

A Summary of NHEERL Ecological Research on Global Climate Change



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1. Introduction

The climate change problem is one of truly global proportions with tremendous implications to ecological, economic and health conditions of the Earth and its human population. “The causes and consequences of the problem are ... intertwined at all spatial and temporal scales, providing a single issue of unrivaled complexity” (Reichle *et al.* 1985). As a result, it is critical that the scientific basis for mitigation and adaptation policies intended to reduce the risks and take advantage of the opportunities presented by climate change be as clear, reliable, and up-to-date as possible, without being policy-prescriptive.

The Global Change Research Act of 1990 mandates that the US Global Change Research Program (USGCRP) assess the potential consequences of global change for the United States. The Environmental Protection Agency’s (EPA) Global Change Research Program within the Office of Research and Development (ORD) is conducting research and assessment activities that contribute to the USGCRP assessment process.

Scientists at the NHEERL, and its predecessor—the Office of Environmental Processes and Effects Research—initiated research in 1988 anticipating the Global Change Research Act. The purpose of this document is to summarize ecological research conducted by NHEERL scientists under the EPA’s contribution to the USGCRP from the onset of research through approximately 2002. The intent is to provide that information as reference material for scientists investigating the potential impacts of climate change on ecosystems.

The research was conducted through grants and cooperative agreements, and through intramural research, which is research conducted directly by EPA scientists. This document focuses on the intramural research in an effort to highlight the expertise and contributions of EPA scientists. The research summarized is, primarily, the result of activities performed at the NHEERL ecology divisions directly involving federal scientists. The objective, here, is to show the diversity of research conducted, and to highlight the research results in support of EPA’s mission to protect the human health and the environment.

The early research addressed health and ecological effects of exposure to ultraviolet radiation resulting from stratospheric ozone depletion as well as the effects of global climate change on forests, agriculture, and water resources. This research supported both the Montreal Protocol and its amendments (UNEP 2000)—an international agreement curbing the release of ozone depleting substances—and the 1989 EPA report to the US Congress on the consequences of global climate change.

From 1990 through 1996, a significant portion of the ORD effort focused on stabilizing the buildup of atmospheric carbon dioxide and other greenhouse gases. The ecological research emphasized terrestrial ecosystem-atmosphere

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carbon cycling, and strategies for enhancing biospheric carbon sequestration.

In 1997 as part of a USGCRP effort to better coordinate activities across federal agencies and to focus each agency's work on those topics most consistent with its mission, ORD redirected its Global Change Research Program to assessing the consequences of global change.

In 1998, EPA's Global Program began conducting regional assessments in support of the USGCRP assessment process. Also, EPA's Global Program shifted resources away from carbon cycle and greenhouse gas mitigation research to assessing the potential consequences of global change. While some research on cause and effect mechanisms continued, ORD's primary responsibility was leading regional assessments on the consequences of global change on air quality, water quality, human health, and ecosystem health within the United States.

NHEERL's research role has changed in concert with EPA's changing research needs regarding global change. Ecological effects research other than that on coral ecosystems ended in 2002. During period between 1988 and 2002, NHEERL scientists conducted numerous projects on the following topics:

- The effects on agriculture, specifically rice—the World's most important grain.
- The effects on the global biomes—forest migration and desertification.
- The effects on aquatic ecosystems—the thermal response of freshwater fish.
- The effects on terrestrial ecosystems—forest response to increased temperature and carbon dioxide, and the interaction of tropospheric ozone.

Currently, NHEERL research is addressing coral ecosystem decline. Coral dominated ecosystems are among the most threatened by global climate change. Research is examining the impacts of global change stressors including UV irradiation, temperature and nutrient loading on coral ecosystems.

The following chapters summarize the published ecological research conducted by NHEERL scientists. The summaries give an overview of the research and provide an entrée to the technical literature. A chapter is devoted to describing the ongoing coral ecosystem research. The final chapter attempts to synthesize the research findings with a perspective on remaining scientific uncertainties.

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2. Water Resources

Statement of the Problem

Climate change is likely to have significant impacts on the availability of fresh water. Already in short supply throughout many parts of the world, water for human consumption, agriculture, and industry will be a major factor in economic growth, ecological sustainability, and global conflict. Research was undertaken to make initial assessments of potential impacts of climate change on stream flow and water balance in the western United States—a region characterized by the shortage of water. Additionally, research was conducted to address the need for models which account for the spatial magnitude and extent of hydrologic processes. The models need to handle key parameters such as precipitation, soil moisture, and evaporation, in response to changing climatic conditions. The models must account for vegetation interactions with soil moisture. This is particularly important for simulating regional vegetation response to climate change since vegetation distribution is controlled in large part by the availability of soil moisture.

Approach

Research focused on developing and refining detailed watershed scale hydrology models to address stream dynamics and water storage. Regional-scale modeling research was directed toward developing physically and mechanically-based water balance models which can be spatially distributed at watershed, regional, and continental scales. The research effort contributed to developing methods for spatially distributing climatic data at scales appropriate for the models, and providing these data bases to the climate change research community. This ORD project has been completed; extensions of this research are continuing within the US Geological Survey.

Main Conclusions

The increasing demand for water by population and industrial growth is creating chronic water shortages throughout the world (Revenga 2000). Add to this the potential impacts of global climate change on water supplies and chronic shortages could reach crisis levels. Throughout much of the western United States the supply of water for human consumption, agriculture, and industry depends on snowpack and reservoir storage. Most global climate warming scenarios suggest warmer winters with more rainfall and less snowfall for much of the western United States, which would substantially reduce snow accumulation and shift the high flow season for many rivers from the spring to the winter (Lettenmaier et. al. 1992). A substantial amount of the natural storage of winter precipitation that presently occurs in the snowpack would be lost resulting in increased spills in the winter and lower reservoir levels in the summer and fall (Lettenmaier and Sheer 1991).

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A significant increase in flood hazard in the western US could result from climate change, primarily due to an increase in rain-on-snow events (Lettenmaier and Gan 1990). Such events occur when warm, wet storms move over existing snowpack. Rapid melting of the snowpack is the result of a combination of warm air temperature, high wind and high humidity which cause significant condensation on the snow and is particularly severe in forest openings and forest clear-cuts (Marks et al. 1998). This research suggests that some mitigation of the adverse effects of global climate change may be achieved by adapting land and water management practices to changes in runoff patterns and maximizing the protective effects of natural vegetation.

Global climate changes are expected to be regional in nature, and affect land cover and land use. Key to understanding such regional effects on water supplies is the response of vegetation. Plant communities play a significant role in regional energy and water balance. While hydrologic models designed to simulate large river systems are good for operating reservoirs systems, they are not adequate for predicting changes to regional water balance and, hence, changes in regional vegetation (Marks et al. 1993). Dolph et al. (1991) developed a spatially distributed regional water balance model to evaluate the sensitivity of large river basins to climate change. The model was exercised for the Columbia River Basin. This research demonstrated that the existing Historic Climate Network of climate monitoring stations underestimate precipitation primarily because mountainous areas are underrepresented. With climate warming, the model predicted increased evaporative loss, decreased runoff and soil moisture. These conditions could have profound effects on vegetation distribution and subsequently regional water resources.

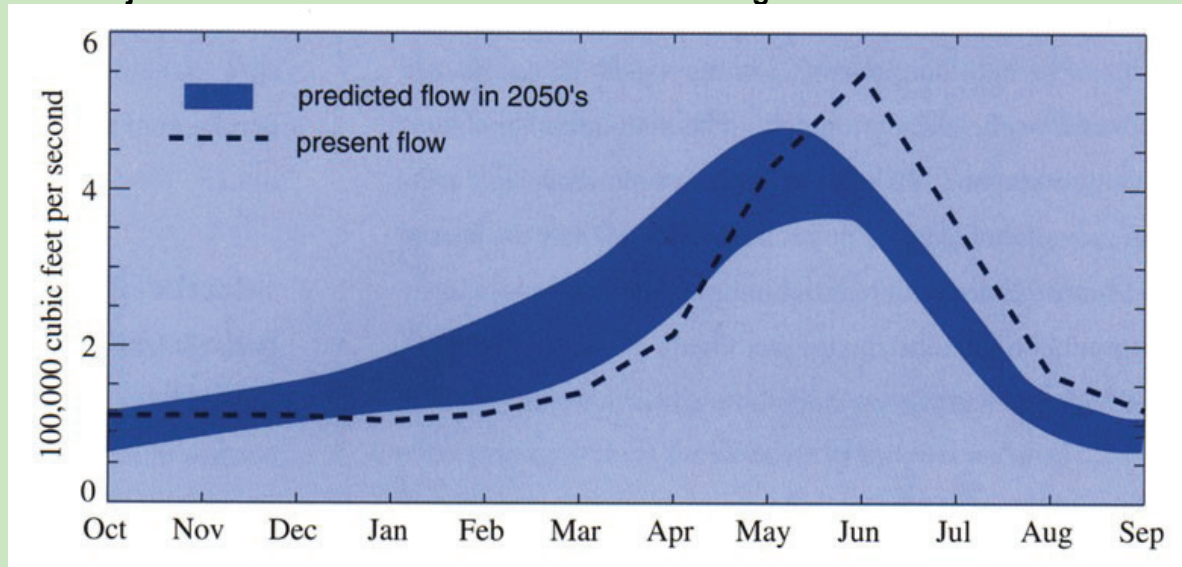
The ability to predict changes in regional vegetation is necessary to evaluate the effects of climate change on forest resources, agriculture, and water supplies. Changes in soil moisture and evapotranspiration resulting from climate will have large impacts on water and vegetation. If changes in the regional water balance are significant, major shifts in vegetation patterns and condition are a likely (Marks et al. 1993). Neilson and Marks (1994) incorporated a distributed water balance model with a vegetation model to produce a biogeographic model, MAPSS (Mapped Atmosphere-Plant-Soil System). This model was used to predict changes in vegetation leaf area index, site water balance and runoff as well as changes in biome boundaries. When applied to potential climate change scenarios, two areas exhibiting among the greatest sensitivity to drought-induced forest decline were determined to be eastern North America and Eastern Europe to western Russia.

Effects of Global Climate Change (GCC) on streamflow

With climate warming, mountain snow accumulation would be substantially reduced, and river's high flow season would shift from the spring to the winter (Lettenmaier et al. 1992). Actual evaporation would peak in late spring and early summer due to reduced summer soil moisture. The result would be increased spills in the winter, lower reservoir levels in the summer and fall, and increased risk of flooding (Lettenmaier and Sheer 1991).

Hydrologic sensitivities across a large part of the western US are driven primarily by runoff shifts due to temperature change, not changes in total precipitation (Lettenmaier and Gan 1990). The exception to the temperature dominance would be in river system with large reservoir storage relative to the mean annual flow. In these cases shifts in the seasonality of runoff would be less important than the changes in the mean annual flow, which would be sensitive to precipitation as well as temperature changes. In populated areas of the western US such as California, changes in water demand will almost certainly overshadow the possible effects of GCC over the next century.

Projected Streamflow Effects from Climate Change in the Pacific Northwest



Relative to present flows (dashed), the wetter winters and drier summers simulated by climate models are very likely to shift peak streamflow earlier in the year, increasing the risk of late-summer shortages. Source: Hamlet, A.F. and D.P. Lettenmaier. 1999. (As shown in the National Assessment Synthesis Team report 2001).

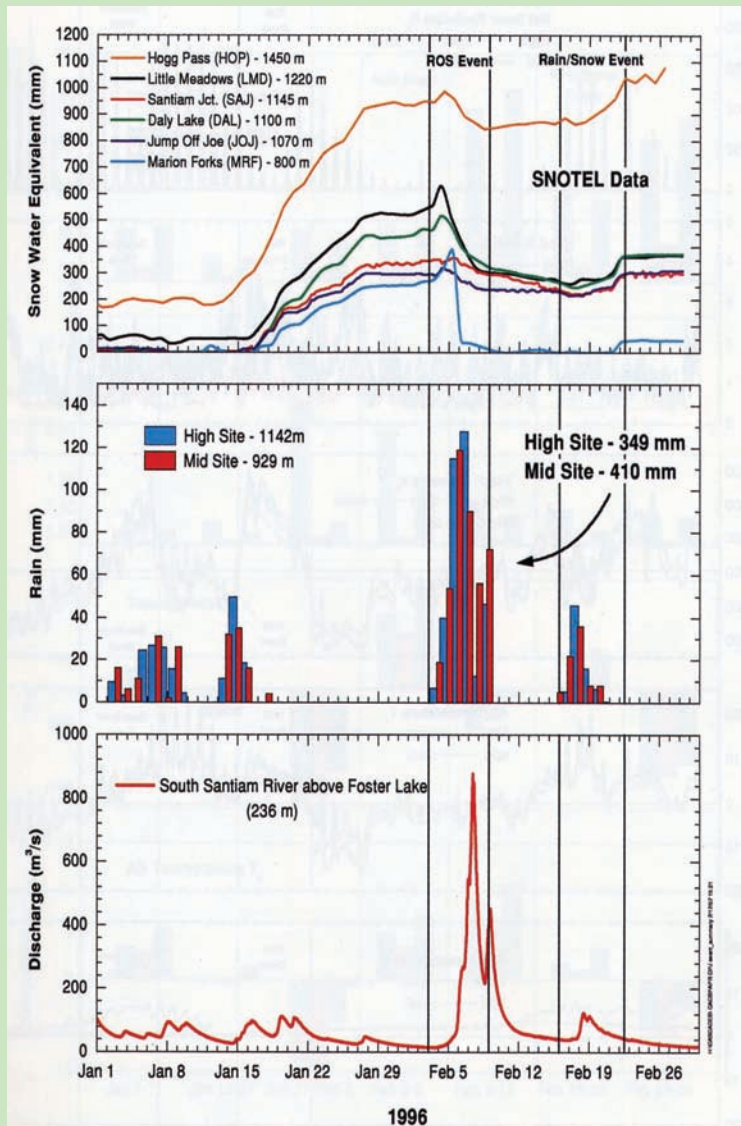
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Rain-on-snow



Willamette River, Oregon 1996 flood

Marks et al. (1998) used an energy balance snowmelt model to simulate snowmelt processes during a warm, very wet Pacific storm that caused significant flooding in the Pacific Northwest during the Winter of 1996. Data from paired open and forested sites located just below the Pacific Crest were used to drive the model. The model accurately simulated snow cover mass and depth during the development and ablation of the snow cover prior to, during, and following one of the most extreme rain-on-snow events on record. The model demonstrated that the melt was caused by condensation on the snow surface during the event, and by the fact that a cold storm had deposited significant snow cover down to relatively low elevations within the snow transition zone. In the snow transition zone of the Cascade Mountains, clear-cutting is a common forest practice. This study showed that during this event, snowmelt was enhanced in forest openings and clear-cuts. If GCC results in a shift to warmer winters such rain-on-snow events could become more frequent.



2. Water Resources

Effects on regional water balance

A spatially distributed regional water balance model was used to look at the sensitivity of the Columbia Basin to climate change (Dolph et al. 1991). A wet year (1972) and a dry year (1977) were simulated and compared to recorded data. The modeled total runoff was significantly less than measured runoff—implying that precipitation data from the Historic Climate Network was underestimated by the existing network of measurement stations in mountainous regions. In response to this need, several new methods for estimating precipitation at regional scales were developed (Phillips et al. 1992, Daly et al. 1994). Spatial data bases of precipitation, temperature, vapor pressure, evapotranspiration, and wind were created for both current conditions and 2xCO₂CO₂ scenarios for several GCMs and were made publicly available for the global climate change research community (NOAA / EPA 1992, 1997).

The table below presents annual water balance results for a very wet (1972) and a very dry (1977) water year, and for 2xCO₂ climate conditions predicted by the GFDL general circulation model for the US portion of the Columbia River Basin. All values are in mm H₂O per unit area, so they represent an average depth of water over the basin. Measured annual runoff at the basin outflow has been corrected to reflect only discharge from the US portion. Annual values refer to water years (Oct. to following Sep.). NA: data not available or not applicable. Standard deviation (SD; in parentheses) is used to indicate the extent of deviation from the basin average reported in the table; no SD is given for measured runoff from 1972 and 1977 because it is derived from single values measured at the basin outflow; SD is given for the long-term average measured runoff because it is based on 40 annual values (Marks et al. 1993).

<i>Year</i>	<i>Measured annual precip.</i>	<i>Measured annual runoff</i>	<i>Modeled annual runoff</i>	<i>Annual PET</i>	<i>Modeled annual ET</i>	<i>Soil initial storage</i>	<i>Soil final storage</i>
Wet year 1972	776 (547)	1447 ^a	437 (475)	878 (315)	311 (151)	65 (61)	93 (60)
Dry year 1977	507 (377)	332 ^a	259 (295)	898 (325)	254 (150)	65 (57)	59 (63)
Long-term average	NA	741 ^b (490)	NA	NA	NA	NA	NA
GFDL 2xCO₂ scenario	636 ^c (543)	NA	276 (319)	1627 (470)	396 (215)	63 (57)	27 (37)

^aAnnual runoff over the US portion of the Columbia River Basin (Canadian portion of the flow subtracted out) from gage measurements at the basin outflow, adjusted for storage effects.

^b40-year average unit runoff for the US portion of the Columbia River Basin (Canadian portion of the flow subtracted out) using historical runoff data.

^cAverage precipitation for the US portion of the Columbia River Basin calculated from the 1972 and 1977 precipitation data.

The water balance approach incorporating a physically based model of potential evapotranspiration and explicit calculation of soil water holding capacity, improved our ability to simulate soil moisture under current and future climate conditions. A 2xCO₂ scenario generated by the GFDL global circulation model provided climate conditions to run the Dolph et al. (1991) water balance model. The model predicted increased PET, and ET, and decreased runoff and soil moisture. Marks et al. (1993) predicted that changes in soil moisture and evapotranspiration resulting from global climate change will have large impacts on water and vegetation resources.

If changes in the regional water balance are significant, major shifts in vegetation patterns and condition are a likely result of global climate change. Neilson and Marks (1994) incorporated a distributed water balance model with a biogeographic vegetation model, MAPSS (Mapped Atmosphere-Plant-Soil System) to predict changes in vegetation leaf area index, site water balance and runoff as well as changes in biome boundaries. 2xCO₂ scenarios from five different global circulation models (GCMs) were used to predict vegetation changes globally. Increased PET due to higher temperatures generally offsets increased precipitation under all 2xCO₂ scenarios. Eastern NA and Eastern Europe to western Russia were among the most sensitive regions to drought-induced forest decline.

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3. Responses of Freshwater Fish to Temperature Increases

Statement of the Problem

Water temperature has long been recognized as one of the most important environmental variables influencing the distribution of fish species. Scientists at the Mid-Continent Ecology Division, Duluth, MN have actively investigated the thermal requirements of freshwater organisms especially fish since the 1960's and 1970's, when a water quality research focused on requirements of aquatic organisms, with a special focus on dissolved oxygen and temperature.

Approach

Laboratory studies were conducted on various fish species to establish temperature requirements for survival, growth and successful reproduction, data needed for development of temperature standards to protect fish against thermal pollution. Since not all fish species are adaptable to laboratory testing, laboratory tests are expensive, and conditions in the environment can alter sensitivity to thermal regimes, we have developed a database (FTDMS = Fish Temperature Database Matching System) linking fish presence records with thermal records in streams and rivers (Eaton *et al.* 1995b). Various alternative methods for estimating an upper extreme habitat temperature (UEHT) from fish field distribution data and matched weekly mean stream temperatures were compared and their respective advantages and disadvantages examined (Eaton *et al.* 1995a). As reported in Eaton *et al.* (1995b), an upper extreme habitat temperature, referred to as a maximum tolerance temperature, was derived for species with adequate data and a standard error calculated by the bootstrap method. Data above the UEHT can be approximated by a three-parameter lognormal distribution; standard error of the estimated UEHT varies among species from 0.1 ° C and 0.6 ° C at the 95% cumulative probability of occurrence. For 30 common fishes of the U.S., maximum weekly mean temperatures derived from the database are less than lethal temperatures derived from laboratory tests, and are similar to temperature criteria derived from laboratory data interpolated using EPA procedures (Eaton *et al.* 1995b).

