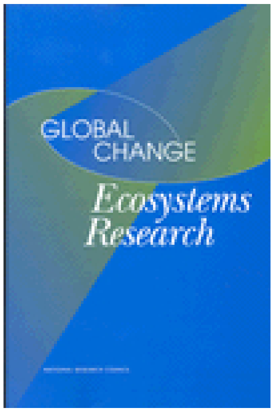

Global Change Ecosystems Research

Ecosystems Panel, Oversight Group for the Ecosystems Panel, Board on Environmental Studies and Toxicology, National Research Council

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THE NATIONAL ACADEMIES
Advisers to the Nation on Science, Engineering, and Medicine

Global Change Ecosystems Research

Ecosystems Panel
Oversight Group for the Ecosystems Panel
National Research Council

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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 NRC's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the NRC in making the published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their participation in the review of this report:

Stephen Carpenter, University of Wisconsin-Madison
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Pamela Matson, Stanford University
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Gordon Orians, University of Washington
William Schlesinger, Duke University
Fred Wendorf, Southern Methodist University

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations nor did they see the final draft of the report before its release. The review of this report was overseen by Robert Paine, University of Washington, appointed by the Oversight Group for the Ecosystems Panel,

who was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the NRC.

The Ecosystems Panel is also grateful to the workshop participants, particularly the presenters and responders, for their thoughtful and constructive contributions. They are listed in the Appendix.

Contents

Executive Summary

The Ecosystems Panel was established by the National Research Council in response to a request from the United States Global Change Research Program (USGCRP). One of the panel's tasks was to review the ecosystems aspects of the USGCRP's research program; that is the focus of this report. The panel first identified the most significant and challenging areas in ecosystem science, then used the areas identified to make recommendations to the USGCRP.

The panel used a broad definition of global change, as the USGCRP does. By *global change* we refer to the interactions between natural changes in the Earth's physical and biological structure and the broader effects of human activities. Global change, therefore, has natural and anthropogenic components. It occurs at all scales, but this report focuses on changes that, when aggregated, are significant at a global scale, affecting the health, welfare, and well-being of humans and other members of the biota. Examples of global changes the panel judged to be significant include conversion of natural landscapes (including coasts) to agricultural and urban ones; intensification of various nutrient cycles; biotic mixing, including the introduction of nonnative species into many ecosystems worldwide and the loss of other species; changes in the hydrological cycle; changes in the climate due to humancaused changes in atmospheric chemistry; changes in the size and distribution of human populations; the conversion of natural landscapes to provide transportation infrastructure such as roads, railways, harbors, and airports; and the greenhouse gases emitted by vehicles using that infrastructure.

The panel developed a conceptual model (see Chapter 3) to focus its assumptions and guide its recommendations. The model shows that humans have many effects on the environment that lead to global change. Climate is one mechanism through which human activities affect their environment, and continuing the research on climate and related phenomena is crucial to further understand these interactions. But other mechanisms operate without direct involvement of climate and also are important. Thus, to understand global change, much research that does not focus on climate is needed in addition to the current efforts on climate-related phenomena.

To evaluate the scientific questions that arise from considering the conceptual model, the panel considered the importance of each factor that produces environmental effects in the model, whether there are areas in which understanding of the factors in the model and their effects are impeded by lack of scientific knowledge, and the degree to which each scientific research topic would be likely to lead to large progress on other, related topics.

The panel recommends a research initiative that comprises efforts to understand four areas of global change research: (a) biogeochemical **C**ycles, (b) **H**abitat changes (land cover and use), (c) **I**nvasive species (biotic mixing), and (d) **E**cosystem **F**unctioning and biological diversity (**CHIEF**). Because ecosystem functioning and biological diversity are relevant to and are affected by cycles, habitat, and invasions, they are discussed under each of those three major topics, rather than separately.

Biogeochemical cycles—especially cycles of carbon, nitrogen, phosphorus, and water—have been pervasively affected by humans, resulting in significant global changes. These changes have altered the composition of plant and animal communities and ecosystem functioning, and have caused changes in climate and in the quality of humans' lives. The various cycles interact in complex ways; better understanding of them is needed, including the role of the oceans in the cycles and the responses of ecosystems to changes in them.

Habitat is a requirement for all species, and habitat loss and degradation accounts for more species extinctions than any other cause. The main cause of global habitat loss and degradation is human use of the land: changes in land use and land cover are important global changes. It thus is important to understand current global patterns and rates of change in land use and land cover and build on that understanding to predict future changes. It also is important to understand the interactions between human activities and ecosystem services.

The Earth's biotic mix—the kinds and proportions of the species in an ecosystem, including extinctions and introductions—has been changing at an accelerating pace. Introduction of nonnative species is the second-largest cause of species extinction, and this global change affects almost every ecosystem and many aspects of human life. We need to understand how to predict whether a given species is likely to be introduced, to survive, and to become established in a new environment, and whether it will cause large effects. We need to understand why some introduced species remain harmless for many generations and then suddenly begin spreading rapidly. Other important research questions involve the role of genetic change in the ability of an introduced species to spread and how the presence of introduced species will affect the structure and functioning of ecosystems.

Mounting a large, coordinated, and sustained effort to understand aspects of global change not emphasized in the current climate-related research agenda is a significant undertaking, but it is essential to understand, predict, and deal with the major global changes that have already occurred and whose pace seems likely to accelerate. Because the subject areas of CHIEF and the current activities of the USGCRP complement one another, work on CHIEF will strengthen the USGCRP and can be accomplished without major structural changes to the administration of the USGCRP.

1

Introduction

In 1997, the National Research Council established the Ecosystems Panel in response to a request from the United States Global Change Research Program (USGCRP). The panel's charge included periodic reviews of the ecosystems aspects of the USGCRP, and this is the first of those reviews. It is based on information provided by the USGCRP, including *Our Changing Planet* (NSTC 1997 and earlier editions[1]); ideas and conversations provided by participants in a workshop held in St. Michaels, Maryland, in July 1998; and the deliberations of the panel. In addition, the panel reviewed the ecosystems chapter of the NRC report *Global Environmental Change: Research Pathways for the Next Decade* (NRC 1999a, known as the *Pathways* report).

THE USGCRP

The USGCRP is an interagency program established in 1989 and codified by the Global Change Research Act of 1990 (PL 101-606). The USGCRP comprises representatives of the departments of Agriculture, Commerce (National Oceanic and Atmospheric Administration and National Institute of Standards and Technology), Defense, Energy, Health and Human Services (the National Institute of Environmental Health Sciences), Interior, and State, as well as the Environmental Protection Agency, the National Aeronautics and Space Administration, the National Science Foundation, the Smithsonian Institution, the Office of Science and Technology Policy, the Office of Management and Budget, and the intelligence community (NSTC 1997). The USGCRP's research program is described in detail in *Our Changing Planet* (NSTC 1997, 1999). In brief, the program focuses on four major areas of earth-system science:

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[1] The panel used the 1997 edition in developing much of this report. The 1999 edition (NSTC 1999) reflects the advice given in the *Pathways* report; the panel considers that it provides an excellent background for the recommendations in this report.

- Seasonal to interannual climate variability.
- Climate change over decades to centuries.
- Changes in ozone, ultraviolet (UV) radiation, and atmospheric chemistry.
- Changes in land cover and in terrestrial and aquatic ecosystems.

The fourth topic is the area in which advice was requested from the ecosystems panel. According to NSTC (1997), “The USGCRP supports research to inventory the current land cover of the Earth and to document changes; to improve understanding of the dynamics of land-cover and landuse change and how terrestrial and aquatic ecosystems react to change; and to document and understand chemical, physical, and biological processes in the oceans and their relationship with the carbon cycle and marine life.”

THE NATIONAL RESEARCH COUNCIL STUDY

The Ecosystems Panel's charge has three parts: to provide a forum for the discussion of questions of ecosystem science of interest to scientists in and out of the federal agencies, to periodically review the ecosystem aspects of the USGCRP's research program, and to help identify general areas of ecosystem science that need additional attention, especially areas that cut across ecosystems and levels of ecological organization. In addressing the second item of its charge for this report, the panel first identified the most significant and challenging areas in ecosystem science, then used that identification as a basis to make recommendations to the USGCRP. Thus, this report is not a detailed review of the USGCRP's program, but rather an attempt to identify those areas that the panel concludes are most in need of attention by a general research program on global change. As noted in this report, some of those areas are already receiving attention by the USGCRP.

