource Economics at Columbia University, where he also serves as vice dean of the School of International and Public Affairs. Professor Barrett previously

[1] Biographies were current at the time of the symposium.

served on the faculty of Johns Hopkins University's Paul H. Nitze School of Advanced International Studies. Before serving Johns Hopkins, Professor Barrett taught at the London Business School, where he was also dean of the Executive MBA Program. Professor Barrett's research focuses on interactions between natural and social systems, especially at the global level. He is best known for his work involving international environmental agreements, such as the Kyoto Protocol. Professor Barrett's work on international environment agreements earned him the Erik Kempe Award in Environmental and Resource Economics, bestowed by the European Association of Environmental and Resource Economists. Published in 2007, Professor Barrett's book *Why Cooperate? The Incentive to Supply Global Public Goods* examines issues such as nuclear proliferation, infectious disease pandemics, overfishing, and the standard for determining the time to international development. His book on international environmental agreements, *Environment and Statecraft: The Strategy of Environmental Treaty-Making*, was published in 2003. Professor Barrett has advised international organizations, including different agencies of the United Nations, the World Bank, the Organization for Economic Cooperation and Development, the European Commission, the Independent World Commission on the Oceans, the International Union for Conservation of Nature Commission on Environmental Law, and the International Task Force on Global Public Goods. He was a lead author of the Intergovernmental Panel on Climate Change second assessment report. He was previously a member of the academic panel of advisors for the U.K. Department of Environment. Professor Barrett holds a Ph.D. in economics from the London School of Economics.

Ann Bartuska is the deputy chief for the U.S. Forest Service Research and Development. An ecosystem ecologist, she has been involved with the issues of forest ecosystem health, ecosystem management, wetlands, and air pollution, both within the federal government and at North Carolina State University. Her past research has focused on ecosystems processes in landscapes disturbed by coal mining. She has extensive experience interacting with Congress, the media, federal and state agencies, and the public. Dr. Bartuska is an active member and pastpresident (2002–2003) of the Ecological Society of America. She has served on the Board of the Council of Science Society Presidents and is a member of the Society of American Foresters. Dr. Bartuska received her Ph.D. in ecology from West Virginia University.

Rodney J. Brown is dean of agriculture and a professor in the Department of Nutrition, Dietetics, and Food Sciences at Utah State University. He spent two years at the Weizmann Institute of Science in Israel before beginning his academic career in 1979 as an assistant professor at Utah State University, where he has served as head of the Department of Nutrition, Dietetics, and Food Sciences; director of the Western Dairy Center; and acting vice president for research. Dr. Brown has been active in the Institute of Food Technologists, American Dairy Science Association, Council for Agricultural Science and Technology, International Dairy Commission, Sigma Xi, American Association for the Advancement of Science, American Chemical Society, and Phi Kappa Phi. He is chair of the Board on Agriculture of the National Association of State Universities and Land-Grant Colleges. He has received the American Dairy Science Association Pfizer, Inc. Award for Cheese and Cultured Products Research, the Utah State University Leone Leadership Award, the Honored Alumnus Award from the College of Biology and Agriculture at Brigham Young University, and was the G. Malcolm Trout Visiting Scholar in the Department of Food Science and Human Nutrition at Michigan State University. Dr. Brown received his Ph.D. in food science from North Carolina State University, with emphases on chemistry and biochemistry.

James P. Collins is the associate director for biological sciences at the National Science Foundation (NSF), where he oversees the NSF's nearly $580 million annual investment in fundamental biological research and serves on the foundation's senior management team. As an investigator, Dr. Collins has focused on how subgroups within a species physically change in response to ecological and evolutionary pressures, and the role of pathogens in the global decline of amphibians. He chairs the task force on declining amphibian populations of the International Union for Conservation of Nature. In addition, he has concentrated on the intellectual history of ecology and has taken an active role in Arizona State University's successful curriculum-enhancement and mentoring programs for undergraduates. Dr. Collins has substantial prior experience with the NSF in his roles as program director, research awardee, and chairman of the external Directorate for the Biological Sciences Advisory Committee (BIO AC). He also represented BIO AC on NSF's Advisory Committee for Environmental Research and Education. Dr. Collins received his Ph.D. from the University of Michigan.