Main Conclusions

Effects on fish communities in streams and rivers

In free-flowing streams, the effect of air temperatures and thus global warming on stream temperatures can be approximated by an adjustment factor of 0.9 times air temperature, based on field studies of air-water temperature relationship (Stefan and Preud'homme 1993; Eaton and Scheller 1996). The effects of a doubling of CO₂ on shifts in suitable fish habitat has been estimated based on predictions of air temperature effects from the Canadian Climate Center general circulation model (CCC-GCM) and thermal

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tolerances for 57 fish species derived from the FTDMS through extreme-value analysis (Eaton *et al.*, 1995b). Loss of cold water or cool water fish species was predicted for between 35 and 70% of 1700 USGS temperature monitoring stations, with habitat losses distributed throughout species ranges. Habitat losses were greatest for species with limited distributions and in areas of the country with greatest warming predicted (e.g., the central Midwest). Results for warm water fishes were less certain because of a relative paucity of data on summer and winter thermal tolerances for species.

Effects of global warming on habitable stream reaches based on temperature effects can be modified either positively or negatively near groundwater or tailwater discharges from reservoirs or lakes (Sinokrot *et al.* 1995). Empirical models to predict groundwater inputs to stream reaches based on watershed slope and hydraulic conductivity (based on soil texture; Baker *et al.* 2001), and models in progress to predict modifications to stream thermal regimes based on stream shading from topography or riparian vegetation and groundwater inputs, will help to fine-tune model predictions of the effects of global change on fish species distributions (V. Snarski, personal communication).

Effects of global climate change on warm water fish species in streams are uncertain due to a relative paucity of data on winter thermal tolerances. Multivariate discriminate function analysis has been used to derive models for warm water fish presence/absence based on a combination of up to six thermal variables: cumulative temperature as degree-weeks, degree weeks during the feeding period (weeks > 8 deg C), degree-weeks during the non-feeding period (weeks ≤ 8 deg C), length of non-feeding period in weeks, the ratio of degree-weeks during non-feeding periods to feeding periods, and the number of weeks at or below 2 deg C (a level associated with mortality due to osmoregulatory dysfunction or other physiological mechanisms). For the 15 species examined, fish presence models had high specificity (60 - 100%, percent absence correctly predicted) and high sensitivity (87 - 100%, percent presence correctly predicted).

Recently, the Fish-Temperature-Database-Matching System (FTDMS; Eaton *et al.* 1995b) has been updated with additional data on fish presence from EMAP and STORET and matched with corresponding stream temperatures from USGS-monitored streams to create additional fish/temperature (F/T) sets. A user-friendly graphical interface was developed to facilitate data import, export and query functions to make F/T data available to clients requesting access (e.g., states and tribes, regions) without requiring extensive programming expertise (Contract #68-W7-0055, Task Order #25, Deliverable 25-15, by Lockheed Martin Services, Inc., for U.S. EPA, Office of Information, National Resources Services Division, Research Triangle Park, NC 27711, March 29, 2000).

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Effects on fish communities in lakes

Our ability to predict climate change effects on fish communities in lakes depends on our ability to model the effect of climate-related variables on suitable fish habitat. Modeling exercises have been conducted to predict fish presence/absence in Minnesota lakes as a function of two key driving habitat variables - temperature and dissolved oxygen (Stefan *et al.* 1995, 1996). Model performance varies with lake class, as defined by lake morphometry (maximum depth, surface area) and trophic status. For northern Minnesota, there is full agreement between fish assemblage presence records and model habitat suitability prediction. For cool and warm water fishes in southern Minnesota, there is full agreement between fish assemblage presence records and model simulation results for all 27 lake classes. For cold water fish, model predictions agreed with fish assemblage presence data for only 18 of 27 lake classes. Disagreements between observations and predictions are related to the presence of a cold water fish (cisco) in lakes predicted to have unsuitable habitat for coldwater assemblages; however, cisco is the most tolerant species in the coldwater fish assemblage (Stefan *et al.* 1995).

Predicted sensitivity of suitable fish habitat to climate change based on thermal and dissolved oxygen requirements varies with fish thermal guild (cold water, cool water, warm water), lake morphometry (surface area: maximum depth ratio), and trophic status (Secchi depth) (Stefan *et al.* 1996). Lake morphometry determines the probability of thermal stratification and trophic status determines the depth of penetration of solar radiation and depth of photic zone and dissolved oxygen generation from photosynthesis. Degree of temperature change in lakes following a doubling of CO₂ levels and average air temperature increase of 3.8 deg C depends on both lake morphometry and lake trophic status. Eutrophic lakes with a geometry ratio ([surface area]^{0.25}/maximum depth) between 2 and 4 and oligotrophic lakes with a geometry ratio of between 1 and 2 are predicted to show the least change in hypolimnetic temperature (0 to 1 deg C as compared to 1-3 deg C). Eutrophic lakes with geometry ratios > 4 and oligotrophic lakes with geometry ratios >2 are expected to experience decreases in hypolimnetic oxygen minima of up to 3 mg/L, with anoxic conditions resulting in eutrophic lakes with geometry ratios of 4 to 20. The length of hypolimnetic anoxia will extend up to 60 days, and will be greatest in eutrophic lakes with geometry ratios < 5 and oligotrophic lakes with geometry ratios of < 2 (Stefan *et al.* 1996). Overall, cold water fish are projected to disappear from southern Minnesota lakes, and experience habitat losses of 41% in northern Minnesota lakes. Losses in cold water fish good-growth potential (as reflected in suitable habitat volume) and increases in cool water fish good-growth potential will be greater in well-mixed lakes. Largest gains in suitable habitat for cool and warm water species will occur in oligotrophic lakes (Stefan *et al.* 1996).

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Status of research

Research on the temperature preferences of fish and predicted effects of climate change on fish populations is no longer being pursued as a separate program under Global Climate Change in NHEERL. However, under the Aquatic Stressors Framework, researchers continue to examine the effects of thermal and flow regimes on fish communities as two of many stressors affecting habitat quality. In particular, the effect of land-use/land-cover changes on thermal regimes is being examined.

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4. Responses of the Irrigated Rice Ecosystem to Enhanced UV-B Radiation and Global Climate Change

Statement of the Problem

When this study was conceived there was a critical need for information on the ecological effects of UV-B radiation (from stratospheric O₃ depletion) and global climate change (increased atmospheric CO₂ concentration and air temperature) in tropical areas to support major international assessments on the environmental effects of ozone depletion (by the United Nations Environmental Programme), and climate change (by Intergovernmental Panel on Climate Change). Rice is a major food source for many of the world's people, especially in Asia, but also in Africa and South America (IRRI 1993). The irrigated rice agroecosystem, where fields are flooded for much of the growing season, is the most widely distributed rice system, with 55% of world's rice field area and 75% of the world's rice production (IRRI 1993). Thus any impacts on rice production from UV-B and climate change could have profound impacts on a key component of the world's food supply. In addition to enhancing rice production, flooding of irrigated rice fields results in anaerobic soil conditions conducive to the production of the greenhouse gas methane (Neue 1993). Therefore, understanding the underlying processes and management factors controlling the emission of methane from rice fields was important in terms of developing strategies for the potential mitigation of emissions of greenhouse gases to the atmosphere (Cole 1996).

Approach

To have the most impact and relevance to real field conditions, research on irrigated rice was conducted in tropical countries, in cooperation with local scientists. Thus, the rice research was conducted through a unique international partnership between the U.S. EPA and the International Rice Research Institute (IRRI) in Los Banos, the Philippines; with collaboration by other institutions and researchers in the United States, the Netherlands, Germany, Japan, China, Korea, India, Malaysia, and Sri Lanka (Olszyk and Ingram 1991). The research approach included field experiments, modeling activities and assessments which presented possible impacts of UV-B and climate change on a regional scale for eastern and southeastern Asia. The research was designed to consider responses of irrigated rice production from an ecosystem viewpoint, considering not only the direct effects of UV-B, CO₂ and temperature on the rice plant, but also indirect effects of these stressors on the insects, diseases of rice, and weed competition. The roles of CO₂ and temperature in methane production were also studied. The EPA/IRRI study was coordinated with other international global change research through the International Geosphere-Biosphere Programme (IGBP) of research on Global Change and Terrestrial Ecosystems (GCTE), Focus 3, Global Change Impact on Agriculture, Forestry and Soils.

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Main Conclusions

This research provided critical data for international assessments on the impacts of UV-B radiation and climate change on rice and on options to mitigate those impacts not only on the rice crop, but on emissions of the greenhouse gas CH₄ from rice fields (Peng *et al.* 1995). The data were included in the extensive literature produced by the project including 3 books, 20 book chapters and over 75 peer-reviewed journal papers.

Key results indicated that rice yields likely will not be affected by increases in UV-B predicted from stratospheric ozone depletion under realistic tropical-field conditions based on extensive and intensive field experiments (Dai *et al.* 1997). Under greenhouse conditions, enhanced UV-B injury was associated with active oxygen metabolism in rice leaves (Dai *et al.* 1997), and could affect the susceptibility of rice to the important disease, rice blast (Finckh *et al.* 1995).

In contrast to enhanced UV-B, elevated CO₂ and temperature likely will have dramatic effects on irrigated rice production, not only by directly affecting the plant, but also through indirect effects on other aspects of the rice ecosystem (insects, diseases, and weed competition). Elevated CO₂ enhanced rice plant growth and grain yield provided that N fertilization was not limiting growth (Olszyk *et al.* 1999; Weerakoon *et al.* 1999; Ziska *et al.* 1998; Moya *et al.* 1998). In contrast, while elevated temperature enhanced plant growth, it decreased crop yield due to spikelet sterility. Combining elevated CO₂ and elevated temperature resulted also resulted in enhanced plant growth, but with spikelet sterility. Climate change also was predicted to affect rice productivity by altering disease occurrence (Luo *et al.* 1995) and insect infestations (Heong *et al.* 1995).

Computer simulations and spatial analysis were used successfully to assess the potential impacts of climate change on rice productivity across south and Southeast Asia (sidebar). In the EPA/IRRI analysis, potential rice yield either decreased or increased depending on the global climate model, crop model, and site within a country. Overall, the analysis found an average 3.8% decrease in rice production across south and Southeast Asia with future increases in CO₂ and temperature compared to current conditions. Though relatively small, this predicted change would occur at a time when rice yields must increase substantially to keep in step with increases in human population in the area.

Unique field experiments indicated that the effects of elevated CO₂ and temperature on rice plants could increase methane emissions from rice fields, providing an important feedback to climate change from rice cultivation (Olszyk *et al.* 1999; Ziska *et al.* 1998). Elevated CO₂ or in combination with elevated temperature produced a large increase in methane emissions from rice fields compared to current conditions; primarily due to a large increase in belowground biomass (see sidebar). In contrast, elevated temperature alone tended to decrease methane emissions from rice fields. The magnitude of these changes in methane emissions from rice fields were not predicted by current plant

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growth simulation models (Olszyk *et al.* 1999).

In addition to demonstrating impacts of climate change on the irrigated rice systems, research indicated avenues to mitigate those impacts for this intensively managed agricultural system. The wide-range in variability among rice cultivars and plant types in terms of adverse effects from enhanced UV-B and elevated temperature, as well as beneficial effects from elevated CO₂, indicates the potential for plant breeding to maintain or enhance rice yields in the future (Moya *et al.* 1998; Dai *et al.* 1994). Similarly, methane emissions from rice fields varied considerably with rice cultivar, fertilizer amount and form, irrigation timing, and other factors, indicating the potential to reduce methane emissions from rice fields through altered management practices (Neue *et al.* 1995).

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Elevated UV-B Radiation from Stratospheric O₃ Depletion not expected to affect Rice Yields

With depletion of the stratospheric O₃ layer, ground-level UV-B levels are expected to increase. The effect of potential increases in UV-B under realistic field conditions was determined in rice fields at the International Rice Research Institute at Los Baños, the Philippines. Over five growing seasons, both wet (cloudy, rainy) and dry (more sunlight, dry) two widely grown (yet potentially UV-B susceptible) rice cultivars IR 72 and IR 74 exposed to current and enhanced UV-B radiation. There was no significant UV-B effect on rice yield for either cultivar in any season. Across all seasons and both cultivars the average yield was the same at 608 g m⁻² for both control and enhanced UV-B rice plants. Source: Dai *et al.* 1997.

Increased Atmospheric CO₂ and Air Temperature Affects Rice Yields and Methane Emissions from Rice Fields

The effects of increased atmospheric CO₂ and consequent predicted increases in air temperature were studied for rice -- the world's most important crop for direct human consumption. Both rice yield and methane emissions, a greenhouse gas produced in rice soils, were measured for rice plants grown in open-top chambers under realistic tropical field conditions at the International Rice Research Institute in the Philippines. Yield and methane emissions were determined for the widely grown rice cultivar, IR 72, grown for two wet and two dry seasons under current ambient CO₂ and temperature conditions (ACAT) and under three future climate scenarios of elevated CO₂ and ambient temperature (ECAT), ambient CO₂ and, elevated CO₂ and elevated temperature (ECET). By itself, elevated CO₂ increased rice yields, as shown for many other crops grown under conditions of optimum N fertilization and water. However, elevated temperature tended to decrease rice yields and thus the increase in rice yield with elevated CO₂ alone was negated when temperature also elevated. Emissions of methane were increased when rice plants were exposed to elevated CO₂ either with or without elevated temperature, which was associated with an increase in root biomass; while elevated temperature alone tended to decrease methane emissions. Source: Olszyk, *et al.* 1999; Moya *et al.* 1998; Ziska *et al.* 1998.

Scenario ^a	Parameter	1994 Wet	1995 Dry	1995 Wet ^b	1996 Dry
ACAT	Grain Yield (g m ⁻²)	366	683	----	874
ECAT	Change Grain Yield (%)	+29	+24	----	+15
ACET	Change Grain Yield (%)	-26	-16	----	-13
ECET	Change Grain Yield (%)	-14	+9	----	-6
ACAT	Methane (mg m ⁻² d ⁻¹)	----	----	142	260
ECAT	Change in Methane (%)	----	----	+60	+48
ACET	Change in Methane (%)	----	----	----	-54
ECET	Change in Methane (%)	----	----	----	+45

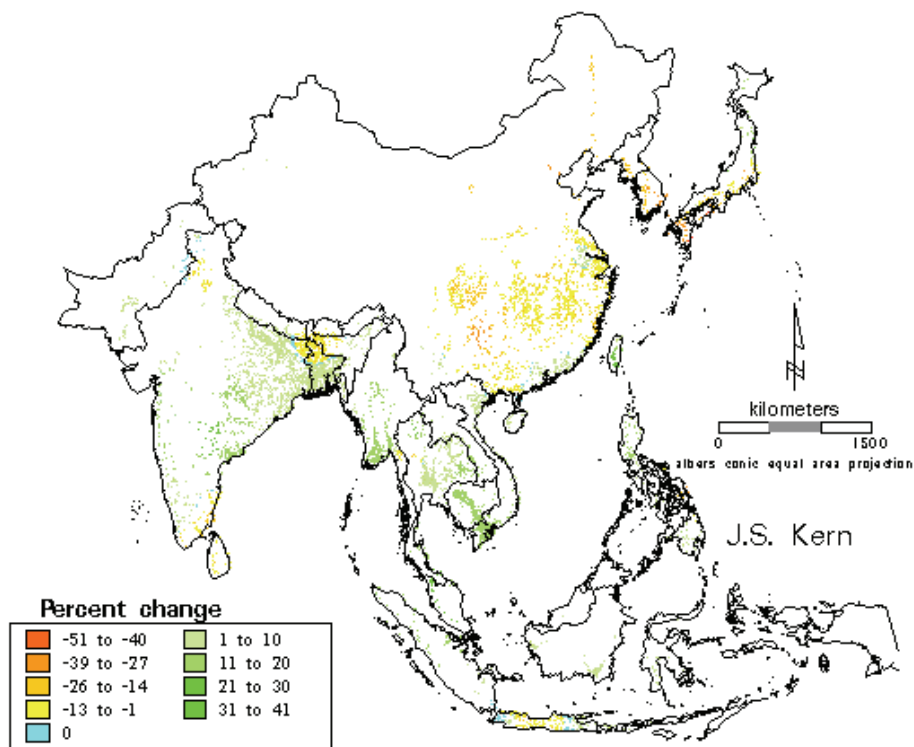
^a Experimental values in bold are significantly different from ambient CO₂ and ambient temperature at p<0.05.

^b Rice yield severely decreased due to typhoon prior to crop maturity.

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Changes in Rice Grain Yield across East and South Asia with Elevated CO₂ and Elevated Temperature

Potential effects of climate change (elevated CO₂ and elevated temperature) on irrigated rice production across south and East Asia were estimated based on computer simulations and spatial analysis. Climate change scenarios from the General Fluid Dynamics Laboratory (GFDL), Goddard Institute of Space Studies (GISS), and United Kingdom Meteorological Office (UKMO) General Circulation Models (GCMs,) were used, assuming a doubling of current atmospheric CO₂. The outputs from those models were used with site-specific weather data and two plant process-based rice crop simulation models, ORYZA1 and SIMRIW to predict potential rice yield under current and future climate conditions at sites across Asia. The changes in rice yield with climate change were assessed using a Geographic Information System (GIS). An example of the pattern of these changes in yield from current climate conditions based on the UKMO GCM and ORYZA1 model is shown below. In this simulation, global climate change produced increases in potential yield (green colors) for much of India and southeast Asia, and decreases in yield (yellow to orange colors) in most of China, Japan and Korea; with an average 5.6% reduction in yield across all of Asia (Source: Matthews, Horie *et al.* 1995).



Percent change in rice yield using UKMO climate compared to current climate.

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5. Agriculture – Crop yields, soil erosion, and soil carbon

Statement of the Problem

Rising atmospheric CO₂ concentrations and global climate change could potentially have significant effects on American agriculture. While elevated CO₂ may have a beneficial effect on crop growth, increased temperature and changes in precipitation, wind, and other climatic variables may alter crop yields. These climatic changes may also affect rates of soil erosion and the carbon content of agricultural soils, which may affect carbon sequestration.

Soils are a major reservoir of global carbon, and are equal in magnitude to the combined global carbon content of the entire atmosphere plus all aboveground biomass. Loss of agricultural soil carbon through erosion, management, and decomposition adds to the atmospheric loading of CO₂. Agricultural management practices which conserve or sequester soil carbon can help mitigate the rate of increase of atmospheric CO₂. Assessments of the potential for such mitigation through widespread adoption of best management practices for major American agricultural areas are needed as well.

Approach

Research focused on model assessments of the sensitivity of soil erosion to precipitation change scenarios across the US, and more detailed evaluations of crop yield, soil erosion, and soil carbon responses to climate change scenarios including temperature, precipitation, wind, and CO₂ in the US Corn Belt. The research focused on two erosional processes: (1) water erosion which is the loss of soil due to rainfall runoff from field crops, and (2) wind erosion which is the loss of soil due to wind blown particles. Assessments were also made of the effects of widespread adoption of various management practices on soil erosion and soil carbon in the United States to mitigate the rate of atmospheric CO₂ increase. Management scenarios included the current mix of tillage and crop rotation practices, and increased use of crop rotation and conservation tillage practices which have become more prevalent in recent years.