To help the panel identify these challenging research areas, a workshop was held in July of 1998 (the Appendix lists the participants). Based on that input as well as its own deliberations and other information provided by the

USGCRP, the panel arrived at the conclusions described in the remainder of this report. This report complements the recent NRC *Pathways* report (NRC 1999a) in that it focuses on ecosystems research, which was only one topic in the *Pathways* report's broader scope.

2

Definitions and Implications Of Global Change

Global change is a term widely used to describe the effects of human activities on the Earth. Although the term sometimes refers only or primarily to global *climate* change, the Ecosystems Panel takes it to mean the interactions between natural changes in the Earth's physical and biological structure and the broader effects of human activity. Thus, global change includes changes in many aspects of the globe's environmental systems, including climate.

Global change defined in this way has natural and anthropogenic components; the latter is largely due to the increasing human population and its activities. The global environment has changed constantly over the history of the Earth and would still be changing in the absence of humans. In this sense, global change is not entirely a byproduct of human actions. Even so, there is ample evidence that humans have vastly accelerated the pace of many otherwise natural kinds of change and have introduced numerous kinds of change previously absent from Earth. These two features of human-induced global change—accelerated changes and new kinds of changes—act together to alter, impair, or eliminate many of the environmental amenities and services on which human societies are based.

The motivation of global change research is to understand the kinds and magnitudes of global change caused by humans, to project the course of change and, where possible, prescribe intervention that would moderate its harmful effects or sustain beneficial effects. Thus the focus is on the anthropogenic rather than the natural component of global change. Even so, prior change is frequently relevant as a scale against which to measure human influences on the magnitude and scope of global changes at present and for the future.

Global change connected with human activities first came to broad public attention through forecasts of global climate change occurring primarily as a result of human-induced enrichment of the atmosphere with greenhouse gases. The analysis of this problem has proven difficult, in part because of its complexity and in part because the scientific community was initially unaccustomed to environmental work of global scope. Many aspects of the global climate change problem now have been explored through the use of models, experiments, and observations on global scales. The breadth and sophistication of climate change analysis have increased over the past two decades. Scientific momentum has developed around studies of the global carbon cycle, which will ultimately be central to an understanding of the mechanism of human-induced climate change.

Global change either in its natural or human-induced forms extends well beyond climate change. Although much is yet to be done in the analysis of climate change, other kinds of change are as immediate and of equally pressing concern from the viewpoint of human welfare and must be added to the research priorities of the USGCRP, as well as international research programs of global scope.

Global change occurs at all scales, but this report focuses only on changes that, when aggregated, are significant at a global scale. We are especially interested in processes whose scale is global and in changes that have cumulative global effects, even if the scale of operation is primarily regional or even local. (By *regional* the panel means areas such as southern Africa, western Europe, or eastern North America; by *local* it means below the size of a medium-sized U.S. state (e.g., Maine) or country (e.g., Austria, Ghana).) What constitutes significance, of course, is a judgment. As an example, the panel judges the conversion of natural landscapes to provide transportation infrastructure—mainly roads, but also railways, harbors, and airports—to be globally significant. Even more significant are the greenhouse gases emitted by vehicles using that infrastructure; the conversion of natural landscapes, including coastal zones, to agricultural and urban landscapes; intensification of various biogeochemical cycles, including nitrogen and carbon; the growing concentration of human populations along coasts and in large urban areas, producing a global change in the distribution of human populations and a global change in the structure and functioning of coastal ecosystems; changes in the structure and functioning of natural ecosystems, including species extinctions and species introductions; changes in the frequency and severity of infectious human diseases; changes in the Earth's climate, both natural ones and those caused by human-caused changes in the atmosphere's trace gases (commonly referred to as global warming); global dispersion of pollutants, such as persistent organic pesticides; and changes in the hydrologic cycle caused by various human uses of water, structural alterations to rivers and their surrounding watersheds, and by climate changes.

The implications of these and other changes are the appropriate topics of a global change research program. We need to know whether a change is merely troubling to those who remember what the world used to be like (but see Pauly 1995 for a description of the “shifting baseline syndrome”) or whether it poses significant threats to the health, welfare, and well-being of humans and the other members of the biota. We need to understand the socioeconomic and biophysical forces affecting global changes and the socioeconomic and biophysical consequences of global changes. These are research questions. The results of such research must be understandable and relevant to policy makers.

3

The Scientific Questions

CONCEPTUAL MODEL

Conceptual models help to focus assumptions and make key assumptions explicit. They focus research by postulating strong connections and processes that can influence and be influenced by other important processes or outcomes. They also provide for changing the research enterprise if information becomes available that leads to a change in the underlying model. To help focus its assumptions and guide its recommendations to the USGCRP, the panel developed a conceptual model of global change[1] (Figure 3-1). Nothing in the model appears to conflict with or contradict current USGCRP research or its interpretations, and we believe that having this model is helpful.

As a means of clarifying the breadth of essential research on global change, Figure 3-1 gives an overview of human influences on the global environment. Human actions, which involve factors related to population size and distribution as well as economic and social trends, are the point of origin for a diverse cluster of environmentally potent changes. In Figure 3-1, these changes are grouped under three broad headings: (1) land use and land cover; (2) biogeochemical and hydrologic cycles as well as the introduction and distribution of potentially harmful substances; and (3) biotic mixing, which encompasses the transportation of species or genotypes from one region of the globe to another as well as direct intervention of humans in community composition through harvesting or management of living communities.

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[1] See somewhat similar models developed by Vitousek et al (1997a) and Watson et al. (1998).

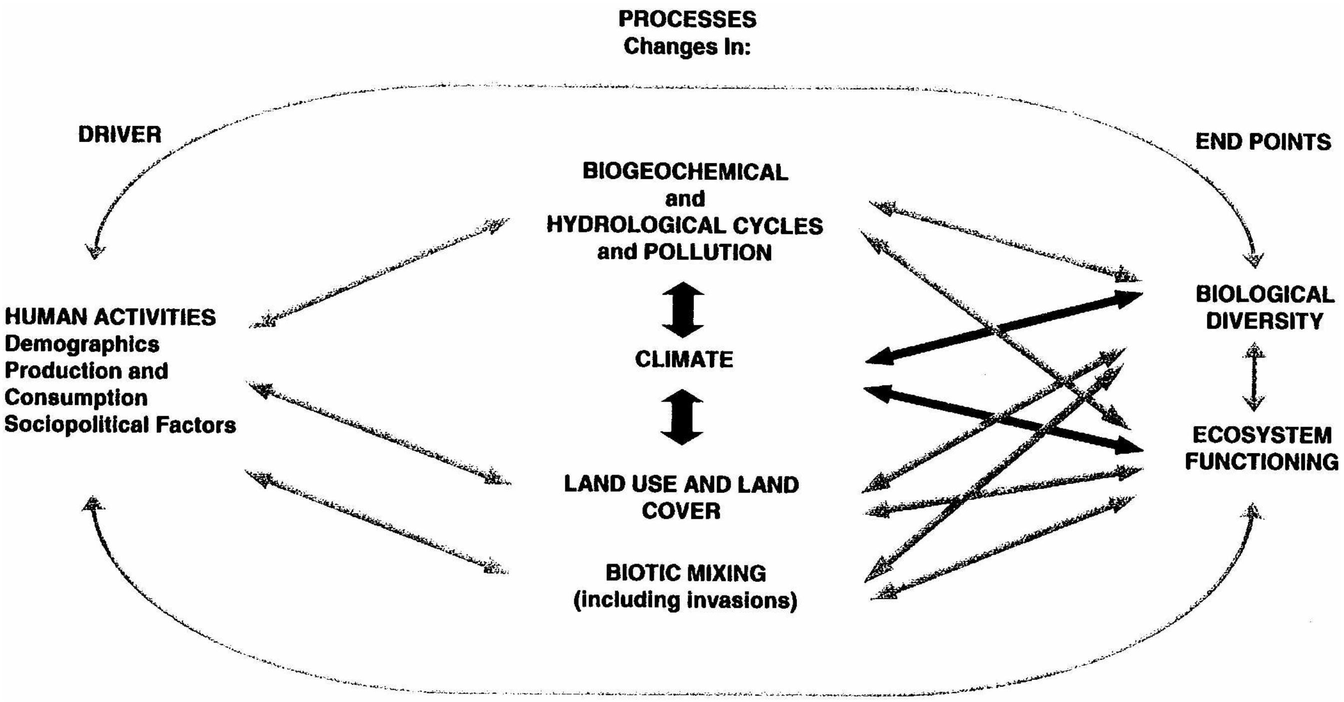

FIGURE 3-1 Conceptual model of global change due to human activities. (For explanation, see text.)