Christopher Costello is an associate professor of resource economics at the University of California, Santa Barbara. His research is primarily in the area of natural resource management and property rights under uncertainty, with a particular emphasis on information, its value, and its effect on management decisions. He is also interested in the process and design of adaptive management programs in which learning (to resolve uncertainty or asymmetric information) is actively pursued. Topical interests include fisheries management, biological diversity, introduced species, regulation of polluting industries, and marine policy. Dr. Costello frequently collaborates with researchers in fields outside of economics, such as statistics, ecology, biogeography, and mathematics. He has authored and coauthored many publications and serves on several councils and boards, such as the Association of Environmental and Resource Economists and the Science Advisory Team for California's Ocean Protection Council. Dr. Costello received his Ph.D. in agricultural and resource economics from the University of California, Berkeley.

Sandra Díaz is a senior permanent research fellow at the National University of Córdoba in Argentina, where she researches and teaches in the field of community ecology and biogeography. Her fields of interest are community ecology, plant functional types, and global environmental change. Professor Díaz has made contributions to the understanding of plant functional types and their links to ecosystem processes and services. She is involved in multidisciplinary projects linking natural and social aspects of environmental vulnerability and sustainability. In recent years, Professor Díaz has been actively involved in international initiatives related to global change, such as the Global Change and Terrestrial Ecosystems Core Project of International Geosphere-Biosphere Program, the Intergovernmental Panel on Climate Change, and the Convention on Biological Diversity.

Michael Donoghue is the G. Evelyn Hutchinson Professor of Ecology and Evolutionary Biology at Yale University and vice president for West Campus Planning and Program Development. His research revolves around understanding phylogeny, and his empirical work focuses primarily on plant diversity and evolution. In particular, he has long-term interests in *Viburnum* and Dipsacales, and in the origin and early evolution of flowering plants. In collaboration with former students, postdocs, and lab visitors, Dr. Donoghue has also published molecular phylogenetic analyses of other angiosperm groups. And, with former postdoc David Hibbett, he has published a series of papers on the phylogeny of basidiomycetes, especially shiitake mushrooms.

He was elected a fellow of the American Association for the Advancement of Science in 1997, a member of the U.S. National Academy of Sciences in 2005, and a fellow of the American Academy of Arts and Sciences in 2008. He has published more than 180 scientific papers, coauthored a popular textbook on plant diversity, and coedited *Assembling the Tree of Life*. He has mentored 25 postdoctoral associates and 22 graduate students. Dr. Donoghue received his Ph.D. in botany from Harvard University.

Paul Falkowski is the Board of Governors' Professor of Marine and Geological Sciences at Rutgers University. His research interests include biogeochemical cycles, photosynthesis, biological oceanography, molecular biology, biochemistry and biophysics, physiological adaptation, plant physiology, evolution, mathematical modeling, and symbiosis. He has been elected to many learned societies, including the American Geophysical Union, the American Academy of Arts and Sciences, and the National Academy of Sciences. He has also received many awards, including the Huntsman Award, the G. Evelyn Hutchinson Award, and the European Geosciences Union Vernadsky Medal. Dr. Falkowski received his Ph.D. in biology and biophysics from the University of British Columbia.

Mary M. Glackin is the deputy under secretary for operations at the National Oceanographic and Atmospheric Administration (NOAA). In this role she is responsible for the day-to-day management of NOAA's domestic and international operations for oceanic and atmospheric services, research, and coastal and marine stewardship. Ms. Glackin has more than 15 years of senior executive–level experience working in numerous NOAA line offices. She served as the acting assistant administrator for weather services and director of the National Weather Service (NWS) from June 12, 2007, through September 15, 2007. Before that, she was the assistant administrator for the NOAA's Office of Program Planning and Integration. From 1999 until 2002, she served as the deputy assistant administrator for the National Environmental Satellite, Data, and Information Service of NOAA. She has worked as the program manager for the Advanced Weather Interactive Processing System with the NWS. Before that, Ms. Glackin was both a meteorologist and computer specialist in various positions within NOAA, where she was responsible for introducing improvements into NWS operations by capitalizing on new technology systems and scientific models. She received the Presidential Rank Award (2001 and 2009), the Charles Brooks Award for Outstanding Services to the American Meteorological Society (2004), the NOAA Bronze Medal (2001), the Federal 100 Information Technology Manager Award (1999), the NOAA Administrator's Award (1993), and the Department of Commerce Silver Medal Award (1991). She is a fellow of the American Meteorological Society and a member of the National Weather Association and the American Geophysical Union. Ms. Glackin received her B.S. degree from the University of Maryland.