Main Conclusions

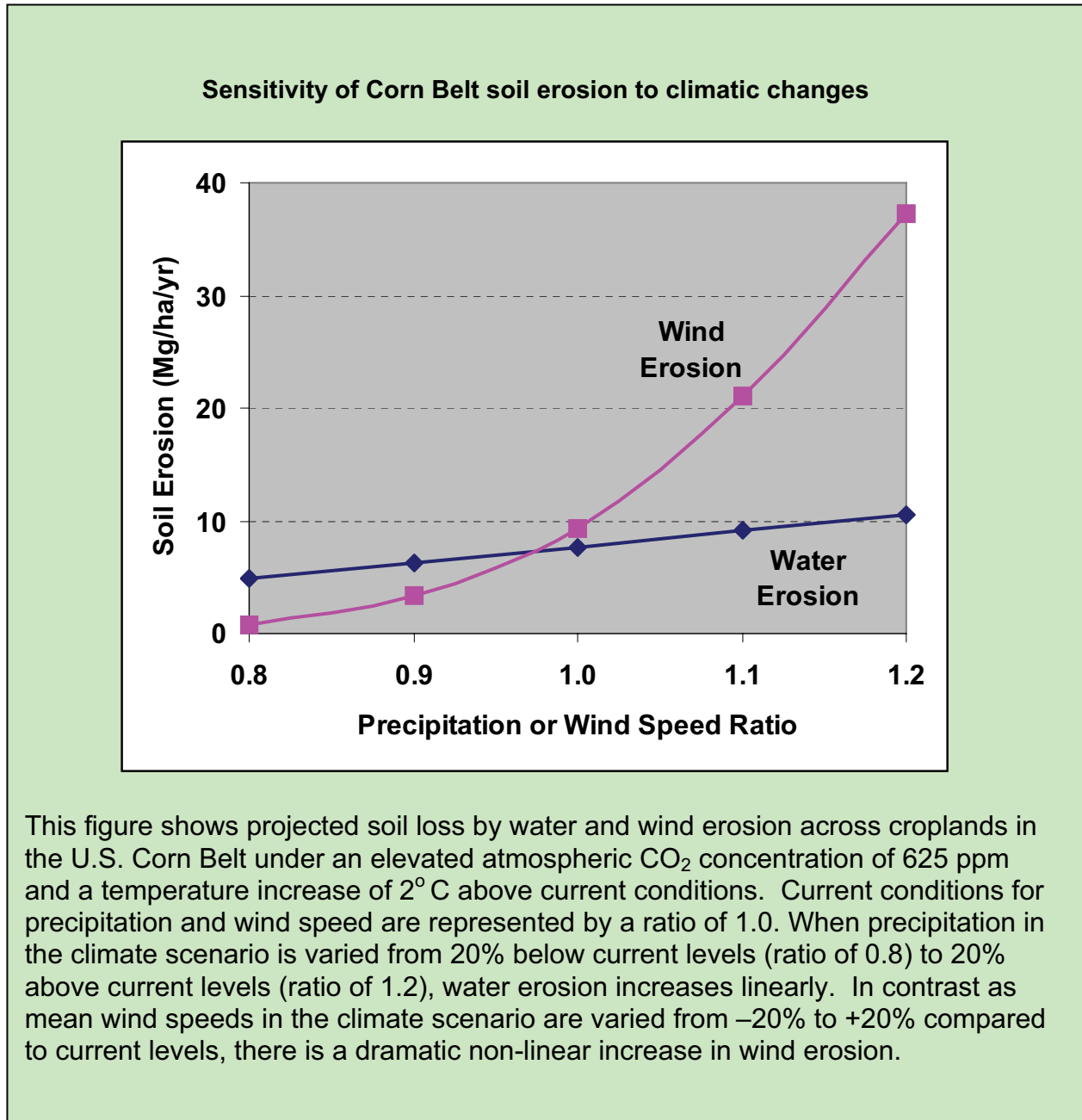
Projected water erosion of soil for U.S. croplands, pasturelands, and rangelands increased with increases in precipitation in the 2xCO₂ climate change scenarios from four atmospheric General Circulation Models (Phillips *et al.* 1993b). Changes in erosion were greater when precipitation changes were assumed to be from changes in storm intensity rather than storm frequency, indicating the importance of the manner in which climatic changes occur in addition to their mean magnitude. Recent reductions in national soil erosion indicate the potential for management changes to mitigate the magnitude of erosion increases projected under these climate change scenarios.

5. Ag Soils

In a detailed model assessment using 36 climate/CO₂ scenarios for croplands in the U.S. Corn Belt, water erosion linearly tracked increasing or decreasing precipitation, but wind erosion showed dramatic increases as mean wind speeds increased (Lee *et al.* 1996). Increasing temperature alone decreased water erosion while increasing wind erosion and total erosion (water and wind). But, beneficial effects of elevated CO₂ on plant growth nullified this effect on total soil erosion.

Typical of agricultural soils under long-term cultivation, soil carbon decreased over the 100 year simulations, adding to atmospheric CO₂ loadings. This carbon loss was accelerated by increased temperature and precipitation, but elevated CO₂ slowed the loss rate. Corn and soybean crop yields were projected to decrease slightly due to temperature or wind increases alone, track precipitation increases or decreases, and increase markedly in response to an 80% increase in CO₂ (Phillips *et al.* 1996).

Model assessments of alternative management practices in the U.S. Corn Belt showed that increasing use of conservation tillage practices such as mulch-till and no-till could substantially reduce the loss of soil carbon due to erosion and decomposition (Phillips *et al.* 1993a, Lee *et al.* 1993). Agricultural soils could become a small sink for carbon with widespread use of no-till cultivation and use of a winter cover crop (Lee *et al.* 1993). This indicates the potential for changing agricultural management practices to mitigate the buildup of atmospheric CO₂ and associated climatic change. Conservation tillage is economically and functionally feasible and is likely to occur because of land and soil conservation benefits from conservation tillage and rising fuel costs (Kern and Johnson 1993).

Wind and water erosion

Carbon Sequestration in Soil

Soil organic matter is the largest global terrestrial carbon (C) pool and is a source of CO₂, CH₄, and other greenhouse gases. Soil management affects the amount of C held in soil and the greenhouse gas emissions from soil. In the agricultural sector conventional tillage practices such as the use of a moldboard plow, lead to a steady loss of soil C to the atmosphere. In contrast, conservation tillage practices that include minimum tillage and no-till conserve soil C and reduce that amount of fossil fuel needed for tillage.

Kern and Johnson (1993) conducted an analysis of the amount of soil C that would either be lost or sequestered and the amount of fossil fuel required for agriculture in the contiguous United States using three scenarios of conservation tillage: 27% (Scenario 1), 57% (Scenario 2) and 76% (Scenario 3). The analysis covered 30 years beginning in 1990. For Scenario 1, the level of conservation tillage was held constant at the actual 1990 level of 27% for 30 years. For Scenarios 2 and 3, both began at 27% in 1990 and linearly ramped up to 57% and 76%, respectively, over the first 20 years of the analysis and were held constant for the remaining 10 years.

Maintaining 1990 levels of conventional and conservation tillage resulted in a net loss of 41 Tg of soil C (1 Tg = 10¹²g) over the 30-year period while using 157 Tg of fossil fuel. A combined 198 Tg of C was estimated to be added to the atmosphere under Scenario 1. For Scenario 2, a net sequestration of C in soil (+80 Tg) was achieved while fuel consumption dropped slightly. Fossil fuel consumption did not drop concomitantly because reduced tillage systems require more herbicides and pesticides -- derived from fossil fuels -- than conventional tillage systems. For Scenario 3, an additional 364 Tg of soil C sequestered and 146 Tg of fossil fuel consumed, for a net gain of 218 Tg of C.

Changes in soil organic C and fossil fuel C emission for three scenarios of conservation tillage (CT) for agriculture in the contiguous U.S. projected from 1990 to 2020.

Tillage System	Scenarios of Conservation Tillage (CT)					
	27% CT ^a		57% CT ^b		76% CT ^c	
	Soil	Fuel	Soil	Fuel	Soil	Fuel
Conventional Tillage	-41	-121	-24	-87	-13	-67
Minimum Tillage	0	-30	0	-52	0	-66
No-Tillage	0	-6	+104	-10	+377	-13
Sums	-41	-157	+80	-149	+364	-146
Net Loss (-) or Gains (+)	-198		-69		+218	

^{a)} 27% CT scenario uses the level of conservation tillage used in 1990 (~27%) held constant for 30 years until 2020.

^{b)} 57% CT scenario begins in 1990 with 27% conservation tillage and linearly ramps up to 57% conservation tillage over 20 years (2010) and remains constant at 57% until 2020.

^{c)} 76% CT scenario begins in 1990 with 27% conservation tillage and linearly ramps up to 76% conservation tillage over 20 years (2010) and remains constant at 76% until 2020.

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6. The Global Carbon Cycle: Managing Forest Systems

Statement of the Problem

The accumulation of CO₂ in the atmosphere due to fossil fuel use, deforestation and other anthropogenic sources is changing the global climate (Harries *et al.* 2001; IPCC 2002). Current understanding of the global carbon cycle suggests that managing forests and agricultural lands to increase the sequestration of greenhouse gases (GHG) provide credible policy options (Dixon and Turner 1991, Winjum *et al.* 1993a, Brown 1996a, Brown *et al.* 1996). EPA/WED research efforts during the 1990's estimated the amount of that carbon which could be sequestered by purposeful management actions, and the incidental amount of carbon that inadvertent land use is likely to release to the atmosphere in the future. The three specific objectives of this research were to: 1) develop or refine global, country-level and regional estimates of carbon pools and fluxes in forests, 2) evaluate the potential to conserve and manage forests to expand the accumulation of carbon, and, 3) project future forest carbon pools and fluxes during expected changes in climate and land-use. The annual exchange of carbon between forests and the atmosphere, and the amounts of carbon stored in forests, varies widely with the nature of forest cover. With land use and management, and with climatic constraints, our research showed that management of forests can significantly increase the long-term sequestration of atmospheric CO₂. However, management efforts aimed at storing carbon in the tropics -- the largest pools on Earth -- are being countered by carbon emissions from forest destruction.

Approach

We developed several methods to quantify the major carbon pools and fluxes in forested ecosystems (Winjum *et al.* 1993b, Turner *et al.* 1995, 1997, Brown *et al.* 1999). Forest carbon budgets were constructed with recently completed national carbon budgets, and with global, national or regional databases of carbon densities in various above and below-ground forest pools (Dixon and Turner 1992; Kolchugina and Vinson 1993a; Cairns *et al.* 1997), in forest products (Winjum *et al.* 1998), and in differing land uses (Brown 1996b) and forest areas (Gaston *et al.* 1994, 1997). NHEERL researchers applied available static geographic models (Turner and Leemans, 1992; King and Neilson 1992, Lugo *et al.*, 1999) or developed new models (Prentice *et al.* 1992; Solomon *et al.* 1993; Neilson 1995; Kirilenko and Solomon 1998), each using the distributions of current climate variables as proxies for vegetation and carbon stocks. The data sets and information developed in these studies were then used as a base against which to contrast the amounts of carbon that is sequestered by various management techniques (e.g., Winjum *et al.* 1993b, Dixon 1995, 1997; Dixon *et al.* 1993, 1994b). The distribution of future climatic conditions projected by climate models could then be used to assess distributions and amounts of future carbon stocks. The future global carbon stock estimates from the static geographic models are discussed under "*F-Vegetation Redistribution*" and will not be reiterated here.

Main Conclusions

Forests play a prominent role in the global carbon cycle and the accumulation of GHG in the atmosphere, but the roles vary regionally (Dixon *et al.* 1994). In the conterminous United States, for example, total forest carbon was calculated to be 36.7 Gt C (Gt = Gigatons, i.e., a billion tonnes), with annual uptake of about 331 Mt (million tons) C, and losses to harvests of 266 Mt C (Turner *et al.* 1995). However, a different method suggested that annual carbon uptake for eastern U.S. forests during the late 1980s and early 1990s was about 416 Mt C/yr (Brown and Schroeder 1999). In the eastern United States, forest carbon stocks were estimated at 20.5 Gt, 80% of that found in hardwoods (Brown *et al.* 1999). Schroeder *et al.* (1997) noted that these carbon stocks were distributed primarily in small stands or lots with small trees, and in larger stands with large trees. This suggests that most carbon in the eastern U.S. is stored in young forests growing on abandoned farms and in forest reserves with large mature trees. An error analysis of the southeastern carbon stocks (Phillips *et al.* 2000) showed that sampling error was only about 1% (95% confidence intervals) but that annual carbon increments carried errors of about +/- 40%.

These carbon stocks and fluxes from the temperate U.S. forests were compared to estimates we developed in boreal and tropical regions, and for the world as a whole. Globally, forest vegetation and soils contain about 1146 Gt of C, with approximately 37% of this carbon in low-latitude forests, 1/7 in mid-latitudes, and 49% at high latitudes. Over two-thirds of the carbon in forest ecosystems is contained in soils and associated peat deposits (Dixon *et al.* 1994a). The carbon stocks and fluxes of the former Soviet Union (FSU) were examined in several papers which focused on the large portion of the world's biomass held by the boreal forests and peatlands.

Based on calculations from mapped ecoregions of the FSU, and estimated carbon stocks and fluxes in those ecoregions, the FSU forests were estimated to contain 69 and 110 Gt C above ground, and 331 and 337 Gt C below ground (Kolchugina and Vinson, 1993b and 1993c, respectively). A third paper in the series (Vinson and Kolchugina 1993) indicated similar values of 118 Gt C above ground for all vegetation, and 423 Gt C below ground. Unique environments (permafrost, peatlands) of the FSU were analyzed separately, indicating that permafrost carried 17 Gt C above ground and 155 Gt C in soils and litter (Kolchugina and Vinson 1993d, 1993e), including peatland carbon. Carbon in peatlands evaluated alone (Botch *et al.* 1995) was estimated at 215 Gt C.

Estimates of carbon stocks and fluxes from several tropical regions provided additional depth to the analysis. Africa, for example, was determined to contain 50.6 Gt C in all vegetation cover, both above and below ground (Gaston *et al.* 1998). In the western Hemisphere, Brazil contains the world's largest expanse of tropical forests, with 136-162 Gt C in above and below-ground vegetation and litter (Schroeder and Winjum 1995a), and net emissions of carbon to the atmosphere of 174-233 Mt yearly (Schroeder and Winjum 1995b) projected for the 20-yr period of 1990 to 2010 (Schroeder and Winjum 1995c, Schroeder 1996). Delany *et al.* (1997, 1998) determined that Venezuelan forests held 300-500 T/ha C, with 20-37% of that on and below ground and

6. Forest Management

with turnover time of litter into CO₂ being very rapid (<2 yrs). Biomass burning in Costa Rica (Helmer and Brown 2000) contributed to considerable CO₂ emissions as well, primarily from lowland forest destruction.

In Mexico, like Costa Rica, most carbon stock changes near the end of the 20th century were attributable to destruction of tropical and subtropical forests (Cairns *et al.* 1995, 1996), from southern Mexico (Riley *et al.* 1997, Schuft *et al.* 1998, Cairns *et al.* 2000), to the Mexican central highlands (De Jong *et al.* 1999, 2000). The data from Brazil, Mexico, the U.S. and the former Soviet Union, were combined in several papers, both for comparing overall carbon budgets (Turner *et al.* 1997, 1998, without Mexico), and to compare land use effects (Cairns *et al.* 1997). The results amplified conclusions reached in earlier analyses, demonstrating the importance of reducing land use impacts on forest biomass in tropical areas, and of applying forest management techniques to enhance carbon sequestration in tropical, temperate and boreal regions.

Slowing deforestation, combined with an increase in forestation and other management measures to improve forest ecosystem productivity, could conserve or sequester significant quantities of C. Future forest carbon cycling trends attributable to losses and regrowth associated with global climate and land-use change are uncertain (Dixon *et al.* 1999). Model projections and field experiments suggest that forests could be carbon sinks or sources in the future (Dixon *et al.* 1994). To the end, forest carbon conservation and sequestration options have become major policy instruments of the UN Framework Convention on Climate Change Activities (UNFCCC) Implemented Jointly (AIJ) pilot over the past decade (Dixon 1999, Dixon 1995).

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Estimates of carbon pools and flux in forest vegetation in world forests

Latitudinal Belt	C Pools (Pg)	
	Vegetation	Soils
<i>High</i>		
Russia	74	249
Canada	12	211
Alaska	2	11
Subtotal	88	471
<i>Mid</i>		
Cont'l US	15	26
European ^a	9	25
China	17	16
Australia	18	33
Subtotal	59	100
<i>Low</i>		
Asia	41 ^b -54	43
Africa	52 ^b	63 ^c
Americas	119 ^b	110 ^c
Subtotal	212	216
TOTAL	359	787
1Pg=10 ¹⁵ g or 1 gigatonne		

The table shows estimated carbon pools and area-weighted carbon densities in forest vegetation (above- and below-ground living and dead mass) and soils (O horizon, mineral soil to a depth of 1 m, and co-located peatlands) in forests of the world (from Dixon et al 1999).

a Includes Nordic nations. A factor of 1.75 was used to convert stem to total vegetation biomass. For soil C, an average of 9 kg m² for temperate forests and the forest area in Table 1 was used.

b Estimated as the product of carbon densities by ecofloristic zone and areas of forest in each zone, corrected for roots, non-tree components, and woody debris.

c Estimated as the product of forest area and an average of 12 kg m² of soil organic C.

Forests are important in the global carbon cycle because they store more than 55% of the global carbon stored in vegetation and more than 45% of that stored in soils, exchange carbon with the atmosphere through photosynthesis and respiration, are sources of atmospheric carbon when they are disturbed by human or natural causes and become atmospheric carbon sinks during regrowth after disturbance. Forests can influence climate change by affecting the level of CO₂ in the atmosphere; through the production of other greenhouse gases such as carbon monoxide, ozone, and nitrous oxide; and through changes in albedo of land as forests are converted to other land cover types.

Globally, forest vegetation and soils contain approximately 359 and 787 Pg of C, respectively (Pg= 1,000 million tonnes). Earlier projections ranged from 953 to 1400 Pg of global C. The allocation of carbon between vegetation and soils differs by latitude, with a large part of the vegetation (25%) and soil (59%) carbon pools located in the high-latitude forests. Mid-latitude forests account for a small portion of the global carbon pool (16 and 13% of the vegetation and soil, respectively). Low-latitude tropical forests are relatively heterogeneous and contain 59 and 27% of global forest vegetation and soil C, respectively (Dixon et al. 1994a).

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Carbon Sequestration Potential

Global estimates of potential amount of C that could be sequestered and conserved by forest management practices between 1995 and 2050 (from Brown et al 1996a)

Latitudinal Belt	Country/Region	Practice	C Sequestered/Conserved (Gt)		
High	Canada	Forestation	0.68		
	Nordic Europe		0.03		
	FSU		1.76		
		Subtotal		2.4	
	Mid	Canada	Forestation	0.43	
		USA		3.07	
		Europe		0.96	
		China		1.70	
		Asia		2.19	
		South Africa		0.44	
South America		1.02			
Australia		0.31			
New Zealand		1.7			
		Subtotal			11.8
Low	USA	Agroforestry	0.29		
	Australia		0.36		
		Subtotal		0.7	
	Tr. America	Forestation	8.02		
			Tr. Africa	0.90	
			Tr. Asia	7.50	
		Subtotal		16.4	
	Tr. America	Agroforestry	1.66		
			Tr. Africa	2.63	
			Tr. Asia	2.03	
		Subtotal		6.3	
	Tr. America	Regeneration ²	4.8-14.3		
			Tr. Africa	3.0-6.7	
			Tr. Asia	3.8-7.7	
		Subtotal		11.5-28.7	
Tr. America	Slow Deforestation ¹	5.0-10.7			
		Tr. Africa	2.5-4.4		
		Tr. Asia	3.3-5.8		
			Subtotal		10.8-20.8
			Total		60-87

¹Includes an additional 25% of aboveground C to account for belowground C in roots, litter, and soil (based on data in Brown et al., 1996); range in values is based on the use of low and high estimates of biomass C density resulting from the uncertainty in these estimates.

