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THE ROLE OF TERRESTRIAL ECOSYSTEMS IN GLOBAL CHANGE

A Plan for Action

Board on Global Change
Commission on Geosciences, Environment, and Resources
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Preface

In a series of reports over the past decade, the National Research Council (NRC) has outlined a broad scientific agenda to advance our understanding of the processes of global change. These studies stimulated and nourished the evolution of international efforts centered on the International Geosphere-Biosphere Program (IGBP) and the World Climate Research Program, and in our own country supported the development of the U.S. Global Change Research Program. As these programs move rapidly from concept to implementation, the NRC Board on Global Change has continued to critically assess the scientific needs. Is the scientific agenda truly comprehensive? Are the priorities appropriate in terms of needs for understanding scientific opportunities, and technological possibilities? Are there gaps that should be and could be filled? Can recommendations be usefully sharpened and focused?

To address such questions, our board organized extended ad hoc consultations in a few selected problem areas with informal groups of experts from the scientific community. The domain of terrestrial ecosystems is clearly central to any discussion of global changes induced by or important to humanity. We live on the land and draw most of our sustenance from its natural and managed living ecosystems. The behavior of these systems in a changing world is thus of more than academic interest. Moreover, these systems powerfully influence the fluxes of energy, moisture, and substance between the land, ocean, and atmosphere that govern our global environment. It is, therefore, appropriate that terrestrial ecosystems have figured strongly in the NRC's studies and that a core project of the IGBP is devoted to global change and terrestrial ecosystems. But what specific research initiatives could be proposed to improve understanding of the role of

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terrestrial ecosystems in global change? In August 1990, our previous chairman, Harold A. Mooney, requested the assistance of a talented group of active research scientists led by F. Stuart Chapin III to address these issues. At that time, "Ecological Systems and Dynamics" had been identified as one of the seven major science elements of the U.S. Global Change Research Program. However, specific research plans were lacking. The group was asked to assist in developing a brief report identifying those aspects of research on terrestrial ecosystems that contribute to an understanding of global change, together with scientific approaches to developing research plans. The indicated scope was broad, encompassing as examples both managed and unmanaged ecosystems, the role of biodiversity in ecosystem function, the terrestrial links between biogeochemistry and hydrology, and the responses of the terrestrial system to global change. The group was also asked to consider the U.S. response to the development of an IGBP core project on global change and terrestrial ecosystems.

We are very grateful to Professor Chapin and his collaborators for working with us to develop a set of specific foci for research in this central problem area. We also thank the following individuals who provided critical reviews of earlier drafts of this report: M.C. Chapin, J. Goudriaan, S.E. Hobbie, D. Hooper, A. Janetos, D. Jensen, P. Kotanen, P.A. Matson, J.E. Miller, H.A. Mooney, M. Power, W.T. Sommers, and B.H. Walker. We are also appreciative of the work of John S. Perry, Ruth S. DeFries, and Claudette Baylor-Fleming of the NRC staff in supporting this effort.

Ralph J. Cicerone, *Chairman*
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Summary of Recommended Research

To reduce uncertainty about the response of terrestrial ecosystems to global changes in climate and land use, and the effect these terrestrial responses may have on global climate, the U.S. Global Change Research Program should address six major questions as its contribution to the International Geosphere-Biosphere Program:

1. ***What are the interactive effects of changes in CO_2, climate, and biogeochemistry on the terrestrial carbon cycle and on food and fiber production?*** Within 10 years a focused research program could determine (1) the magnitude and general location of those carbon emissions to the atmosphere that become sequestered in terrestrial ecosystems and (2) the extent and conditions under which elevated CO_2 influences production.
2. ***What factors control trace-gas fluxes between terrestrial ecosystems and the atmosphere?*** Within 5 to 10 years an experimental research program could determine the major controls over fluxes of radiatively important trace gases from the terrestrial biosphere, yielding an explanation for current rapid increases in these gases in the atmosphere.
3. ***What are reasonable scenarios of the future distribution, structure, and productivity of both managed and unmanaged ecosystems based on changes in land use, disturbance regime, and climate?*** Two to 5 years should be adequate for development of a strong theoretical framework and understanding of the links between the natural and social sciences that are necessary to predict the future distribution and structure of terrestrial ecosystems. Within 10 to 20 years models that project future productivity and the role of terrestrial ecosystems in global

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processes should be sufficiently realistic to serve as a strong basis for management decisions affecting the rate of global change.

4. ***How will global change alter biotic diversity and what are the ecosystem consequences?*** Within 2 to 5 years a theoretical framework and research plan could be developed through workshops that could, in the long term (10 to 20 years), explain the major ecosystem consequences of losses of biotic diversity and provide programs to maintain or restore the ecological functioning of damaged ecosystems.

5. ***How will global change affect biotic interactions with the hydrologic cycle and surface energy balance?*** Within 5 to 10 years models should be sufficiently realistic to describe how changes in the physiology and structure of vegetation affect regional and global water balance and climate.

6. ***How will global change affect biotic controls over transport of water, nutrients, and materials from land to freshwater ecosystems and to coastal zones of the ocean?*** Within 2 to 5 years a research plan and theoretical framework can be expected that will identify the role of aquatic ecosystems in the global carbon cycle. Within 10 to 20 years our understanding should be sufficiently advanced to predict how global change will affect the flux of materials through aquatic systems to the ocean and the impacts this will have on the global carbon cycle, aquatic species composition, and the productivity of fisheries that affect the human carrying capacity of the earth.

Within each of these six major research topics, this report presents a general research program that prioritizes topics according to their potential to reduce uncertainty about the role that terrestrial ecosystems play in global change over time scales of decades to centuries. Three elements are highlighted for immediate action because they are key components of the terrestrial research program that are unlikely to proceed without focused attention:

a. ***Experiments that determine ecosystem responses to interactions among elevated CO_2, temperature, water, and nutrients.*** This program requires establishment of large-scale expensive field experiments in selected managed and unmanaged ecosystems to determine how the response of entire ecosystems to elevated CO_2 is constrained by temperature, water, and nutrients. The experiments required are well defined so that an experimental program can be implemented immediately. These are the most critical experiments required to improve our understanding of the response of terrestrial ecosystems to climate change and of the feedbacks to climate. Because of the expense and magnitude of these experiments, they cannot be implemented without focused attention.

b. ***Research to predict the role of landscape-scale processes, especially disturbance and land-use change, in governing the future structure and distribution of ecosystems.*** Because the socioeconomic and ecological disciplines required to accomplish this task are not well integrated, work should begin with

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interdisciplinary workshops to define the major uncertainties and research required to establish a strong theoretical framework. In the coming decades, human alterations of land use and disturbance regimes will have the largest impact on the terrestrial biosphere. Without explicit study of this phenomenon, the consequences of these changes for the earth system cannot be predicted, nor can informed policy decisions be made that would modify this human impact.

c. ***Research to determine how changes in species composition (e.g., invasion or extirpation of species or functional groups with strong ecosystem impacts) affect the functions of managed and unmanaged ecosystems.*** This activity should also begin by synthesizing existing information and convening workshops to develop research approaches. This program is critical because habitat destruction, human introductions of exotic species, and rapid climate change are causing rapid changes in species composition and loss of species diversity. Yet, these changes cannot be predicted, and little is known about their ecological consequences.

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1

Introduction

Terrestrial ecosystems provide most of the food, fodder and fiber that support human populations. The freshwater ecosystems embedded in terrestrial landscapes provide water for drinking, industry and agriculture, and the coastal zones of the ocean provide important fisheries. Human-induced global environmental changes—encompassing changes in climate, land use, water, soil, and atmospheric chemistry—challenge the ability of the biosphere to support the world's growing human population. Changes in land use, for example, will increase the proportion of land area overtly managed by humans, with implications for the long-term ability of the soil to sustain productivity. Direct CO_2 effects on vegetation and indirect effects due to changes in temperature and precipitation have both obvious and subtle implications for agriculture and forestry. These changes in ecosystems have important consequences for the earth system—through changes in fluxes of water, energy, CO_2, and trace gases to the atmosphere. The rising human population, with its doubling time of 40 years, advances in technology, and the increasing per capita impacts of human populations on natural systems are the basic causes of most recent large-scale changes in terrestrial ecosystems. It is imperative, therefore, that our understanding of the nature and consequences of these changes be improved rapidly in order to generate meaningful policy options and to ensure human persistence in a sustainable biosphere (Lubchenco et al., 1991; NRC, 1991).

Several efforts are under way nationally and internationally to coordinate research aimed at understanding how ecosystems will respond to global environmental changes over the coming decades and centuries (see Appendix). The U.S. Global Change Research Program (USGCRP) includes "Ecological Systems and

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Dynamics" as one of the seven science elements (CEES, 1990). The International Geosphere-Biosphere Program (IGBP) includes a core project on Global Change and Terrestrial Ecosystems (GCTE) whose objectives are "to develop the capability to predict the effects of changes in climate, atmospheric CO_2, and land use on terrestrial ecosystems, and how these effects can lead to feedbacks to the physical climate systems" (IGBP, 1990a). The Human Dimensions of Global Environmental Change Programme, the social science counterpart to IGBP at the international level, includes research on economics, societal development and land use.

In 1990 the Committee on Global Change, predecessor group to our board, initiated an effort to identify those aspects of research on terrestrial ecosystems that contribute to an understanding of global change and to define scientific approaches to the development of research plans for this element of the USGCRP. Specifically, the group assembled to address these tasks was charged to:

1. develop scientific priorities for U.S. contributions to the IGBP projects related to terrestrial ecosystems (i.e., core projects on GCTE and Global Change and Ecological Complexity);
2. identify specific priorities and research strategies for the USGCRP science element on "ecological systems and dynamics," taking full account of existing plans for the program; and
3. ensure involvement of the ecological community in defining the scientific priorities for global change research related to terrestrial ecosystems.

In view of this charge, this report identifies major research initiatives for the USGCRP where substantial progress could be made within the next decade in reducing uncertainty about the responses of terrestrial ecosystems to global changes in climate, land use, and the feedbacks of ecosystem charges to climate. These initiatives, which represent the initial U.S. contribution to the IGBP core projects, would be a step toward acquiring the ecological knowledge needed to ensure the sustainability of the biosphere, which is a research priority of the Ecological Society of America (Lubchenco et al., 1991). A secondary objective of this report is to outline ways in which the agricultural and ecological scientific communities can contribute to improved prediction of the role of terrestrial ecosystems in global change.

