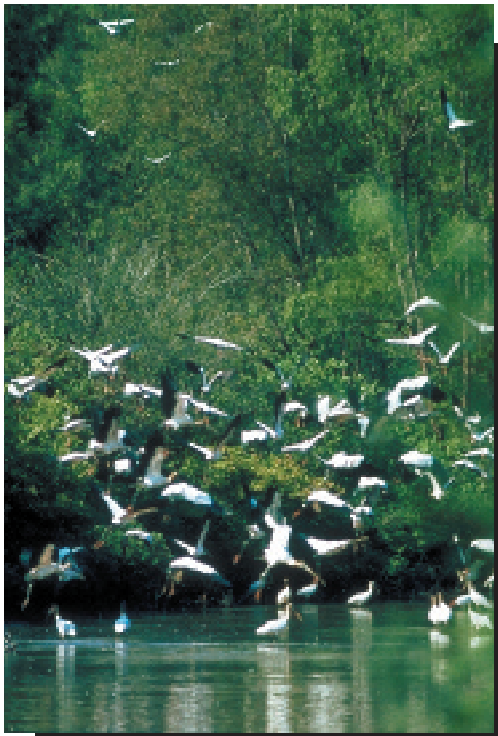
CHAPTER 8

Ecosystems



CHAPTER CONTENTS

Ecosystems shape our societies and nations by providing essential renewable resources and other benefits. They sustain human life by providing the goods and services it depends on, including food, fiber, shelter, energy, biodiversity, clean air and water, recycling of elements, and cultural, spiritual, and aesthetic returns. Ecosystems also affect the climate system by exchanging large amounts of energy, momentum, and greenhouse gases with the atmosphere. The goal of the Ecosystems research element of the U.S. Climate Change Science Program (CCSP) is to understand and be able to project the potential effects of global change on ecosystems, the goods and services ecosystems provide, and ecosystem links to the climate system (see Box 8-1 and Figure 8-1).

Global change is altering the structure and functioning of ecosystems, which in turn affects availability of ecological resources and benefits, changes the magnitude of some feedbacks between ecosystems and the climate system, and could affect economic systems that depend on ecosystems. Research during the last decade focused on the vulnerability of ecosystems to global change and contributed to assessments of the potential effects of global change on ecological systems at multiple scales.

We now know that effects of environmental changes and variability may be manifested in complex, indirect, and

BOX 8-1

TWO KEY DEFINITIONS

Ecosystem
A community (i.e., an assemblage of populations of plants, animals, fungi, and microorganisms that live in an environment and interact with one another, forming together a distinctive living system with its own composition, structure, environmental relations, development, and function) and its environment treated together as a functional system of complementary relationships and transfer and circulation of energy and matter.

Ecosystem Goods and Services
Through numerous biological, chemical, and physical processes, ecosystems provide both goods and services. Goods include food, feed, fiber, fuel, pharmaceutical products, and wildlife. Services include maintenance of hydrologic cycles, cleansing of water and air, regulation of climate and weather, storage and cycling of nutrients, provision of habitat, and provision of beauty and inspiration. Many goods pass through markets, but services rarely do.

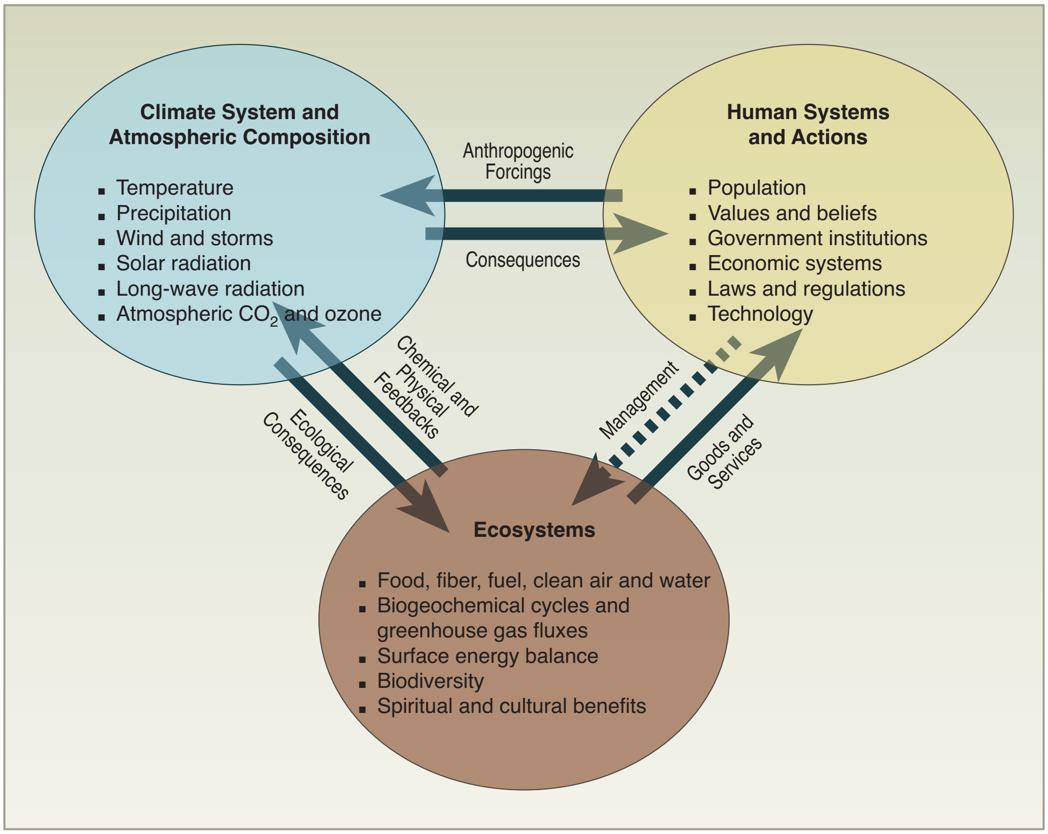


Figure 8-1: Key linkages and feedbacks between ecological systems, human systems (societies), and the climate system and atmospheric composition. Spatial scales are implicit and span from local to global. Humans manage some ecosystems intensively and others lightly. All ecosystems are affected to some degree, positively or negatively, by major global changes.

conflicting ways. For example, warming may enhance tree growth by extending growing season length (in temperate and cool regions), but pathogens better able to survive the winter because of higher temperatures may decrease forest productivity and increase vulnerability of forests to disturbances such as fire. Subtle changes in winds over the ocean can affect currents which in turn may alter the ranges and population sizes of fish species and increase or decrease fish catches. Whether environmental changes are anthropogenic or natural in origin, human societies face substantial challenges in ensuring that ecosystems sustain the goods and services on which we depend for our quality of life and survival itself.