Humans change the size of carbon pools and alter the flow of carbon between them through forest management. Forests can become atmospheric carbon sinks during regrowth and can be managed to alter their role in the carbon cycle. Local forests management for carbon conservation and sequestration could mitigate emission of carbon CO₂ by an amount equivalent to 11 to 15 percent of fossil fuel emissions (Brown et al. 1996).

Estimates of unrealized global forest carbon conservation and sequestration range from 1 to 3 Pg C annually for as much as a century. Forest management practices to conserve and sequester carbon can be grouped into four major categories: 1) maintain existing carbon pools (e.g., slow deforestation) (Dixon et al. 1993), 2) expand existing carbon sinks and pools through forest management (Dixon 1997), 3) create new sinks and pools by expanding tree and forest cover (Winjum et al. 1992), and, 4) substitute renewable wood-based fuels and products for those derived from fossil fuels (Dixon et al. 1994b). Management of forests as carbon reservoirs often complements other environmental goals including protection of biologic, water, and soil resources.

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7. Vegetation Redistribution

Statement of the Problem

Global CO₂ emissions may generate two classes of ecological impacts at the global scale. One involves the global carbon cycle and another involves the Earth's biodiversity. Both are affected in large part by the potential redistribution of vegetation on the Earth. Currently, the many different kinds of unmanaged vegetation are adapted to today's climate; as climate changes, each kind of vegetation must change as well, dying out in places where climate becomes too stressful, and prospering where climate becomes salubrious. As the Earth warms from increasing atmospheric greenhouse gases, the redistribution of vegetation can induce the terrestrial biosphere to become either a source of additional CO₂ (quickening the warming) or a sink for CO₂ (reducing the warming). Which course it will take is not known. For example, a warmer earth should support more forests that contain high carbon densities, but the warmest places on earth today support only sparsely-vegetated deserts. As vegetation changes, so do the ecosystems on which populations of plants and animals depend for their existence. Hence, biodiversity will also be impacted by vegetation redistribution. The NHEERL research effort of the 1990's focused on the carbon cycle implications of vegetation redistribution.

Approach

Estimating future vegetation redistribution was based on developing predictive models. One group of models was designed to correlate the geography of climate with the geography of vegetation types. Then the future distribution of climate was used as a basis for redrawing the geography of the vegetation types (including agriculture). Once the new distributions of vegetation types were defined, the carbon they could store was calculated -- assuming that their current carbon densities would be supported in their future distributions.

A second group of models accounted mechanistically for processes which determine the growth, shifting density, and carbon uptake of vegetation during chronic climate change. These processes include the rapid dieback, reproduction, and slow regrowth of forests -- all processes which induce lags in vegetation response to rapid climate change. Although these processes could not be treated mechanistically in the correlative models described above, we did approximate the process effects in the correlative models, using values consistent with known biotic change rates.

Main Conclusions

The redistribution of global vegetation in response to climate and land use change during the next century is likely to generate a several-decade long pulse of carbon dioxide from the biosphere into the atmosphere. The result will enhance the buildup of greenhouse gases resulting from anthropogenic emissions.

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Critical to the modeling effort was developing precise data bases for climate and vegetation (e.g., EPA/NOAA 1992, 1993). Early work used life form classifications (e.g., Sedjo and Solomon 1988; King and Neilson 1992). Later work used known climate thresholds to assemble different plant functional types (PFTs) in each $\frac{1}{2} \times \frac{1}{2}$ degree of latitude and longitude (Prentice *et al.* 1992). The presence of different combinations of PFTs defined biomes (temperate deciduous forest, cold grasslands, etc.). In addition to assessing vegetation redistribution impacts on the carbon cycle (e.g., Solomon, *et al.* 1993, 1996; Solomon 1996, 1997), we also assessed land use effects (Cramer and Solomon 1993, Leemans and Solomon 1993, Solomon and Leemans 1997), rapid tree dieback, differential availability of seeds, and slow regrowth of vegetation (Solomon and Kirilenko 1997, Kirilenko and Solomon 1998). Primary conclusions were:

- 1) The capacity of the terrestrial biosphere to remove and store atmospheric carbon should be greater under a warmer global climate.
- 2) The slow death and growth responses by vegetation would generate a pulse of carbon from vegetation 15-20% as great as that from anthropogenic emissions.
- 3) Increasing intensity of agriculture in higher latitudes would permanently reduce the capacity of the earth to store carbon below its' current storage capacity.

A second modeling approach used climate correlations (rather than climate thresholds) to define the climate space occupied by U.S. vegetation types (Neilson *et al.* 1992), and then applied a physiology model which calculated the uptake of CO₂ by photosynthesis and emission of CO₂ by respiration in each vegetation type (Neilson 1993a, 1995). This approach used climate projections calculated by global climate models to define new vegetation distributions. Then, based on the new distributions of vegetation types, the projected balance of carbon uptake and emission from vegetation was determined. Expanded to a global scale (Neilson 1993b, 1998, Neilson and Marks 1994), this approach could simulate the direct effects of increasing CO₂ (a plant nutrient) on biomass storage. Applied to future climate conditions using several climate scenarios, this research suggested, but did not confirm, the potential presence of a multi-decade transient pulse of atmospheric carbon (Neilson 1993b, 1998).

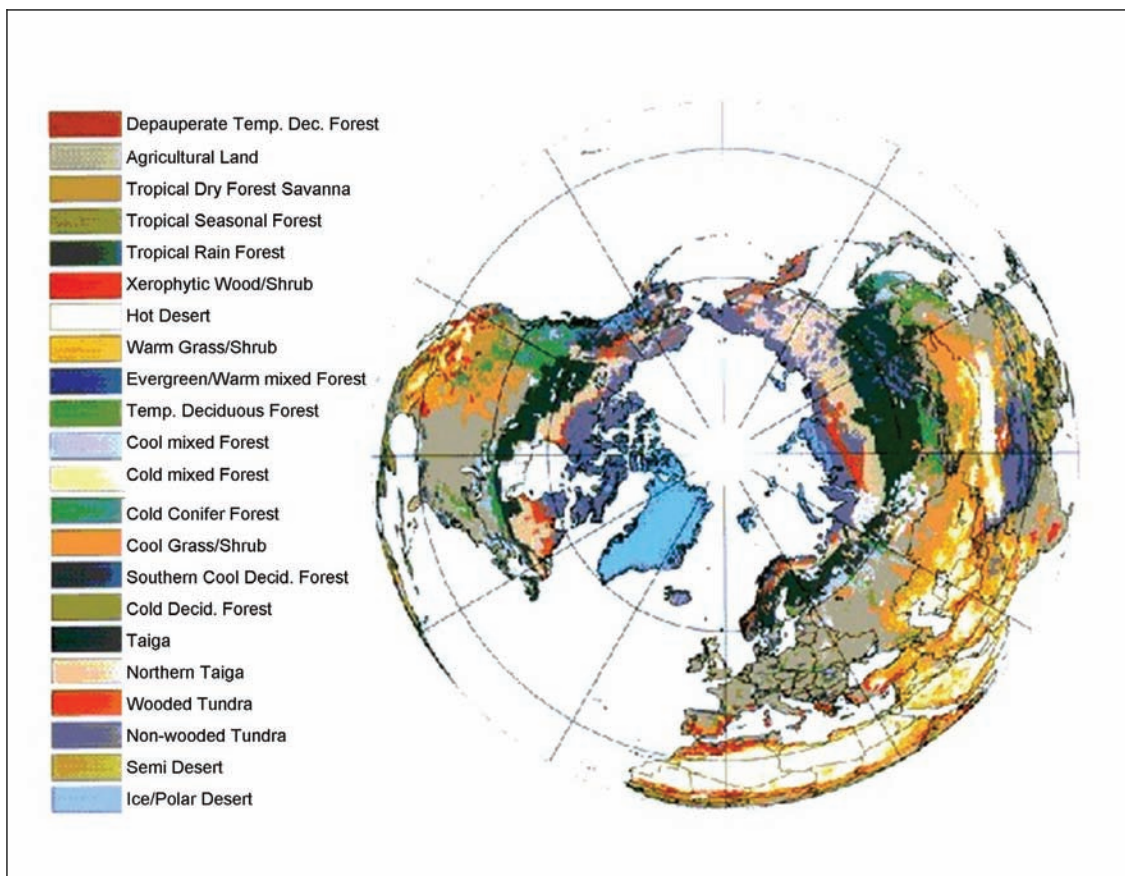
The modeling effort could not estimate the effects on carbon storage of slow vegetation responses to rapid climate changes. Instead, carbon storage was projected assuming that climate and vegetation distributions are stable. However, "there is no indication that a stable climate will appear in the foreseeable future. Indeed, the global change problem to be assessed involves rapidly changing climate, not stable climate" (Solomon *et al.* 1996). Forest gap models were used to estimate the time-related responses of vegetation to rapid climate change. These models replicate the death, reproduction, growth, and maturity of trees, and the development of forest ecosystems (Solomon and Bartlein 1992, Solomon and West 1993,

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Bugmann and Solomon 1995, 2000). Although assessment exercises with these models (Solomon and Bartlein 1992, Bugmann *et al.* 2001) confirmed the potential for the long-term carbon pulse that was described by the static correlative models, the gap models have not yet been applied on the globally-comprehensive basis needed to thoroughly evaluate the carbon pulse phenomenon.

Measured Global Vegetation Biomes

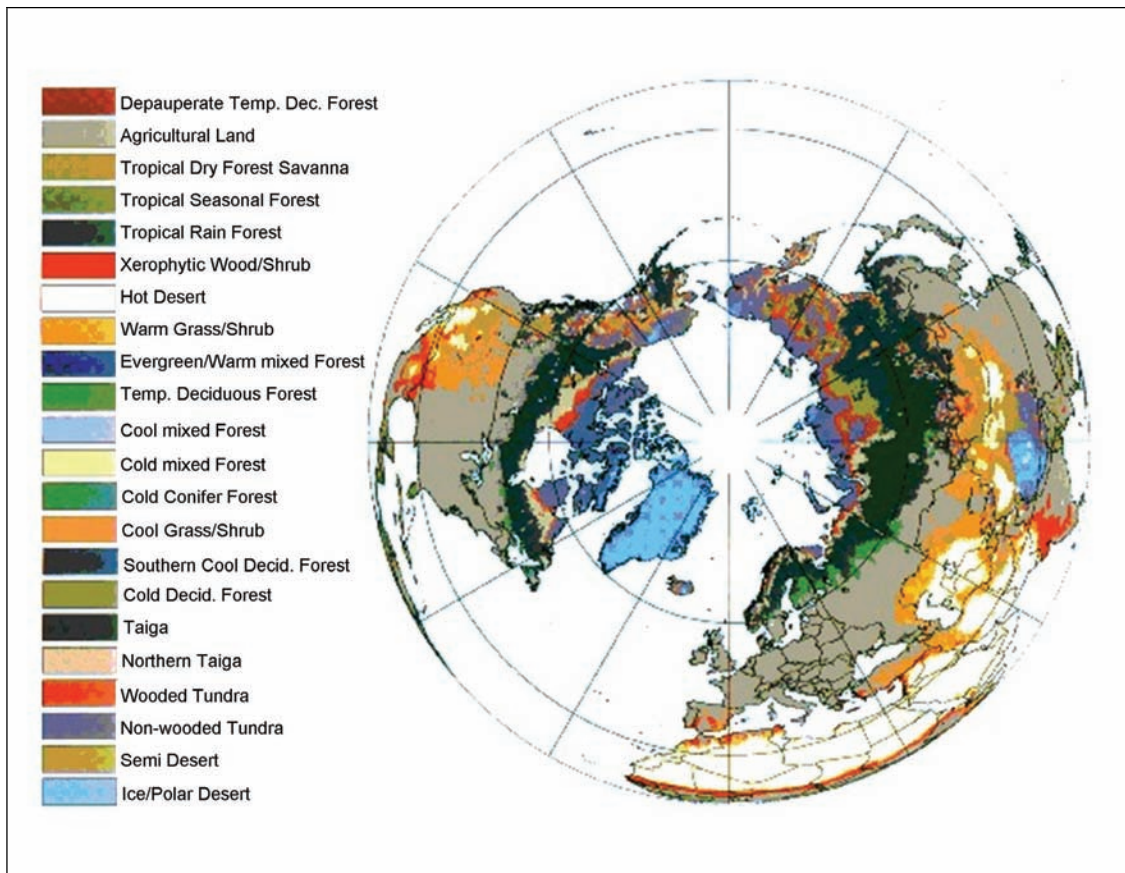
Map of measured global vegetation biomes, including land dominated by agriculture, from various literature sources compiled and mapped by J. S. Olson, *et al.*, 1983 (from Solomon and Leemans, 1997, p. 141). Notice the effects of low temperature limits to plant growth shown by the latitudinal bands of boreal vegetation in the polar regions, and the dominance of low moisture limits to plant growth (1) in temperate and regions, shown by the longitudinal bands of agricultural and natural vegetation, and (2) in tropical regions shown by the latitudinal presence of hot deserts along the subtropical convergence zone where sinking air blocks frontal passage and thus precipitation. The finer-scale complexity of the global biome distribution patterns is derived from the local and regional variations in soils, topography, and land use.



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Modeled Global Vegetation Biomes

Map of modeled global vegetation biomes, including land suitable for agriculture. This map is defined entirely by known cardinal climate thresholds applied through the BIOME model, with no reference to the actual vegetation present. Modeled biomes are identified in the legend above (from Solomon and Leemans 1997, p. 141). Comparing this map with the previous one, notice that the model maintains the biome distribution patterns with regard to low temperature and low moisture dominance in polar, temperate and tropical regions, as well as many of the finer-scale biome distribution patterns derived from the local and regional variations in soils, topography, and land use. The ability to use climate data as proxy vegetation to reproduce the known patterns of biome distribution is critical to subsequent efforts aimed at projecting maps of future vegetation and carbon storage under climate warming scenarios.



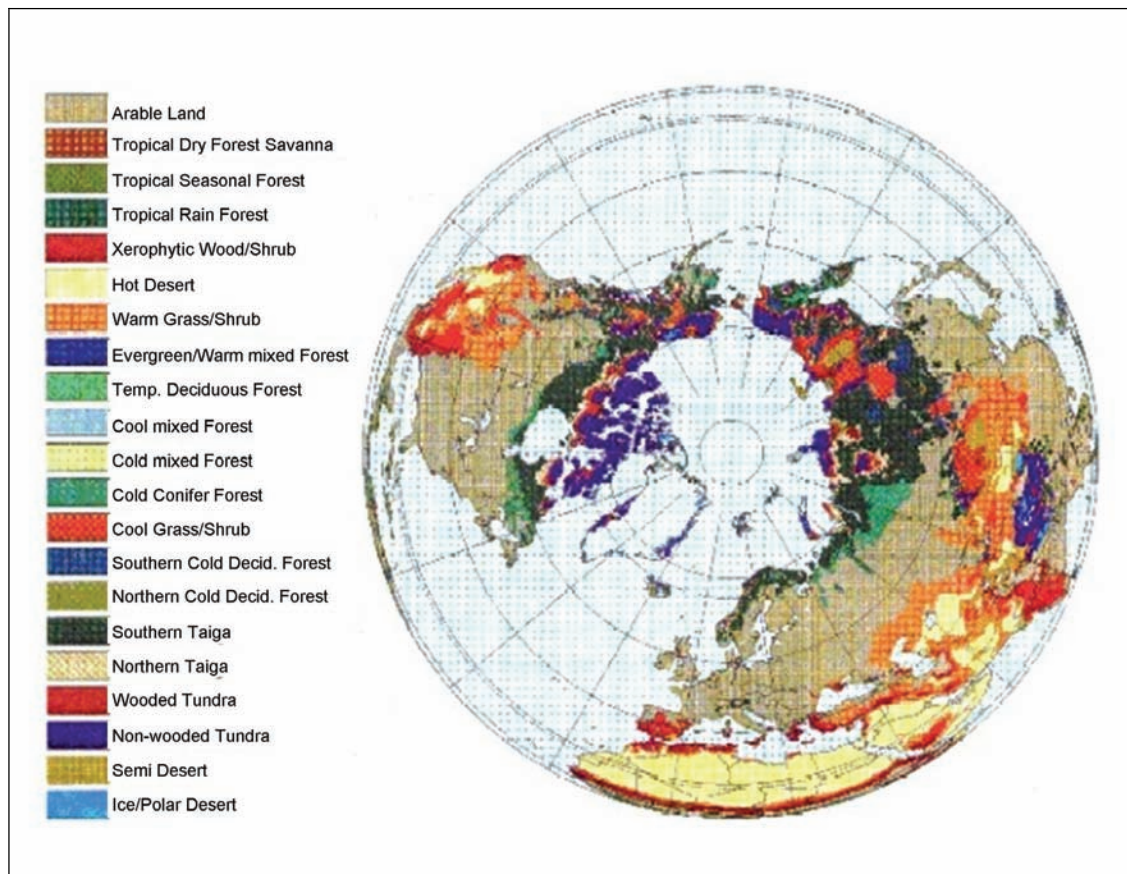
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Future Global Vegetation Biomes

Map of future global vegetation biomes, including land suitable for agriculture, under a future climate at the time atmospheric CO₂ concentrations double. The climate changes used to drive the BIOME model are among the mildest simulated by general circulation models of the atmosphere, that is, the global climate model (ECHAM-1 by the Max Plank Institute, Hamburg; see Greco *et al.* 1994) is only moderately sensitive to greenhouse gas concentrations.