Selection of research approaches was guided by several themes:

- Traditional distinctions between studies of managed and unmanaged ecosystems must be overcome. Methods and theories used to study managed ecosystems must be applied to unmanaged systems, and vice versa.
- An understanding of species interactions and interactions among ecosystems in a landscape is critical to prediction of the role of terrestrial ecosystems in global change. Thus, methods and theories from specialties ranging from agronomy to population, community, and landscape ecology need to be integrated.
- Freshwater, estuarine, and coastal marine ecosystems are explicitly in-

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cluded in the definition of "terrestrial" ecosystems because they are integrally linked through biogeochemical and hydrological fluxes and have not been included in IGBP programs developed to study the oceans or the atmosphere—the other major components of the earth system.

- The ecological, economic and cultural forces causing human population growth and land-use change must be included in models designed to predict terrestrial responses to global change.

Many previous reports have described extensively the rational and potential designs for global change research in terrestrial ecosystems (e.g., IGBP, 1989, 1990a, 1990b; Schimel et al., 1989; Stern et al., 1992). The present report builds on this research planning and sets priorities among this large range of important topics by focusing on those research efforts that will contribute most within the next decade to improved understanding of the role of terrestrial ecosystems in global changes of the earth system. Many of these research levels are currently progressing at both national and international levels, but others will require new research initiatives.

A central theme of this report is the development and use of comprehensive models of ecological and physical systems. Current general circulation models, some of which include the surface biota in a highly parameterized fashion, have widely acknowledged deficiencies, and their ability to predict responses to unprecedented long-term changes is as yet untested. Nevertheless, these models represent the best available methodology for linking our small-scale understanding of ecological processes with our understanding of the large-scale processes determining climate.

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2

Role of the Terrestrial Biosphere in the Earth System

RECENT ADVANCES

The terrestrial biosphere plays a central role in global change as the cause of anthropogenic changes in the atmosphere and as the point of many critical feedbacks that govern the behavior of the earth system. In this section recent advances in our understanding of the role of the terrestrial biosphere in the earth system are briefly reviewed. These advances give us confidence that continued research in this area can rapidly reduce uncertainty about future global change.

Rising atmospheric CO_2 concentrations, as documented in the 35-year measurement record on Mauna Loa (Keeling et al., 1989) and the 200-year ice core record (Neftel et al., 1985), demonstrate that human-induced changes in the terrestrial biosphere strongly influence atmospheric chemistry. Data from the geographic network of monitoring stations, when incorporated into tracer models based on general circulation models, and supporting data from oceans and forests suggest that the terrestrial biosphere of the northern hemisphere may exert a strong negative feedback on the rate of atmospheric CO_2 accumulation through increases in terrestrial carbon storage (Tans et al., 1990; Innes, 1991; Quay et al., 1992; Kauppi et al., 1992).

Human impact on the terrestrial biosphere is also largely responsible for the rapid increase in atmospheric concentrations of greenhouse gases other than CO_2 (e.g., methane, nitrous oxide; see Cicerone and Oremland, 1988; Schimel et al., 1989; Matson and Vitousek, 1990). Although methane production can be partially predicted from patterns of soil moisture, its transport to the atmosphere is strongly influenced by microbial oxidation at the soil surface and by transport through

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plants (Sharkey et al., 1991). In unflooded soils, nitrogen deposition and fertilization are reducing the strength of soils as a sink for atmospheric methane, thus contributing to rising atmospheric concentrations (Steudler et al., 1989; Mosier et al., 1991). Changing land use, particularly in the tropics, is a major contributor to increased nitrous oxide flux to the atmosphere (Matson and Vitousek, 1990). Together, increases in terrestrial sources of trace-gas flux (including consumption of fossil fuels) to the atmosphere (CO_2, CH_4, N_2O, chlorofluorocarbons) are largely responsible for the increased radiative forces that causes global warming.

The seasonal and geographic variations in terrestrial productivity can be qualitatively monitored with satellite-based remote sensing (Tucker et al., 1984), documenting the location and timing of terrestrial CO_2 uptake and demonstrating changes in the land use of the globe. Simulation models that predict productivity from climate and nutrient cycling are now much more sophisticated and testable than even 5 years ago (e.g., Parton et al., 1987; Pastor and Post, 1988; Running et al., 1989; Rastetter et al., 1991). When linked to geographic information systems, these models provide reasonable estimates of productivity and CO_2 flux on regional to continental scales (Vorosmarty et al., 1989; Burke et al., 1991). Global data bases of model inputs (e.g., biomass, soil carbon stores, physical properties) are being assembled and extrapolated globally with remote sensing (Matthews, 1983; Post et al., 1985; Botkin and Simpson, in press; Wessman et al., 1988; Aber et al., 1990). These models and data bases provide a means of predicting the current and future roles of the terrestrial biosphere as a source and/or sink of CO_2, trace gases, water, and energy that are, some of the major parameters responsible for global changes in the earth system.

Integration of confusing information from remote sensing, paleoecological studies and field research by means of models indicates that humans are substantially changing the productive capacity of the earth as a result of deforestation, pollution, overgrazing and other disturbances (Tucker et al., 1984; Schlesinger et al., 1990). For this reason the future behavior of the earth system cannot be predicted from simple extrapolation of its present response to climate. Research into factors governing sustainability of managed systems (NRC, 1991; Lubchenco et al., 1991) has provided information on the long-term consequences of different patterns of land use. The global extent of changes in land use and their socioeconomic causes (Stern et al., 1992) must be documented to predict how humans respond to and effect further changes in the earth system.

Major advances in our understanding of the role of the terrestrial biosphere in the earth system have come from whole-ecosystem experiments that document responses to CO_2 (Curtis et al., 1989; Hendrey and Kimball, 1990; Grulke et al., 1990; Mooney et al., 1991), acid rain (Schindler et al., 1990), and climate (Lauenroth et al., 1978; Chapin and Shaver, 1985). These experiments demonstrate that ecosystems are remarkably resistant to many environmental changes, but that critical thresholds exist, beyond which alterations in the environment cause dramatic, and often unexpected, changes in ecosystem function (Carpenter

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et al., in press). Thus, the future role of the terrestrial biosphere in the earth system cannot be predicted without understanding the internal controls over ecosystem response to the environment (Schimel et al., 1990).

In the past decade there have been major breakthroughs in understanding the roles of individual species in community and ecosystem processes. Certain species are strong interactors or "keystone species" that dramatically alter feedbacks with the atmosphere through changes in canopy structure, water use, trophic dynamics, nitrogen cycling, productivity, and disturbance regime (Vitousek and Walker, 1989; Bryant et al., 1991; Carpenter et al., in press). Paleoecological and experimental research demonstrates that each species has a unique distribution or growth response to climate (Davis, 1981; Chapin and Shaver, 1985; COHMAP, 1988) and that dispersal can limit the rate at which species come into equilibrium with climate (Davis, 1981). Consequently, predictions of the future distribution and productivity of ecosystems must incorporate understanding of environmental responses and controls over migration of individual species or functional groups of species (Pastor and Post, 1988).

Recent research has demonstrated the large impact of terrestrial vegetation on local and regional climate. The canopy structure and the physiology of individual plants govern water loss and energy budgets of vegetated surfaces (Jarvis and McNaughton, 1986; Rosenberg et al., 1989) in a way that can have dramatic and long-lasting effects on temperature and precipitation at regional and continental scales (Running et al., 1989; Shukla et al., 1990). Albedo of vegetation can also strongly influence regional climate (Schlesinger et al., 1990).

REMAINING UNCERTAINTIES

The brief summary presented above demonstrates that detailed knowledge of the terrestrial biosphere is essential to understanding the causes and consequences of global changes in the earth system. The rapid progress in understanding the global role of the terrestrial biosphere permits a focus on six key research questions that will substantially reduce uncertainty in predicting the response of the earth system to global change:

1. ***What are the interactive effects of changes in CO_2, climate, and biogeochemistry on the terrestrial carbon cycle and on food and fiber production?*** Previous research has largely ignored interactions of CO_2 with other factors and provides only limited evidence of CO_2 effects on ecosystem processes.

2. ***What factors control trace-gas flux between terrestrial ecosystems and the atmosphere?*** Current understanding is based on environmental correlations rather than on whole-ecosystem experiments.

3. ***What are reasonable scenarios of the future distribution, structure and productivity of both managed and unmanaged ecosystems based on changes in land use, disturbance regime and climate?*** Predictions of patterns of land use,

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disturbance regimes and species movements are critical to predicting the future rate of global change.

4. ***How will global change alter biotic diversity and what are the ecosystem consequences?*** Little is known about consequences of losses in biological diversity to ecosystems or to global processes.

5. ***How will global change affect biotic interactions with the hydrologic cycle and surface energy balance?*** The general understanding of physiological and canopy controls of plant-water relations must be integrated into landscape-level analyses.

6. ***How will global change affect biotic controls over transport of water, nutrients, and materials from land to freshwater ecosystems and to coastal zones of the ocean?*** The impact of global change on the integration of terrestrial, freshwater and coastal ocean ecosystems has received little attention.

For each of these six research topics the remaining uncertainties, the necessary research, and the timing and nature of results that can be expected from the research are described in Chapter 3. The new research programs needed are emphasized, as well as ongoing ones whose continuation is critical.

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3

Research Program

INTERACTIVE EFFECTS OF CO_2, CLIMATE, AND BIOGEOCHEMISTRY

The Problem

Since the beginning of the Industrial Revolution, the atmospheric CO_2 concentration has risen 21 percent (Houghton et al., 1990). This rise has led to predictions of increased global temperature and changes in the global hydrologic cycle that may already be occurring (Hansen and Lebedeff, 1987). However, atmospheric CO_2 concentration is increasing less rapidly than would be predicted from known rates of fossil fuel use, deforestation, and CO_2 uptake by the land and oceans (Houghton et al., 1990). Several lines of evidence based on interhemispheric gradients in atmospheric CO_2 concentration, intra-annual variations in atmospheric CO_2, models of ocean-atmosphere CO_2 exchange, and patterns of forest growth together suggest that the terrestrial biosphere of the northern hemisphere may be the sink for this "missing carbon" (Tans et al., 1990; Innes, 1991; Quay et al., 1992; Kauppi et al., 1992). However, current estimates of CO_2 exchange, based on carbon inventories of ecosystems and patterns of land-use change, suggest that the terrestrial biosphere should be a net carbon source (Houghton et al., 1990). Until the current global carbon budget can be balanced, there is little hope of predicting future changes in atmospheric CO_2 concentration and, therefore, the radiative properties of the atmosphere that will determine future climatic changes.