Climate change, the best recognized and most successfully studied aspect of global change, appears in Figure 3-1 as a combined byproduct of changes in land use and cover and alteration of biogeochemical cycles (primarily of carbon) through human action. The relationships of these variables with climate change are reciprocal, which explains much of the difficulty in understanding and predicting climate change in relation to human activities.

Although climate change and its consequences occupy a substantial portion of Figure 3-1—climate is connected directly and indirectly to biodiversity and the functioning of ecosystems—other kinds of global change operate through pathways other than climate, and thus appear in other parts of the figure. Some categories of global change not derived from climate change have profound economic and social effects. These effects are driven by population growth, income growth, job creation, global transportation networks, and other activities that benefit people, at least in the short term, and so it is unlikely that the driving forces can be eliminated in the short term, if at all. But the effects need to be understood if they are to be managed. For example, biotic mixing through the dissemination of species beyond their natural ranges has resulted in hundreds of biological invasions causing billions of dollars in losses worldwide (OTA 1993, Vitousek et al. 1996). Conversion of tropical moist forest to other forms of land cover is causing a rapid loss of global genetic capital and is reducing potential yield of a variety of valuable medicinal and food products over a large portion of the Earth's surface. Global intensification of the nitrogen cycle and perturbations of many other natural cycles are influencing living communities (biodiversity) and ecosystem processes (e.g., productive capacity of ecosystems). The case for understanding and projecting these effects is compelling and yet must be developed alongside research on climate change.

Figure 3-1 was developed with terrestrial environments in mind. Although studies of global change, especially climate change, have developed primarily with reference to the Earth's atmosphere, oceans, and the major terrestrial biomes, the descriptions of USCGRP's ecological research programs (e.g., NSTC 1999) emphasize terrestrial ecosystems more than marine ones. As yet, human activities do not seem to have affected the open oceans ecologically on a global basis as much as they have the land, although impacts have been substantial. Probably the largest human ecological impact on the oceans to date is fishing (see for example NRC 1999b). Fishing has probably had global effects on trophic relationships by removing large amounts of biomass from marine ecosystems (e.g., Pauly et al. 1998) and probably has had regional effects on the species composition of marine ecosystems (e.g., NRC 1996a). Fishing with some kinds of trawling gear also has affected bottom topography (e.g., Auster et al. 1996), but as yet these effects are only local or perhaps regional, but certainly not global.

Probably the largest human-caused global effect on marine ecology other than fishing is (or will be) changes resulting from altered biogeochemical cycles. At present, very little is known about how those altered cycles affect the open ocean, and that is one reason that oceans do not constitute a major part of this report. However, lack of information should not be taken as lack of any effect, and understanding how altered biogeochemical cycles interact with the ocean and marine ecosystems is of great practical and scientific importance.

Inland waters and coastal zones also deserve increased attention. Although they account for only 1% of terrestrial surface, and coastal zones are only a small fraction of the world's oceans, these environments have an extraordinarily high collective importance to human well being. Matters specific to them of global scope include eutrophication, pollution by toxic chemicals, major physical alterations, and major changes to volumes and flow rates. These ecosystems are also particularly vulnerable to the effects of biotic mixing.

Inland and coastal waters are connected to global changes in two ways. First, they reflect and are linked directly to global changes in terrestrial environments. For example, land-based changes in land cover, pollution, and nutrient cycling through human activities have had large effects on aquatic environments (NRC 2000). Second, these environments show global commonalities in the ways they respond to specific kinds of human-caused environmental changes. For example, inland and coastal waters respond to enrichment of nutrients in ways that can be generalized on a global scale.

A mature and effective agenda for global change research will include climate change, and its connections as shown in Figure 3-1, as well as other components of global change equally important to human interests but not primarily explained by climate change. The challenge for the immediate future of this agenda is to add these new elements to research on global change, and in this way broaden the analysis of global change to match the full extent of its causes and consequences.

The conceptual model leads to the following general questions:

- What do we know about the status and trends of the components of the model?
- By what mechanisms do the connections in the figure operate?
- How important is it to understand the mechanisms as opposed only to the size and direction of the effects?
- At what scales are the connections operating?
- What are the probable trends in the forcing functions, the primary factors, and the end points?
- What can we learn by knowing the histories of these model com

ponents, i.e., how their magnitudes and relationships to other components have changed over time?

- Are these trajectories related to the mechanisms, and if so, how?

CRITERIA FOR IDENTIFYING THE QUESTIONS

In evaluating the scientific questions that arise after consideration of the conceptual model, the panel used the following criteria for deciding their relative importance to the USGCRP.

- How important is each factor that produces environmental effects in the model? In other words, for each factor, are changes likely to be global in scale and significant? To what degree and over what periods are the changes likely to be irreversible?
- Are there areas in which understanding of the factors in the model and their effects is impeded by a lack of scientific knowledge? Would advances in techniques or analysis or new data help us move beyond our current lack of understanding?
- Is there potential for a significant breakthrough in the level and scope of our scientific understanding if we work on this scientific question? If we work on this question, are we likely to be able to make significant progress on other, related scientific questions?

4

The Panel's Advice to the USGCRP

The USGCRP's research program has emphasized climate change and variability (NSTC 1997); three of its four main foci are related to climate, and the fourth—changes in land cover and terrestrial and aquatic ecosystems—is strongly oriented toward how those changes interact with climate change. The *Pathways* report (NRC 1999a) reflects that emphasis, although it makes strong recommendations that more attention be paid to biological diversity, and its recommendation for more research on carbon and nitrogen cycles includes a strong recommendation for research on how those cycles directly affect ecosystems. The Ecosystems Panel fully endorses the emphasis on climate change. Climate change is a global phenomenon and has the potential to have large effects that are irreversible over many decades, perhaps centuries. Understanding climate variability and change over periods from months to centuries could well lead to the solution of related scientific questions and could lead to breakthroughs in understanding. Climate change itself has the potential to produce surprising effects, something that the *Pathways* report identified as important to understand and be prepared for. Understanding climate variability and change requires large, national and international cooperative research programs, and requires a large and expensive scientific infrastructure (e.g., satellites and supercomputers).

However, the model shown in Figure 3-1 makes clear that a focus on climate variability and change is not sufficient. Global change has many facets that do not act through the climate system. Some of these have already had profound economic, sociological, biological, and political effects. For example, biotic mixing has had much larger economic effects already than climate change has or is likely to have over the next decade, even according to the most pessimistic climate and economic models. The General Accounting Office reported that federal departments spent more than $630 million in fiscal 2000 for invasive species activities and state governments spent more than $230 million (GAO 2000). Those expenditures do not include most losses to nongovernment entities and are only for the United States. Many species have become extinct as a result of biotic mixing. As another example, the concentration of people and their infrastructure in urban areas has changed the local climate (mainly temperature) of those areas faster than even the most pessimistic climate models predict for global means over the next decade; as a result, a significant proportion of the Earth's human population has already experienced significant climate changes through a nonglobal mechanism. The transformation of landscapes from natural ecosystems to agricultural ones—and to deserts in many places—has had profound effects on people and biota, as have the spread and evolution of resistance of many infectious diseases. Changes in biogeochemical cycles—in particular carbon and nitrogen—have affected many aspects of the Earth's environments, as have changes in hydrological cycles, in ways not mediated through climate.

Many of the most important environmental problems of the coming decades are likely to reflect the combined action of several driving forces, acting at a range of different spatial and temporal scales. Both the experimental evidence and the theory for understanding these responses are in the early stages of development, leaving many unanswered questions.

Some of the problems will involve related causes. For example, elevated carbon dioxide (CO_2) is likely to occur in a context that is simultaneously altered by warming and increased or decreased precipitation. But changes will not be limited to climate and CO_2 only. Atmospheric CO_2 is changing in the context of a system that includes nitrogen deposition, a history of changing land use, and widespread biological invasions. Some sites will mix responses to these factors with contamination from pollutants, diminished biological diversity, and altered frequency of disturbance.