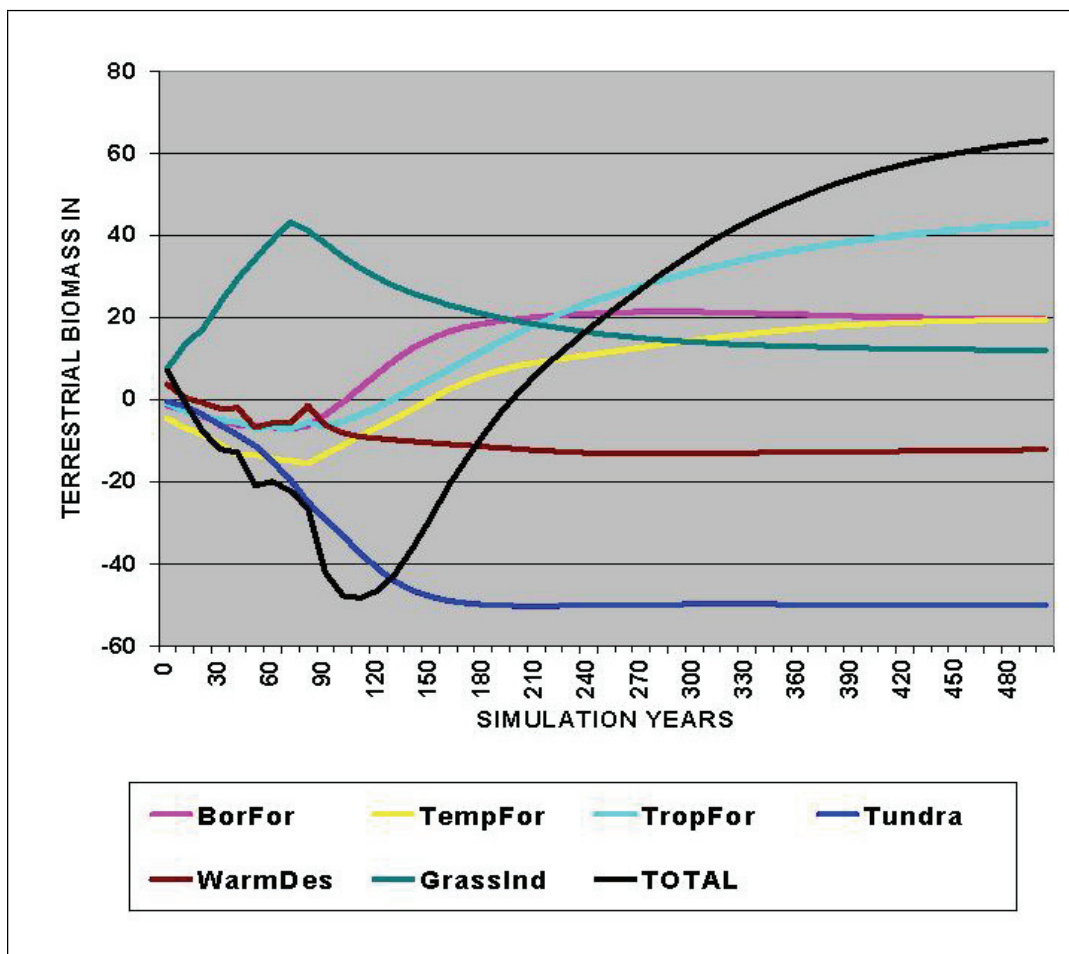
Note the great increase in land suitable for agriculture toward polar areas, a feature which follows from expected climate changes: all general circulation models of the atmosphere (global climate models) project a greater increase in warming at the poles than at the equator, a greater warming in winter than in summer, and a greater warming at night than in daytime. As a result, the projected climate in high latitudes is expected to increase greatly in days with temperatures constantly above freezing, and in the annual growing season length. Indeed, polar growing seasons have already increased 12 to 18 days since 1980, as measured by satellites.

Note also that, compared with the previous map, this map shows areas of natural vegetation in temperate areas dominated by dryland biomes, especially thorn shrub vegetation, and boreal forests severely reduced as potential agriculture covers low latitude growing areas, with little space to grow toward the higher latitudes.



The CO₂ Pulse

Total carbon stored by the terrestrial biosphere in separate biomes and in total in Pg (petagrams, 10^{15} g). Carbon storage is simulated for 500 years into the future, with a warming scenario from ECHAM-1, by the Max Plank Institute in Hamburg (Greco *et al.* 1994), from year 0 to that from a doubling of atmospheric CO₂ concentrations at year 100. Minus values represent release of carbon from the terrestrial biosphere to the atmosphere, positive values represent storage of carbon into the terrestrial biosphere from the atmosphere (from an unpublished version of the MOVE model (Kirilenko and Solomon 1998) which includes stochastic rather than constant rates of tree mortality and growth).



The total biomass of the terrestrial biosphere declines markedly for the first 100+ years of this simulation, defining the multi-decadal pulse of carbon to the atmosphere discussed in the text. Note that only grassland vegetation initially increases in biomass, as it replaces the woody vegetation types which dieback during early warming and which only gradually regrow to out compete the herbaceous vegetation.

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8. Effects of Elevated Atmospheric Carbon Dioxide Concentration and Temperature on Forests

Statement of the Problem

Concentrations of carbon dioxide (CO₂) and other trace gases have been increasing in the atmosphere due to human activity. By the 1980s, accumulating evidence suggested that increasing levels of these gases could produce higher global temperatures and changes in precipitation patterns. More information on how the biosphere controls atmospheric CO₂ was needed to understand the Earth's carbon cycle. Foremost, an understanding of source-sink relations between the atmosphere and the various components of the biosphere was needed. Consequently, research was undertaken to delineate the relations between atmospheric CO₂ concentrations, changes in global climate drivers, and responses of the soil-plant-atmosphere continuum (EPA 1993). The science questions governing the research were:

- What are the effects of elevated CO₂ and climate change on the growth and productivity of forest trees?
- Will elevated CO₂ and climate change alter the sequestration/exchange of carbon in the soil-plant-atmosphere continuum?
- What is the magnitude of these elevated CO₂ and climate change impacts and will they be widely distributed?

Approach

Research was conducted to investigate ecosystem responses to elevated atmospheric CO₂ and associated increases in atmospheric temperature over several years. NHEERL scientists built a state-of-the-science, sun-lit, controlled-environment chamber facility in which climatic and edaphic factors could be controlled and/or monitored during the multi-season exposure period (Tingey *et al.* 1996). A tree forest ecosystem was reconstructed in the chambers using Douglas-fir seedlings supported by one of its widely represented soil types (Rygiel *et al.* 2000). Climatic treatments were applied based on the natural, temporal variations in ambient climatic conditions found at the facility site, thus subjecting the reconstructed ecosystem to a realistic climatic profile (Tingey *et al.* 1996). Experimental treatments included increased levels of atmospheric CO₂ and elevated temperature (Olszyk and Tingey 1996).

Main Conclusions

Generally, the effects of increasing the atmospheric CO₂ concentration on the reconstructed Douglas-fir-soil ecosystem appear to have been limited by low nitrogen availability in the soil – a condition common in forest soils of the Pacific

Northwest. This result was supported by the Maine Biological Laboratory's General Ecosystem Model (GEM), used after completing the climate change experiment, to project longer-term and broader-scale consequences of climate change in Pacific Northwest Douglas-fir forests. Application of GEM to various sites in the western Cascades suggests that soil nitrogen is a primary constraint on changes in ecosystem carbon storage (McKane *et al.* 1997). For the nitrogen-poor montane site where the soil for the chamber experiment was obtained, the model predicts that total ecosystem carbon storage will increase by less than 10% during the next 100 years in response to projected increases in atmospheric CO₂ and temperature. In contrast, GEM predicts that carbon storage will increase by over 25% during the same period for a nitrogen-rich site in the western Cascades foothills.

Even though elevated atmospheric CO₂ increased photosynthetic rates (Lewis *et al.* 1999, Lewis *et al.* 2001), and while chlorophyll and carotenoid concentrations in the needles decreased under elevated CO₂ (Ormrod *et al.* 1999), the additional carbon acquired was not allocated to produce seedlings of greater biomass (Olszyk *et al.* 2003). Rather, it appears that the carbon was allocated to soil organisms which convert stored, unavailable forms of nutrients into available forms (Lin *et al.* 1999, Lin *et al.* 2001). These available forms can then be acquired by diverse and stable mycorrhizal fungi resident on the ephemeral, nutrient-absorbing fine roots (Rygielwicz *et al.* 2000, Hobbie *et al.* 2001).

While total carbon storage in the soil increased during the experiment, due to seedling growth and decomposition processes in the soil and litter layer, the amount of total stored carbon was not different among the climatic treatments. However, stable isotopic data suggest that a variable allocation of carbon into soil organic matter (SOM) of different qualities may have occurred, thus altering the long-term storage potential of the soil for carbon. In a related project on ponderosa pine, the effect of nitrogen to alter the seedlings' responses to atmospheric CO₂ concentration was clearly evident (Johnson *et al.* 2000), and reinforced the results found in the chamber study done on Douglas-fir. Taken collectively, these results indicate the overriding influence of the low nitrogen found in Pacific Northwest forests.

Projecting to larger scales, the responses of forest ecosystems to elevated CO₂ may be highly variable temporally and globally. In particular, the responses appear highly dependent on the quantity and availability of nutrient resources, and the capacity of nutrient acquisition processes relative to the increased amount of carbon available in the atmosphere. As the Douglas-fir study was run for only four growing seasons, it is uncertain if the observed responses to elevated CO₂ were transient, and eventually would change as ecosystem compartments continued to adjust to the altered ratios of available carbon to available nutrients.

Elevated temperature had a greater, and negative, impact on the seedlings than

8. CO₂ & Temperature Effects

did the elevated CO₂ treatments. Elevated temperature directly and negatively affected the development and morphology of the seedlings. Seedlings grown under elevated temperatures had greater numbers of aborted and malformed buds, and abnormal needle primordial tissue compared with seedlings in the ambient temperature treatments (Apple *et al.* 1998, Apple *et al.* 2000). In addition, the seedlings grown under the higher temperatures were shorter and more “bush-like” in morphology, thus hindering their ability to gain height (Olszyk *et al.* 1998a, Olszyk *et al.* 1998b). Elevated temperature delayed needle hardening in the fall, slowed dehardening in the spring and reduced the maximum hardness; rendering the trees less resistant to low temperatures (Guak *et al.* 1998).

Climate change will affect forested ecosystems differentially. While elevated temperature will most likely affect the growth of plant species directly, the effects on ecosystem structure and functioning may be more subtle to discern, but no less significant. Elevated temperature could lead to the replacement of sensitive species by more heat tolerant species. In the Pacific Northwest, the predominant lumber species, Douglas-fir, could experience abnormal growth patterns. But as Douglas-fir is a genetically diverse species, adaptation, either natural or managed, is likely. However, the cost to timber production is unknown.

Ecosystem effects of increasing levels of atmospheric CO₂ will depend on the nutrient status of specific forests. Increased forest production will occur where soils contain adequate nitrogen. In areas where nitrogen is limiting, elevated CO₂ levels will not increase the growth of trees -- even though photosynthesis may increase. Without sufficient nitrogen, the trees cannot use the additional CO₂ for growth. The additional carbon is used by soil organisms and respired to the atmosphere (Rygielwicz and Andersen 1994). In addition to contributing to CO₂ buildup in the atmosphere such changes in the soil foodweb, which controls nutrient availability for plants, could have long-term effects on ecosystem functioning.

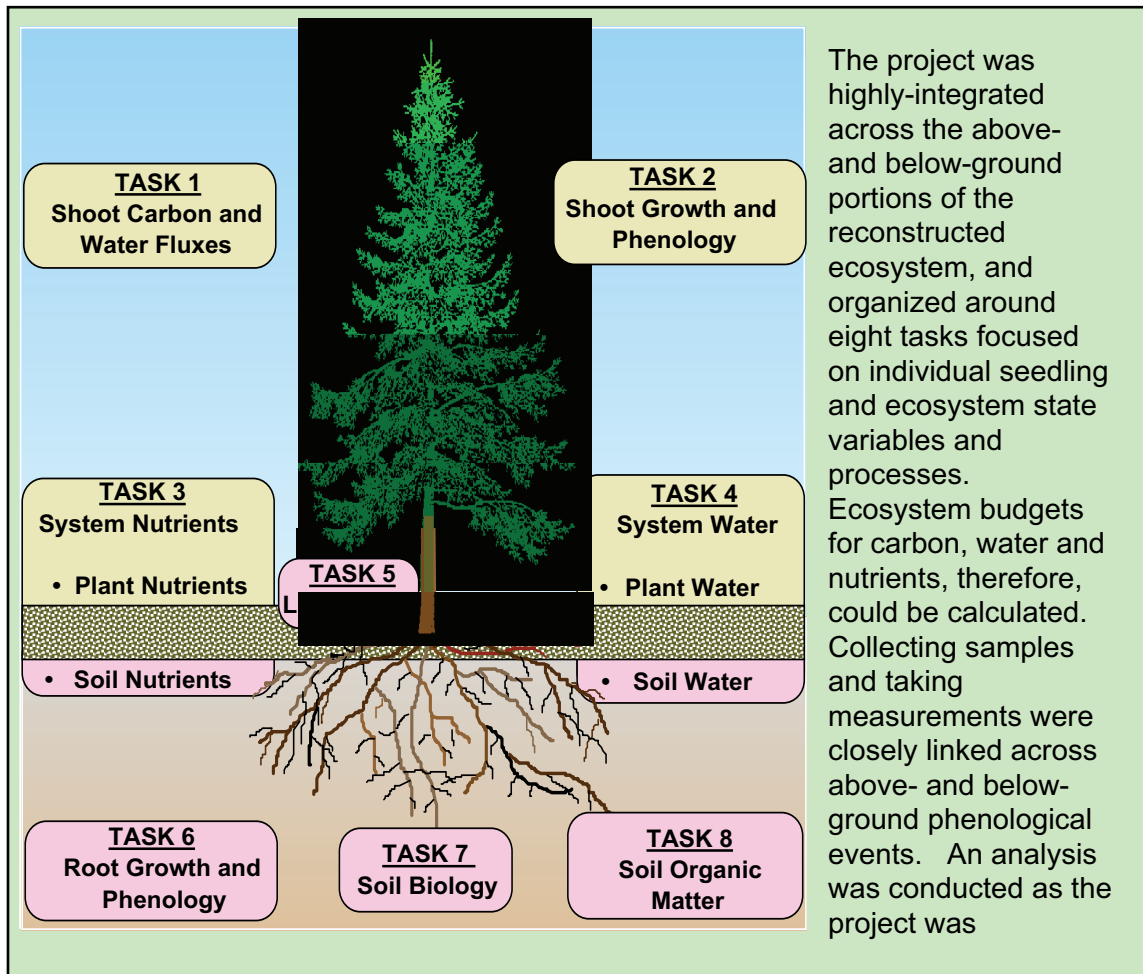
Experimental Approach to Study Seedling and Ecosystem Processes



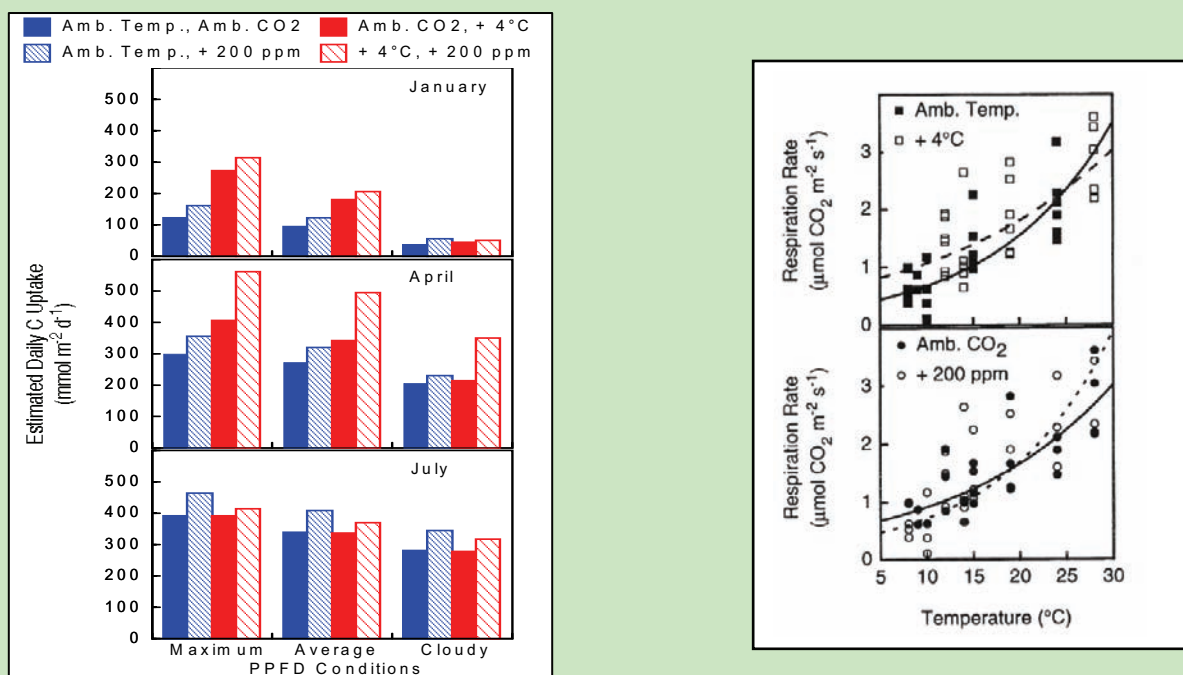
A 2 X 2 factorial treatment design was used: [ambient CO₂ and ambient + 200 ppm CO₂ (179 ppm achieved), ambient temperature, and ambient + 4 °C (3.8 °C achieved)]. Each of the four climatic conditions was replicated three times, which resulted in a total of 12 chambers being used for the experiment

SPAR (Soil-Plant Atmosphere Research) chambers (1 x 2 m footprint) were used to simulate natural seasonal and diurnal changes in atmospheric [CO₂], air and soil temperatures, vapor pressure deficit (VPD), and soil moisture. Fourteen, two-year-old Douglas-fir seedlings were planted in each chamber in a natural, widely-represented, Cascade Mountains, high-elevation (1220 m) soil. The seedlings originated from open-pollinated seeds harvested from 5 low-elevation (300 to 460 m) seed zones in the Cascade and Coastal Mountain Ranges near Corvallis. Total N in the soil was < 0.1% (w/w), and NO₃⁻ and NH₄⁺ in soil solution were below detection limits (0.04 and 0.10 mg l⁻¹, respectively). Six cm of forest floor were placed on top of the soil. Climatic treatments were imposed for 4.5 growing seasons.

An Integrated Sampling Approach Was Designed to Track Carbon, Water and Nutrients through the Reconstructed Ecosystem



The project was highly-integrated across the above- and below-ground portions of the reconstructed ecosystem, and organized around eight tasks focused on individual seedling and ecosystem state variables and processes. Ecosystem budgets for carbon, water and nutrients, therefore, could be calculated. Collecting samples and taking measurements were closely linked across above- and below-ground phenological events. An analysis was conducted as the project was

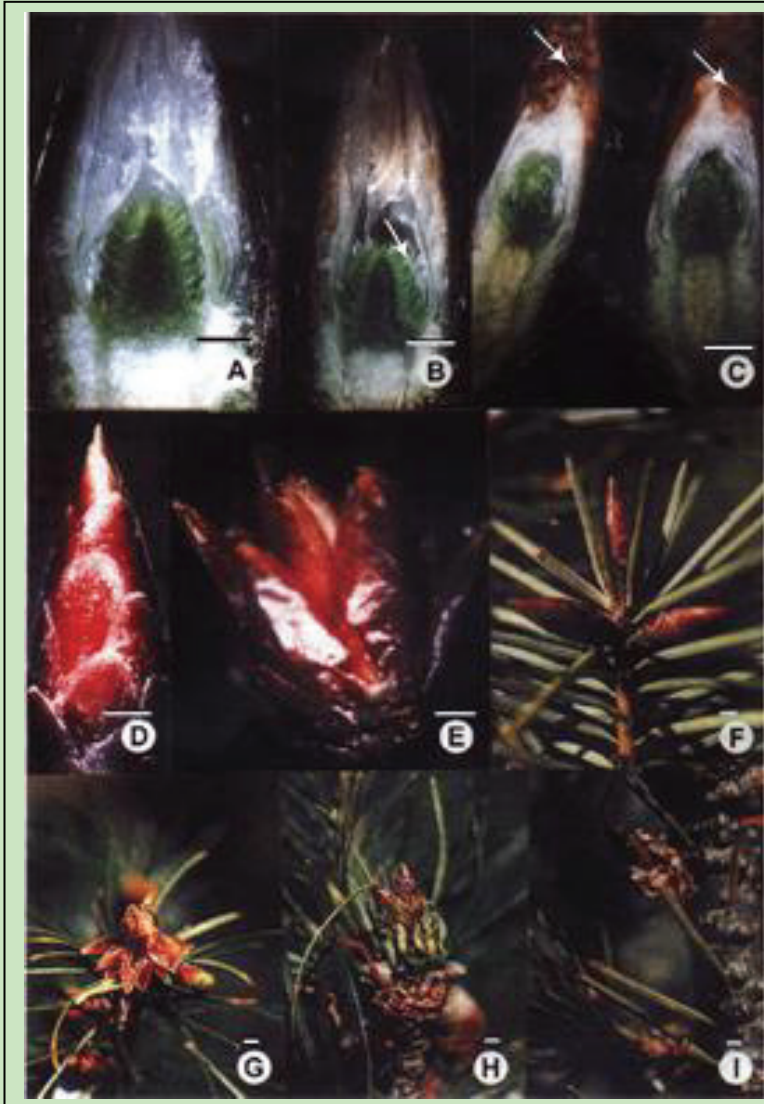
Elevated CO₂ Increased Photosynthesis but not Growth

Greater instantaneous photosynthetic rates (left panel) were observed under elevated CO₂ and temperature in the spring and winter. Some acclimation of photosynthetic rates to elevated CO₂ was evident as the exposure to climatic treatments progressed (data not shown). Even so, by the third and fourth growing seasons, elevated CO₂ increased net photosynthesis by an average of 21% across the two temperature treatments. The additional carbon acquired under elevated CO₂ was not released through increased “dark” respiration (respiration not associated with the process of photosynthesis).