Rebecca Goldburg is the director of marine science at the Pew Environment Group, which is the conservation arm of the Pew Charitable Trusts. Trained as an ecologist, Dr. Goldburg is active in public policy issues concerning food production—primarily ecological and food safety issues in agricultural biotechnology, aquaculture (fish farming), and antibiotic resistance from overuse of antibiotics in agriculture. Dr. Goldburg is a member of the U.S. Department of Agriculture's (USDA) Advisory Committee on Agricultural Biotechnology, the U.S. State Department's U.S.-EU Consultative Forum on Biotechnology, and the USDA's National Organic Standards Board. She recently served on the National Academy of Science's Committee on Genetically Modified Pest-Protected Plants. Dr. Goldburg is a frequent speaker and an author of numerous publications, including *Biotechnology's Bitter Harvest: Herbicide Tolerant Crops and the Threat to Sustainable Agriculture* (Biotechnology Working Group, 1990), *A Mutable Feast: Assuring Food Safety in an Era of Genetic Engineering* (Environmental Defense Fund [EDF], 1991), *Murky Waters: Environmental Effects of Aquaculture in the United States* (EDF, 1997), and "Effect of Aquaculture on World Fish Supplies" (*Nature*, 2000). Dr. Goldburg holds a Ph.D. in ecology from the University of Minnesota.

Andrew Hendry is a professor at McGill University in Montreal, Quebec. He was born in California, grew up in Alberta, went to university in Victoria, did his graduate work in Seattle, and did postdoctoral work in Vancouver and Massachusetts. His research focuses on how evolutionary changes in natural populations, particularly on how rapidly populations can adapt to changing environmental conditions. He has worked on salmon in Alaska and New Zealand, guppies in Trinidad, stickleback fishes in British Columbia, lemon sharks in the Bahamas, and Darwin's finches in the Galapagos. Taken as a whole, his work has shown that populations experiencing environmental change can show rapid evolutionary responses that may improve the ability of those populations to persist. Dr. Hendry's most recent work examines how these evolutionary changes may affect the rest of the environment; that is, rapid evolution may have considerable ecological consequences.

Ann Marie Kimball is a professor of epidemiology and health services at the University of Washington and director of the Asia-Pacific Economic Cooperation Emerging Infections Network. Her research interests include global trade and infectious disease, emerging infections, surveillance and informatics, and global health policy for infectious disease control. Dr. Kimball has authored several publications and completed both her medical degree and her master's in public health at the University of Washington.

Christian Körner is a professor in the Institute of Botany at the University of Basel, Switzerland. His current research projects include the influence of increasing atmospheric carbon dioxide concentration on natural vegetation including the Swiss Canopy Crane project, which studies the effects of exposing a naturally grown mature forest to a future carbon dioxide concentration), alpine plant ecology and biodiversity, global comparisons of high-elevation tree-line research, implications of climate change in the Mediterranean, and various projects in bioclimatology. Dr. Körner is a member of many academies, national committees, and international committees, and has been honored with many awards and academic achievements. He received his Ph.D. from the University of Innsbruck, Austria.

David Lodge is a professor of biology at the University of Notre Dame. His research interests include conservation biology, especially the overlapping spheres of interest that relate to current global changes. Dr. Lodge, his students, and postdocs have conducted field work in the inland lakes and streams of northern Indiana–southern Michigan, the upper peninsula of Michigan (for the University of Notre Dame Environmental Research Center), the Great Lakes, the coastal plain of North Carolina, and in Denmark and Kenya. As a way to inform policy, Dr. Lodge has participated in the Aldo Leopold Leadership Program at Stanford University, served as chair of the national Invasive Species Advisory Committee, testified before a congressional committee, and published an op-ed piece in the *New York Times*. Dr. Lodge has authored many publications and has received many awards. He received his Ph.D. from the University of Oxford.