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One mechanism by which the terrestrial biosphere could sequester additional carbon is "CO_2 fertilization" of plant production. Many greenhouse studies and a few field studies of agricultural and natural ecosystems suggest that vegetation and soils could sequester much of the CO_2 added to the atmosphere by human activities (Curtis et al., 1989; Bazzaz, 1990; Idso and Kimball, 1991). Other ecosystem studies suggest that much of the terrestrial vegetation is so strongly limited by other resources that, in the short term, it shows little response to increases in atmospheric CO_2 (Mooney et al., 1991; Oechel and Billings, 1992). Until this issue is resolved, the nature or strength of the negative feedback exerted by the terrestrial biosphere on rising atmospheric CO_2 concentrations cannot be predicted, and global atmospheric models will be unable to project future climate. These CO_2 responses and their interactions with other environmental factors must also be known in order to predict future food and fiber production and, therefore, the human carrying capacity of the earth.

Current Efforts

The Global Change and Terrestrial Ecosystems (GCTE) project of the International Geosphere-Biosphere Program (IGBP, 1992) has developed a research agenda that includes study of the consequences of simultaneous changes of multiple resources for ecosystems (GCTE, focus 1). The project's research plan calls for a series of large-scale field manipulations of CO_2, temperature, nutrients and water coupled with measurements of changes at various levels of organization; including those at the physiological, population, community and ecosystem levels. The field manipulations are to be supplemented by controlled-environment experiments, as needed, to provide the mechanistic basis for process models. More thorough documentation of current terrestrial carbon pools and fluxes also is a component of the IGBP plans. This compilation is essential to establish baseline conditions in regional and global models of biogeochemical cycles. Several research groups are now engaged in compiling such data.

Research Questions

A major question motivating this research is whether terrestrial ecosystems are a net source or sink for atmospheric CO_2. Is the net primary productivity of terrestrial ecosystems changing? To predict future changes in terrestrial carbon storage and its sensitivity to changes in climate, it must be known under what conditions (particularly conditions of temperature, nutrients and water), terrestrial ecosystems will respond to rising atmospheric CO_2 concentrations. How will experimental manipulations of ecosystems affect patterns of productivity and nutrient cycling, the competitive interactions among plants, and the interactions among plants, herbivores, pathogens, and other trophic levels?

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General Strategy

The international planning efforts for research that will increase our understanding of the interactive effects of changes in CO_2 and other resources at a variety of scales, ranging from physiological processes to whole ecosystems, merit strong support (IGBP, 1990a). Such research programs should emphasize whole-ecosystem experiments and associated process-based modeling in both managed and unmanaged ecosystems to clarify the importance of ecosystem-level feedbacks and indirect CO_2 effects. Research should be designed to test conceptual understanding of ecosystem processes and their response to environmental forcing. Carefully controlled greenhouse and laboratory experiments should focus on controls over specific processes that are shown to be critical in ecosystem responses. The field experiments should be accompanied by efforts to improve geographically explicit regional models of ecosystem function and biogeochemistry, using remote-sensing data to extend experimental results to large areas.

Research Program

The research program outlined here is discussed in greater detail in international documents (IGBP, 1990a, 1992).

1. GLOBAL CARBON POOLS AND FLUXES. ***Objective: To develop an inventory of dynamic terrestrial carbon pools and fluxes that is linked to global carbon models.*** Current estimates of terrestrial carbon pools should be used as input to process-based models that predict fluxes over broad regional areas. These flux estimates should then be linked to tracer models based on general circulation model (GCM) runs, using inverse modeling. (Inverse modeling is the process by which known outputs of a model—fluxes between the atmosphere and the biosphere in this case—are used as constraints on model behavior.) A remote-sensing program should be developed that is capable of estimating plant production on the basis of satellite observations validated by adequate field studies. Initially, this will require development and verification of relationships between vegetation reflectivity and production for different ecosystems due to regional and seasonal variations in leaf display. Carbon fluxes from land to freshwater and near-shore marine ecosystems should be quantified (see the section on land-water interactions at the end of this chapter). The global inventory should be maintained as a data bank available to the scientific public. The offices that house these data banks could serve as centers for ecosystem synthesis and modeling.

2. WHOLE-ECOSYSTEM RESPONSES. ***Objective: To determine the mechanisms by which linked plant-soil systems respond to simultaneous changes in CO_2, temperature, water, and nutrients—that is, critical environmental factors that may constrain ecosystem responses to rising atmospheric CO_2.*** This experiment will involve factorial field manipulations of these factors conducted for at

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least a decade, using free-air CO_2 enrichment (FACE) technology or large field greenhouses. Critical measurements include gross primary production, net primary production, changes in soil and plant carbon storage, litter quality, carbon and nitrogen mineralization by soil microbes, nitrogen loss to groundwater, trace-gas fluxes, evapotranspiration, water and nutrient use efficiencies, reproductive output, phenology, and changes in species composition of plants and animals. To explain the mechanisms by which species composition changes in whole-ecosystem experiments, supplementary experiments examining species interactions such as competition, disease, herbivory, and plant-microbe interactions may be necessary. Particular attention to below-ground processes is warranted. Experimental work should begin in ecosystems where nutrients, water, or temperature constrain CO_2 response (e.g., semiarid grasslands or dryland wheat, where CO_2-water-nutrient interactions are probably important, or temperate forests, where changes in wood or woody litter could affect carbon storage and nitrogen availability). Other critical ecosystems with greater logistical challenges that should be addressed include tundra and boreal forest, which may respond sensitively to climate change, and whose large carbon stores are potentially strong positive feedbacks to global climate. A range of approaches should be considered to alter CO_2 concentration, particularly FACE arrays and large field-installed greenhouses. The FACE arrays provide more natural conditions of wind, humidity, animal movement and the like, but make it difficult to manipulate air temperature.

3. BELOW-GROUND RESPONSES. ***Objective: To determine how interactions between elevated CO_2 and temperature, water, and nutrients affect below-ground processes***. Experimental work and process-based models should clarify mechanisms and conditions under which elevated CO_2 increases carbon flux to soils, and the consequences of this increase for nutrient availability and carbon storage, and for interactions among plants, mycorrhizal fungi, pathogens, below-ground herbivores, and decomposer organisms.

4. WHOLE-PLANT RESPONSES. ***Objective: To determine how simultaneous changes in CO_2, temperature, water, and nutrients affect plant growth and yield.*** Experiments should be undertaken where necessary to explain the results of the whole-ecosystem experiments described above. Experimental work should be closely integrated with process-based modeling to predict plant growth and competitive balance on the basis of whole-plant carbon and nutrient allocation and water use. The use of isotopes, both stable and radioactive, may be required in these studies. Where necessary to explain whole-plant performance, controlled-environment experiments and associated models should explore organ and cellular processes (e.g., stomatal conductance, respiration, root exudation). In managed systems these experiments should be conducted on critical crop and forest species (IBSNAT, 1989; IGBP, 1989). Similar lists should be developed for representative functional groups of wild plants, as mentioned in the section on ecosystem distribution later in this chapter.

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Status and Priorities

There has been considerable research on single-factor CO_2 effects on plants under controlled-environment conditions. At present, the greatest uncertainty in predicting the role of the terrestrial biosphere in the global carbon cycle is knowing to what extent low nutrient or water availability constrains the response of ecosystems to elevated CO_2 and temperature. Therefore, the highest research priority should be accorded to several whole-ecosystem experiments in which CO_2 is manipulated in combination with temperature, nutrients, and water in both managed and unmanaged ecosystems. Research in managed ecosystems is critical to predicting and sustaining future yields of food and fiber. Because unmanaged or little-managed systems comprise most of the terrestrial biosphere, their response to elevated CO_2 and temperature is critical to global predictions of terrestrial CO_2 responses. Ecosystem experiments should be supplemented by controlled-environment experiments to address specific questions raised by the whole-ecosystem experiments. Knowledge and technical expertise are currently sufficient for the initiation of such experiments immediately in logistically tractable managed and unmanaged ecosystems. Whole-ecosystem manipulations in other ecosystems could be phased to build on experience gained initially. Such research efforts will be expensive; each experiment will require about $2 million annually (IGBP, 1992). Within 10 years this research program should provide the information necessary to predict the conditions under which elevated CO_2 alters (1) production of food and fiber and (2) the role of the biosphere as a feedback to atmospheric CO_2.

An additional area of high priority is the development and validation of remote-sensing procedures to estimate productivity and soil processes on a regional scale. These measurements could provide validation for the substantial data on terrestrial carbon pools that are currently being synthesized, mapped and used in process models to predict global carbon fluxes. They would also provide a direct measure of the extent to which the productivity of the biosphere is being sustained. Together these programs should determine the extent to which terrestrial ecosystems constitute the missing sink for CO_2.

CONTROLS OVER TRACE-GAS FLUX TO THE ATMOSPHERE

The Problem

During the past decade, there has been increasing awareness of how strongly the physical and chemical properties of the earth's atmosphere are influenced by biologically mediated trace-gas exchanges between the land and the atmosphere. Microbial processes in soils play a major role in the generation and/or consumption of CH_4 and N_2O, greenhouse gases that are accumulating in the atmosphere at

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annual rates of 0.9 percent and 0.25 percent, respectively (Houghton et al., 1990). These microbial processes respond to a variety of environmental factors, including soil temperature, moisture, redox, and nutrient status. At present, the responses of trace-gas fluxes to simultaneous changes in these variables cannot be adequately predicted. For this reason, the major causes of the increases in atmospheric concentrations of biogenic trace gases are not known, and the isotopic budget of methane, a major trace gas, is severely out of balance given current estimates of sources and sinks (Cicerone and Oremland, 1988).