For these reasons, the panel recommends the development of a new research initiative that emphasizes Cycles, Habitat (land cover and use), Invasive species (biotic mixing), and Ecosystem Functioning (CHIEF), as described in more detail below. This initiative is complementary to (and partially overlaps) the four Research Imperatives in Chapter 2 of the *Pathways* report (land surface and climate, biogeochemistry, multiple stresses, and biodiversity). It is similar in many aspects to the research recommendations of the Ecological Society of America's Sustainable Biosphere Initiative (Lubchenco et al. 1991) and complements a recent National Science Board report's recommendations (National Science Board 2000). It is also based on the panel's conclusion that much of the current ecosystem science research agenda is applicable to understanding global change: to understand change, we need to understand key processes before the change occurs. Ecosystem functioning and biological diversity are related to cycles, habitat, and invasive species, and they are discussed under each of those major headings in the CHIEF initiative below.

Mounting a large, coordinated, and sustained effort to understand those aspects of global change not emphasized in the current climate-related research agenda is a significant undertaking but it is essential to understand, predict, and deal with the major global changes that have already occurred and whose pace seems likely to accelerate. Research on CHIEF issues would add value to the current USGCRP by providing insight into what is at risk and how risk might be reduced, much as medical and public health research adds value.

The panel recommends that the USGCRP be broadened to include the CHIEF issues raised in this report. Many productive reoptimizations of global change research will result from including these ecological research areas. Because the subject areas of CHIEF and those of the current USGCRP complement one another, work on CHIEF will strengthen the USGCRP.

CYCLES

Nitrogen, carbon, phosphorus, and hydrologic cycles are critically important to the nature and quality of life on Earth. Human activities have pervasively affected those cycles, resulting in significant global changes. All of these cycles affect nonhuman living organisms but they also are affected by them. Because the cycles and humans' effects on them are not completely understood, the panel recommends a substantial research effort on them. The carbon cycle receives much attention, especially as it relates to climate. Much better understanding of nitrogen and phosphorus cycles is needed, including the role of the oceans in the cycles, the response of natural ecosystems to nitrogen and phosphorus, and the interactions between them.

Hydrologic cycles have been profoundly altered and aquatic ecosystems have been altered or destroyed by human activities (Dahl 1990, Postel et al. 1996, 1999). Rivers have been regulated and channeled; in some cases, rivers that used to flow year-round have become intermittent. Groundwater has been mined and polluted and recharge has often been reduced, affecting springs and the quantity and quality of surface water in general; for example, Trautman (1981) describes dramatic changes in Ohio's surface waters over the past 200 years. Much information and better understanding is needed of the details and consequences of these processes on regional and global scales (Postel et al. 1996, 1999).

These cycles operate through a variety of mechanisms, some of which are global in scale and others, although not global in scale individually, are cumulative, and thus produce effects at global scales. For example, both water and nitrogen are volatilized into gases (e.g., water vapor, ammonia) and can be spread globally by atmospheric circulation. Nitrogen and phosphorus fertilizers are applied over large areas of the Earth and the sum of regional excesses and runoff in rivers produces global effects. Excesses of phosphorus, nitrogen, and other nutrients in the ocean can also be spread globally, especially because they, like atmospheric nitrogen and water, are added to the environment in many areas over the globe.

Changes in cycles of nitrogen and phosphorus are important because they often are limiting nutrients for terrestrial and aquatic plants, which have evolved in environments where the available forms of those nutrients are not abundant. When their concentrations are increased by human activities, plants are freed from these limitations and grow faster. In aquatic and marine ecosystems, a process called eutrophication results: species compositions change, the water often becomes less transparent, and dissolved oxygen often decreases. In terrestrial systems, plants often store more carbon energy and biomass in the presence of increased phosphorus and nitrogen, especially when atmospheric CO_2 is increased as well.

Nitrogen Deposition and Global Changes

Of the major global changes, human impacts on the nitrogen cycle are among the most significant. Human actions more than double the natural inputs to terrestrial ecosystems. Manufactured fertilizer, fossil-fuel combustion, and cultivation of legumes with nitrogen-fixing symbioses are the dominant anthropogenic sources (Vitousek et al. 1997a,b).

Nitrogen deposition plays a role in a diverse array of global changes, many of which link to an even broader array of effects through interactions with other factors. Nitrogen fixation for fertilizers has increased sharply since the 1940s (Vitousek et al. 1997b). The surplus accumulates in soils, erodes, and leaches to groundwaters (Vitousek et al. 1997b) and runs off into surface waters (Carpenter et al. 1998). From fresh waters, it arrives in estuaries and coastal marine ecosystems. Some of the added nitrogen moves to the atmosphere through volatilization of ammonia (NH_3) (Schlesinger and Hartley 1992). Much of the nitrogen volatilized to the atmosphere re-enters aquatic and terrestrial ecosystems when it is deposited from the atmosphere (Howarth et al. 1996). Nitrogen in the atmosphere as oxides of nitrogen (NO_x) is a key factor in atmospheric chemistry, especially ozone and photochemical smog. It also contributes, along with sulfur, to acid precipitation. Nitrogen in the atmosphere as nitrous oxide (N_2O) is a major greenhouse gas, accounting for approximately 10% of the greenhouse effect of anthropogenic gases (Schimel et al. 1996). The mechanisms through which ecosystems regulate nitrogen emission are incompletely understood, though agricultural practices can have a large impact on fluxes as can land-use change, including the conversion of tropical forest to pasture (Matson et al. 1997).

Elevated CO_2 and Global Changes

Observed and projected increases in atmospheric CO_2 will have direct physiological effects on plants but not on animals. Carbon dioxide is a nutrient for plants and increases growth, especially in the presence of other nutrients. Changes in plant performance can range from changes in species composition to changes in tissue chemistry and are likely to have significant effects on the relationships between plants and their herbivores and among plants and soil organisms. These effects are likely to be felt by animals at higher trophic levels as well.

Most of the research on ecosystem responses to elevated CO_2 has focused on the prospect for increased carbon storage as a consequence of increased photosynthesis (Mooney et al. 1999). The large body of research on this topic has uncovered leads about a wide range of other kinds of responses, many with the potential for major impacts on ecosystem structure and functioning. Interactions between the carbon and nitrogen cycles have been identified as important. Elevated CO_2 is likely to intensify nitrogen limitation (Pan et al. 1998). In at least some cases, this leads to decreased emissions of nitrogen trace gases (Hungate et al. 1997) or increased success of plants with symbiotic nitrogen fixation (Hebeisen et al. 1997).

Understanding the balance between sources of carbon and sinks is important. The so-called “missing sink” is an important object of research, because the known sources of carbon emissions—mainly CO_2—are greater than the known sinks, but our models have not accounted for the fate of the excess carbon until recently, when evidence was presented that accumulation of carbon in terrestrial forests or reforestation in the Northern Hemisphere accounted for at least a substantial portion of it (Tans et al. 1990; Nabuurs et al. 1997; Schimel et al. 2000). Complicating matters is the discovery that the carbon budget is affected by nitrogen (e.g., Curtis et al. 2000; Pregitzer et al. 2000; Zak et al. 2000a,b). Increasing availability of soil nitrogen increases the photosynthetic rate of some plants and hence their rate of storage of atmospheric CO_2 as carbon. Thus nitrogen pollution, a cause of eutrophication in many freshwater and marine ecosystems, perhaps helps to reduce or counteract some effects of CO_2 emissions. These interactions in ecosystems need much additional research.

Indirect effects of elevated CO_2 can also be mediated through effects on the water budget. Several empirical and modeling studies provide evidence for local warming as a result of the tendency for elevated CO_2 to decrease water loss (Kimball et al. 1994, Bremer et al. 1996). This affects temperature because decreased water loss entails a decreased use of energy for evaporating water, which leaves more energy to heat the air. In some simulations, the warming caused by this mechanism is, at least in some locations, 25-50% of the warming caused by solar radiation (Sellers et al. 1996). This is an example of a class of ecosystem impacts on climate that is very poorly understood but potentially important. Such effects clearly deserve increased research emphasis, including dedicated efforts to address interdisciplinary issues.

Other indirect effects of elevated CO_2 can lead to changes in species composition, though current capability to predict the nature and consequences of these changes is quite limited. One of the pervasive ecosystem changes in the last century—the expanding dominance of woody plants in grassland and savanna ecosystems worldwide—may be at least in part a response to increased CO_2 (Polley et al. 1996). Most of the woody plants invading grasslands use the C_3 photosynthesis pathway (the terms C_3 and C_4 refer to specific sequences of biochemical reactions to fix carbon). Photosynthesis in C_3 plants increases strongly under elevated CO_2, while that of the grasses using the C_4 photosynthesis pathway changes only slightly, if at all. Some of the woody species expanding in grasslands are legumes, suggesting the possibility that symbiotic nitrogen fixation further enhances these species' competence as competitors. Of course, most terrestrial ecosystems have been subjected to diverse human impacts over the past century, and it is possible, even likely, that changes in fire regime, grazing management, and climate interact with the elevated CO_2 to modulate the changing composition of grasslands.