Mark Lonsdale is the chief of entomology at the Commonwealth Scientific and Industrial Research Organization in Canberra, Australia. His research interests include biological invasions, ecological implications of genetically modified organisms, environmental risk assessment, biological control of weeds, and plant population ecology. Dr. Lonsdale has authored many publications and serves as a member of the Editorial Board for *Biological Invasions* and chair of the Global Invasive Species Program. Dr. Lonsdale worked in Darwin, Northern Territory, until 1995, and researched the impact of invasive weeds on biodiversity, especially *Mimosa pigra*; intersectoral conflict in plant introductions; the effects of weed biological control on plant populations; rates of spread of exotic weeds, the impacts of fire on tropical savannas; and seed bank ecology. Dr. Lonsdale received his Ph.D. from the University of East Anglia, United Kingdom. His doctoral research was on plant population ecology, specifically, thinning in pure and mixed populations of plants.

Yadvinder Malhi is a professor of ecosystem science at the Oxford University Center for the Environment, University of Oxford, program leader of the Ecosystems Group at the Environmental Change Institute, and the Jackson Senior Research Fellow at Oriel College, Oxford. Dr. Malhi is also an honorary research fellow at the Institute of the Atmosphere and Biosphere, School of GeoSciences, University of Edinburgh, and at the Institute of the Environment at the University of California, Los Angeles. His research addresses fundamental questions about ecosystem function and dynamics, while providing outputs of direct relevance for conservation and adaptation to climate change. A particular new focus is on the role that the international carbon markets and climate change framework can play in protecting tropical forests. He applies a range of techniques, including field physiological studies, large-scale and long-term ecological monitoring, satellite remote-sensing and geographic information systems, ecosystem modeling, and micrometeorological techniques. Dr. Malhi has authored many publications and received his Ph.D. in meteorology from the University of Reading.

Steve Polasky is the Fesler-Lampert Professor of Ecological/Environmental Economics at the University of Minnesota. His research interests include ecosystem services, natural capital, biodiversity conservation, endangered species policy, integrating ecological and economic analysis, renewable energy, environmental regulation, and common property resources. His papers have been published in *Biological Conservation*, *Ecological Applications*, *Journal of Economics Perspectives*, *Journal of Environmental Economics and Management*, *International Economic Review*, *Land Economics*, *Nature*, *Proceedings of the National Academy of Sciences*, *Science*, and other journals. He has served as coeditor and associate editor for the *Journal of Environmental Economics and Management* and as associate editor for the *International Journal of Business and Economics*, and he now serves as an associate editor for *Conservation*

Letters and *Ecology and Society*. Dr. Polasky received his Ph.D. in economics from the University of Michigan.

Alison Power is a professor in the Department of Ecology and Evolutionary Biology and the Department of Science and Technology Studies at Cornell University. She is a member of Cornell's Graduate Fields of Ecology and Evolutionary Biology, Entomology, International Agriculture, and Conservation and Sustainable Development, and the Latin American Studies Program. She also serves as dean of the Graduate School. Her research focuses on biodiversity conservation in managed ecosystems, interactions between agricultural and natural ecosystems, agroecology, the ecology and evolution of plant pathogens, invasive species, and tropical ecology. She leads a working group on the roles of natural enemies and mutuality in plant invasions at the National Center for Ecological Analysis and Synthesis (NCEAS). Dr. Power serves as vice president for public affairs for the Ecological Society of America and as the Presidential University Fellow of the Nature Conservancy. She also serves on the National Research Council (NRC) Committee on California Agricultural Research Priorities and the McKnight Foundation Oversight Committee of the Collaborative Crop Research Program. Dr. Power's past activities include serving on the NCEAS Science Advisory Board, the NRC Committee on Sustainable Agriculture and Environment in the Humid Tropics, the Executive Committee of the Organization for Tropical Studies, the Environmental Protection Agency Scientific Advisory Panel on Transgenic Bt Crops, the Sustainable Biosphere Initiative Steering Committee of the Ecological Society of America, and the Technical Committee of the Sustainable Agriculture and Natural Resource Management, Collaborative Research Support Program, of the U.S. Agency for International Development. Dr. Power received her Ph.D. in ecology from the University of Washington.