The increased carbon uptake under elevated CO₂ and elevated temperature did not increase the final size of the seedlings. Moreover, elevated CO₂ had no other significant effects on whole seedling or individual seedling component biomass, % biomass allocation, or leaf area (not all data are shown). Other sinks for the additional carbon acquired are the continual production, death and decomposition of the ephemeral, nutrient-absorbing fine roots; the various organisms of the soil food web (both their biomass and respiration); and the soil organic matter (SOM). PPF is Photosynthetic Photon Flux Density, expressed as μmol photons m⁻² s⁻¹. (Lewis *et al.* 1999).

Under elevated temperature, compared with the ambient condition, shifts occurred only in the amounts of carbon allocated to needles and buds (Olszyk *et al.* 2003). Allocation of carbon related to the production, death and decomposition of the ephemeral, nutrient-absorbing, fine roots can not be determined from the final biomass of the seedlings as these roots were produced and decayed during the exposure period. The retrospective analysis of the allocation of carbon to produce these roots throughout the exposure is ongoing.

Elevated Temperature Affected Needle and Bud Growth

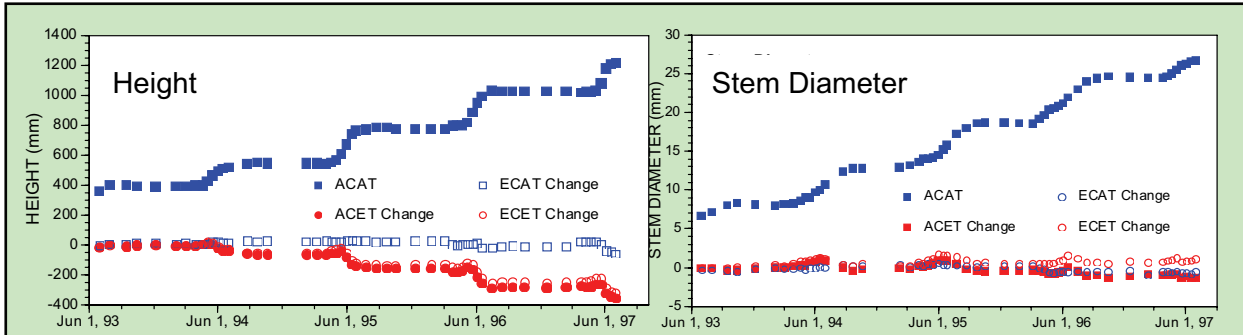


Douglas-fir buds (left panel) showed several signs of damage due to elevated temperature: (A) Dissected normal bud from the ambient climatic treatment; (B) Dissected abnormal bud from elevated temperature treatment with bud-scale-like needle primordium (arrow), and (C) convoluted bud scales (arrows); (D) Exterior of normal bud from ambient conditions; (E) Exterior of rosetted bud from elevated temperature treatment; (F) Normal buds from ambient conditions; (G) to (I) all are elevated temperature treatment showing - (G) rosetted abnormal buds, (H) a shoot with two small buds and reduced needles, and (I) a bud with reduced needles and elongated stalk originating from tree trunk. Scale = 1 mm. Source: Apple *et al.* 1998.

Under elevated temperature, a greater percentage of leader and branch buds opened early in the growing season (lower left panel). However, by the end of bud burst, a smaller total percentage of buds had opened under the higher temperatures. Needles produced under elevated temperature conditions were less able to withstand the colder temperature of winter (lower right panel). Indicated is the freezing temperatures at which 50% of the needles displayed visible signs of tissue damage (L_{50} °C). Source: Guak *et al.* 1998.

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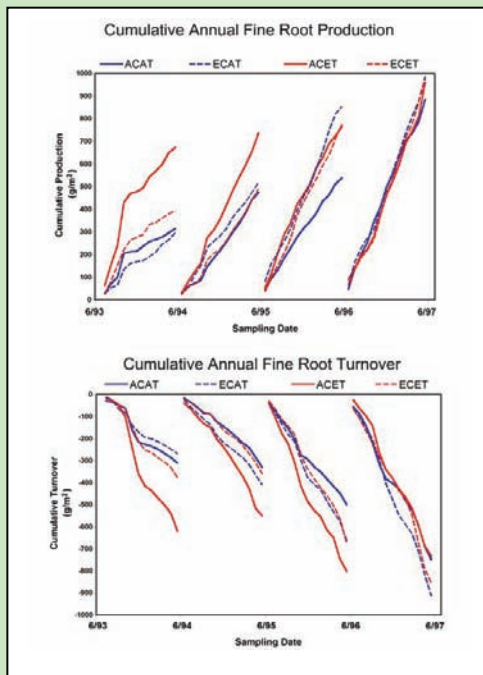
Seedling Size Was Negatively Affected by Elevated Temperature



Legend: ACAT = ambient CO₂, ambient temp.; ECAT = elevated CO₂, ambient temp.; ACET = ambient CO₂; elevated temp.; ECET = elevated CO₂, elevated temp.

Elevated temperature resulted in shorter Douglas-fir seedlings, beginning during the second growing season. The left graph indicates the increase in height over time for seedlings grown under the ambient CO₂ and temperature levels (ACAT). The other three treatments are shown as changes relative to the ACAT treatment. For example the ACET Change = ACET - ACAT. Elevated CO₂ by itself had no effect on plant height (ECET Change). In contrast, neither elevated temperature nor elevated CO₂ affected stem diameters. The right graph indicates annual increases in stem diameter for the ACAT seedlings and the lack of any relative change in stem diameter for seedlings grown under any of the other elevated temperature or elevated CO₂ treatments. Modified from: Olszyk *et al.* 1998a.

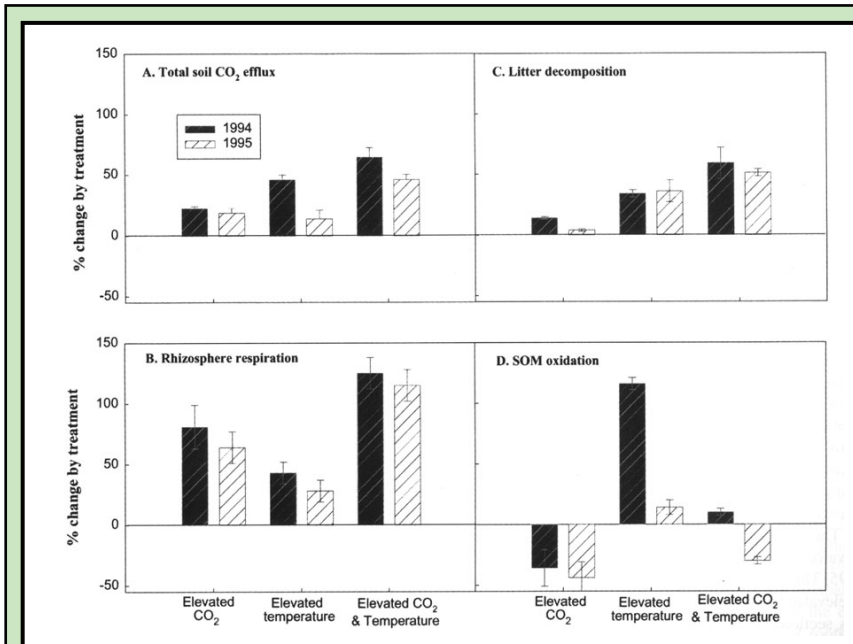
Elevated CO₂ and Temperature Altered Fine Root Distribution but not Production and Turnover



Fine roots play a key in the acquisition of water and nutrients needed to sustain growth. The growth of fine roots is coordinated with shoot growth so that the plant has sufficient resources.

The effects of elevated CO₂ and temperature on fine production and turnover were determined over a 4-year period. Elevated CO₂ and temperature altered fine root distribution; there were more fine roots deeper in the soil. There were no CO₂ effects on annual fine root production or turnover. During the first 2 years, elevated temperature (at ambient CO₂) increased fine root production, but there were no differences in the latter part of the experiment. Limited N availability likely minimized CO₂ response belowground as it did aboveground.

The Rhizosphere Responded to Elevated Atmospheric CO₂

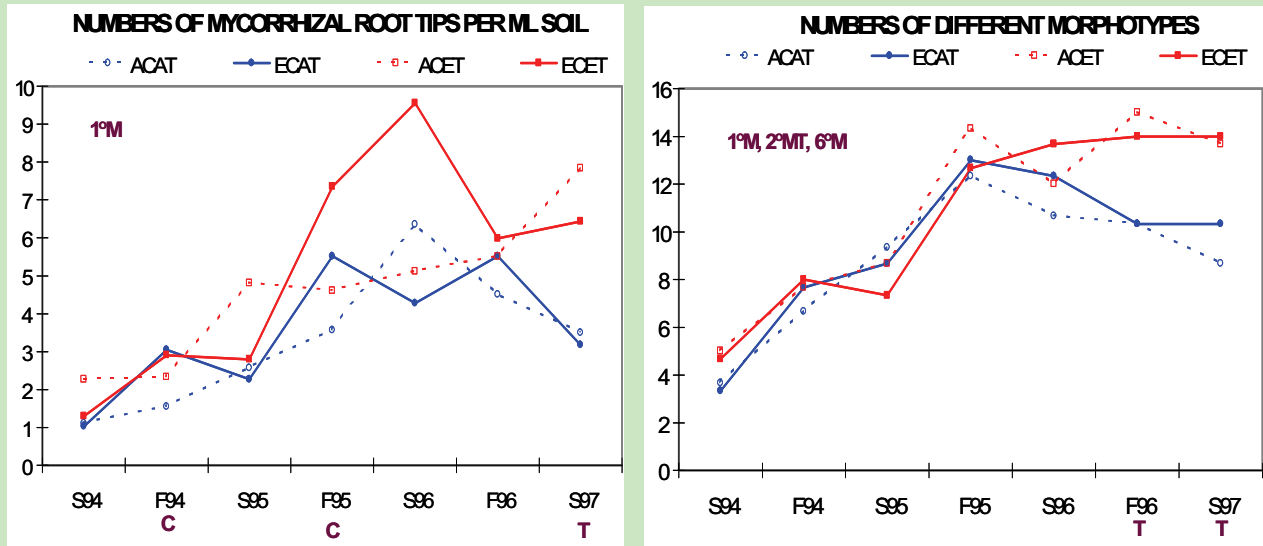


Percent increase or decrease in the total flux of CO₂ released from the soil (A), and from its component sources (B, C, D) relative to respective CO₂ fluxes in the ambient climatic treatment.

The amounts of carbon forming the total soil CO₂ efflux were mathematically partitioned into their source compartments within the soil. Since the atmospheric carbon delivered to the seedlings was depleted in ¹³C, it served as a tracer to analyze soil carbon dynamics. The dominant source of the soil CO₂ efflux in the soil-Douglas-fir ecosystem was the decomposition of the litter, followed by rhizosphere respiration (= root respiration + respiration of root-associated soil biota), and then from the oxidation of soil organic matter (SOM) (data not shown). Elevated CO₂ stimulated total soil respiration (Graph A).

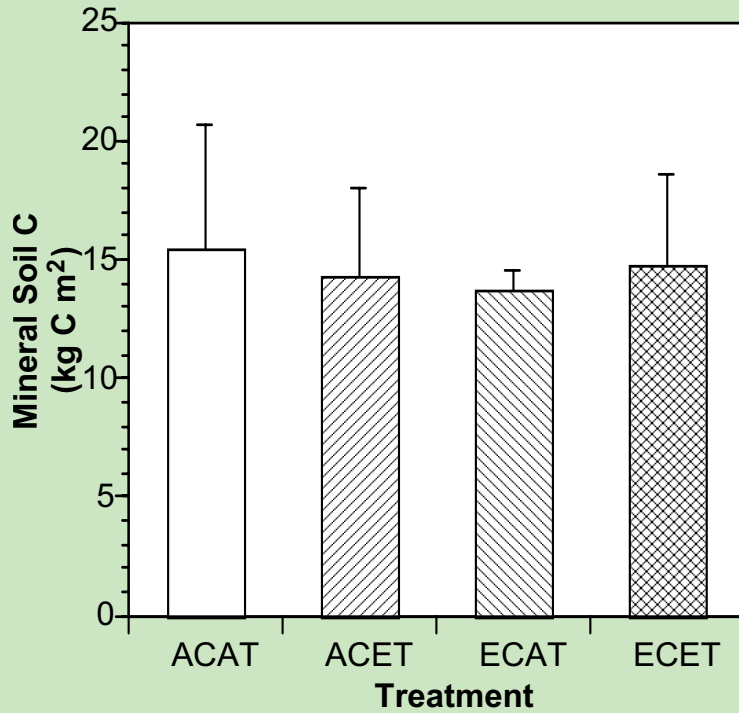
Rhizosphere respiration was stimulated by elevated CO₂ and less so by temperature (Graph B). In contrast, litter decomposition was stimulated mostly by temperature (Graph C). The SOM response was highly variable (Graph D): from a decrease in oxidation under elevated CO₂, to an increased oxidation under elevated temperature; note that elevated CO₂ in the double elevated treatment countered the oxidation found in the elevated-temperature-only treatment. Differences in responses between 1994 and 1995 are attributed to the physical disruption done to the soil when it was transported from the Cascade Mountains to the chambers. The likelihood that the increased rhizosphere respiration was due to a transient, increased standing crop of the ephemeral, fine roots is still being analyzed.

Carbon Delivered to Soil Foodweb to Explore Ecosystem for Nutrients



Legend: ACAT = ambient CO₂, ambient temp.; ECAT = elevated CO₂, ambient temp.; ACET = ambient CO₂; elevated temp.; ECET = elevated CO₂, elevated temp.

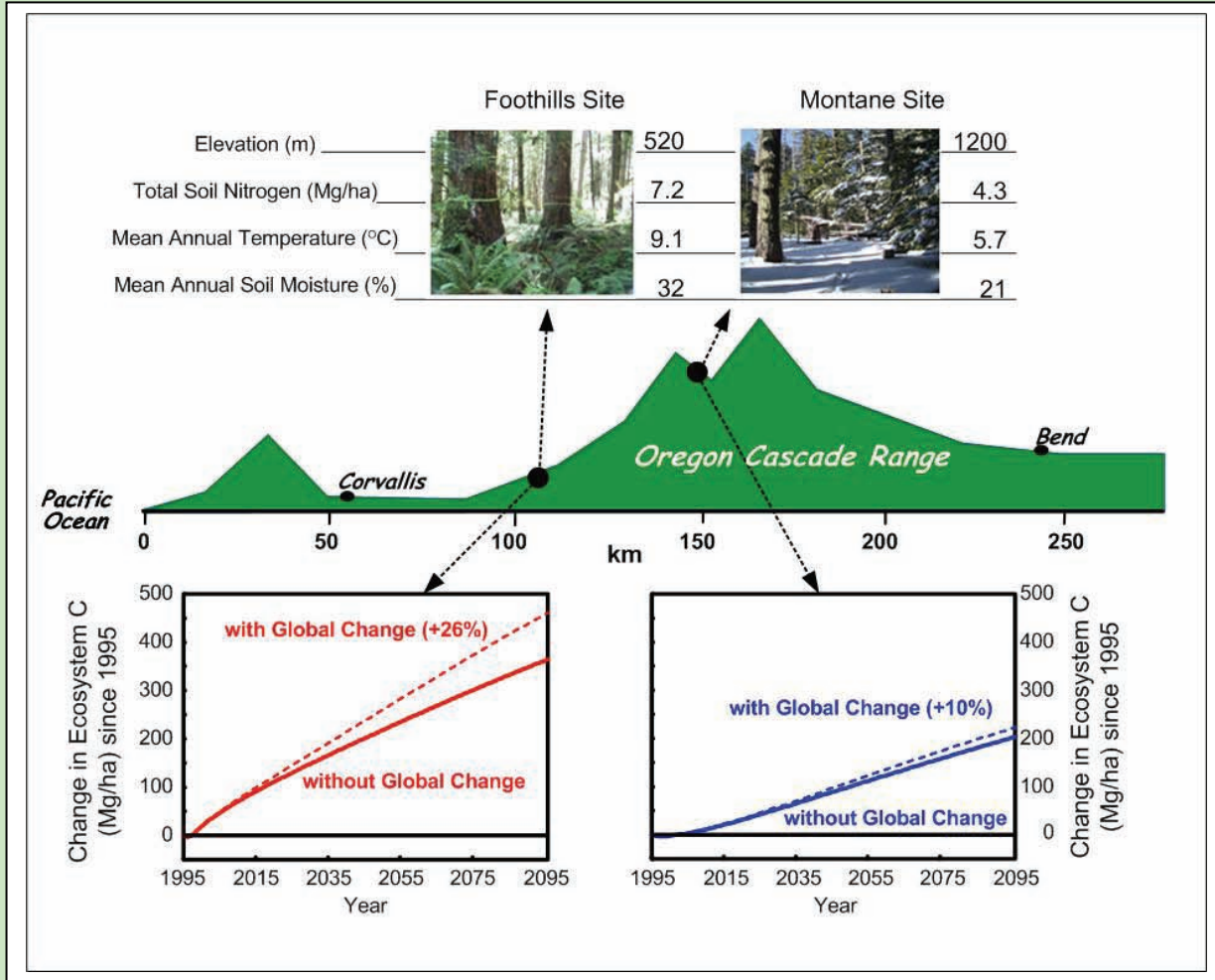
The increased soil CO₂ efflux attributed to rhizosphere respiration (= root respiration + respiration of root-associated soil biota) (previous sidebar) likely is due to increased standing crop of the ephemeral, fine roots and their decomposition, and/or the standing biomass, activity and decomposition of soil fungi. Coniferous forest ecosystems rely on free-living and symbiotic fungi (attached to the fine roots) to mobilize nutrients stored in the forest floor and soil, and to transport the mobilized nutrients to, and into, the plants to balance the carbon acquired aboveground. All low-nutrient terrestrial ecosystems increase their dependence on these fungi compared to higher nutrient conditions. The Douglas-fir seedlings formed high concentrations of mycorrhizal root tips in the low-nutrient soil (left graph), and exhibited a high degree of root colonization (nearly 100% of the root tips that developed were colonized, data not shown). The fungal community formed on the roots was highly-diverse and its structure was resistant to the climatic treatments (right graph). However, the most extensive portion of the symbiotic fungal biomass is the portion living at distance from the roots, and which explores the soil for nutrients, delivering them to the tree. Through the use of direct counting procedures and measuring the amounts of stable isotopes delivered into the soil foodweb, we anticipate identifying to which trophic structure(s) in the soil ecosystem the additional carbon acquired under elevated CO₂ was allocated, and then subsequently deposited as soil organic matter (SOM).