Biogeochemical and Hydrologic Cycles and Potentially Harmful Substances: Interactions with Biological Diversity and Ecosystem Functioning

These climate-related issues are addressed in Chapter 2 of the *Pathways* report, here the emphasis is on the ecosystem structure and functioning rather than on the carbon budget. These factors affect biological diversity and functioning primarily at local and regional scales but occur globally. The time scales of the processes and responses vary from instantaneous to cumulative and long-term (century or greater) impacts.

Biogeochemical processes emphasized here relate to cycling of nutrients significant for enhancement or limitation of primary production, those aspects of the hydrologic cycle affecting the biological diversity of ecosystems and the consequences of potentially harmful substances (e.g., toxic substances and wastes) released into the habitat. Phosphorus is of particular concern as a pollutant that causes eutrophication and significant changes in biotic composition of freshwater ecosystems (Carpenter et al. 1998). Phosphorus is also significant as a limiting resource to primary producers in the ocean as well as in fresh waters (Vitousek and Howarth 1991; Tyrrell 1999). Nitrogen also is a concern for both marine and freshwater ecosystems as discussed below.

For most terrestrial ecosystems, the availability of freshwater is the limiting resource for net ecosystem production and for delivery of ecosystem services for human use. Freshwater resources are predicted ultimately to become the limiting factor for expanding agricultural production, creating competition between supplies for human services and natural resources. This has already occurred in some arid regions (e.g., NRC 1999c).

The availability of water, its abundance, seasonal distribution, and predictability exert significant controls on the composition, structure, and biological diversity of ecosystems. The composition and structure of terrestrial ecosystems feeds back on the hydrologic cycle through ecosystem functioning, including patterns of evapotranspiration, and through canopy interception, infiltration, storage, and runoff. Biological diversity is frequently greatest at soil moistures midway between soil drought and saturated conditions, when there is little seasonal pattern in moisture distributions, and when predictability of soil moisture is high. Either extreme of water resources results in ecosystems having fewer species and lower complexity.

The availability of water in the environment affects the rates of soil weathering and decomposition and availability of nutrients for vegetative growth, factors affecting the composition and diversity of ecosystems. Differential growth responses of species to nutrient limitations and inputs ultimately will influence how specific nutrients affect ecosystems. Changes in availability of nutrients will affect competitive and trophic relationships, potentially causing significant shifts in biodiversity. Under excessive water inputs, soil nutrients may become leached from the soil and become deficient (e.g., in the wet tropics). With most nutrients sequestered in tropical plant canopies, ecosystem production and biodiversity depends on the quantity and rate of decomposition for recycling of essential nutrients. Under water-limited conditions, essential nutrients may be limiting due to low water uptake; salts may accumulate in the soil to toxic conditions. Under saturated conditions, pH, electrical conductivity, and solubility of heavy metals may increase. Relatively few species tolerate high accumulations of soil ions. The recent NRC report on the hydrologic science content of the USGCRP (NRC 1999d) has research recommendations that complement the ones in this report and also emphasize the coupling of hydrologic and biogeochemical cycles through ecosystems.

Human activities have caused significant translocation of soil nutrients to groundwater and surface runoff, in some systems through poor irrigation management, irrigation with high salinity water sources, and excessive fertilizer inputs, which cause additions and enhancements of nutrients to downslope and downstream systems. For example, the hypoxic zone in the Gulf of Mexico is presumed to be brought about by agriculture in the Mississippi River watershed (Moffat 1998; Mississippi River/Gulf of Mexico Watershed Nutrient Task Force web site available at http://www.nos.noaa.gov/products/pubs_hypox.html). A region defined by a dissolved-oxygen concentration of less than 2 mg/L that is unable to sustain most forms of multicellular organisms, this hypoxic zone forms along the bottom of the Gulf each summer as the seawater stratifies. Planktonic organisms die and sink, and the dissolved oxygen at lower depths is consumed as decomposition occurs. The area of the hypoxic zone has been about 18,000 km^2 in recent years. There is evidence that plankton growth in the Gulf is stimulated by nitrogen runoff from fertilized fields and livestock in the Mississippi River Basin.

Human activities also affect water quality though the addition of a wide range of potentially harmful substances and chemicals, e.g., herbicides, pesticides, and industrial and household substances and through enhanced soil erosion and sediment transport. Cumulative local problems have global impact. Because of differential species growth and toxicity responses to individual substances, it is difficult to generalize these impacts. In some cases, primary producers may show little sensitivity, but devastating impacts may occur at other trophic levels. Clearly, the time scales related to impacts of toxic substances can vary from nearly immediate gradual, such as the leaching of substances into groundwater, resulting in serious but delayed impacts on ecosystems over decades or even centuries.

Requirements for Sustainable Production

Where biological production is actively managed, as in agriculture and forestry, much remains to be learned about the amounts of various nutrients and micronutrients that must be returned (recycled) to the land if sustainable production and sustainable ecological functioning are to be achieved. The results of such research are required for the management of crop and forestry wastes and to minimize the use of fertilizers and other external inputs.

Excess nitrogen that ends up in water has a range of impacts. It can help stimulate blooms of harmful algae or enhance the success of the heterotrophs that lead to dead zones deprived of oxygen. Extra nitrogen can also stimulate other kinds of less dramatic but potentially important changes in the composition and function of aquatic ecosystems.

In terrestrial ecosystems, nitrogen deposition leads to diverse effects. Some of these are biogeochemical, for example long-term decreases in the availability of calcium (Likens et al. 1996). Others are ecological, for example, the replacement of heathland vegetation adapted to nutrient-poor sites with vegetation that is dramatically different in form and function (Berendse and Elberse 1990). Nitrogen addition is a powerful cause of vegetation changes, altering the balance of competition in many habitats (Tilman and Downing 1994). Especially in nutrient poor sites, the species that profit most from nitrogen additions are often normative, providing additional pressure for an expanding influence of biotic mixing (e.g., Lauenroth et al. 1978).

Elevated CO_2, especially in combination with other global changes, could lead to a variety of other kinds of ecosystem responses. One hypothesis clearly deserving more study involves water resources. When elevated CO_2 leads to decreased transpiration, possible responses include increased runoff and success of water-demanding species (Field et al. 1995). When the species that succeed under elevated CO_2 are nonnative invaders, control becomes more difficult, and negative impacts on native species become more likely (Dukes and Mooney 1999).

Many experimental and modeling studies document the impacts of elevated CO_2 on photosynthesis, transpiration, nutrient dynamics, and growth of individual species. Yet it is very difficult to use these results as a foundation for predicting changes in ecosystem structure and functioning, because of our still-limited ability to model changes in species composition. These challenges expand markedly when the context shifts from only elevated CO_2 to a broader array of global changes. For example, developing the capacity to predict changes in disturbance regimes, especially fire, presents a suite of challenges different from those posed by elevated CO_2.

To address these gaps in our knowledge, three kinds of approaches are critical. First, experimental studies must run for long enough and on a large enough spatial scale that investigators can observe species dynamics and disturbance responses. Second, it is important to develop and explore model systems where the full range of interactions and dynamics can be observed in a tractable framework. Third, it is critical to take advantage of long-term natural experiments, as in areas surrounding naturally occurring CO_2 springs, to understand the effects of elevated CO_2 on plants and biological communities (e.g., Cook et al. 1998). Finally, the community must work to integrate information from these three approaches, so it all contributes to answering a single set of questions.

Much remains to be learned about the transport and fate of nitrogen nutrients, about the rate at which anthropogenically fixed nitrogen is denitrified in terrestrial and aquatic systems, and about the ecological consequences of increased inputs of fixed nitrogen to aquatic and terrestrial ecosystems (Schnoor et al. 1995; Vitousek et al. 1997; Galloway 1998; Socolow 1999). The fates and effects of anthropogenic nitrogen in the oceans are also of great importance, and we know little about them. For example, Lapointe et al. (in press) have argued that excess nitrogen loading has adversely affected corals and other marine organisms in Florida Bay. Because nitrogen enhancement through atmospheric pathways is global (Howarth et al. 1996; Vitousek et al. 1997a,b), open-ocean ecosystems could be affected, as coastal systems have been (Vitousek et al. 1997a,b; NRC 2000).