Other Current Efforts

The International Global Atmospheric Chemistry (IGAC) project of the IGBP has developed a comprehensive research agenda that includes research on the biological controls of trace-gas fluxes in high-latitude, temperate, and tropical ecosystems (IGBP, 1990b). Research on ecological controls over trace-gas flux is being planned by the biogeochemistry activity of GCTE. Research planned at high latitudes includes surveys, environmental correlation studies, and mechanistic process studies, all emphasizing CH_4. In the temperate zone, the IGBP programs focus on exchanges of N_2O, CH_4, CO, and CO_2 between natural and managed ecosystems and the atmosphere. The IGBP tropical program focuses on the effects of land-use change and rice agriculture on exchanges of NO, N_2O, CH_4, CO, and CO_2. The information available on patterns of trace-gas flux between terrestrial ecosystems and the atmosphere has expanded dramatically in the past 5 years, but much less is known about the controls over these fluxes under natural conditions.

In high-latitude, temperate, and tropical regions, the GCTE project of the IGBP is recommending whole-ecosystem manipulations to study the consequences of changing environmental variables on trace-gas fluxes.

Research Questions

The major research question is: What is causing the rapid increase in trace-gas flux from terrestrial ecosystems to the atmosphere? In tundra and boreal forests, where soils contain large stocks of potentially decomposable carbon, the most critical question is: How does soil warming, soil drainage, and their interaction affect CO_2 and CH_4 fluxes from soils? A recent National Science Foundation-sponsored workshop evaluated experimental approaches and recommended sites for soil-warming experiments. In temperate forest and grassland soils and upland boreal soils, which are CH_4 sinks and sources of N_2O (Steudler et al., 1989; Mosier et al., 1991; Whalen et al., 1991), a key research question is: How will increases in temperature and precipitation, as well as increases in nitrogen deposition from acid rain and agricultural fertilization, affect the uptake of CH_4 and the release of N_2O? How are these processes affected by conversion from

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unmanaged to agricultural systems or by management practices? In the tropics, where land-use change causes major changes in trace-gas flux (Matson and Vitousek, 1990), critical questions are: How does temperature, moisture, and nutrient availability change at various times following forest clearing and pasture abandonment? How do these changes affect fluxes of CO_2, CO, CH_4, N_2O, and NO?

General Strategy

The research program developed internationally by the IGAC and GCTE (IGBP, 1990a, 1990b) merits strong support. This program emphasizes (1) experimental and modeling studies of biotic controls over trace-gas fluxes in natural and managed systems and (2) inverse modeling, which links information from terrestrial ecosystems with global atmospheric budgets.

Research Program

The research program outlined here is discussed in greater detail in international documents (IGBP, 1990a, 1990b).

1. LINKAGE TO GLOBAL ATMOSPHERIC MODELS. ***Objective: To determine the major terrestrial sources and sinks for trace-gas exchange with the atmosphere.*** Inverse modeling using tracer models based on GCM runs should be done to estimate the general location and magnitude of terrestrial sources and sinks for trace-gases. This modeling would provide a basis for allocating efforts in regional experimental studies and studies that measure trace-gas fluxes at a variety of scales (e.g., the National Aeronautics and Space Administration's Boreal Ecosystem-Atmosphere Study [BOREAS] project). Better information on the isotopic composition of terrestrial trace-gas sources will be required to fully implement a program in inverse modeling.

2. CH_4/CO_2 FLUXES FROM TUNDRA AND BOREAL WETLANDS. ***Objective: To determine how changes in temperature and hydrology affect CH_4 and CO_2 fluxes from tundra and boreal wetlands to the atmosphere.*** Laboratory microcosms, field manipulations, and latitudinal transects should be used to determine how changes in temperature and hydrology interact to affect CH_4 and CO_2 exchanges between wetlands or lakes and the atmosphere. For example, a northern wetlands ecosystem should be drained and warmed in factorial combination; measurements of controlling variables, including temperature, moisture, redox, pH, and nitrogen availability, would be made over time, along with measurement of CO_2 and CH_4 fluxes. Studies should be designed to consider spatial heterogeneity at the watershed and regional scales, as well as seasonal variations in environment. For high-latitude ecosystems and for the regional studies described below, the results should be synthesized into process-based models of trace-gas produc-

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Role of Terrestrial Ecosystems in Global Change: A Plan for Action
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tion, consumption, and transport, and these models should be coupled with data bases organized in a geographic information system (GIS) to estimate regional trace-gas fluxes under various scenarios of future climate. Particular attention should be paid to nonlinearities and thresholds in the response of trace-gas fluxes to the environment because these responses cannot be predicted from observations over a limited range of conditions.

3. CH_4/N_2O PRODUCTION/CONSUMPTION IN UPLAND TEMPERATE ECOSYSTEMS. ***Objective: To determine how changes in soil temperature, moisture, and nitrogen input affect CH_4 uptake and N_2O production by temperate and boreal forests, grasslands, and agricultural ecosystems.*** Possible field experiments include soil warming, precipitation exclusion, wet-up/dry-down plots, and nitrogen fertilization. Results from these studies should be used to develop process models of CH_4 and N_2O fluxes. Ultimately, these models should be linked with a regional GIS so that estimates of current regional CH_4 and N_2O fluxes, and the changes in these fluxes as a result of future climatic change and past agricultural conversion, reversion to forest, and acid deposition can be made.

4. TROPICAL LAND-USE CHANGE. ***Objective: To determine how clearing of tropical forests for crop and pasture, management of the latter systems and their abandonment affect the fluxes of CO_2, CO, CH_4, N_2O, and NO between soils and the atmosphere.*** Changes in soil fluxes of these gases and their controls should be linked to factors regulating carbon and nitrogen cycling in replicated managed sites (including grazing systems, dryland agriculture and rice paddies), fallow systems, and undisturbed forests and savannahs. Plots of different ages (i.e., a chronosequence) should be used to determine the time course of trace-gas flux following land clearing and pasture abandonment. Transects across precipitation and temperature gradients should be used to estimate patterns of environmental control. Examination of plots with different management regimes (e.g., for rice cultivation) will allow evaluation of different management practices. The results should be synthesized with process models and GISs to develop regional trace-gas exchange estimates for future regional land-use scenarios.

Status and Priorities

Most of the research areas described above are being actively investigated or plans to do so exist. Research to date has documented patterns of trace-gas flux and has led to hypotheses about environmental and biotic controls. The highest priority should be given to field manipulations and associated process-based modeling to test these hypotheses; and to inverse modeling, linking terrestrial sources and sinks to patterns of atmospheric changes in trace-gas concentrations. Field manipulation experiments and process-based models are essential to delineate controls over processes, which must be the basis of meaningful scenarios of future trace-gas flux. Inverse modeling provides constraints on current flux estimates.

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A clearly focused experimental and modeling program could determine the major causes of increased flux of trace gases to the atmosphere within 10 years.

Programs that document patterns of trace-gas flux have been useful in developing hypotheses about which regions and environmental controls are critical to global patterns of trace-gas flux. These programs should continue, now focusing on environmental gradients of factors that are expected to change with altered climate (e.g., latitudinal temperature and moisture gradients in northern regions, moisture gradients in semiarid grasslands, successional changes following land clearing in the tropics). These measurements should be closely tied to measurements of ecosystem processes so that controls over trace-gas flux can be linked to understanding of biogeochemical and carbon cycling (see the section on interactive effects of CO_2 and climate above).

FUTURE DISTRIBUTION AND STRUCTURE OF ECOSYSTEMS

The Problem

It is a major challenge to predict how the present ecosystems of the world will respond to global change. However, if predictions of GCMs are correct, the climate will change at least an order of magnitude more rapidly than at any time in the Pleistocene, probably more rapidly than many species can migrate (Houghton et al., 1990). As a result, future ecosystems will consist of new combinations of species, structured by new patterns of species interactions. Moreover, the world's future ecosystems will experience novel combinations of environmental factors, an altered disturbance regime, and exploitation by a larger human population. Patterns and intensity of land and water management for food, fuel, and fiber are highly responsive to human demand as well as to climate, but the ecological impact of a given rate of population growth will differ dramatically between societies (Stern et al., 1992). A critical challenge, therefore, is to predict the future distribution and structure of ecosystems and the resulting changes in energy balance, trace-gas flux, and hydrologic balance (Mooney et al., 1987; IGBP, 1990a).

Other Current Efforts

A three-tiered hierarchical modeling approach has been the major basis of the research planned by GCTE to predict the future structure and distribution of ecosystems (Prentice et al., 1989; NRC, 1990; IGBP, 1990a). In brief, the strategy consists of developing models of processes operating at patch, landscape, and regional scales. Patch-scale models describe the response of a relatively homogeneous community (e.g., a farmer's field or a forest stand) to changes in climate, atmosphere and land use. Patches interact through exchanges of soil, water and biological propagules, and through contagious disturbances such as fire and pest outbreaks. Finally, regional-scale models that predict the distribution of broadly defined vegetation types can be coupled to GCMs, allowing feedback between vegetation properties and atmospheric processes. Functional groups (i.e., a group of species with similar effects on ecosystem processes), have been characterized in aquatic and terrestrial ecosystems (Minshall et al., 1985; IGBP, 1990a), allowing generalized predictions of conditions necessary for successful establishment, growth, and reproduction. Research in the social sciences has begun to quantify the magnitude of the ecological impact of a given population size, technology, and growth rate (Meyer and Turner, 1992; Stern et al., 1992), and the changes in water use and agricultural output that result from altered climate (Rosenberg and Crosson, 1991). However, there has been little attempt to link socioeconomic predictions with ecological projections.

Research Questions

The major research questions in this section are: How can the future structure and distribution of terrestrial ecosystems be predicted as they change in response to global change? How will increasing CO_2 and climatic change alter the rate and extent of disturbances to influence the interaction and distribution of currently widespread species and of general types (functional groups) of organisms? What are the important biological factors (e.g., soil properties, seed banks, long-lived individuals) that respond slowly to global change and may modify the predicted changes in distribution of functional groups? What will be the rate and distribution of land-use change in the future? What social, cultural and economic factors govern the ecological impact of a given rate of human population growth? What are the impacts of land-use changes on climate, disturbance regime, and ecosystem structure and distribution?