Soil Organic Matter May Be Depository for the Acquired Carbon

The amount of carbon stored in soil as organic matter (SOM) increased during the exposure, predictably as one might expect because of plant growth. However, none of the climatic treatments affected the total amount of carbon stored as SOM (graph at left). Soil ¹³C data suggest that SOM levels actually may have increased under elevated CO₂. As the total amount of SOM may not have been altered by the climatic treatments, the isotopic data suggest that certain quality fractions of SOM may have been differentially affected by the treatments. Thus the large total amount of SOM may be masking the more subtle responses in the individual quality fractions. Ultimately, the quality of SOM that is formed determines long-term storage of carbon in, and productivity of, forested ecosystems. SOM from the experiment has been separated into its quality fractions, and stable isotopic analyses are underway to address this aspect of the fate of the additionally-acquired carbon.

Soil Nitrogen Availability Constrained Carbon Storage in Response to Elevated CO₂ and Temperature

We used the General Ecosystem Model (GEM), a process-based model of terrestrial ecosystem biogeochemistry, to project longer-term and broader-scale consequences of increases in atmospheric CO₂ and temperature in Pacific Northwest Douglas-fir forests.



GEM was used to predict and analyze the effects of projected changes in CO₂, temperature & soil moisture on ecosystem carbon storage at the Foothills and Montane mature forest sites. The model was run with and without the projected changes in CO₂, temperature & soil moisture. All simulations started in 1995 with post-harvest conditions (90% of tree biomass removed).

Results illustrate that elevated CO₂ increases plant growth and net ecosystem C storage only when there are sufficient supplies of soil nitrogen as at the Foothills Site. A sensitivity analysis showed that CO₂ was much more important than temperature in increasing ecosystem C storage, and that elevated CO₂ increased storage of C in plants more than in soils.

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9. Interactive Effects of O₃ and CO₂ on the Ponderosa Pine Plant/Litter/Soil System

Statement of the Problem

Carbon dioxide is required by plants to grow and is a major greenhouse gas contributing to global climate change. Tropospheric ozone (O₃) is the major phytotoxic air pollutant in the U.S. which adversely impacts crops and forests. While much is known about the effects of O₃ or CO₂ alone, there has been little research on the potential interactive effects of these gases on terrestrial ecosystems, even though they co-occur. Most of the research has focused on the response of individual species rather than at the ecosystem level. There is a growing interest in O₃ x CO₂ combinations fueled by concerns regarding potential effects on vegetation from increases in regional O₃ levels. These increases occur concurrently with an increased global CO₂ concentration.

Approach

Therefore, we carried out an in-depth study to address three general hypotheses regarding the effects of O₃ and CO₂ on C, N, and H₂O cycling through ecosystems (Olszyk *et al.* 1997):

- 1) Elevated O₃ decreases C, N and H₂O cycling rates.
- 2) Elevated CO₂ increases C, N, and decreases H₂O cycling rates.
- 3) Elevated CO₂ eliminates negative effects of O₃ on C and N cycling rates and has an additive negative effect on H₂O cycling rates.

Our hypotheses were tested using experimental data and simulation models to evaluate C, N, and H₂O cycles (Olszyk *et al.* 2001). A reconstructed ponderosa pine soil/tree seedling ecosystem was used, as this is system widespread in the western U.S., and is known to be affected by both increasing CO₂ and O₃. The experiment was conducted in sunlit, controlled environment chamber facility (see sidebar in previous section) to examine above- and belowground responses. These chambers allowed for precise monitoring and control of climatic and edaphic—soil—conditions and for calculation of whole system CO₂ and H₂O balances (Tingey *et al.* 1996, Olszyk and Tingey 1996). The experimental design was a 2 x 2 factorial with 2 levels of CO₂, 2 levels of O₃ and three replicate chambers per treatment. Carbon dioxide was an elevated level of +280 ppm above ambient reflecting an increase in greenhouse gases vs. the ambient concentration. Ozone was at a high level representative of regional oxidant pollution vs. a low level which is representative of a more pristine area. Research tasks measured: i) system CO₂, O₃ and H₂O gas exchange; ii) plant phenology, allometry and carbon allocation; iii) litter and soil/rhizosphere microbiological community structure and function; iv) litter and soil chemical and physical properties; and v) system C, N and H₂O budgets, pools and fluxes. The modeling research used

the Marine Biological Laboratory's General Ecosystem Model (GEM) (Rastetter *et al.* 1991) to evaluate for system scale C and N cycling, and the process-based whole-tree growth model TREGRO (Tingey *et al.* 2001), to study the potential impact of increased O₃ and CO₂ on photosynthesis, respiration, carbon accumulation, and carbon allocation.

Main Conclusions

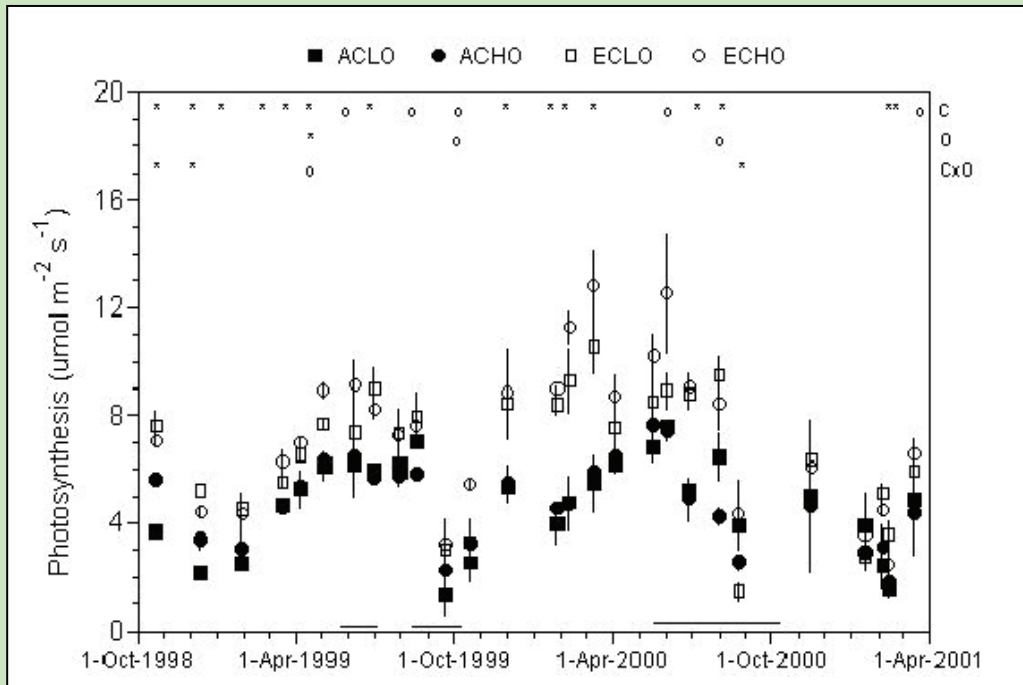
Elevated CO₂ increased the photosynthetic C uptake by the seedlings beginning early in the study (Olszyk *et al.* 2001) and persisting to the end (Olszyk *et al.* 2002) (sidebar). The increase in photosynthesis was associated with an increase in water use efficiency (the ratio of CO₂ taken up to H₂O loss by transpiration). The increased C uptake appeared to stimulate plant growth as elevated CO₂ increased stem diameters (sidebar). This CO₂ induced-increase in stem diameter was especially noticeable early during the study. Over time, the stimulation in stem diameter leveled off, possibly due to growth-limiting factors such as a low soil-N fertility level. Elevated CO₂ also affected N cycling in the system as indicated by lower leaf N concentrations with elevated CO₂ (Olszyk *et al.* 2001).

In contrast to CO₂, O₃ alone had little effect on the plants, and those responses that did occur were affected by the variable O₃ concentrations among the three years. There were suggestions of significant CO₂ x O₃ interactions for some parameters where the response to the combined pollutants was different from that expected based on the responses to the individual pollutants. For example, in late August 2000 photosynthesis decreased with high O₃ for seedlings at ambient CO₂ but increased with high O₃ for seedlings at elevated CO₂. There also was a significant CO₂ x O₃ interaction on plant growth early in the study, as stem diameters were greater with elevated CO₂ and low O₃ compared with elevated CO₂ and high O₃ (Olszyk *et al.* 2001).

When the data have been completely evaluated from this study, the results will provide unique information on the responses of ecosystem functions due to the interactions of CO₂ and O₃, as well as responses to the individual gases.

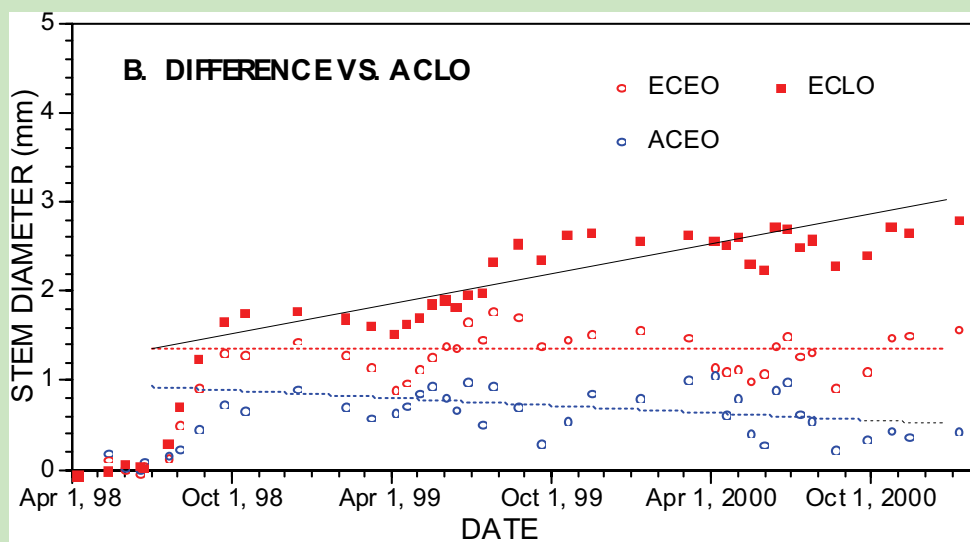
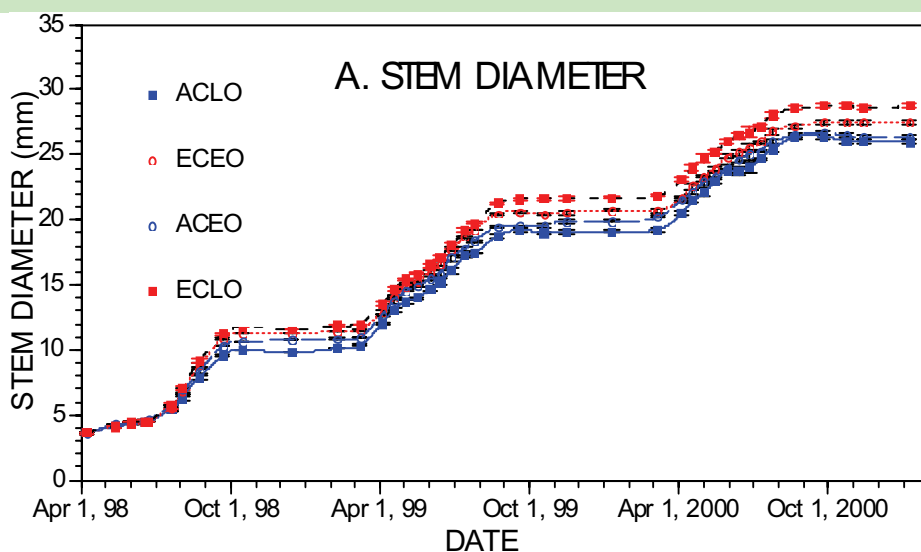
Effects of Elevated CO₂ and O₃ on Net Photosynthesis in Ponderosa pine

Elevated CO₂ increased photosynthetic rates over much of the experiment as shown by the higher values for seedlings grown under elevated CO₂ at either low O₃ (ECL0) or elevated CO₂ and high O₃ (ECHO) vs. seedlings grown under ambient CO₂ and either low O₃ (ACLO) or high O₃ (ACHO). The "*" and "o" symbols in the "C" row at the top of the figure indicate those periods during which there was a significant CO₂ effect on photosynthesis based on analysis of variance at the p<0.05 and p<0.10 levels, respectively. High O₃ had only a minor effect on photosynthesis, with significant O₃ alone effects for only three periods as shown by the symbols in the "O" row at the top, and significant CO₂ x O₃ interactions for only 4 periods in the "CxO" row at the top. The symbols are averages ±SE (bars) for 3 replicate chambers except for 2 replicate chambers for the treatment. The dashed lines at base of figure are approximate dates of O₃ exposures. Source: Olszyk *et al.* 2002.



Effects of CO₂ & O₃ on Ponderosa Pine Seedlings

Stem diameter was measured as a key indicator of the overall growth of Ponderosa pine seedlings. Rapid growth periods, as shown by an increase in stem diameter, occurred during spring and summer of 1998, 1999, and 2000. Over three years, seedlings growing with elevated CO₂ and either with low (ECLO) or high (ECHO) O₃, had larger stem diameters than seedlings grown under ambient CO₂ and low (ACLO) or high (ACHO) O₃ (top figure). Beginning early in the study, compared to plants growing under control conditions (ACLO), there was a greater increase in stem diameter for ECLO compared with ECHO seedlings, indicating that high O₃ inhibited some of the effect of elevated CO₂ (lower figure). Source, Olszyk *et al.* 2001 and unpublished data.



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10. Effects of Elevated CO₂ and Nitrogen Fertilization on Fine Root Growth in seedling *Pinus ponderosa*

Statement of the Problem

In forest trees, less than 20% of the total biomass is belowground while more than 50% of the carbon acquired annually by plants may be allocated belowground (George & Marschner 1996). With rising atmospheric carbon dioxide (CO₂) the potential for effects of elevated CO₂ on forest trees is large. A number of studies have evaluated the effects of elevated CO₂ on plants (e.g., Ceulemans & Mousseau 1994; Curtis & Wang 1998, Norby 1994, Rogers *et al.* 1999, Taylor *et al.* 1994). Their general conclusion is that elevated CO₂ leads to increased photosynthesis and increased plant biomass, including increased root biomass. Will this increase in biomass lead to a greater proportion of the carbon being allocated belowground and potentially sequestered there?

Three science questions guided the study on ponderosa pine (*Pinus ponderosa* Dougl.):

- Will the size of the root systems of ponderosa pine seedlings increase to facilitate resource (water or nutrients) acquisition in response to elevated CO₂?
- Will ponderosa pine root systems be affected by the availability of nitrogen?
- Will the dynamics of ponderosa pine fine root production and mortality be affected by elevated CO₂ and/or nitrogen treatments?

Approach

Plants were exposed to CO₂ and nitrogen (N) fertilization in open-top field-exposure chambers located at the US Forest Service Institute of Forest Genetics near Placerville, CA. The experimental design was a replicated 3x3 factorial with 3 CO₂ levels (ambient air [\sim 350 $\mu\text{mol mol}^{-1}$]; ambient air + 175 $\mu\text{mol mol}^{-1}$ and ambient air + 350 $\mu\text{mol mol}^{-1}$) and 3 levels of nitrogen (N) addition (0, 100 and 200 kg ha⁻¹); however, the 100 kg ha⁻¹ N treatment at ambient + 175 $\mu\text{mol mol}^{-1}$ CO₂ was omitted from the experimental design because of financial limitations. There were 3 replicates of each CO₂ and N treatment. The nitrogen was broadcast applied each March as ammonium sulfate. Soils were kept moist and relatively constant over the course of the study. Root images were collected from three minirhizotron tubes in each chamber every 2 months on S-VHS tape using a minirhizotron camera. The root images were analyzed using software that allows the user to measure the length and diameter of all roots and annotate mycorrhizae and fungal hyphae occurrence.

Main Conclusions

Fine roots explore soil for water and nutrients to support plant growth. Plants produce more or fewer fine roots as their resource needs change. A given species may produce more fine roots in nutrient poor soils than in nutrient rich soils. In arid environments plants typically produce more fine roots than in wetter environments. In this experiment the ponderosa pine trees – normally a dry forest species -- were well watered in order to examine the effects of elevated atmospheric carbon dioxide (CO₂) and nitrogen (N) on fine root dynamics.

Elevated CO₂ and N treatments both increased plant height, stem diameter and leaf area (Tingey et al. 1996, 1997). Elevated CO₂ resulted in significantly higher root biomass in the first 3 years and higher fine root turnover in the last 2 years. No significant N effects were noted for annual root biomass production, or turnover. Fine root nutrient cycling rates varied from 74 to 362 g m⁻² yr⁻¹ for C and 0.9 to 4.6 g m⁻² yr⁻¹ for N (Phillips et al, unpublished results).

Fine-root production and life span were strongly influenced by season and soil temperature (Johnson et al. 2000). Fine roots declined in importance with time and were replaced with mycorrhizae which continued to increase with time. This temporal pattern of root and shoot growth was not altered by providing additional CO₂ or N fertilization (Tingey et al. 1996).

Both CO₂ and N affected the fine roots, but the effects were independent and displayed contrasting effects. In this study, elevated CO₂ increased above and below ground plant growth because nitrogen was not limiting even in the unfertilized plots. Although elevated CO₂ increased fine root growth, it did not change the relationship between fine roots and needles indicating that elevated CO₂ did not increase the proportion of carbon allocated belowground (Tingey et al. 1996). Elevated CO₂ increased root lifespan but N decreased it (Johnson et al. 2000, Tingey et al. 1997). Initially, elevated N reduced the fine root area relative to the needle area, but this ratio was not altered by elevated CO₂ treatments.

Soil exploration by the roots increased with elevated CO₂, but was unaffected when nitrogen was abundant as in the fertilized plots. Fine root production was increased by elevated CO₂ whereas N fertilization had no effect on fine root production (Tingey et al. 1996, 1997). This suggests that as the limiting resource, nitrogen in this case, increases the plants do not need to produce as many fine roots to explore more soil to acquire enough of the resource. In contrast, increased CO₂ resulted in more images containing roots suggesting more soil exploration by roots.