During the next 10 years, research on ecosystems will focus on two overarching questions:

- How do natural and human-induced changes in the environment affect the structure and functioning of ecosystems at a range of spatial and temporal scales, including those processes that can in turn influence regional and global climate?
- What options does society have to ensure that ecosystem goods and services will be sustained or enhanced in the face of potential regional and global environmental changes?

Research should be focused on building the scientific foundation needed for an enhanced capability to forecast effects of multiple environmental changes (such as concurrent changes in climate, atmospheric composition, land use, pollution, invasive species, and resource management practices) on ecosystems, and for developing products for decision support in managing ecosystems. Near-term priorities will be placed on economically important ecosystems (e.g., Figure 8-2) and special studies relevant to regions where abrupt environmental changes or threshold responses by ecosystems may occur. Investigations will emphasize changes in ecosystem structure and functioning and changes in the frequency and intensity of disturbance processes anticipated to have significant consequences for society during the next 50 years, including altered productivity, changes in biodiversity and species invasions (including pests and pathogens), and changes in carbon, nitrogen, and water cycles.

Ensuring the desired provision of ecosystem goods and services will require an understanding of interactions among basic ecosystem processes and developing approaches to reduce the vulnerabilities to, or take advantage of opportunities that arise because of, global and climatic changes. Scientific research can contribute to this societal goal by addressing three questions that focus on linkages and feedbacks between ecosystems and drivers of global change, important consequences of global change for ecological systems, and societal options for sustaining and enhancing ecosystem goods and services as environmental conditions change. This research will produce critical knowledge and provide a forecasting capability that will continuously improve decisionmaking for resource management and policy development.

Question 8.1: What are the most important feedbacks between ecological systems and global change (especially climate), and what are their quantitative relationships?

State of Knowledge

Biological, chemical, and physical processes occurring in ecosystems affect and are affected by weather and climate in many ways. For example, ecosystems (and the organisms they contain) exchange large amounts of greenhouse gases with the atmosphere, including water vapor, carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). Moreover, the reflection (or absorption) of solar radiation by ecosystems is important to the temperature of Earth's surface. Linkages among the physical, chemical, and biological components of ecosystems are important on short (minutes to days) and long (years to millennia) time scales, as well as local to global spatial scales.

Global change has the potential to alter ecosystem structure (e.g., amount of leaf area, plant height, or species composition) and ecosystem functioning (e.g., rates of evapotranspiration, carbon assimilation, and biogeochemical cycling), and those potential changes in ecosystems might enhance or reduce global change through numerous feedback mechanisms (see Box 8-2). In addition to its direct linkages with ecological systems, global change could alter human actions that affect the structure, functioning, and spatial distribution of ecosystems, which in turn could alter important feedbacks from ecological systems to climate.

The most important feedbacks, either positive or negative, are likely to involve:

- Altered ecosystem/atmosphere exchanges of greenhouse gases
- Altered releases of aerosols from ecosystems (including black carbon and sulfur resulting from controlled and uncontrolled ecosystem burning)
- Altered releases of volatile organic compounds from ecosystems
- Changes in surface albedo resulting from changes in ecosystems
- Changes in the fraction of absorbed solar radiation that drives evapotranspiration compared to directly heating the plants and soils in terrestrial ecosystems
- Long-term changes in ecosystem structure or shifts in the geographic distribution and extent of major ecosystem types.

Illustrative Research Questions

- How might changes in temperature and precipitation affect net ecosystem exchanges (or timing or geographic distribution of those exchanges) of greenhouse gases and aerosols?
- How might changes in climate and atmospheric composition, in combination with other factors such as land-use/cover changes, affect ecosystem albedo, evapotranspiration, and nutrient cycling?
- How might changes in regional air quality (including chemicals and aerosols released from industrial sources or ecosystem disturbances such as wildfires and crop residue burning), in combination with climatic variability and change, affect ecosystem albedo and exchange of greenhouse gases?
- How might changes in ecosystems alter Earth's radiation balance, freshwater cycle, and carbon cycle, and could any such alterations contribute to abrupt climate change?
- How might human activities affect the release or uptake of greenhouse gases by ecosystems?

Figure 8-2: Landscapes and ecosystems are managed (some intensively, some lightly) by humans to produce grain, timber, and cattle, among many other goods and services desired by societies. For example, according to the United Nations Food and Agriculture Organization, 96% of the protein and 99% of the energy (usable calories) in the U.S. food supply come from terrestrial ecosystems (the remainder is derived from the ocean). Globally, about 94% of protein and 99% of energy in the human food supply come from terrestrial ecosystems. Photo sources: Tim McCabe (left and right) and Jeff Vanuga (bottom), USDA NRCS.

BOX 8-2

FEEDBACKS

A feedback from an ecosystem to climate or atmospheric composition occurs when a change in climate or atmospheric composition causes a change in the ecosystem that in turn alters the rate of the "original" change in climate or atmospheric composition. A *positive feedback* intensifies the original change whereas a *negative feedback* slows the original change (but does not change its sign). A positive feedback could occur, for example, if warming and drying (caused by increasing atmospheric CO_2 concentration) of high-latitude terrestrial ecosystems containing large amounts of carbon in plants and soils (e.g., tundra and peatland) resulted in greater ecosystem respiration, and this increased the rate of atmospheric CO_2 increase, which then accelerated the warming and drying. A negative feedback might occur, for example, if increasing atmospheric CO_2 concentration increased primary production in aquatic and/or terrestrial ecosystems, and that increased production resulted in greater carbon storage on land and in waters. This could slow the increase in radiative forcing from greenhouse gases in the atmosphere.