Key Questions

1. How will elevated atmospheric CO2 and anthropogenic acceleration of the nitrogen and phosphorus cycles interact with other elements of global change, especially climate change and biotic mixing, to alter the future trajectory of primary production and the species composition of terrestrial, aquatic, and marine ecosystems?
2. What are the impacts of freshwater diversion and contamination on the resilience of terrestrial and aquatic ecosystems (i.e., their ability to cope with global changes)?
3. What are the two-way interactions between changes in biological diversity (at all scales) and changes in the global cycles of water, carbon, and nutrients?
4. How will global changes in climate, land-use, and the composition of the atmosphere alter frequency and intensity of disturbances like fire, disease, and pest outbreaks, and how will these disturbances affect ecosystems over the long term?

HABITAT: LAND USE AND LAND COVER

Among the most important global changes are the alteration of landscapes and degradation of habitats. *Land cover* is the ecological state and physical appearance of the land surface (e.g., closed forests, open forests, grasslands) (Meyer and Turner 1994). Change in land cover converts land of one type to another, regardless of its use. *Land use* refers to the purpose for which the land is used by people (e.g., forests used for timber, recreation, or pasture; industrial areas; human settlements) (Meyer and Turner 1994). Change in land use may cause a significant change in land cover, but need not. For example, change from selectively harvested forests to protected forests will not cause much discernible cover change in the short term, but change to cultivated land will cause a large change in land cover.

The accumulation of small local changes poses a substantial long-term challenge for research and land management. Individual changes in land use may appear to have only local significance, but the large number of local changes is transforming the surface of the earth. Gradual but widespread change leads to significant impacts on vegetative cover, wildlife habitat, soils, and water quality. Land-cover changes have profound global effects because they are so pervasive and have such strong influences on biological diversity and ecosystem functioning.

Human activities have strong effects on land use and land cover. As global human population and the per-capita resource use have increased, there have been changes in the area, type, and intensity of land use and land management (Perlin 1989; Turner et al. 1990; Dale et al. 2000). Forests and grasslands have undergone extensive changes as agriculture and managed forest lands have expanded (Houghton 1995). Lands in some temperate regions have been reforested during the past century as agricultural lands were abandoned. Desertification provides an extreme example of land-cover change that can result from land use (e.g., broad-scale loss of tropical forest can disrupt local hydrological regimes) (Shukla et al. 1990). Patterns of land use and land cover in the terrestrial landscape also affect aquatic systems, directly (e.g., construction of dams and impoundments, drainage of wetlands for agriculture, construction of aquaculture ponds in coastal areas) and indirectly (e.g., through the nutrient-laden runoff that enters aquatic systems).

Land-cover patterns are also generated by disturbance regimes. Therefore, changes in the frequency, intensity and extent (size) of natural disturbances have important implications for spatial pattern of land cover (Pickett and White 1985). For example, the reduction of natural fire frequency in much of the southwestern United States has changed many forests from a mosaic of young and old forests to forests dominated by mature late-successional trees, which often have dense fuel loads (Cooper 1960). Instead of frequent surface fires, the new pattern of land cover fosters more severe crown fires that burn larger areas and create greater expanses of similar cover across the landscape. These landscape changes alter the amount and distribution of cover and forage available for animals and thus affect faunal diversity as well. As another example, alterations to flood regimes can influence the structure of riparian habitat, modifying the composition and spatial and temporal distribution of species that use those places and changing ecosystem processes (Naiman and DeCamps 1997). If the current path of land-use changes continues, continued loss of wildlife and vegetation, erosion of soils, and nonpoint pollution of groundwater and surface water is likely (Turner et al. 1998).

Comprehensive global and accurate data on land-use and land-cover types is an urgent data need, and the panel strongly endorses the USGCRP's effort to obtain detailed, precise, and comprehensive data on land cover and land use. Much of that effort is properly devoted to obtaining remotely sensed data from satellites and aircraft. Information on land-cover patterns and the location and rates of land-cover change needs to be global, but regional and local data are also important because such changes occur at finer spatial scales. The panel recommends that increased effort be devoted to ground-based studies, especially outside the United States and Western Europe. In the less-industrialized countries, the changes are faster and greater, and more information is needed on the mechanisms of change and factors that influence rates of change. In addition, the prediction of trends in land cover must include consideration of socioeconomic factors that drive land use and of changes in disturbance regimes that may result from changes in climate (especially variation in extreme events, such as drought) and land use.

This report focuses on the ecological aspects of the USGCRP, and so the panel does not provide specific advice on how to incorporate research on social and economic drivers here. However, such interdisciplinary work is essential, and we recommend that USGCRP encourage collaborations between the Human Dimensions part of USGCRP and the research proposed here.

Biological Diversity

Worldwide, land cover today is altered principally by direct human use: by agriculture, raising of livestock, forest harvesting, and construction (Meyer 1995). Changes in land use and land cover can result in loss and fragmentation of natural habitats as well as the introduction of new types of habitat. Each of these changes can influence biodiversity. Indeed, global land-use change can be considered as an enormous uncontrolled experiment in how habitat changes influence the biota and ecosystem functioning.

Land-use patterns have important influences on biodiversity for several reasons (Turner et al. 1998). First, land-use activities may alter the relative abundances of natural habitats and result in the establishment of new landcover types. The introduction of new cover types can increase the variety of species by providing a greater diversity of habitats, but natural habitats are often reduced, leaving less area available for native species. Nonnative species also may gain a foothold and outcompete the native species (see next section, Changed Biotic Mix). For example, the presence of livestock facilitates the spread of Eurasian grasses that can survive trampling. The livestock defoliate areas, reduce the abundance of native grasses that cannot survive trampling, and thus allow for the spread of normative grasses.

Second, the spatial pattern of habitats may be altered, often resulting in the fragmentation of once-continuous habitat. The effects of habitat fragmentation on animals, plants, and their habitats are numerous (see summaries by Saunders et al. 1991 and Noss and Csuti 1994), and the biodiversity of native species is almost always reduced. Habitat fragmentation may disrupt biological processes, such as location of mates, predation, herbivory, dispersal of juveniles, and migration, that are necessary for persistence of a species. For example, the fragmentation of forests of the eastern United States into mosaics of forested and open areas has led to numerous edge-related effects such as increased nest parasitism by cow birds (*Molothrus ater*) on neotropical migrant birds there. Fragmentation of Midwestern forests into smaller pieces, along with overhunting, caused the disappearance of many wide-ranging mammals by 1860 (especially animals at high trophic levels with large home ranges, e.g., black bear [*Ursus americanus*], gray wolf [*Canis lupus*], and mountain lion [*Felis concolor*]) (Reeves 1976). Interestingly, increased connectivity of habitat for iris species has resulted in hybridization among species and changes in mating systems (Arnold and Bennett 1993). Even though the fragmentation of habitats is local or regional in scale, it is so pervasive that there is a global loss of large, continuous habitat types as a result. Although a topic of much research, many questions remain about the effects of habitat fragmentation because it affects different species in different ways (Robinson et al. 1992).

Third, land-use activities may change the natural pattern of environmental variation, especially by causing changes in natural patterns of disturbance. For example, the environment may be changed directly when fire control and logging alter the frequency and extent of natural fires. Natural disturbances create and maintain biodiversity by creating a mosaic of habitats; in general, the chances of losing native species and disrupting ecological functioning increase when the patterns of natural habitats are altered (Turner et al. 1998).

The importance of understanding the legacy of past land use as a factor explaining variability in present-day communities is increasingly recognized. In the eastern United States and Upper Midwest, where reforestation has dominated land use for the past one to two centuries, modern forests have not returned to their presettlement composition, and land-use history explains much variation in current community composition (Foster 1992; Foster et al. 1992; Mladenoff and White 1994). Animals that thrive in early successional habitats also increased in abundance when cleared areas predominated and are now declining. For example, as forest cover across the New England states increased to 75-90% during the past century (Irland 1982), the New England cottontail (*Sylvilagus transitionalis*) has declined substantially throughout its range (Chapman and Stauffer 1981). The pattern of decline is correlated with losses of old fields and young forest habitats (Litvaitis 1993). Recent work in the southern Appalachians revealed a persistent effect of historical land use on stream fauna (Harding et al. 1998). Studies of forest-harvesting patterns have also demonstrated that landscape patterns created by land use may persist for a long time, even after the regime changes or all harvesting ceases (Wallin et al. 1994). Thus, increased understanding of the legacy of past land use and the trajectory of landscapes and their biotic communities when land use changes is important, and research is needed.