Peter Raven is the president of the Missouri Botanical Garden and George Engelmann Professor of Botany at Washington University. Dr. Raven's research interests include Onagraceae, conservation, sustainable development, and plant geography. He received the Arthur Hoyt Scott Medal and the National Medal of Science, and he was a member of former president Bill Clinton's Committee of Advisors on Science and Technology. In 2000 the American Society of Plant Taxonomists established the Peter Raven Award in his honor to be conferred to authors with outstanding contributions to plant taxonomy and "for exceptional efforts at outreach to non-scientists." Dr. Raven is possibly best known for his important work *Coevolution of Insects* *and Plants*, published in the journal *Evolution* in 1964, which he coauthored with Paul R. Ehrlich. Since then he has authored numerous scientific and popular papers, many on the evening primrose family, Onagraceae. Dr. Raven is also an author of the widely used textbook *Biology of Plants*, now in its seventh edition, coauthored with Ray F. Evert and Susan E. Eichhorn (both of the University of Wisconsin, Madison). Dr. Raven received his Ph.D. in botany from the University of California, Los Angeles.

Andrew Revkin is a journalist and author who, since the mid-1980s, has spent a quarter of a century covering subjects ranging from the assault on the Amazon to the Asian tsunami, from the troubled relationship of science and politics to climate change at the North Pole. From 1995 through 2009, he reported on the environment for the *New York Times*. In 2003, Mr. Revkin became the first *Times* reporter to file stories from the North Pole area, and in 2008 he became the first science reporter to win a John Chancellor Award from Columbia University. In 2010 he is joining Pace University's Academy for Applied Environmental Studies as senior fellow for environmental understanding. Mr. Revkin has also authored books on the Arctic, the Amazon, and global warming, including *The North Pole was Here*, which was published in 2006. Two films have been based on his work, including *The Burning Season*, which was based on his biography of Chico Mendes. Mr. Revkin received a B.S. in biology from Brown University and an M.S. in journalism from Columbia University.

Philip Robertson is the University Distinguished Professor of Ecosystem Science in the Department of Crop and Soil Sciences at Michigan State University. Dr. Robertson's research interests include the biogeochemistry and ecology of field crop ecosystems, including biofuel systems and, in particular, nitrogen and carbon dynamics, greenhouse gas fluxes, and the functional significance of microbial diversity in these systems. His undergraduate teaching includes agricultural ecology, biogeochemistry, and soil biology courses. His service includes current membership on the U.S. Department of Energy Biological and Environmental Research Advisory Committee, past membership on the U.S. Carbon Cycle Scientific Steering Committee, chairmanships of competitive grants panels at the U.S. Department of Agriculture (USDA, the National Research Initiative [NRI] and Fund for Rural America Programs), and membership on several National Science Foundation panels in the biological and geosciences directorates. He served on the National Research Council (NRC) Committee to Evaluate the USDA NRI Program

(1998–1999), and chaired the Environment Subcommittee of the NRC Committee on Opportunities in Agriculture (2000–2002). He has testified before the U.S. Senate Agriculture, Forestry, and Nutrition Committee and has participated in briefings on science, technology, and agriculture for U.S. House and Senate committees. He has also served as an editor for the journals *Ecology, Ecological Monographs, Plant and Soil,* and *Biogeochemistry*. In 2003 he was elected a fellow in the Soil Science Society of America. Dr. Robertson received his Ph.D. in biology from Indiana University.

Cristián Samper is the director of the National Museum of Natural History of the Smithsonian Institution. As its director, Dr. Samper is responsible for the largest natural history collection in the world and a museum that welcomes more than 6 million visitors each year. Since his arrival in 2003, Dr. Samper has reinvigorated the research staff by hiring new curators to replace retiring staff, built major new collections storage facilities and laboratories, and raised more than $100 million to support new long-term exhibitions and programs, including the Encyclopedia of Life and the Sant Ocean Hall. Known for his work in the ecology of the Andean cloud forests, conservation biology, and environmental policy, Dr. Samper sits on the boards of directors for the American Association of Museums, the Center for International Forestry Research, and the Nature Conservancy. Dr. Samper was the founder and first director of the Alexander von Humboldt Institute, which is the national biodiversity research institute of Colombia. He was responsible for developing Colombia's National Biodiversity Policy and promoting research on biological inventories, conservation biology, and sustainable use of biodiversity. At the same time, he served as chief science adviser for biodiversity for the Colombian government and served on the boards of many environmental institutions. For his contributions, he was awarded the National Medal of the Environment by the president of Colombia in 2001. Dr. Samper received his Ph.D. in biology from Harvard University.