Research Needs

Research needs include improved experimental facilities and capabilities for making measurements in those facilities, ecosystem models, and ecosystem observing capabilities (and their related measurements) at multiple scales (to scale up from point observations with remotely sensed data). Initial efforts will be directed at enhancing existing capabilities and improving use of existing data streams. Studies should include identification of early indicators of changes in ecosystems that may be important as feedbacks to climate and atmospheric composition. Specific research needs include:

- Field and controlled-environment experimental facilities and long-term ecological observing systems at multiple locations to quantify ecosystem-environment interactions (focusing on ecosystem greenhouse gas and energy exchanges) to better parameterize, calibrate, and evaluate models of land-ocean-atmosphere chemistry feedbacks. Primary linkages are to the Carbon Cycle and Water Cycle research elements to share data and experimental sites and facilities.
- Spatially explicit ecosystem models capable of representing complex interactions between diverse ecosystems and their physical and chemical environments.
- Models that link remote sensing of land surface albedo to changes in the spatial distribution of ecosystems and exchanges of mass, energy, and momentum for implementation in climate models. It is anticipated that these models will be developed in collaboration with the Water Cycle and Carbon Cycle research elements. A primary linkage is to the Land-Use/Land-Cover Change research element to provide model-based projections of future land cover.
- Social science research to explore human factors in ecosystem-climate linkages and feedbacks. The Human Contributions and Responses element must supply information on the magnitude and significance of the primary human drivers of global change.

Milestones, Products, and Payoffs

- Reports presenting a synthesis of current knowledge of observed and potential (modeled) feedbacks between ecosystems and climatic change to aid understanding of such feedbacks and identify knowledge gaps for research planning [2-4 years]; *Arctic Climate Impact Assessment* [2 years].
- Definition of the initial requirements for ecosystem observations to quantify feedbacks to climate and atmospheric composition, to enhance existing observing systems, and to guide development of new observing capabilities [2-4 years]. This will provide key input to the Observing and Monitoring component of CCSP research.
- Quantification of important feedbacks from ecological systems to climate and atmospheric composition to improve the accuracy of climate projections [beyond 4 years]. This product will be needed by the Climate Variability and Change research element to ensure inclusion of appropriate ecological components in future climate models.

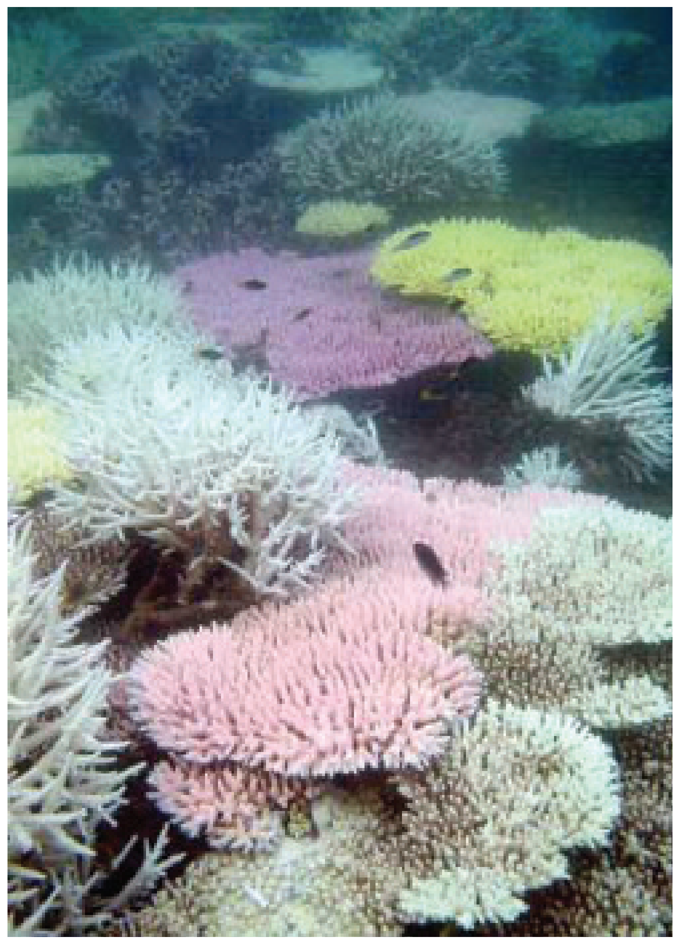


Figure 8-3: When stressed, corals frequently expel their symbiotic algae en mass, leaving coral bereft of pigmentation and appearing nearly transparent on the animal's white skeleton, a phenomenon referred to as coral bleaching. This image of bleached coral colonies was obtained during the January-March 2002 coral bleaching event in Great Barrier Reef, Australia, the worst bleaching event on record for this reef. Bleaching events reported prior to the 1980s were generally attributed to local phenomena (e.g., major storm events, sedimentation, or pollution); but, since then, a direct relationship between bleaching events and elevated ocean temperature (see Figure 8-4) was found. Source: Ray Berkelmans, Australian Institute of Marine Science.

Question 8.2: What are the potential consequences of global change for ecological systems?

State of Knowledge

Many research programs that support long-term observations [e.g., forest productivity, ultraviolet-B (UV-B) radiation received by ecosystems, greenhouse gas concentrations and fluxes, atmospheric nitrogen deposition, nutrient loading, fisheries, and the spread of invasive species] have unambiguously established that large-scale ecological changes are occurring, and there is considerable evidence that some of those changes are the result of ecological responses to climatic variability and change. For example, recent warming has been indicated as potentially linked to longer growing seasons (i.e., period of leaf display) in temperate and boreal terrestrial ecosystems, grass species decline, changes in aquatic biodiversity, and coral bleaching (IPCC, 2001b) (see Figures 8-3 and 8-4). Natural modes of climatic variability (e.g., El Niño-Southern Oscillation, North Atlantic Oscillation, and Pacific Decadal Variability) are known to affect plankton and fisheries, such as those yielding sardine, anchovies, and salmon. Soil-borne plant pathogens and parasitic nematodes have been found to move northward (in the Northern Hemisphere) with increased surface temperature. Because survival and spread of pathogens and their vectors (carriers) depend on climate and weather, climatic change and increased natural climatic variability would be expected to affect disease-causing organisms that could alter the ecological status of fauna and flora. These and other observations and expectations have come from both experiments and *in situ* monitoring.