General Strategy

Predictions of changes in ecosystem distribution should begin with species that are currently widespread dominants of major ecosystem types (e.g., trout, white-tailed deer, Douglas fir) and/or are of critical economic importance (e.g., major food or fiber sources), because a great deal is already known about these species and changes in their distribution will have profound biotic and economic consequences. Boundaries between major ecosystems are places where changes in species distributions may be detected most readily. More general predictions should focus on "functional groups" of wild and cultivated species, defined by properties that have predictable responses to soil resources, disturbance regime and land use (Hobbie et al., 1992). Models must be developed that predict changes in disturbance regime and land use as functions of human population growth, per capita ecological impact, and other aspects of global change (Rosenberg and Crosson, 1991). Because of the uncertainty of these predictions, it is more reason-

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able to develop alternative scenarios based on explicit assumptions than to attempt a single prediction based on many uncertainties.

Research Program

Human Impact on Ecosystems

1. PATTERNS OF LAND-USE CHANGE. ***Objective: To predict the rate and distribution of land-use changes.*** Socioeconomic models that predict these changes should be validated with historical data and satellite observations of current trends and used to predict ecosystem structure, landscape structure, and dispersal of organisms. These efforts should be focused in areas where land-use changes (including altered management practices) are causing the greatest change in ecosystem structure (e.g., tropical forests, arid grasslands, and temperate agricultural fields that are reverting to forests) and where land-use change might cause the greatest atmospheric feedbacks (e.g., tropical wet forest, boreal forest).

2. INTERACTIONS BETWEEN CO_2-INDUCED ENVIRONMENTAL CHANGE AND LAND-USE CHANGE. ***Objective: To predict how CO_2-induced environmental change may alter rates or patterns of land-use change.*** Models that predict the biological consequences of changes in climate and CO_2 should be linked to socioeconomic models in order to predict changes in human population growth, water use, and land use (Rosenberg and Crosson, 1991). For this linkage to be successful, the ecological models must include probabilities of critical ecological or agricultural catastrophes as a function of climate variability and land use. The feedbacks of these changes on climate and atmospheric composition similarly require attention.

Climatic Effects on Ecosystems

1. FORECASTS OF FUTURE DISTRIBUTION AND PRODUCTIVITY OF CURRENTLY DOMINANT SPECIES. ***Objective: To develop empirically based models that predict changes in distribution and productivity of species that are currently widespread community dominants or are critical as sources of food or fiber.*** Observations at current limits of distribution and transplant experiments within and beyond the current ranges of these species can suggest the climatic and biotic controls over establishment, growth, reproduction, and mortality. Such baseline information can be used to design controlled-environment or field transplant experiments in which species' responses to temperature, water, CO_2 and nutrients, as well as the interactions of these factors with pathogens and herbivores, are quantified (see the carbon-cycle section at the beginning of the chapter). For crop species those changes in productivity and allocation that determine economic yield should be emphasized.

Experimental results should be synthesized by modeling to predict (1) to what

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extent genetic and physiological plasticity can allow species to sustain productivity despite altered climate and (2) how the distribution of these species and the nature of species interactions might respond to changes in climate, water supplies, and other environmental factors such as ozone, UV-B, and nitrogen deposition. These species-specific scenarios provide a basis for monitoring at community boundaries those parameters that would be the most sensitive indicators of biotic response to climatic change. In the case of crop species, the scenarios will provide critical information relevant to the sustainability of human populations.

2. CLIMATIC CONTROLS OF FUNCTIONAL GROUPS. ***Objective: To predict how functional groups of soils and organisms respond to a changing environment.*** Beginning with information on the widespread and/or critical species described above, species should be combined into functional groups according to general patterns of response to environmental resources (e.g., water and nutrients) and life-history traits determining migration. The predictive value of grouping species or soils into functional groups should be tested, and models incorporating climate responses to predict the future distribution of these types should be validated against the paleoecological record. Predictions of changes in energy and water balance and in CO_2 and trace-gas flux resulting from altered vegetation structure due to novel combinations of species should be incorporated into GCM projections. The functional group approach is intended to complement the individual species approach (described in paragraph one above), in situations where the physiological and population traits of individual species are poorly known or when computational constraints limit the number of taxa that can be considered in integrated vegetation/climate models. The criteria used to define functional groups must be flexible and will change depending on the specific goals, scales, and geographic location pertinent to the research question.

Rates and Patterns of Community Change

1. DISTURBANCE EFFECTS ON ECOSYSTEM STRUCTURE AND DISTRIBUTION. ***Objective: To predict the relationship between climate or resource management and the type, extent, and ecological consequences of disturbance.*** Paleoecological data (e.g., fire scars in trees, charcoal in lake sediments) and historical data should be the basis of models that predict the type, extent, frequency, and consequences of disturbance from information on climate, resource management practice (e.g., fire suppression, thinning), and human modification of the landscape (e.g., urban encroachment, road networks). Similarly, floods, droughts and species invasions can be critical disturbances to aquatic systems. These models should incorporate climatic and land-use forcing functions, ecosystem feedbacks and species interactions (e.g., insect outbreaks) that modify the disturbance regime; and processes governing the abundance of both juvenile and mature individuals.

2. MIGRATION RATES. ***Objective: To determine factors that govern rates of species movement.*** Rates of species movement in response to past changes in

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climate can be deduced from fossil pollen data. Historical data on rates of movement of invading exotic species can be used to deduce spread rates under conditions of human disturbance. Such data should be combined with general considerations of life-history traits, germination and seedbed requirements (water-flow requirements for aquatic species), dispersal mechanisms, and successional status to formulate general models of the potential migration rates of species and functional groups under changing climate regimes and human use of the landscape. Both changes in mean conditions and changing frequencies of extreme events need to be considered in modeling climatic constraints on species movement.

3. BIOLOGICAL LEGACIES. ***Objective: To determine the importance of biological legacies (e.g., soil properties, seed storage in soils, long-lived individuals, mycorrhizal inocula) in altering rates of ecological change.*** Field experiments and modeling should be combined to predict the importance of biological legacies. For example, the patterns and rates of change in soil properties following transplant into different climatic zones should be determined.

Status and Priorities

There has been considerable research in all of the above areas, particularly in forestry and aquatic systems, but it has not been generalized in a fashion that allows broad predictions for the globe. Priority should be given to synthesis and modeling focused on processes likely to cause large functional or structural changes in ecosystems. The following areas are particularly critical:

- predicting the types and magnitude of human impact on terrestrial ecosystems;
- determining the role of CO_2 concentration and climate, as mediated by species interactions, in governing future distribution of currently widespread species and of generalized functional groups; and
- understanding the role of landscape-scale processes, especially disturbance and land-use change, in governing ecosystem change. Modeling should be supplemented by monitoring of regions thought to be particularly sensitive to changes induced by increased CO_2 concentrations (particularly at community boundaries) and regions in which changes may feedback to climatic change.

With 2 to 5 years of research focused on the development of a strong theoretical framework and links to the social sciences, it should be clear what types of research are necessary to predict the future distribution and structure of terrestrial ecosystems. Within 10 to 20 years, models that project future productivity and the role of the biosphere in the earth system should be sufficiently realistic to serve as a solid basis for management decisions affecting the rate of global change.

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GLOBAL CHANGE AND ECOLOGICAL COMPLEXITY

The Problem

Ongoing global changes in ecological diversity resulting from land-use change and species introductions will probably be exacerbated by future atmospheric and climatic changes. Loss of biological diversity is the least reversible of the many ongoing and anticipated global changes to terrestrial ecosystems. While changes in the atmosphere and climate are reversible on the time scale of centuries, and land degradation may be reversed on a similar scale, the loss of species is truly permanent. However, as yet there is neither a clear understanding of the interaction between global change and biological diversity in terrestrial ecosystems nor a coherent program to develop such an understanding. Diversity is directly important to people for aesthetic and recreational reasons and because it provides a wide range of plant and animal products critical to human societies.

Other Current Efforts

The effects of global change on ecological diversity have received considerable attention, notably, but not wholly focusing on loss of species diversity. Agronomists are concerned that the genetic base of major crops is being narrowed dangerously. Taxonomists and population ecologists have proposed urgent national and international efforts to address the loss of genetically distinct populations, subspecies, and species—many of which have not been and may never be cataloged. Community and ecosystem ecologists are concerned about changes in landscape diversity and their consequences. Aquatic ecologists have analyzed the interactions among eutrophication, toxic contaminants, and species alterations in regulating the structure and functioning of freshwater and intertidal ecosystems. All of these changes have been driven primarily by human-caused changes in land use and industrialization, and this is likely to remain the major component of global change for some decades. However, climatic and atmospheric changes loom as increasingly important factors. This is true because (1) while the present species have persisted through glacial/interglacial cycles of climate and atmospheric change, the predicted changes are both more rapid and outside the bounds of glacial/interglacial cycles (Houghton et al., 1990) and (2) the migration of species in a human-dominated landscape will differ qualitatively from that in earlier times of rapid climatic change.

The other area of concern, the effects of ecological complexity (i.e., genetic diversity in populations, species diversity, landscape diversity) on ecosystem function, has received less attention. Global change and ecological complexity is a focus within GCTE that will consider both the effects of global change on complexity and the effects of complexity on ecosystem function (IGBP, 1990a).

A Scientific Committee on Problems of the Environment (SCOPE) project

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has been established to address the effects of ecological complexity on ecosystem function. It is designed to review and synthesize knowledge in the field. Following an initial meeting to define issues and set directions, this project will organize 12 system-based meetings and syntheses, followed by an overall synthesis. The IGBP-GCTE steering committee will use results from the SCOPE process as it develops to define research needs in its core program.

Research Questions

Although it is well established that human activity is causing a loss of diversity within and among species as well as an increase in landscape diversity, there is little ability to predict the patterns and consequences of these changes. Several major questions arise: Are there predictable patterns of change in ecological diversity—by level of diversity, functional or taxonomic group, or region? Are there components of global change that are particularly important to ecological diversity (e.g., the breakdown of barriers to species dispersal caused by human travel, or the erection of such barriers by land use or dams)? Once ecological and genetic diversity has been lost, can it be restored? What controls the rates at which diversity is generated? To answer these questions it is critical to integrate scenarios of land-use change with ecological predictions.