José Sarukhán is a professor in the Institute of Ecology at the National University of Mexico. He holds numerous honorary doctoral degrees from such institutions as New York University, University of Wales, and Main National University of San Marcos in Lima, Peru, and the University of Colima, University of Hidalgo, and Graduate College in Mexico. Dr. Sarukhán has played very important roles in the establishment of biosphere reserves and biological research stations in Mexico. He has also held officer appointments in many professional organizations and has been appointed as scientific advisor to many international committees addressing problems of the environment. He has published nearly 100 papers and 7 books on tropical ecology, plant population ecology, ecology, and biodiversity and handbooks on weeds and tropical trees of Mexico, as well as many publications on higher education and scientific development in Mexico. Dr. Sarukhán received his Ph.D. in ecology from the University of Wales.

Rodger Schlickeisen is the president and chief executive officer (CEO) of Defenders of Wildlife. Under his leadership, Defenders has grown from 62,000 members and activists to more than 1 million and is recognized as one of the nation's prominent conservation advocacy organizations. Before joining Defenders, Dr. Schlickeisen was CEO of Craver, Mathews, Smith and Company, a leading consulting firm for progressive advocacy organizations. He also served in the Carter White House as associate director of the U.S. Office of Management and Budget, and as chief of staff to U.S. Senator Max Baucus. Dr. Schlickeisen is also president of Defenders of Wildlife Action Fund, a political nonprofit that works to elect a proconservation Congress and White House, and to advance conservation programs and policies. He was the founding chair of the nonprofit Partnership Project, established to help build a more unified and potent national environmental movement. He also serves on the advisory committees of the Earth Communications Organization and the Environmental Media Association. He is the author of numerous published opinion pieces and articles, including an influential law review article on the need for a constitutional amendment to protect the natural environment for future generations. Dr. Schlickeisen received his Ph.D. in finance from George Washington University.

Steve Schneider (deceased, 2010) is a professor of biology and codirector for the Center for Environmental Science and Policy at Stanford University. Internationally recognized for research, policy analysis, and outreach in climate change, Dr. Schneider focuses on climate change science, integrated assessment of ecological and economic impacts of human-induced climate change, and identifying viable climate policies and technological solutions. He has consulted with federal agencies and White House staff in the Nixon, Carter, Reagan, G. H. W. Bush, Clinton, and G. W. Bush administrations. Actively involved with the Intergovernmental Panel on Climate Change (IPCC), an initiative of the United Nations Environment Program and the World Meteorological Organization, since its origin in 1988, Dr. Schneider was coauthor of *Uncertainties in the IPCC Third Assessment Report: Recom-*

mendations to Lead Authors for More Consistent Assessment and Reporting (2000) and *Cross-cutting Theme Paper 4: Assessing the Science to Address UNFCCC Article 2* (2004). He has been a contributor to all four IPCC assessment reports and is a coordinating lead author of *Climate Change 2007: Working Group II: Impacts, Adaptation, and Vulnerability*, Chapter 19, "Assessing Key Vulnerabilities and the Risk from Climate Change." He was also a member of the core writing team for the 2001 IPCC Third Assessment Report (TAR) and the 2007 Fourth Assessment Report (AR4). In addition, he has authored, coauthored, or edited more than 400 scientific papers, proceedings, legislative testimonies, books and book chapters, and has written more than 200 book reviews, editorials, and other pieces for popular media. Currently, Dr. Schneider is counseling policy makers about the importance of using risk management strategies in climate-policy decision making, given the uncertainties in future projections of global climate change and related impacts. In addition to continuing to serve as advisor to decision makers, he consults with corporate executives and other stakeholders in industry and the nonprofit sectors about possible climate-related events and is actively engaged in improving public understanding of science and the environment through extensive media communication and public outreach. Dr. Schneider received his Ph.D. in mechanical engineering and plasma physics from Columbia University.