Most ecosystems are now subject to multiple environmental changes. The dynamics and interactions of those changes and the consequences for ecological systems are poorly understood (NRC, 1999a). Recent reviews (e.g., IPCC, 2001b) summarized the range of observed and potential consequences of combinations of changes in climate, atmospheric composition, and local drivers (e.g., invasive species, pollution, and physical habitat modification) on ecological systems. For example, in aquatic systems, alterations in wind speeds and precipitation patterns, in combination with increased air temperature, would affect water column stratification and circulation, resulting in changes in the rates of nutrient supply and productivity at all trophic levels. For terrestrial ecosystems, a large knowledge base of effects of a change in a single environmental parameter exists, but effects of multiple changes on most ecosystem processes are uncertain (see, e.g., Table 8-1). Nonetheless, we know, for example, that interactions among changes in temperature, precipitation, and fire regimes can influence vulnerability to invasive species in terrestrial ecosystems. We also know that elevated atmospheric CO_2 concentration can sometimes eliminate the negative effects of elevated tropospheric ozone (O_3) concentration and warming on crop yields.

Illustrative Research Questions

- How might the combination of increasing CO_2 concentration, increasing tropospheric O_3 concentration, and warming affect yield of major U.S. crops?
- What are the effects of changes in atmospheric CO_2 concentration, precipitation, and temperature on the structure and functioning of boreal forests?
- What are the effects of increased UV-B radiation, increased rates of sea-level rise, temperature changes, and elevated concentration of CO_2 on biodiversity, structure, and functioning of coastal ecosystems?

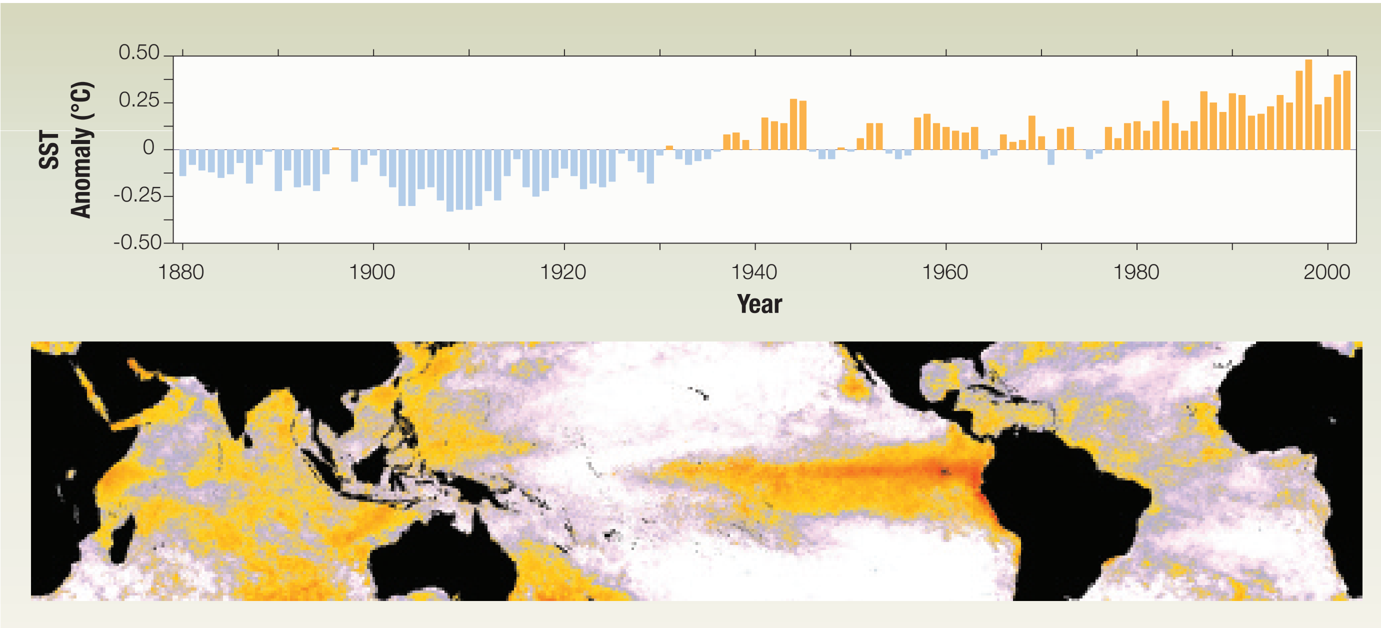


Figure 8-4: *Top*: Annual global sea surface temperature (SST) anomalies relative to the 1880-2002 mean based on *in situ* and satellite measurements. The warmest annual global SST occurred in 1998. *Bottom*: Incidences of coral bleaching were influenced by unprecedented SST anomalies in 1998, due to a severe El Niño event as shown by this satellite retrospective annual composite monthly mean coral bleaching "HotSpot" chart for 1998. A coral bleaching HotSpot is defined as an SST anomaly above a coral-bleaching threshold SST climatology. HotSpot charts illustrate the magnitude and spatial distribution of thermal stresses that may contribute to coral bleaching. This chart was derived from the NOAA/NASA 9-km satellite AVHRR (Advanced Very High-Resolution Radiometer) Oceans Pathfinder SST data set, the most refined available. Source: NOAA National Climatic Data Center.