There is even less basis for predicting how changes in ecological diversity will affect the functioning of ecosystems. Does there exist a threshold for diversity within functional groups (defined here as groups of organisms that perform an ecosystem function), above which diversity has no further detectable effects on ecosystem function? If so, do managed ecosystems exhibit these effects?

General Strategy

The two-pronged approach to this problem involves (1) determining how global change (particularly land-use change) affects ecological and genetic diversity at population, species, and landscape levels and (2) identifying the thresholds at which changes in ecological diversity feedback to alter patterns of human activity and climate and the nature of the feedback.

Research Program

1. LOSS OF GENETIC DIVERSITY. ***Objective: To determine the causes and consequences of the loss of genetic diversity associated with global change.*** Information from managed systems should be synthesized to establish the effects of management practice on genetic diversity of critical crops, fisheries, and timber species over their geographic ranges to determine what causes such loss. The relationship of the genetic diversity of a crop species to the range of conditions under which it can grow should be examined, with emphasis on important food

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crops in Third World countries. The relationship between genetic diversity and climatic tolerance should then be examined in long-lived wild species to predict how much climatic change a given species might tolerate without migration or extinction. Genetic models should seek to identify the factors governing rates of evolutionary change as well as management approaches that will reduce probabilities of extinction for different types of species.

2. PATTERNS OF CHANGE IN SPECIES DIVERSITY. ***Objective: To predict future patterns of change in species diversity.*** Information on past and present patterns of species extinctions and endangerment should be synthesized to rules and models that predict (1) what kinds of species are most prone to extinction resulting from global change and (2) what types of habitat fragmentation and change are most likely to cause species extinctions or speciation. Because one can never hope to catalog all the species that are being lost, it is essential that the factors controlling species extinction be determined so that extinction rates can be minimized. Traits that might influence extinction are as diverse as trophic level, human utility, population size, home range, habitat complexity, habitat or biome type, or number of species in a functional group or community. At the same time, political and economic scenarios of future land-use patterns should be linked with ecological models of populations and communities to predict those community types that are particularly vulnerable to species extinction.

3. ECOSYSTEM CONSEQUENCES OF SPECIES DIVERSITY. ***Objective: To determine the ecosystem consequences of changes in species diversity.*** The ecosystem consequences of changes in species diversity can be addressed using species addition/removal experiments (including simplified managed systems) in conjunction with modern ecosystem-level measurements of functions. Such studies should emphasize those ecosystem functions that will alter terrestrial feedbacks to the atmosphere or interactions among landscape units, or cause further changes in ecological diversity. Particular attention should be paid to the impact of diversity within as well as between functional groups and to thresholds of diversity below which ecosystem function is seriously impaired. The purpose here is to identify the types of species that are critical to ecosystem function and the extent of species diversity required to ensure that these functions can be maintained.

4. CHANGES IN SPECIES INTRODUCTION/MIGRATION. ***Objective: To predict patterns of genetic and species diversity in a world with fewer barriers to species introduction but more barriers to migration.*** Paleoecological studies can now be integrated with studies of current population processes to determine the controls over species migration into new communities. While it has proved difficult to predict which species will establish new populations, models should be developed to predict which types of species are most likely to establish populations beyond their current ranges and the ecological and human cultural factors that most strongly influence these probabilities. Historical, observational, and experimental studies should examine the effects of migration and exotic introductions on ecosystem function.

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http://www.nap.edu/catalog.php?record_id=18688

5. CHANGES IN PATTERN OF LANDSCAPE DIVERSITY. ***Objective: To predict future patterns of landscape diversity and their significance for the functioning of landscape units.*** Observational studies can now take advantage of past human alterations of landscape diversity to examine what types of landscape units are most sensitive to changes in the size and arrangement of patch types within a landscape or barriers such as chains of rivers and lakes. Predictions of future patterns of landscape diversity will need to make use of socioeconomic models of human populations and land use, as well as the developing understanding of patch interactions on a landscape scale. These models can be compared with satellite data on habitat fragmentation.

6. RECOVERY AND RESTORATION OF ECOSYSTEM DIVERSITY. ***Objective: To develop principles leading to practical programs to restore ecological diversity.*** Principles developed in forestry and aquatic ecology (NRC, 1991) should be generalized to determine how management practice, abandonment of managed systems, species interactions, and natural succession alter ecological complexity at all levels (genetic diversity to landscape diversity). Innovative programs will be needed that use basic ecological principles to speed the recovery of ecological complexity. These studies are critical if the ecological impacts of global change are to be mitigated.

Status and Priorities

There are programs and scientific consortia actively concerned with most factors governing ecological diversity. However, many of these studies have been oriented toward a basic understanding of ecological diversity rather than toward predictions of how it will respond to changing climate and land use or how changes in ecological diversity influence ecosystem function. The most rewarding approach would be a program designed to determine causes of loss in diversity and its consequences for feedbacks to land use, water quality, biogeochemistry, and atmospheric chemistry.

This program should begin with workshops to synthesize the current state of knowledge and to define critical experimental and modeling approaches (an effort already initiated by SCOPE) that can be rapidly implemented. These workshops should emphasize species diversity because this is the level at which ecological diversity is being lost most irrevocably.

A second high-priority area is the development of protocols to maintain and restore ecological diversity that are based on existing expertise in forestry and aquaculture. Understanding of the importance of genetic and landscape diversity is less mature and will require a phase of workshops to develop critical research agendas.

Within 2 to 5 years a theoretical framework could be constructed through workshops and research initiated that could, in the long term (10 to 20 years),

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explain the major ecosystem consequences of losses of biotic diversity and provide programs to maintain or restore effective functioning of damaged ecosystems.

BIOTIC EFFECTS ON WATER AND ENERGY BALANCE

The Problem

Global environmental change introduces new uncertainties in predicting the future water supply, a parameter that is critically important in determining how ecosystems and human societies function. Although GCMs predict that precipitation patterns will change (Houghton et al., 1990), there is wide disagreement about the direction and degree of change. A change in precipitation would have far-ranging impacts for streamflow, groundwater recharge, and the characteristics of terrestrial ecosystems. These changes in ecosystem properties feedback to affect the partitioning of energy at the earth's surface, altering sensible heat flux and evapotranspiration. These changes in water and energy balance, if extensive enough, can affect regional and possibly global climate (IGBP, 1990b; Shukla et al., 1990; Schlesinger et al., 1990). Soil-vegetation-atmosphere transfer (SVAT) models predict water flux to the atmosphere from large land areas, using relatively crude assumptions about the role of vegetation. General hydrologic models (GHMs) incorporate greater detail of vegetation characteristics (e.g., canopy structure and rooting depth) and can predict partitioning of water for selected ecosystems under current conditions. At present however, how the current vegetation will partition water and energy under novel combinations of CO_2, water, and nutrition cannot be predicted accurately, much less how future communities with different canopy structures would regulate water and energy flux. Under what conditions do physiological controls over stomatal conductance exert strong effects on canopy conductance (Jarvis and McNaughton, 1986; Rosenberg et al., 1989)?

Although our understanding of the processes that regulate the partitioning of water and energy is incomplete, an even more pressing problem is how to integrate our understanding of canopy-level processes at small spatial and temporal scales with (1) climate models whose grid-cell resolution lumps together many ecosystems and blurs topographic controls and (2) successional models that predict vegetation change on time scales of decades to centuries but ignore the effects of vegetation on regional water and energy balance. Even when geographically explicit simulation models are used to predict evapotranspiration and production across broad spatial scales, the appropriate satellite-based technology to validate such broad-scale predictions has not yet been developed (Running et al., 1989).

Other Current Efforts

There is a long history of study of the exchange of water and energy between individual leaves and the atmosphere. More recently, this work has been extended

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to estimates of water vapor conductances by canopies of selected ecosystems using SVAT and GHM models (Running and Couglin, 1988). Efforts are under way to develop remote-sensing technology that can be used in combination with ground-based data for determination of evapotranspiration over large areas (Moran et al., 1989). At the international level, these studies are being organized within IGBP from the atmospheric perspective by the Biospheric Aspects of the Hydrologic Cycle program and from the vegetation perspective by the GCTE program (focus 1, activity 3; IGBP, 1990a, 1990b). Several agencies within the United States have developed global change research programs with a hydrology component (CEES, 1990; see Appendix, this volume).

Research Questions

The major question motivating this research is: How do changes in vegetation structure and physiology alter regional climate and hydrologic budgets? How do changes in cropping patterns, decertification from overgrazing, land-use change, or wholesale species changes in unmanaged ecosystems affect the surface energy balance and the various components of the hydrologic cycle? The ecosystem questions are important because changes in surface energy and water balance may feed back to alter the rate of global change. If the albedo, architecture, or canopy conductance changes, how are the patterns of global warming and precipitation affected, as predicted by the GCMs? Similarly, at the mesoscale, how do changes in evapotranspiration affect regional precipitation?

Changes in terrestrial ecosystems can affect the hydrologic cycle through several mechanisms, and it is important to know the sensitivity of water flux to each. At the leaf level, how sensitive is stomatal conductance of water vapor and foliage temperature to interactive changes in solar radiation, CO_2, air temperature, water supply, and the nutrients in different vegetation types? Similarly, how do longer-term changes in growth, which alter canopy architecture and rooting patterns, affect canopy conductance, interception, runoff, soil water storage, groundwater recharge, and long-term water flux to the atmosphere? Will these factors change crop water requirements?

General Strategy

The major issue to be resolved is how to incorporate our current understanding of vegetation effects on water and energy budgets, which is well developed at the levels of leaves and canopies, into GCM models so as to predict vegetation effects on climate at regional and global scales. The research program outlined in focus 1, activity 3, of the GCTE in the international program should be supported. Briefly, the general approach is to determine the role of canopy conductance in mediating plant response to CO_2 and climate and the effect of vegetation structure on canopy conductance and energy balance, so that successional models of vegetation structure can be used to predict water partitioning and energy balance.

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Role of Terrestrial Ecosystems in Global Change: A Plan for Action
http://www.nap.edu/catalog.php?record_id=18688

Finally, these patch-level models must be aggregated to the scale of GCM grids, incorporating the interactions of vegetation patches and topography in order to predict the effects of vegetation on regional and global climate.