Achim Steiner is the executive director of the United Nations Environment Program (UNEP) and an expert on environmental matters. His professional track record in the fields of sustainable development policy and environmental management; his first-hand knowledge of civil society, governmental, and international organizations; and his global experience spanning five continents make him an excellent choice to lead UNEP. Mr. Steiner serves on many international advisory boards, including the China Council for International Cooperation on Environment and Development and the Environmental Advisory Council of the European Bank for Reconstruction and Development. Mr. Steiner received his M.A. in economics and regional planning from the University of London, specializing in development economics, regional planning, and international development and environment policy.

David Tilman is the Regents Professor and Distinguished McKnight University Professor at the University of Minnesota. His research interests include the ecological effects of human domination of the earth, including effects on ecosystem services of value to society; the ecological mechanisms controlling speciation, community assembly, species invasions, and the evolution and maintenance of biodiversity; population ecology and theory of community dynamics and biodiversity; the role of resource competition; biodiversity and ecosystem functioning; and the effects of habitat destruction. He is an elected member of the American Academy of Arts and Sciences and the National Academy of Sciences, was the founding editor of the journal *Ecological Issues*, and has served on editorial boards of nine scholarly journals, including *Science*. He serves on the Advisory Board for the Max Planck Institute for Biogeochemistry in Jena, Germany. He has been a member of the Institute for Advanced Study in Princeton, New Jersey, and a fellow of the National Center for Ecological Analysis and Synthesis. Dr. Tilman has received the Ecological Society of America's Cooper Award and its MacArthur Award, the Botanical Society of America's Centennial Award, and the Princeton Environmental Prize, and he was named a Guggenheim fellow. He has written 2 books, edited 3 books, and published more than 200 papers in peer-reviewed literature, including more than 30 papers in *Science, Nature*, and the *Proceedings of the National Academy of Sciences USA*. The Institute for Scientific Information designated him as the world's most highly cited environmental scientist of the decade for 1990–2000 and for 1996–2006. Dr. Tilman received his Ph.D. in zoology from the University of Michigan.

Justin Ward is the vice president of business practices within Conservation International's (CI) Center for Environmental Leadership in Business (CELB). During the last several years, he has directed CELB's industry program activities on agriculture, forestry, and fisheries, working with major companies such as Wal-Mart, Starbucks, McDonald's, Office Depot, and International Paper. Before joining CI, Mr. Ward was a senior policy specialist with the Natural Resources Defense Council (NRDC). During more than 17 years with NRDC, he directed the organization's activities on farm policy, international trade, and global forest conservation. He is the author of numerous publications and the recipient of a 1988 Agricultural Conservation Award from the American Farmland Trust. In 1996, Mr. Ward was elected to a 3-year term on the international Board of Directors of the Forest Stewardship Council, and he serves as coleader of the Forests Dialogue, a multistakeholder forum hosted by the Yale School of Forestry and Environmental Studies. Mr. Ward received his M.A. from the University of Minnesota.

Boris Worm is an associate professor in marine conservation biology at Dalhousie University in Nova Scotia. He has made leading scientific contributions to the fields of marine ecology and fisheries conservation. His interests focus on global patterns and changes in marine biodiversity, and specifically in understanding how these patterns were created and how they are changing, particularly in response to perturbations such as fishing and climate change. Dr. Worm also has an active interest in marine conservation and ecosystem management, particularly in the conservation of large marine predators. He has authored and coauthored many publications and has served on several boards. Dr. Worm received his Ph.D. from the University of Kiel, Germany.

Appendix D

Biographies of Symposium Committee Members

Sir Peter Crane is the Carl W. Knobloch Jr. Dean of the School of Forestry and Environmental Studies at Yale University, chair of the U.S. National Committee for DIVERSITAS, and a member of the National Academy of Sciences in Washington, D.C. His work focuses on the diversity of plant life: its origin and fossil history, current status, and conservation and use. From 1992 to 1999, he was director of the Field Museum in Chicago, with overall responsibility for the museum's scientific programs. From 1999 to 2006, he was director of the Royal Botanic Gardens, Kew, one of the largest and most influential botanical gardens in the world. His tenure at Kew saw strengthening and expansion of the gardens' scientific, conservation, and public programs. Dr. Crane was elected to the Royal Society (the U.K. academy of sciences) in 1998. He is a fellow of the American Academy of Arts and Sciences, a foreign member of the Royal Swedish Academy of Sciences, and a member of the German Academy of Sciences Leopoldina. He was knighted in the United Kingdom for services to horticulture and conservation in 2004. Dr. Crane serves on the boards of the Global Crop Diversity Trust, the Missouri Botanical Garden, the Chicago Botanic Garden, the Lady Bird Johnson Wildflower Center at the University of Texas, and the Gaylord and Dorothy Donnelley Foundation.