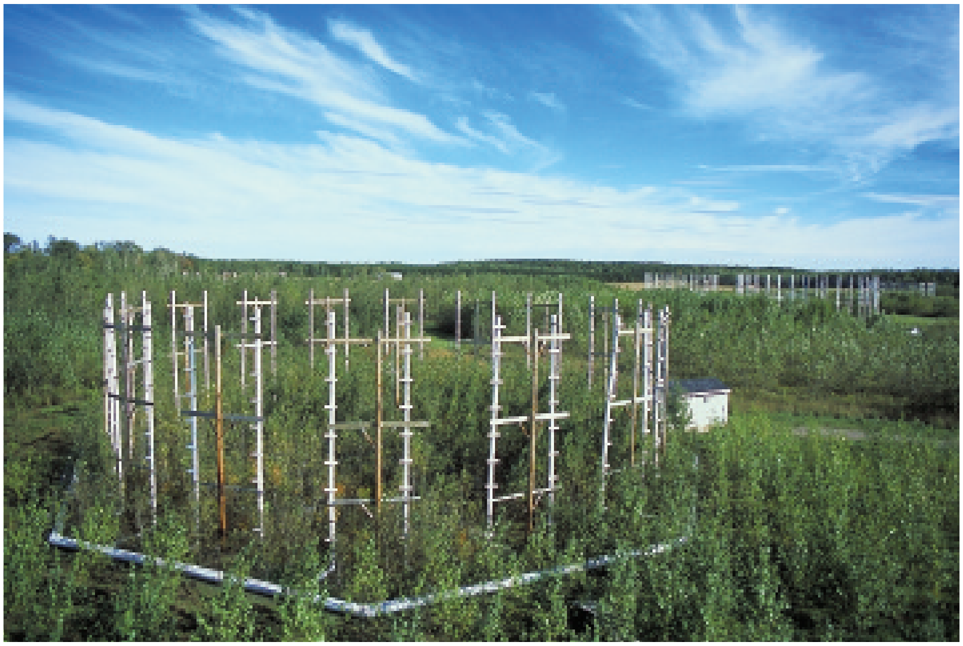


Figure 8-5: Scientific user facility for the study of effects of simultaneous changes in concentrations of CO_2 and O_3 on the structure and functioning of northern hardwood tree stands. This facility is located near Rhinelander, Wisconsin, and is supported by DOE, USDA, NSF, and others. Source: North Central Station, U.S. Forest Service.

- Does climatic variability and change modify effects of other changes (e.g., pollution, invasive species, and changes in land, water, and resource use) on ecosystems?
- How will basin-scale changes in physical forcing mechanisms affect the productivity, distribution, and abundance of plankton, fish, seabird, and marine mammal populations in coastal marine ecosystems?
- How do changes in climate and weather (both its variability and extremes) affect the ecology and epidemiology of infectious pathogens, dissemination by their vectors, and susceptibility of the humans, animals, and plants that are their hosts?
- How rapidly might ecosystems, or individual species, move poleward and to higher elevations in response to regional warming?
- What are the effects of increasing atmospheric CO_2 concentration, warming, and sea-level rise on wetland plant contributions to soil elevation and shoreline stability?
- How will changes in the hydrologic cycle affect aquatic, riverine, and inland wetland ecosystems?

Research Needs

Identifying and quantifying the rates and consequences of global change for ecological systems is essential for appropriately evaluating options for responding to such changes. Determining the most important and societally relevant effects of global change on ecosystems will require collaboration among physical, biological, and social scientists and an improved understanding of complex interactions between natural and human disturbances and climatic variability. Near-term research priorities should include both ecosystems of special importance to society (e.g., major crops, commercial forests, and parks and preserves) and regions where abrupt changes or threshold responses may occur, such as high-altitude and high-latitude ecosystems and transitional zones between ecosystems (e.g., forest-grassland, agriculture-native prairie, ocean boundary currents, coastal zones, and/or rural-urban interfaces). Field studies should, where appropriate, share experimental facilities and research sites (see, e.g., Figure 8-5) with the Carbon Cycle and Water Cycle research elements. High-resolution ocean shoreline topographic data will be needed to adequately project effects of sea-level rise on coastal ecosystems.

Specific research needs include:

- Experiments to study the interactive effects of climatic variability and change, elevated atmospheric CO_2 concentration, nutrient/pollution deposition, increased UV-B radiation, invasive species, and land use on key species and intact ecosystems. Understanding the effects of warming, increasing CO_2 concentration, and

TABLE 8-1

Documented effects of environmental changes on net primary production (NPP) of terrestrial ecosystems

Environmental Change Factor	Observed Effect on NPP
Increasing atmospheric CO_2 concentration	Stimulation
Increasing tropospheric O_3 concentration	Inhibition
Increasing temperature	Stimulation *or* inhibition[a]
Changes in regional hydrologic cycles	Inhibition *or* stimulation[a]
Increasing atmospheric nitrogen deposition	Stimulation *or* no effect[a]
Increasing land-surface UV-B radiation	No effect *or* inhibition[a]
Combinations of the above	Highly uncertain for most combinations and ecosystems

[a] Depends on other factors and circumstances. For example, warming might stimulate NPP in a presently cool region, but inhibit NPP in a presently warm region.

changing precipitation on the structure and functioning of ecosystems will require improved projections of the rate of change of climate and atmospheric CO_2 concentration. These improved projections will be provided by the Climate Variability and Change and Carbon Cycle research elements, and will be needed to both design experiments and interpret experimental results.

- Quantification of biomass, species composition, and community structure of terrestrial and aquatic ecosystems in relation to disturbance patterns, through observations, modeling, and process studies. Information on disturbance patterns will require inputs from the Land-Use/Land-Cover Change research element and information on biomass (carbon) pools will require inputs from the Carbon Cycle research element.
- Experiments and models that can identify threshold responses of ecosystems and species to potential climatic variability and change.
- Studies to connect paleontological, historical, contemporary, and future changes and rates of change in ecosystem structure and functioning. Long-term data sets and projections of climate and the spatial distribution and intensity of various land uses will be required from the Climate Variability and Change and Land-Use/Land-Cover Change research elements.
- Maintenance and enhancement of long-term observations to track changes in seasonal cycles of productivity, species distributions and abundances, and ecosystem structure. Improved spatial, spectral, and especially temporal resolution in observing systems from the Observing and Monitoring research element is needed to better understand and project ecological processes to parameterize models and verify model projections.
- Determination of organismal rates of adaptation and the magnitude of subsequent effects on community structure in relation to rates of global change.
- Investigations of the link between biodiversity and ecosystem functions and resulting services.
- Studies of effects of changes in "upstream" ecosystems on receiving-water ecosystems. Primary linkages are to the Water Cycle and Land-Use/Land-Cover Change research elements.