Ecosystem Functioning

Land use and management often have a direct influence on nutrient and water cycling and soil quality. For example, agricultural practices often add nutrients in fertilizer and water by means of irrigation. However, there are sometimes indirect effects on ecosystem cycling. The presence of large expanses of concrete and asphalt or compaction due to livestock can change patterns of nutrient and water runoff. Patterns of soil erosion or sedimentation are often altered with intensified land management. Changes in water flows and temperature in aquatic ecosystems often occur as a result of land-use changes. Thus, elements of the landscape may serve as sources, sinks, or transformers for soils, nutrients, sediment, and pollution loads.

Agriculture, forest harvest, and urban areas contribute to degradation of freshwaters by increasing inputs of silt, nutrients, and pollutants (Carpenter et al. 1996). The nutrients most often considered in studies of land-water interactions are nitrogen and phosphorus. Economic and health concerns about excess nitrogen inputs into aquatic ecosystems are growing throughout the world (e.g., Cole et al. 1993, Vitousek et al. 1997a). In rivers, nitrogen biogeochemistry is sensitive to land-use patterns, the structure of the riparian zone, and river flow-regimes. Accumulation of excess phosphorus in lake and stream systems has long been recognized as a cause of eutrophication.

Riparian vegetation zones, including wetlands and floodplain forests, are conspicuous elements of many landscapes and important mediators of land water interactions (Naiman and DeCamps 1997). Riparian vegetation can take up large amounts of water, sediment, and nutrients from surface water and groundwater draining agricultural areas within a catchment, substantially reducing the discharges of nutrients to aquatic ecosystems. Thus, freshwaters are especially sensitive to changes in these adjacent lands (Correll et al. 1992; Osborne and Kovacic 1993; Correll 1997; Lowrance et al. 1997). Worldwide, wetlands, floodplains, and riparian vegetation zones have often been altered by agricultural and urban development. For example, woody riparian vegetation once covered an estimated 30-40 million ha in the contiguous United States (Swift 1984); at least two-thirds of that area has been converted to nonforest land uses, and only 10-14 million ha remained in the early 1970s. It is important for scientists to better understand the interactions between land (soil) and water, the scales over which they are manifest, and how future land-cover changes are likely to affect riparian zones.

Many land uses are specifically designed to enhance productivity (e.g., agriculture and managed forests). Other land uses, such as suburbanization, reduce the biological productivity of a site. Alteration in the managed productivity of a system often changes the vegetation structure, which influences faunal diversity dependent on those structures. For example, timber harvesting in oak forests jeopardizes the endangered cerulean warbler (*Dendroica cerulea*), which nests only in oak canopy.

Key Questions

1. What are the current global patterns and rates of change in land use and land cover? What explains the differences among regions? How might the answers to these questions be used to predict future patterns of land use and land cover? What are the critical socioeconomic and cultural driving variables that are needed?
2. How do changes in climate, land use, and disturbance regimes interact to produce dynamic landscapes? Are there thresholds in land-cover patterns (e.g., connectivity of habitats or sizes of patches) beyond which large changes in biodiversity and ecosystem functioning are likely to occur? Under what combinations of climate, land use, and disturbance are these thresholds likely to be crossed?
3. Are the legacies of prior land-use activities and spatial patterns similar among different world biomes? To what extent are today's communities explained by historical land use?
4. How well do we understand the interactions between human activities and ecosystem services? In other words, how well do we understand the

factors that influence the human activities that most strongly affect ecosystem services, and how well do we understand humans' responses to changes in ecosystem services?

CHANGED BIOTIC MIX

By *changed biotic mix,* we mean changes in the kinds or proportions of the species constituting a community. Any addition or deletion of a species automatically constitutes a changed biotic mix, but so do disproportionate increases or decreases in existing species.

Species Diversity

Conserving biological diversity, especially species diversity, has received much attention. The ecological significance of species diversity is discussed in the next section. Here, we point out that protecting endangered species and biological diversity in general has been important to many people for a long time. Although it has been difficult to establish an economic argument for protecting species diversity, there are strong ethical, moral, cultural, and aesthetic reasons for doing so (Sagoff 1996). Many societies reflect those values in their laws, as for example the U.S. Endangered Species Act of 1973 (see NRC 1995), which declares it to be the policy of Congress to conserve endangered and threatened species.

Nonindigenous invasive species (NIS) are radically changing the biotic mix in many communities (Bright 1998, Cohen and Carlton 1998), with a variety of potential impacts on biological diversity and ecosystem functioning. When they become established, such invaders can eliminate particular native species, either globally or locally, through a variety of means. For example, the Nile perch (*Lates nilotica*) in Lake Victoria has driven more than 100 species of endemic cichlid fishes to extinction (Goldschmidt 1996). The brown tree snake (*Boiga irregularis*) has eliminated almost all the forest birds in Guam (Williamson 1996; NRC 1997). Goats have extinguished more than 50 plant species just on the island of St. Helena (Groombridge 1992). NIS can compete with native species (e.g., rangeland plants in the western United States [Mack 1989]; house gecko (*Hemidactylus frenatus*) on islands [Petren and Case 1996]) or attack them (e.g., the brown tree snake [NRC 1997]; African ice plant [*Mesembryanthemum crystallinum*] in California, whose salty leaves make the surrounding soil uninhabitable for other plants nearby [Vivrette and Muller 1977]; fire ants [*Solenopsis invicta*] [Tschinkel 1993]).

NIS also can cause diseases in native species (e.g., whirling disease [the metazoan parasite *Myxobolus cerebralis*] in trout [Robbins 1996], avian pox virus and malaria [*Plasmodium* species] in Hawaiian birds [van Riper et al. 1986]). NIS can even hybridize with native species, causing a kind of genetic extinction (e.g., mallards [*Anas platyrhynchus*] with the Hawaiian duck [*Anas wyvilliana*] and New Zealand gray duck [*Anas superciliosa*] [Rhymer and Simberloff 1996], introduced rainbow trout [*Oncorhynchus mykiss*] with native cutthroat trout [*O. clarki*] in the Rocky Mountains [Varley and Schullery 1998]).

The global sum of these impacts of NIS is staggering, even if many of them are individually small. It is almost impossible to estimate the total annual cost of damage caused by NIS and of attempts to control them, but Pimentel et al. (1999) recently reviewed the literature. Examples of cost estimates in the United States include $97 billion for 79 species from 1906 through 1991 (OTA 1993); $14.5 million per year in Florida alone to control the aquatic plant hydrilla (*Hydrilla verticillata*) (Center et al. 1997); $44 million per year in economic damage to commercial shellfish caused by the green crab *Carcinus maenas* (Lafferty and Kuris 1996); and $200 million in yearly damage to docks and ships by the shipworm *Teredo navalis* (Cohen and Carlton 1995). After habitat loss, nonindigenous species are the second greatest cause of recent endangerment and extinction (NRC 1995, Bright 1998). As noted previously, the Nile perch alone has globally eliminated at least 100 species, while the New World rosy wolf snail (*Euglandina rosea*) has caused the global extinction of at least 30 endemic snail species on Pacific islands (Civeyrel and Simberloff 1996). Just three introduced tree species in south Florida form nearly monospecific stands over nearly 600,000 ha (Schmitz et al. 1997), while invasive nonindigenous weeds in rangelands of the West moderately or heavily infest more than 40 million ha and currently spread by more than 2,000 ha per day (Westbrooks 1998). This is a global change of the first order.

Various types of harvest can locally or totally remove one or more species from the landscape. For instance, commercially valued tree species like mahogany are often locally eliminated by selective forestry. Agriculture can also eliminate particular species or groups of them, while leaving others relatively unscathed. For example, freshwater mussels in the United States have proven extremely vulnerable to water pollution and sedimentation largely generated by agriculture; perhaps 10% are already extinct, while another 60% are threatened (Stein and Flack 1997). Aquaculture similarly can eliminate particularly sensitive species through pollution and also by habitat conversion. For example, the effluent from shrimp-farming is toxic to some species, and large areas of mangrove habitat have been converted to aqua culture, with loss of typical mangrove forest inhabitants (Jin-Eong 1995; NRC 1999b).

A modified disturbance regime may be inimical to one species and favorable to another. In southern U.S. pine forests, routine controlled burning that was substituted for lightning-caused fires was generally performed in the winter, whereas lightning in that region occurs primarily May through July. This change led to the gradual replacement of the originally dominant ground-cover plant in longleaf pine (*Pinus opalustrus*) forests, wiregrass (*Aristida stricta*), by other species, such as *Bromus* spp. (Clewell 1989; Seamon et al. 1989).