Research Program

1. DETERMINATION OF EVAPOTRANSPIRATION OVER LARGE AREAS. ***Objective: To determine water and energy exchange rates over land areas from patch scales up to GCM grid scales.*** Regional models of atmospheric energy and water transport are needed to determine whether changes in canopy conductance and evapotranspiration affect regional precipitation patterns. These models require better hydrologic interfaces between the lower boundary of GCMs and terrestrial ecosystems. To validate these regional models, methods should be developed to estimate water and energy flux over large areas. Remote-sensing techniques need to be developed and improved to estimate leaf area index (LAI) and canopy temperature, which can then be combined with standard meteorological measurements to infer water and energy flux at a regional scale. Critical problems to be resolved include time scale, spatial resolution, and methods of estimating aerodynamic resistance. These models and methods must be tested by field campaigns that measure input parameters and fluxes at a variety of temporal and spatial scales (e.g., First International Satellite Land Surface Climatology Project Field Experiment, BOREAS). Combined with measurements of streamflow, these large-scale measures of evapotranspiration should be developed until they give better estimates of soil water storage, a sensitive but poorly known component of GCMs. Combining data on LAI and evapotranspiration may allow improved estimates of ecosystem productivity, a goal of carbon balance studies (see the first section in this chapter, on CO_2 and interactive effects).

2. MANIPULATION AND MONITORING OF WATERSHEDS. ***Objective: To determine the effects of changing vegetation on streamflow, evapotranspiration, and groundwater storage of a watershed.*** Mechanistic distributed hydrologic models need to be developed or modified to predict the effects of changing canopy conductance, canopy architecture, and rooting patterns on evapotranspiration, runoff, soil water storage, snowpack, groundwater recharge, and the watershed supplies of surface water and groundwater, using data from watershed manipulations. Monitoring of streamflow in these watersheds should be continued because streamflow may be one of the more sensitive parameters of global change. These experiments should be closely integrated with biogeochemical studies of nutrient and material transport from land to streams and lakes (see the section below on land-water interaction).

3. CANOPY WATER AND ENERGY EXCHANGE. ***Objective: To determine the effects of increasing CO_2 and changing climate on energy and water balance at the patch scale.*** Process-based modeling, supplemented by field plot experiments where necessary, are required to determine the effects of changing CO_2, tempera-

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ture, water supply, nutrients, and light on canopy conductance, canopy architecture, canopy temperature, albedo, evapotranspiration, soil water storage, groundwater recharge, and runoff for representative ecosystems. These experiments should be an integral part of the CO_2 enrichment and trace-gas experiments described in earlier sections because they require the same experimental design. Because of the strong effect of enclosure walls on wind speed and evapotranspiration, CO_2 enrichment experiments that incorporate studies of water and energy balance should be made using the FACE approach.

Status and Priorities

SVAT and GHM models that predict which and energy partitioning for selected ecosystems have been developed and parameterized. Measurement of canopy conductance as a function of CO_2, temperature, water supply, nutrients, and growth form is required before the current models can predict water budgets under future climatic scenarios.

The highest priorities should be given to regional hydrologic modeling, development of remote-sensing methods to measure model inputs, and the field measurements needed to validate these models in order to link the relatively sophisticated current understanding of patch-scale water and energy balance (SVAT and GHM models) with GCMs. This is essential to all questions of biospheric feedbacks to regional and global climate. Continuation of watershed research and of integration of the information from these experiments with regional hydrologic models merits strong support. At the patch level, the highest priorities are to validate the effectiveness of canopy models in simulating the effects of CO_2, climate, and canopy structure on water flux and partitioning, and to link patch-level measurements to regional models.

In general, research is well advanced in tackling these objectives. Within 5 to 10 years models are expected to be sufficiently realistic to describe how changes in the physiology and structure of vegetation affect regional climate.

ECOLOGICAL CONTROLS OVER LAND-WATER INTERACTION

The Problem

Global change is likely to alter the location and flux of major freshwater resources around the globe. In addition, sea-level rise will alter coastal ecosystems and the extent of tidal rivers and streams. Associated with changes in pools and fluxes of water will be changes in the nature of linkages among land, freshwater, and coastal marine ecosystems. The most pressing scientific need is to understand the controls over fluxes of water, carbon, and nutrients among these ecosystems.

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Transport of water and materials from land to freshwater ecosystems is strongly influenced by vegetation, particularly by vegetation at the margins of lakes and streams, and by nutrient loading through atmospheric deposition and fertilizer inputs. However, the role of vegetation in controlling these fluxes is poorly known. The magnitude and timing of inputs of water and associated nutrients and sediments to aquatic systems are critical to their functioning (Schindler et al., 1990; Grimm and Fisher, 1991) and affect both the processing of materials of terrestrial origin and the magnitude of additional carbon inputs through aquatic primary production. Reductions of water inputs are likely to exacerbate the effects of contaminants in lake (Schindler et al., 1990) and groundwater systems. With global changes in the transfer of water and materials from land to aquatic systems, changes in species composition will probably occur, with as-yet-unknown consequences for ecosystem function. Certain fisheries are likely to expand (Magnuson et al., 1990) while others collapse (Schindler et al., 1990). Range shifts of nuisance species, parasites, and pathogens may be expected. However, relatively little is known about the consequences of these species changes for the aquatic systems or their coupling to the terrestrial landscape, including consumption by humans. Little is known too about how these changes in community structure affect the transport of carbon and other materials through lakes, streams, rivers, and estuaries to the coastal marine zone. A landscape view integrating lakes, streams, rivers, and coastal zones with terrestrial systems can now be developed. Critical ecosystem couplings occur through hydrologic fluxes, movements of nutrients and organic detritus, and harvest of aquatic resources by species, including humans, that play important roles in terrestrial ecosystems.

Other Current Efforts

A major reason for highlighting aquatic systems in this report is that they have not received focused attention in IGBP planning, with the exception of the coastal zone, in which case research is being organized in the Land-Ocean Interactions in the Coastal Zone program. At the national level there are several programs that focus on aquatic ecosystems (see Appendix).

Research Questions

The most critical questions relate to coupling among terrestrial, stream, lake, river, estuarine, and marine ecosystems and the role of aquatic community structure in controlling the strength of these linkages. The role of terrestrial vegetation in controlling water inputs is covered in the previous section. How do vegetation type and land use affect the capacity of terrestrial vegetation to filter nutrients from groundwater, prevent sediment input to aquatic systems, and add carbon and nutrients through litterfall? How do terrestrial inputs (or removal of water for irrigation) affect the species composition, production, and biogeochemical cy-

Role of Terrestrial Ecosystems in Global Change: A Plan for Action
http://www.nap.edu/catalog.php?record_id=18688

cling in lakes and rivers and, therefore, the role of these ecosystems in processing and transporting carbon to the ocean? How will these changes in aquatic systems affect water quality and the capacity of lakes and rivers to support higher trophic levels, including humans, and how does this affect the carrying capacity and patterns of land use of adjoining terrestrial ecosystems? How do changes in freshwater aquatic systems affect the coastal marine ecosystems? How will changes in sea level alter estuarine ecosystems? How does processing of carbon and nutrients by freshwater and marine organisms affect their rates of deposition in sediments?

General Strategy

The general approach is to examine the controls over fluxes of carbon and nutrients from terrestrial to aquatic systems, fluxes among aquatic systems, and fluxes back to the terrestrial system (e.g., harvest by humans and other predators). Controls that may be expected to be critical and deserving of study are:

1. the role of terrestrial vegetation in governing hydrologic budgets (see the section on filtering nutrients),
2. the role of aquatic community structure in governing the processing of carbon and nutrients (and therefore their rates of longitudinal transport to the ocean and extent of deposition in sediments), and
3. factors governing the harvest of aquatic resources by people and other animals and the impact of this harvest on the carrying capacity and land use of adjoining terrestrial ecosystems.

Research Program

1. IMPACT OF TERRESTRIAL VEGETATION ON TRANSPORT OF CARBON, NUTRIENTS, AND SEDIMENTS TO AQUATIC SYSTEMS. ***Objective: To determine how vegetation structure and land use influence material transport to aquatic systems.*** Information from watershed studies should be synthesized to develop hypotheses about how the biomass and structure of vegetation influence the magnitude and seasonality of inputs of water (see the previous section on water/energy balance), nutrients, and sediments to aquatic systems. Particular attention should be paid to watersheds exhibiting different degrees of nutrient loading from agriculture to acid rain. This information should be used to develop process-based models of nutrient and sediment transport to aquatic systems. These models should be validated where land management practices (e.g., logging, wetland restoration) are modifying the presumed controls over this coupling.

2. THE HYDROLOGIC CYCLE AND ECOSYSTEM FUNCTION. ***Objective: To determine how changes in the hydrologic cycle will alter productivity and biogeochemical cycling and transport in aquatic systems and associated riparian***

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and near-shore marine areas. There is a need to establish sites, in a range of landscape types, where biotic-hydrologic interactions among upland, stream, and lake systems can be studied. Activity at each site would have three foci. The centerpiece would be ecosystem-scale experiments aimed at large-scale effects of changes in water flux (through vegetation modification or removal of irrigation water), nutrients, contaminants, and community structure (i.e., species composition). Where appropriate, these ecosystem experiments would be coordinated with field mesocosms and laboratory experiments. The supporting foci would be modeling (aimed at integration and synthesis at the landscape level) and background measurement of key structural components, fluxes, inputs, and outputs. Also required are large-scale, long-term studies of the effects of hydrologic change on the linkages between freshwater systems and adjoining riparian and coastal marine areas.

3. EFFECTS OF AQUATIC PRODUCTION AND COMMUNITY STRUCTURE ON HUMAN HARVEST AND LAND USE. ***Objective: To determine the feedback between aquatic productivity and human land-use change.*** Information from Third World countries should be synthesized to determine the effect that harvest of freshwater and marine resources has on patterns of human land use and harvest of terrestrial and aquatic resources.

4. EFFECTS OF AQUATIC COMMUNITIES ON SEQUESTRATION OF CARBON AND NUTRIENTS IN SEDIMENTS. ***Objective: To determine the factors that control the fate of organic and inorganic carbon that enters aquatic systems.*** Information on rates of carbon flux to the atmosphere as CO_2 or CH_4 versus its burial in sediments of lakes, estuaries, and near-shore marine ecosystems should be summarized to determine what biotic factors are correlated with these sequestration rates. This information should be incorporated into models that predict carbon sequestration in sediments and should be validated with appropriate observations and experiments.