Ann Kinzig is a professor of biology at Arizona State University. Her research focuses on urban ecology, the resilience of human-environment interactions across long timescales, and science policy. She has authored and coauthored many publications and served on many boards. Dr. Kinzig received her Ph.D. in energy and resources from the University of California, Berkeley.

Thomas E. Lovejoy is past president of the Heinz Center (2002–2008) and became the first recipient of the newly created Heinz Center Biodiversity Chair in 2008. Before joining the Heinz Center, he was the chief biodiversity advisor to the president of the World Bank and its lead specialist for environment for Latin America and the Caribbean, and he was senior advisor to the president of the United Nations Foundation. Dr. Lovejoy has been assistant secretary and counselor to the secretary of the Smithsonian Institution, science advisor to the secretary of the interior, and executive vice president of the World Wildlife Fund–U.S. In 1980 he coined the term "biological diversity" and drew up the first projections of global extinction rates for the *Global 2000 Report to the President.* He conceived the idea for the Minimum Critical Size of Ecosystems project (a joint project between the Smithsonian Institution and Brazil's National Institute for Amazonian Research), originated the concept of debt-for-nature swaps, and is the founder of the public television series *Nature.* In 2001 he was awarded the prestigious Tyler Prize for Environmental Achievement. Dr. Lovejoy served on science and environmental councils or committees under the Reagan, Bush, and Clinton administrations. He received his Ph.D. in biology from Yale University.

Harold Mooney is the Paul S. Achilles Professor of Environmental Biology at Stanford University and chair of the DIVERSITAS Science Committee. His research interests include global change impacts on terrestrial ecosystems, the role of biodiversity in ecosystem processes, and how to deal with invasive species in a global context. A leader in the global scientific community in the areas of biodiversity and climate change, Dr. Mooney has received numerous honors and awards and is a member of a small group of premier researchers. He has demonstrated that convergent evolution takes place in the properties of different ecosystems that are subject to comparable climates, and has pioneered in the study of the allocation of resources in plants. Research in his laboratory is centered on the study of the effect of enhanced carbon dioxide on ecosystem structure and function. Dr. Mooney received his Ph.D. in biological sciences from Duke University.

Charles Perrings is professor of environmental economics at Arizona State University (ASU). At ASU he directs (with Ann Kinzig) the ecoSERVICES Group of the College of Liberal Arts and Sciences. The group studies the causes and consequences of change in ecosystem services—the benefits that people derive from the biophysical environment. Dr. Perrings cochairs (with Shahid Naeem) the ecoSERVICES core project of DIVERSITAS, the international program of biodiversity science. The group contributes to international research projects on issues relating to biodiversity change, conservation, and development, and it supports training in biodiversity and ecosystem services both within ASU and internationally. It runs the Biodiversity and Ecosystem Services Training Network, a research coordination network funded by the National Science Foundation. Dr. Perrings was an editor of the Cambridge University Press journal *Environment and Development Economics*, and he remains on its editorial board and those of several other journals in environmental, resource, and ecological economics, and in conservation ecology. He is past president of the International Society for Ecological Economics, a society formed to bring together the insights of the ecological and economic sciences to aid understanding and management of environmental problems. He has advised various governmental, intergovernmental, and international nongovernmental organizations, as well as research-funding agencies. In Britain he served on the Royal Society's Environment Committee, the WHAT Commission on Genetic Diversity in Food Crops and the Center for Ecology and Hydrology (Natural Environment Research Council) Program Review Board. Dr. Perrings has published extensively in leading journals, including the *Journal of Marine Science, Ecological Modelling*, *Trends in Ecology and Evolution*, and *Ecological Economics*. Dr. Perrings received his Ph.D. from the University of London.