Milestones, Products, and Payoffs

- Data from field experiments quantifying aboveground and belowground effects of elevated CO_2 concentration in combination with elevated O_3 concentration on the structure and functioning of agricultural [less than 2 years], forest [2-4 years], and aquatic [beyond 4 years] ecosystems. Some of the data will be obtained in collaboration with the Carbon Cycle research element.
- Reports describing the potential consequences of global and climatic changes on selected arctic, alpine, wetland, riverine, and estuarine and marine ecosystems; selected forest and rangeland ecosystems; selected desert ecosystems; and the Great Lakes based on available research findings, to alert decisionmakers to potential consequences for these ecosystems [2-4 years]. Results will be important input to the Human Contributions and Responses research element.
- Field experiments (and user facilities) in place to study responses of ecosystems (including any changes in nutrient cycling) to combinations of elevated CO_2 concentration, warming, and altered hydrology, with data collection underway. Such facilities will be essential for evaluating ecosystem models used to assess effects of climatic variability and change on ecosystem goods and services (and therefore input to the Human Contributions and Responses research element), as well as feedbacks to the climate system and atmospheric composition (and therefore input to the Climate Variability and Change and Atmospheric Composition research elements). Where appropriate, these research facilities will be developed in collaboration with the Carbon Cycle research element [2-4 years].
- Synthesis of known effects of increasing CO_2, warming, and other factors (e.g., increasing tropospheric O_3) on terrestrial ecosystems based on multi-factor experiments [2-4 years]. This synthesis will be developed with the Carbon Cycle research element.
- A new suite of indicators of coastal and aquatic ecosystem change and health based on output from ecosystem models, long-term observations, and process studies [2-4 years].
- Definition of the initial requirements for observing systems to monitor the health of ecosystems, to serve as an early warning system for unanticipated ecosystem changes, and to verify approaches for modeling and forecasting ecosystem changes [2-4 years]. This will be an important input to the Observing and Monitoring component of the program.
- Development of data and predictive models determining the sensitivity of selected organisms and their assemblages to changes in UV-B radiation and other environmental variables relative to observations of UV-B radiation in terrestrial, aquatic, and wetland habitats [beyond 4 years].
- Development of data and predictive models determining the sensitivity of selected organisms and their assemblages to contaminants and other environmental variables in terrestrial, aquatic, and wetland habitats [beyond 4 years].
- Spatially explicit ecosystem models at regional to global scales, based on data from remote-sensing records and experimental manipulations focused on effects of interactions among global change variables, to improve our understanding of contemporary and historical changes in ecosystem structure and functioning [beyond 4 years].
- Enhanced understanding of potential consequences of major global changes on key ecological systems [beyond 4 years].

Question 8.3: What are the options for sustaining and improving ecological systems and related goods and services, given projected global changes?

State of Knowledge

Experiments and observations have demonstrated linkages between climate and ecological processes, indicating that future changes in climate could alter the flow of ecosystem goods and services (IPCC, 2001b). Several specific mitigation and adaptation measures have been identified and evaluated, including integrated land and water management; genetic selection of plants and livestock; multiple cropping systems; multiple use of freshwater and terrestrial ecosystems; programs for protection of key habitats, landscapes, and/or species; intervention programs [e.g., captive breeding and (re)introduction programs]; more efficient use of natural resources;

and institutional and infrastructure improvements (e.g., market responses, crop insurance, and water flow and supply management) (IPCC, 2001c).

It is clear that management practices can affect climate-related ecosystem goods and services. For example, management can influence the emission of greenhouse gases and aerosols from ecosystems; the rate at which ecosystems gain or lose carbon, nitrogen, phosphorus, and other elements as well as the total amount of those elements stored; the radiation balance of ecosystems (i.e., land surface albedo); and the production of goods valued by humans. While some management strategies have been studied, society's knowledge and ability to manage the broad array of ecosystem goods and services in the context of increasing and potentially conflicting demands (e.g., increasing food and fiber production while storing more carbon in soils and reducing CH_4 emissions) is very limited.

Illustrative Research Questions

- How can aquatic ecosystems be managed to balance the production and sustenance of ecosystem services across multiple demands (e.g., management of rivers to supply freshwater for drinking, irrigation, recreation, hydropower, and fish), considering potential effects of interacting environmental changes?
- How can terrestrial ecosystems such as rangelands, forests, woodlands, and croplands be managed (e.g., maintaining wildlife corridors) to balance the production and sustenance of ecosystem goods and services across multiple demands (e.g., food, fiber, fuel, fodder, recreation, biodiversity, biogeochemical cycles, tourism, and flood control), considering the future effects of interacting environmental changes?
- What options exist for society to preserve genetic diversity; respond to species migrations, invasions, and/or declines; and manage changing disease incidence and severity in the face of global change?
- How can coral reefs be managed for tourism, erosion protection, refugia for commercially and recreationally important species, and biodiversity, considering potential global changes?
- How can coastal and estuarine ecosystems be managed to sustain their productivity and use in the face of existing stresses (e.g., pollution, invasive species, and extreme natural events) and potential global changes?
- What options exist for responding to abrupt changes in ecological systems?
- What are the effects of management practices on global and regional environments (e.g., atmospheric chemistry, water supply, and water quality), nitrogen cycling, and the health, productivity, and resilience of ecosystems?

Research Needs

Much ecosystem management for the foreseeable future will proceed with imperfect knowledge about the effects of multiple global change processes and about fundamental aspects of ecosystem structure and functioning. Routine monitoring (see, e.g., Figure 8-6), scientific evaluation, and feedback from managers could enable adaptive shifts in management strategies as knowledge about an ecological system grows, and at the same time will provide important opportunities for scientists to test hypotheses about ecosystem responses to environmental change. Substantial improvements in modeling capabilities are also needed to develop and deploy effective options to maintain and enhance the supply of critical goods and services and to evaluate alternative management options under changing environmental conditions. Modeling alternative management