Status and Priorities

There have been few large-scale, long-term studies that have linked freshwater and marine ecosystem studies with terrestrial hydrologic patterns. The technical capabilities and expertise needed for these studies exist, but they have usually been applied to smaller-scale questions delimited by disciplinary boundaries. High priority should be assigned to achieving the necessary synthesis at appropriately large scales. Key elements are (1) integrated analyses of streams, lakes, and their catchments; (2) interdisciplinary teams of aquatic ecologists, terrestrial ecologists, hydrologists, and climatologists; (3) integration of basic and applied research objectives; and (4) long-term observation, experimentation, and modeling to determine feedbacks between global environmental change and fresh waters at the scale of landscapes. At this time, workshops and discussions are needed to define the scientific issues and approaches in more detail and develop the interdisciplinary linkages needed to carry the research forward.

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Role of Terrestrial Ecosystems in Global Change: A Plan for Action
http://www.nap.edu/catalog.php?record_id=18688

The conceptual basis for studies on the role of vegetation as a filter for materials entering aquatic systems, the impact of human harvest from aquatic systems, and controls over carbon sequestration in sediments are less developed than is the area of aquatic community structure. Workshops and literature syntheses in these areas will also be required prior to the development of an experimental program.

Within 2 to 5 years a research plan that identifies the role of aquatic ecosystems in the global carbon cycle may be expected. Within 10 to 20 years our understanding should be sufficiently advanced to predict how global change will affect the flux of materials through aquatic systems to the ocean and the impacts these changed fluxes will have on the global carbon cycle, aquatic species composition, the productivity of fisheries, and the quality of water for drinking, industry, and agriculture, all of which affect the human carrying capacity of the earth.

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Role of Terrestrial Ecosystems in Global Change: A Plan for Action
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APPENDIX

Current International and National Programs

The six questions identified in this report provide a framework for understanding how the national U.S. Global Change Research Program (USGCRP) relates to international global change initiatives and to current research programs by national agencies. Summarized here are the current activities of federal agencies in the USGCRP as they relate to the six questions specified in the report, indicating which agencies are addressing each question and the foci within Global Change and Terrestrial Ecosystems (GCTE), as well as the type of research they are sponsoring: observations, experiments, and modeling.

1. At the international level, study of the effects of CO_2 on terrestrial ecosystems has been organized as focus 1 of GCTE (Table 1). At the national level, efforts to describe the terrestrial carbon cycle have been funded most prominently by the National Aeronautics and Space Administration (NASA), the National Science Foundation (NSF), and the Department of Energy (DOE). These activities are tied in with modeling efforts described below. DOE and the U.S. Department of Agriculture (USDA) have funded CO_2 enrichment experiments to determine direct CO_2 effects on plants, and the Environmental Protection Agency (EPA) is planning additional studies of such effects. DOE projects have pursued the implications of these effects by examining CO_2 effects on litter quality and decomposition. Only NSF, DOE, and USDA have funded research on CO_2 effects on ecosystem processes and soil-based feedbacks, the area where international planning (GCTE) suggests that the greatest uncertainty currently exists. This research would benefit from closer ties with modeling programs. Modeling of CO_2 effects on plants has been funded primarily by DOE and USDA. NSF and DOE

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TABLE 1 Major international programs and national funding agencies that currently support research related to the six major research questions addressed in this report.[a]

International Programs	National Funding Agencies		
Research Question	Observation	Experiments	Modeling
1. Terrestrial Carbon Cycle			
GCTE (foci 1, 3)	NASA	DOE	USFS
	NSF	NSF	NSF
	USDA	DOE	USDA
	EPA	USFS	NASA
	USFS		
2. Trace-Gas Flux			
IGAC (foci 2, 4, 7)	NASA	NSF	NSF
	NSF	EPA	EPA
	EPA	DOE	NASA
	NOAA	USDA-ARS	USFS
	DOE	NASA	
	USDA-ARS	USFS	
	USFS		
3. Future Distribution and Structure of Ecosystems			
GCTE (focus 2)	NSF	NSF	NSF
HDP	NASA	USFS	DOE
	EPA		EPA
	NPS		NASA
	USGS		USFS
	FWS		
	USFS		
4. Ecological Complexity			
GCEC	NASA	NSF	
	NSF	USFS	
5. Biotic Regulation of Hydrologic Cycles			
BAHC	NASA	NSF	NSF
GCTE (Focus 1)	USDA-ARS		
	USGS		
6. Transport Through Aquatic Systems			
LOICZ	NASA	DOE	DOE
	NSF	NASA	NASA
	DOE	NSF	
	USGS	USDA	
	COE	COE	
	USFS	USFS	

[a] Acronyms are defined at the end of the report.

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have funded modeling of the carbon cycle, and NASA, NSF, and DOE have funded additional programs in process-level modeling of the carbon cycle. USDA is beginning to implement planned research in this area. No federal program currently emphasizes interactive effects of CO_2 and other factors, although several have discussed plans to do so.

2. Trace-gas flux studies at the international level are organized under the aegis of the International Global Atmospheric Chemistry (IGAC) project. At the national level, there has been a recent upsurge in efforts to describe patterns of trace-gas flux, funded by NASA, NSF (ecosystems and atmospheric chemistry programs), EPA, the National Oceanic and Atmospheric Administration, DOE, and USDA. Experimental work has been more limited. EPA, DOE, and NSF have funded soil-warming experiments, with NASA support for students. The USDA and NSF ecosystems programs have funded experimental studies of the response of trace-gas flux to soil nitrogen status. NASA, USDA, and EPA have instituted a series of projects on trace-gas fluxes and land-use change in the tropics. These will complement IGAC atmospheric chemistry missions. To date, there has not been adequate manipulative studies of the effects of soil drainage, soil nutrient status, land-use change, and disturbance frequency on trace-gas flux. Modeling studies have been funded primarily by NASA, EPA, and NSF.

3. At the international level, future ecosystem structure and distribution have been the major concern of focus 2 of GCTE, which will approach this question through modeling studies. There has been substantial NSF funding for descriptive studies of how community structure has changed in the past in response to events such as El Niño, invasions, and successional development. NASA and EPA have also funded descriptive studies focusing on the current relationships between ecosystem processes and structure. Development of models that represent these relationships predictively is beginning in ways that can permit model validation by remote sensing. The National Park Service, U.S. Geological Survey (USGS), Fish and Wildlife Service, and USDA have all traditionally performed extensive surveys and conducted observational programs on the natural history and abundances of wildlife populations. These studies have provided invaluable data on the natural variability in ecosystem structure and function and its ties to fluctuations in plant and animal abundances. Such observations have naturally led to experimental studies, largely sponsored by NSF. The NSF population biology, ecology, and ecosystems (Long-Term ecological Research [LTER]) programs have funded many plant and animal removal experiments on land, and the NSF biological oceanography program has funded comparable experiments in the marine intertidal zone. NSF has also funded population-based forest modeling studies. Additional modeling studies of future ecosystem structure have been funded by NASA, DOE, and EPA, and related ecosystems research has been conducted by the Department of the Interior. Most observational and experimental studies of species interactions, sponsored primarily by NSF, have been oriented toward theo-

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retical questions of population and community ecology. The challenge in the future is to link these to predictions of global change.

4. Relatively little effort has been made at either the international or the national level to understand the functional role of ecological complexity. At the international level, this complexity will be the subject matter of the Global Change and Ecological Complexity focus of GCTE, but a program has yet to be formulated. The Scientific Committee on Problems of the Environment is currently planning a meeting to synthesize such information. At the national level, descriptive studies have been funded by NASA and NSF, with a few experimental studies by NSF.

5. Biotic interactions and the hydrologic cycle are being examined at the international level by Biospheric Aspects of the Hydrological Cycle and GCTE (focus 1). At the national level, efforts to describe the biotic role in the hydrologic cycle have included studies funded and planned by NASA (e.g., First International Satellite Land Surface Climatology Field Experiment, Boreal Exosystem-Atmosphere Study), as well as studies by USDA, USGS, and other agencies to elucidate the impacts of management and soil and vegetation characteristics on watershed hydrology and on surface water and energy balance.

6. Transport from terrestrial to aquatic systems and to the marine coastal zone is being examined at the international level by Land-Ocean Interactions in the Coastal Zone. Observational work has been funded nationally through the geosciences program at NSF and the DOE-funded Response, Resistance, Resilience, and Recovery from Disturbance (R4D) program in the Arctic. In addition, monitoring programs by USDA, USGS, and the Corps of Engineers (COE) have provided information on stream and river runoff. Experimental work has been funded by DOE (the R4D program), NSF (Hubbard Brook and the LTER programs), USDA (e.g., Hubbard Brook and Coweeta), and COE. Modeling has been funded by DOE, NASA, and USDA.

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Abbreviations and Acronyms

ARS	Agricultural Research Service
BAHC	Biospheric Aspects of the Hydrologic Cycle
BOREAS	Boreal Ecosystem-Atmosphere Study
CEES	Committee on Earth and Environmental Sciences
COE	Corps of Engineers
COHMAP	Cooperative Holocene Mapping Project
DOE	Department of Energy
EPA	Environmental Protection Agency
FACE	free-air CO_2 enrichment
FWS	Fish and Wildlife Service
GCEC	Global Change and Ecological Complexity
GCM	general-circulation model
GCTE	Global Change and Terrestrial Ecosystems
GHM	general hydrologic model
GIS	geographic information system
HDP	Human Dimensions of Global Environmental Change Programme
IGAC	International Global Atmospheric Chemistry project
IGBP	International Geosphere-Biosphere Program
LAI	leaf area index
LOICZ	Land-Ocean Interactions in the Coastal Zone
LTER	Long-Term Ecological Research
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Administration

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NPS	National Park Service
NRC	National Research Council
NSF	National Science Foundation
R4D	Response, Resistance, Resilience, and Recovery from Disturbance
SCOPE	Scientific Committee on Problems of the Environment
SVAT	soil-vegetation-atmosphere transfer
USDA	U.S. Department of Agriculture
USFS	U.S. Forest Service
USGCRP	U.S. Global Change Research Program
USGS	U.S. Geological Survey
WCRP	World Climate Research Program

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