Large changes are occurring in the genotype frequencies of many species (e.g., Policansky 1993), although the scope and consequences of these changes are far more poorly understood than changes at the species level. Many of the invasive species mentioned above certainly change the genotypes of the native species they affect, even if they do not cause their extirpation. In many cases, supplementation of depleted wild populations through hatcheries changes genotypes and ecotypes of the remaining wild populations (e.g., NRC 1996b; Waples 1999).

Ecosystem Functioning

The ecological significance of species diversity has been of scientific interest for many years (e.g., Hutchinson 1959). How species diversity affects ecosystem functioning continues to be of great scientific interest today (e.g., Mooney et al. 1995; Tilman 1996; Grime 1997). While it is clear that if enough species are lost, ecosystem functioning will be impaired, it is not clear how many species are “enough,” and in general how the kinds and numbers of species in an ecosystem affect a variety of ecological processes. Because human activities are affecting both the number and kinds of species in most ecosystems, especially terrestrial and freshwater ones, this general scientific question assumes heightened importance and urgency in any global change research program.

The most far-reaching ecosystem-wide impacts are usually caused by plant NIS that replace the previous dominants. In south Florida, Australian *Melaleuca quinquenervia* (paperbark tree), introduced ca. 1900, increased to 200,000 ha, replacing sawgrass (*Cladium* spp.) and muhly prairies, as well as some cypress (*Taxodium* spp.) swamps. It overgrows the native plants, outcompeting them for light. In addition, *Melaleuca* is flammable; it reseeds readily after fires, but the native plants do not. It uses large amounts of water and has lowered the water table in many areas. It also changes water flow patterns by deposition of abscised leaves. All of these changes have led to virtual monocultures of *Melaleuca,* as few native plants can tolerate the environment *Melaleuca* has created. Animals that typically inhabit the native plant communities then largely disappear (Schmitz et al. 1997). Eurasian cheatgrass (*Bromus tectorumi*) dominates 7 million ha of rangeland in Idaho and Utah alone, not by overgrowing native plants, but by facilitating fires and by having a deep taproot, as opposed to the shallow root mass of the natives. Once established by virtue of its impact on the fire regime and hydrology, cheatgrass replaces native plants and populations of many animals subsequently plummet (Westbrooks 1998). South American water hyacinth (*Crassipes eichhornia*) at one time completely covered over 50,000 ha of Florida waters. Today it blankets thousands of hectares of Lake Victoria. The mats shade out submersed vegetation, which dies. Eventually the dying parts of water hyacinth itself contribute to a growing oxygen deficit, and animal populations decline. In all these cases, the NIS has direct population impacts on certain species (usually by competition), but many more indirect impacts on numerous species generated through ecosystem effects. A similar situation arises in Hawaii, where the Atlantic firebush (*Myrica faya*), a nitrogen-fixer, has heavily invaded nitrogen-poor volcanic soils. Its subsequent nitrogen-fixing activities have changed successional pathways to favor other nonindigenous plant species that could not have thrived in the original volcanic soils (Vitousek 1986).

Nonindigenous plant species can hybridize with natives to form an invasive pest. The North American cordgrass *Spartina alterniflora,* introduced to England around 1829, was a harmless minor component of the British flora, occasionally producing sterile hybrids with the native *S. maritima.* Then, sometime before 1890, one such hybrid underwent a spontaneous doubling of chromosomes to become fertile, becoming a major invasive weed (Thompson 1991).

A nonindigenous pathogen that removes a formerly dominant native plant can also have ecosystem impacts. The chestnut blight, *Cryphonectria parasitica,* virtually eliminated American chestnut (*Castanea dentata*) from the forest canopy. The chestnut had been the dominant tree in much of the Eastern U.S. (von Broembsen 1989). This near extinction almost certainly had numerous ripple effects on both ecosystem processes and particular species associated with chestnut, but few were studied. It is known that at least ten insect species host-specific to chestnut subsequently went extinct (Opler 1979). A pathogen that attacks dominant herbivores can similarly greatly change the mix of species in native communities. For example, the introduction into African cattle of the rinderpest virus led to the infection of many native ungulate species, with mortality in some species reaching 90%

and geographic distribution of certain species altered for a century (Dobson 1995).

A nonindigenous animal can effect substantial changes in ecosystem functioning, for example, by either modifying the dominant plants (e.g., the periwinkle on the coast of the Northeastern United States and adjacent Canada [Bertness 1984]) or by constituting a new habitat (e.g., zebra mussels on soft-bottom areas in U.S. rivers and lakes [Ricciardi et al. 1997]).

Change in a disturbance regime over large areas can affect entire ecosystems. For example, suppression of fire in longleaf pine forests of the South-east has led to the replacement of pine-dominated forests by hardwoods. The precise ecosystem consequences have not been studied, but such processes as nutrient cycling must be greatly changed. Replacement of storm-driven floods along the Colorado River by floods regulated by dams built for hydroelectric power led to the establishment of forests of Asian tamarisk (*Tamarix* spp.) and native willows (*Salix* spp.) on formerly bare banks.

Key Questions

1. What combination of nonindigenous species and potential recipient community will lead to establishment and spread of the NIS? Only about 10% of species introduced to and surviving in a new range actually become invasive (Williamson 1996). Sometimes the same species can be invasive in one region and rare and innocuous in another. There has been some limited success in attempting to predict invasiveness simply from species traits (e.g., Rejmanek and Richardson 1996), but little experimentation to understand why some habitats appear more susceptible to invasion than others.
2. Why do many NIS remain harmlessly noninvasive for many generations, then suddenly begin spreading rapidly (e.g., Brazilian pepper [*Schinus terebinthifolius*] in Florida)? Is this due to a change in the species, a change in the community, or an expected demographic lag? Conversely, why do some NIS that are so invasive as to be considered scourges dramatically decline, sometimes to near-rarity (e.g., Canadian pondweed [*Elodea canadensis*] in Great Britain and the giant African snail [*Achatina fulica*] on many Pacific islands)?
3. What role does genetic change play in changed invasiveness? To what degree are lessons learned from the evolution of virulence in pathogenic disease vectors transferable to the understanding of genetic changes leading to invasiveness or to increased invasiveness after an exotic becomes established?
4. The substitution of normative genotypes, often uniform ones, in

populations of forest trees, game and food fishes, and other organisms, may have major consequences for both biodiversity and ecosystem functioning, but these have barely been studied. Brook trout (*Salvelinus fontinalis*) have been genetically homogenized by repeated introductions and use of hatchery stock, while tree species like *Pinus radiata* have been planted in huge expanses. Will such populations be as resilient to subsequent biotic and abiotic environmental change as the genetically more heterogeneous ones they replaced? Will they be able to evolve as quickly?

IMPLEMENTATION

The research questions at the core of each element of CHIEF are so important for the future of ecosystem science, global change research, and the sustainability of the biosphere that each warrants a substantial and sustained investment. Some of the questions are ripe for rapid progress in the next few years. Others, no less important, will yield more slowly, and the major breakthroughs may be a decade or even more in the future.

Progress in answering each of the major questions posed in this report will almost certainly require information and insights from and even beyond the full sweep of global change research. Ultimately, the answers to each question will need to be integrated with all of the others. Indeed, it is likely that the major factors that control processes within each element in CHIEF are mechanisms that unfold in other elements as well. For example, invasive species may be among the strongest influences on ecosystem functioning; similarly, changes in land use might be the strongest influences on changes in the major cycles. As the elements of CHIEF, plus other components of the global change research agenda, converge into a single suite of interlocking processes, the agenda will reach its richest phase.

Mounting a coordinated and sustained commitment to advancing the CHIEF agenda should be a priority for the USGCRP. Although significant new funding will be required, and the distribution of resources among program elements will likely need to be adjusted, the initiative should not require major changes in the current administrative structure of the USGCRP. The structural changes needed to implement this research initiative involve primarily a shift in focus that is more inclusive than exclusive, and the incorporation of current federal research programs that would benefit from the initiative. A CHIEF research initiative would do for ecological research what the USGCRP has done for atmospheric research: it would stimulate and better coordinate, at the highest administrative level, agency research programs in nutrient cycles, habitat changes, invasive species, and ecosystem functioning.

Recent progress has been so rapid, and the need for integration is so great, that the identity of key questions and the boundaries between disciplines need to be flexible at a level that has never been required in the past. The world is changing too rapidly for science to address the challenges of global change with traditional, incremental approaches.

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Appendix

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