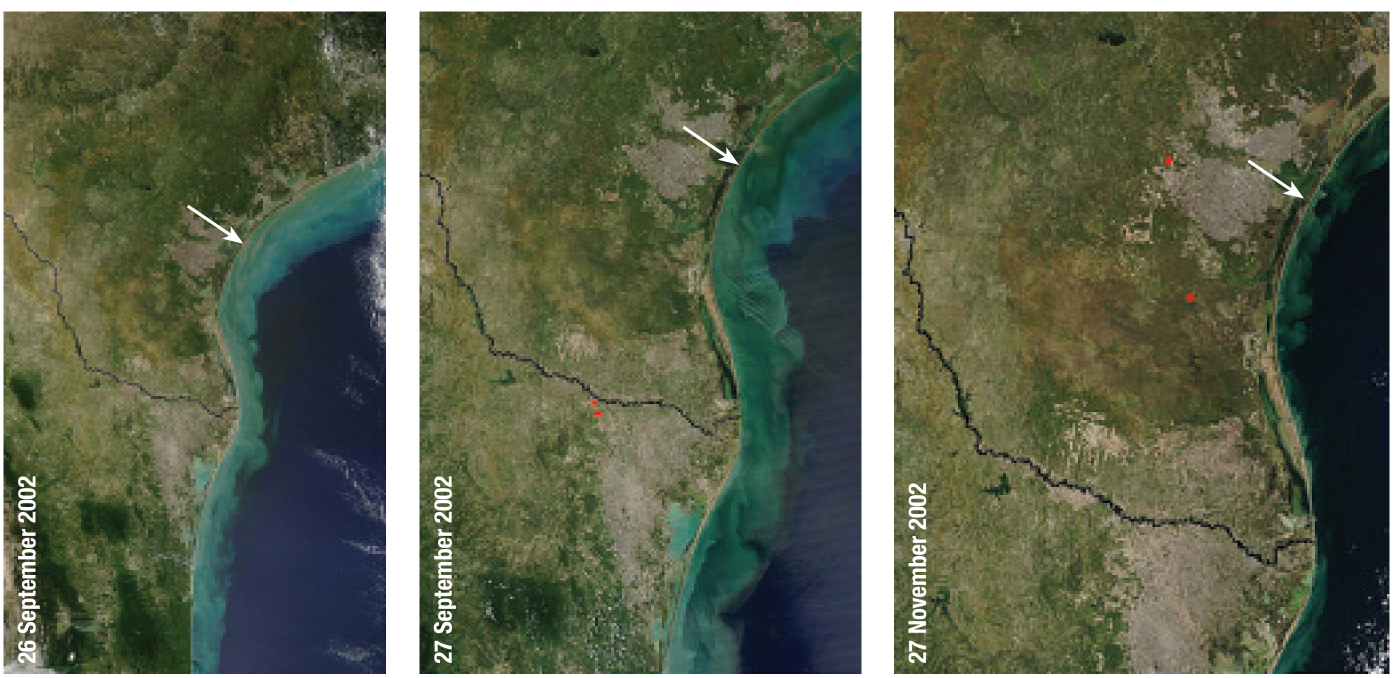


Figure 8-6: Brightly colored waters in the Gulf of Mexico indicate the presence of sediment, detritus, and blooms of marine plants called phytoplankton (noted by arrow). The blooms may be caused, or enhanced, by changes in land management "upstream" and/or changes in regional climate. By late November, this bloom appears to have subsided. Images are true-color Moderate-Resolution Imaging Spectroradiometer (MODIS) products. This type of remote-sensing technology is essential to monitoring and quantifying ecosystem and landscape states and changes. Source: NASA MODIS Ocean Team.

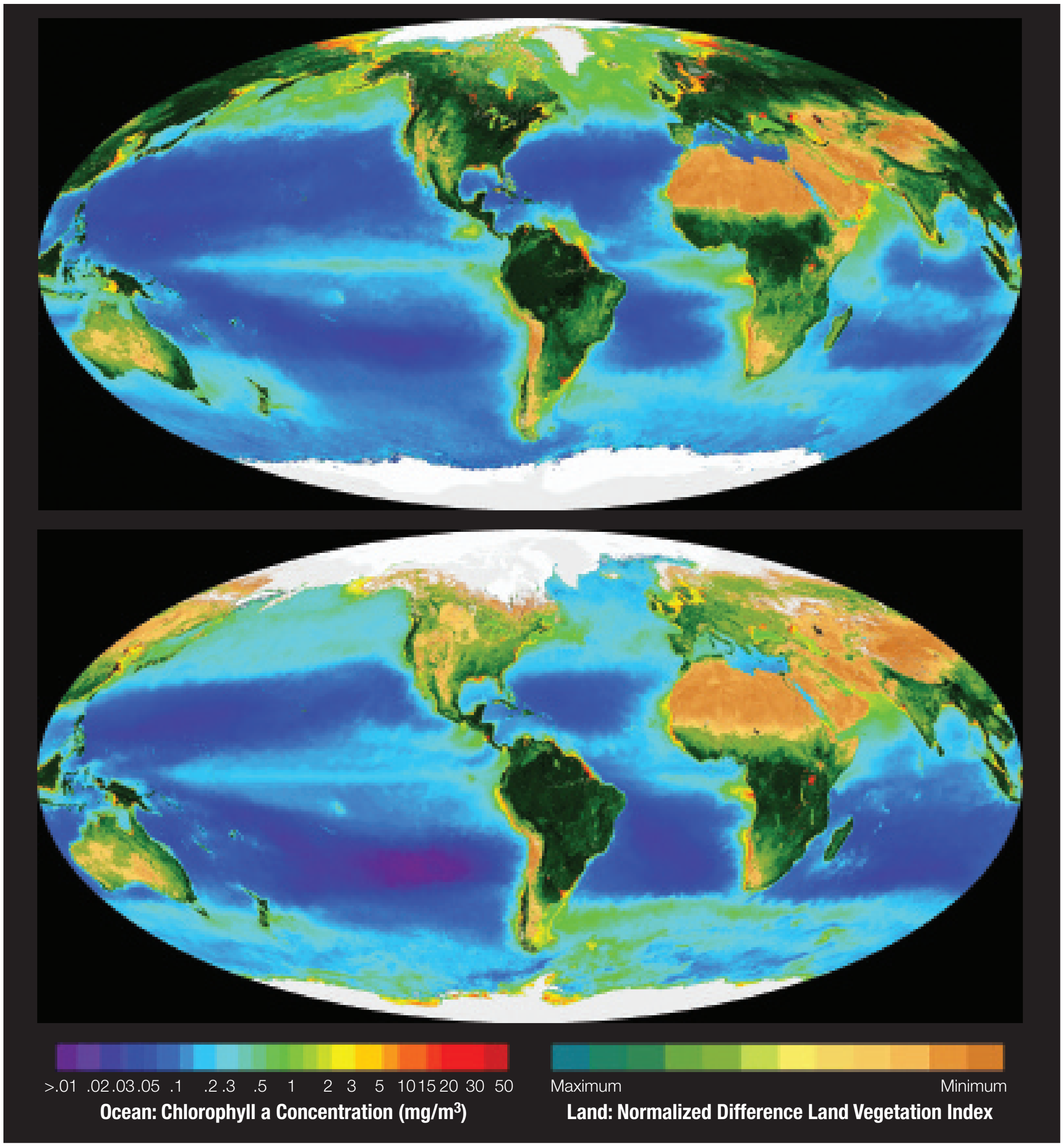


Figure 8-7: Summer (top) and winter (bottom) composite of global ocean chlorophyll *a* concentration (a surrogate for phytoplankton biomass) and terrestrial vegetation "greenness" (a measure of potential productivity) from September 1997 to December 2001. Some responses to global change may be evident on extremely large spatial scales, requiring global-level observing systems and international collaborations for detecting and interpreting changes. When evaluated over time, composite photographs such as this may reveal global-scale changes in the spatial distribution, structure, and functioning of ecosystems. Source: SeaWiFS Project, NASA/Goddard Space Flight Center and ORBIMAGE.

options will require evaluation of the influence of societal demands on ecosystems.

Specific research needs include:

- Improve understanding of causal mechanisms that drive complex changes in ecological systems, including robust indicators and likely rates of change, to develop predictive management tools such as ecological forecasting models using socioeconomic data as an input.
- Identify ecological systems susceptible to abrupt environmental changes with potentially significant (positive or negative) impacts on goods and services in order to develop adequate mitigation and adaptation responses.
- Evaluate the use of ecological information and projections in decisionmaking.
- Apply information on water quantity, quality, and delivery from the Water Cycle research element and frequency of extreme events from the Climate Variability and Change research element to evaluate ecosystem performance and management options.
- Develop and evaluate local- to regional-scale ecosystem-climate models.
- Assess the direct and indirect ecological effects and economic costs of management practices through regular monitoring, evaluation, and experimentation with a goal of enabling adaptive shifts in management.
- Explore obstacles to the implementation of ecosystem management strategies.
- Understand consequences of harvest practices in marine fisheries on changes in the age structure of the harvested populations, the structure and productivity of fisheries ecosystems, and responses of fisheries to global change.

Milestones, Products, and Payoffs

- For forests, agricultural systems, rangelands, wetlands, fisheries, and coral reefs, conduct preliminary comparisons of the effectiveness of selected management practices in selected regions focusing on greenhouse gas exchange, health, productivity, and biodiversity of the targeted ecosystems and their goods and services under changing environmental conditions [2-4 years].
- Initiation of development of decision support tools relevant to regions where abrupt or threshold ecological responses may

occur, especially high-altitude and high-latitude ecosystems and transitional zones between ecosystems (i.e., ecotones) such as forest-grassland, agriculture-native prairie, riparian and coastal zones, and rural-urban interfaces [2-4 years].
- Data sets and spatially explicit models for examining effects of management and policy decisions on a wide range of ecosystems to predict the efficacy and tradeoffs of management strategies at varying scales [beyond 4 years]. A subset of these products will be developed in collaboration with the Carbon Cycle research element.

National and International Partnerships

Interagency and international facilities and mechanisms must be in place to process, archive, and distribute the data collected and to generate relevant products. Given the nature of global change, research must span large spatial scales (from small experimental plots to global satellite image mosaics; see, e.g., Figure 8-7) and long time scales (paleontological data from ice cores, tree rings, and fossil pollen to near-real-time forecast models), and monitor a wide range of variables important for characterizing the state of ecosystems. National and international observing systems at multiple spatial scales are needed to develop a consistent record of environmental change over time. Data from such observing systems would provide inputs to models and allow evaluation and improvement of model performance. The resulting large collections of ecological and environmental data will necessitate large databases and new approaches to data integration and analysis and will require new and enhanced national and international partnerships.

Future experimental and observing systems may rely on networks of terrestrial and aquatic ecosystem observatories within particular biomes or larger ecoregions. They should link together efficiently and build on existing networks of field stations, experimental forests and ranges, environmental and resource monitoring programs, and long-term ecological research sites sponsored by many governmental and nongovernmental organizations, some of which have lengthy records (many in non-machine-readable forms) of ecological and environmental data.

Scientists conducting research under the Ecosystems research element of the CCSP will participate in the planning of international collaboration activities, including those sponsored wholly or in part by the International Geosphere-Biosphere Programme (IGBP), such as the Global Climate and Terrestrial Ecosystems (GCTE) project, the Global Environmental Change and Food Systems (GECaFS) project, the Land-Ocean Interactions in the Coastal Zone (LOICZ) project, the Surface Ocean-Lower Atmosphere Study (SOLAS), the Global Ocean Ecosystem Dynamics (GLOBEC) program, the Global Ecology and Oceanography of Harmful Algal Bloom (GEOHAB) program, and the Biospheric Aspects of the Hydrological Cycle (BAHC) project. Also important are the Global Ocean Observing System (GOOS), the Global Terrestrial Observing System (GTOS), the Global Climate Observing System (GCOS), the Millennium Ecosystem Assessment, and the International Long-Term Ecological Research (ILTER) network.

CHAPTER 8 AUTHORS

Lead Authors

Susan Herrod Julius, USEPA
Steve Shafer, USDA
Jeff Amthor, DOE
Paula Bontempi, NASA
Marilyn Buford, USDA
John Calder, NOAA
Stan Coloff, USGS
Susan Conard, USDA
Sara Mirabilio, NOAA
Knute Nadelhoffer, NSF
Bill Peterson, NOAA
Don Scavia, NOAA
Bryce Stokes, USDA
Woody Turner, NASA

Contributors

Larry Adams, USDA
Nancy Cavallaro, USDA
Pat Megonigal, Smithsonian Institute
Jessica Orrego, CCSPO
Catriona Rogers, USEPA
Chuck Trees, NASA