Elevated CO₂ increased mycorrhizal and fungal occurrence earlier than N fertilization, and elevated CO₂ increased C flux into mycorrhizae (Rygielwicz et al. 1997, Tingey et al. 1997). Higher levels of N resulted in increased mycorrhizal activity relative to fine root production. The amount of mycorrhizae relative to the amount of fine roots did not change with increased CO₂ – they both increased in the same proportion. However, N fertilization resulted in more mycorrhizae relative to

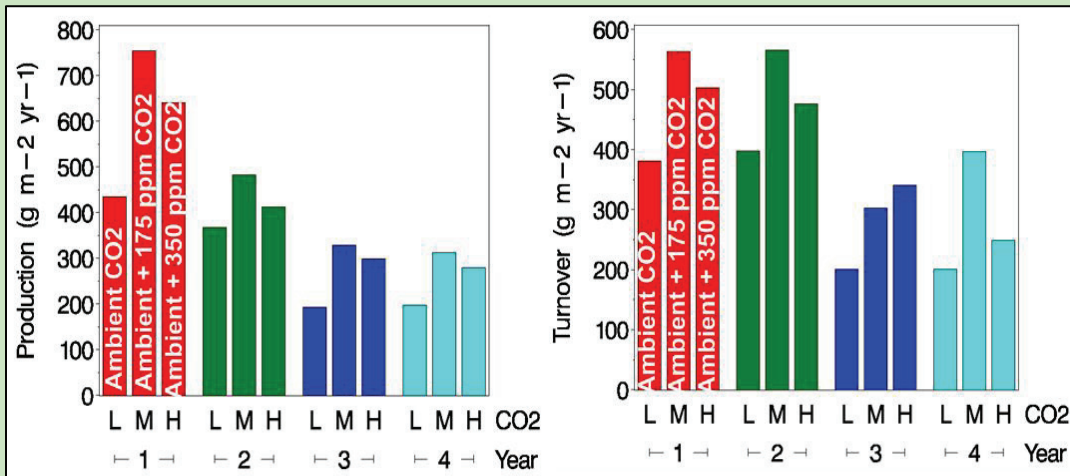
10. Fine Roots

roots. Under elevated CO₂ fine roots increased providing additional infection sites, and, consequently, mycorrhizal occurrence increased proportionally. In contrast, nitrogen fertilization increased root branching without increasing the amount of fine roots, thereby providing more site for mycorrhizal infection.

In summary, limiting resources determined the response of ponderosa pine root systems to changes in atmospheric CO₂ and soil nitrogen. As plants needed more nitrogen their roots explored more soil area to acquire this resource. Elevated CO₂ allowed the trees to take up more carbon for growth both above and below ground, but the amount allocated to the root system decreased as soil nitrogen became more available. Again, in this study water was not limiting and consequently did not affect the root system. With time mycorrhizae became more important to the root systems and effectively replaced the fine roots. Their abundance increased proportionally with fine roots under increased levels of CO₂, but increased in greater proportion than fine roots with higher levels of soil nitrogen.

Effects of Elevated CO₂ on Root Production & Turnover

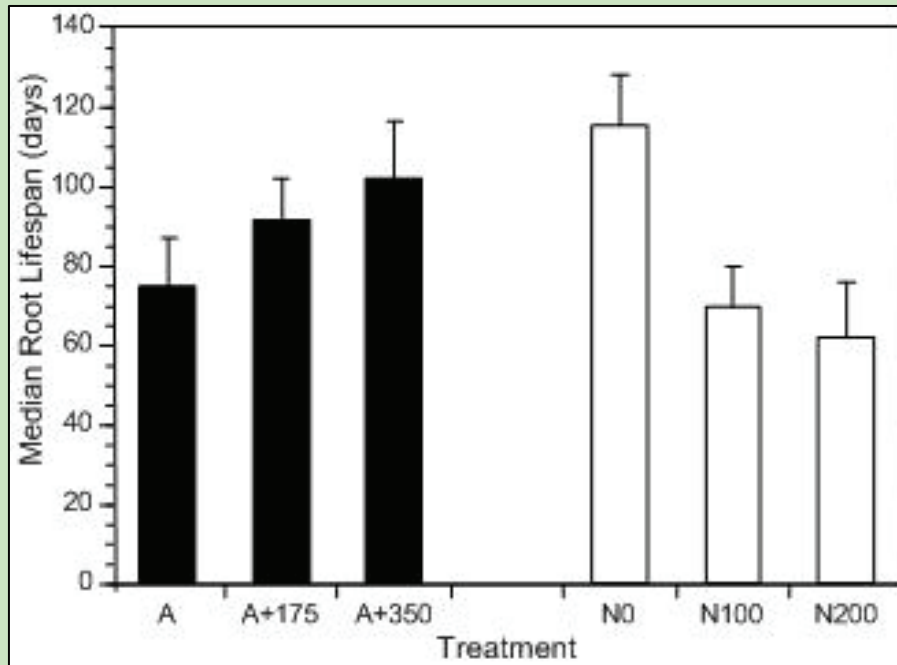
A 4-year study was conducted to determine the effects of atmospheric CO₂ and N-fertilization on *Pinus ponderosa* fine root ($\leq 2\text{ mm}$) responses. Seedlings were grown in open-top chambers at 3 CO₂ levels (ambient, ambient+175 ppm, ambient+350 ppm) and 3 N-fertilization levels (0, 10, 20 g·m⁻²·yr⁻¹). Length and width of individual roots were measured from minirhizotron video images collected bimonthly over 4 years. Biomass estimates were made by cross-calibrating with soil core root biomass. Neither CO₂ nor N-fertilization treatments affected root production and turnover seasonal patterns. Elevated CO₂ resulted in significantly higher biomass (g·m⁻²) in the first 3 years and higher turnover (g·m⁻²·yr⁻¹) in the last 2 years. No significant N effects were noted for annual root biomass, production, or turnover. Fine root nutrient cycling rates varied from 74-362 g·m⁻²·yr⁻¹ for C and 0.9-4.6 g·m⁻²·yr⁻¹ for N. Higher turnover in elevated CO₂ was due to higher biomass rather than shorter life-span. Fine roots lived longer in elevated CO₂, and turnover relative to biomass was generally \leq that in ambient CO₂, emphasizing the importance of root turnover definitions.



Effects of CO₂ and Nitrogen Fertilization of Fine Root Life Span

Ponderosa pine seedlings were grown at varying atmospheric CO₂ concentrations paired with varying concentrations of exogenously-applied nitrogen. Increasing CO₂ levels increased the lifespan of the ephemeral, nutrient-absorbing fine roots. Whereas, increasing the amount of applied nitrogen decreased root lifespan. These results illustrate: (1) the enhanced role of the ephemeral, nutrient-absorbing fine roots under elevated CO₂ to acquire nitrogen needed to balance the increased available CO₂, and (2) how the role of these roots was reduced as the available nitrogen increased.

Source: Johnson *et al.* 2000.



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11. Free-Air CO₂ Enrichment (FACE) Experiment

Statement of the Problem

A number of effects of elevated atmospheric CO₂ concentrations on plants have been demonstrated in greenhouse and controlled environment chamber studies. However, such studies have inherent limitations that reduce their value in predicting responses to rising CO₂: (1) physical facilities constrain the plant size and complexity of system which can be used, (2) the experimental conditions in these chambers which may be unrealistic, and (3) the experiments are short-term and may be unable to detect either delayed or transient effects. Greater understanding of direct effects of elevated CO₂ requires experiments on intact natural ecosystems, composed of multiple interacting species of a variety of sizes and ages, and continued over an extended period of time (multiple years).

Approach

Technology has been developed for Free-Air CO₂ Enrichment (FACE) facilities which allow CO₂ exposure experiments to be performed on large (~500 m²) plots in intact ecosystems. US EPA scientists are collaborating with scientists in the US Department of Energy and the University of Nevada at the Nevada Test Site in the Mojave Desert -- the only desert ecosystem FACE facility. EPA scientists are conducting long-term monitoring of belowground responses to elevated CO₂.

Main Conclusions

To date, University of Nevada scientists found that elevated CO₂ increases photosynthetic rates and aboveground biomass growth -- at least in years where sufficient soil moisture is available (Hamerlynck *et al.* 2000, Smith *et al.* 2000, Huxman and Smith 2001). The desert plants generally showed decreases in stomatal conductance (loss of water through leaf pores) and higher water use efficiency when grown in elevated CO₂ (Nowak *et al.* 2001, Pataki *et al.* 2000). However, soil moisture was no higher in elevated CO₂ plots. Presumably this was because the increased water use efficiency per unit biomass was balanced by higher aboveground biomass.

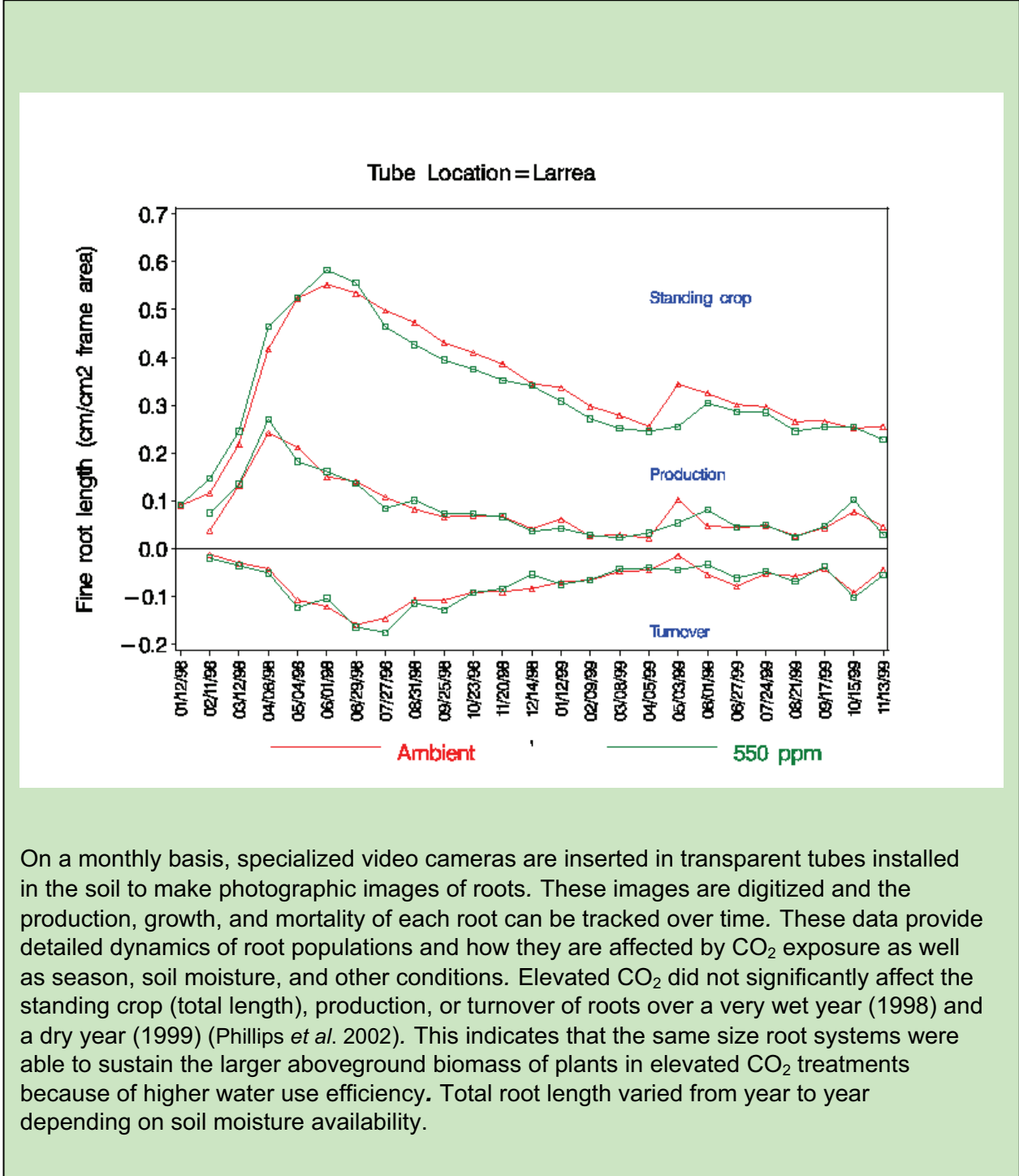
Belowground, EPA researchers have found no differences in the total length, production, or turnover of roots, indicating that the same size root systems were able to sustain larger aboveground biomass of plants because of the higher water use efficiency (Phillips *et al.* 2002). These results are important in helping us understand the likely responses of large tracts of arid lands under global changes of atmospheric CO₂ content.

Nevada Desert FACE Facility

FACE system maintains elevated CO₂ over 25 m diameter plots



The Free-Air CO₂ Enrichment (FACE) technology developed by the Brookhaven National Laboratory enables CO₂ exposure experiments to be performed on intact ecosystems. The Mojave Desert ecosystem, shown here, is one of eight such state-of-the-art facilities that have been constructed in various ecosystems across United States. Atmospheric CO₂ concentrations and wind speed and direction are continuously monitored. In elevated CO₂ plots, computer controlled valves on the vertical pipes open on the upwind side of the plot, releasing CO₂ to maintain a CO₂ concentration 200 ppm higher than the ambient CO₂ of ~360 ppm. Transparent plastic tubes inserted to a depth of 1 m in the soil (shown here with white insulating caps on top) are used with specialized video cameras to monitor the growth and mortality of roots in the experimental plots, to determine the belowground effects of elevated CO₂.

Elevated CO₂ did not affect fine root standing crop, production, or turnover

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12. Effects of Global Change on Coral Reef Ecosystems

Statement of the Problem

Corals and coral reefs of the Caribbean and throughout the world are deteriorating at an accelerated rate. Several stressors are believed to contribute to this decline, including global changes in atmospheric gases and land use patterns (Fig. 1). In particular, warmer water temperatures and elevated exposure to ultraviolet radiation has been linked to coral bleaching, which occurs when corals lose symbiotic algae. Bleached corals may recover, contract infectious diseases, or become overgrown with a layer of macroalgae. Loss of corals has significant socioeconomic repercussions; in Florida, Hawaii and most U.S. territories in the Caribbean and Pacific Ocean, coral reefs provide valued services in the form of fisheries, recreation, tourism and coastal protection from storm erosion. Furthermore, with hundreds of thousands of interdependent species, coral reefs are one of the largest global reservoirs of biodiversity and a potential wealth of undiscovered natural products. The abundant and diverse reef species are the substance of a flourishing and extensive marine ecosystem.

Geological records show that coral community structure has been stable over the last 220,000 years (Chadwick-Furman 1996, Aronson and Precht 1997). Yet, during the last 30 years, coral bleaching and disease have escalated worldwide (Hughes 1994, Hughes and Tanner 2000, Gardner et al. 2003, Hughes et al. 2003, Pandolfi et al. 2003). In 1998, the largest bleaching event on record affected about 16% of the world's coral reefs. It has been estimated that 27% of the world's reefs were lost in the last three decades and that 60% will be eliminated by 2030 (Wilkinson 2000). Many believe that ecological extinction for coral reefs could occur in this century if current trends persist (Gardner et al. 2003, Hughes et al. 2003).

Although the situation is alarming, relatively little is known about the environmental factors and interactive stresses that lead to coral bleaching. The term 'bleaching' refers to the loss of color when corals lose their symbiotic algae (Fig. 2), which are photosynthetic dinoflagellates often called zooxanthellae. Usually bleaching signifies environmental stress leading to a breakdown of the coral-algae symbiosis. In fact, bleaching at the local scale has been associated with several stressful environmental conditions (Goreau 1964, Glynn 1984) including high and low temperatures, high and low solar radiation, reduced salinity, and coral exposure to air, ultraviolet radiation, sediments, toxic chemicals, and high levels of bacteria (Mitchell and Chet 1975, Hoegh-Guldberg and Smith 1989, Glynn 1996, Brown 1997a).

Large-scale bleaching, however, is most strongly associated with elevated sea water temperature (Williams et al. 1987, Glynn and de Weerd 1991, Milliman 1993, Brown 1997b, Hoegh-Guldberg 1999, Barber et al. 2001, Fitt et al. 2001). Many coral species may be susceptible to thermal bleaching because they live near the upper limit of their temperature tolerance

12. Coral Health

(Scavia et al. 2002). Prior to 1980, bleaching was infrequent and events were confined to local scales (Goreau 1964, Goreau and Hayes 1994, Aronson et al. 2000). Since then, however, the extent, severity and frequency of bleaching events have increased dramatically.

The link between coral bleaching and global climate change is compelling. Massive episodes of coral bleaching have accompanied the last several El Niño phases of the Southern Oscillation (ENSO). These events have occurred world-wide and irrespective of other local anthropogenic stressors (Hoegh-Guldberg 1999, Wilkinson et al. 1999). Greater frequency, intensity, and spatial extent of bleaching have been documented since the 1982-1983 ENSO, including an exceptionally strong 1997-1998 ENSO that exhibited record sea-surface temperatures and coincided with the most geographically widespread and severe bleaching in history (Glynn 1984, Wilkinson 1998). Up to 95% of the living coral reefs from the central Indian Ocean and its margins were bleached, and bleaching occurred along the margins of the Caribbean Sea, the Indian Ocean and the Pacific Ocean. Although ENSO phases are measured in the Pacific Ocean, climate and weather patterns are altered worldwide. In the Caribbean, ENSO phases generate higher sea water temperatures and calm, stratified water conditions (doldrums) that allow increased penetration of solar radiation. These conditions are tailor-made for bleaching because of the interactive effects of high temperature and the high ultraviolet light that reaches coral reefs.

Corals rely on photosynthetic energy derived from algal symbionts found within the polyps, or colonial units of the coral. Since photosynthesis requires solar radiation, most corals are confined to shallow coastal waters penetrated by sunlight. Coral reefs are located in tropical and sub-tropical oceans that are exposed to the most intense solar radiation on Earth (Madronich et al. 1998). This distribution, however, places corals at risk from exposure to ultraviolet light (UV), particularly the damaging UV-B wavelengths (Shick et al. 1996). Increased penetration of UV-B to the earth's surface has been attributed to a decline in UV-absorbing ozone in the stratosphere. Although stratospheric ozone depletion in the tropics is not as great as at the poles, there is concern that any increase in the high levels already experienced could affect coral health. The most variable aspect of coral exposure to UV-B is its penetration through the water above reefs. Many local variables, such as water quality and weather, can influence attenuation of UV-B with depth. For example, dissolved organic matter absorbs UV-B and reduces its penetration, whereas hot, windless conditions create thermal stratification of the water column that increases UV-B penetration.

Approach

To fulfill EPA's assessment role in the US Global Change Research Program, NHEERL research is directed toward reducing assessment uncertainties and developing assessment tools. Specifically, the NHEERL program uses field and laboratory studies to determine which coral species, reefs and geographic regions are most valuable (i.e., providing ecosystem services), most at risk, and most responsive to management

12. Coral Health

alternatives. Research is focused in two principal areas: Development and application of methods to assess and compare coral reef condition, and characterization of stressor-response patterns to determine thresholds for global climate stressors. The research approach emphasizes the fact that changes in the environment affect both partners, the corals and the algal symbionts, and that effects on either can alter the symbiotic relationship. The primary stressors under investigation are elevated temperature and UV-B. Other environmental stressors, such as nutrients, contaminants and sediments, are expected to exacerbate bleaching at local scales.

Methods to Assess and Compare Coral Reef Condition

The Florida Keys coral reef tract provides a substantive opportunity to investigate the causes and effects of global change on coral reefs. Not only is it a relatively large tract (44 km²) with reefs in both remote areas and near human population centers, but it has experienced major declines in coral health and coral cover during the last thirty years. A Coral Reef Monitoring Project has been supported by US EPA Region 4 since 1996 to annually determine the total percent of live coral coverage at 160 permanent stations in the Florida Keys National Marine Sanctuary (FKNMS). After 5 years (1996-2000), a 38% decline in live coral coverage has been documented (Fig. 3; Jaap et al. 2000, Wheaton et al. 2001, Porter et al. 2002). Much of this loss has been attributed to bleaching events and the emergence of new diseases (Antonius 1981, 1985, 1988, Dustan and Halas 1987, Santavy and Peters 1997, Richardson et al. 1998, Santavy et al. 1999, 2001, 2004). Of particular concern has been the dramatic decline of fast-growing, reef-building acroporid corals (Patterson et al. 2002), including elkhorn coral (*Acropora palmata*) and staghorn coral (*A. cervicornis*).

A complementary survey has been conducted by NHEERL scientists to document bleaching and disease across the entire reef tract. Performed in collaboration with NOAA (FKNMS), the NHEERL survey includes 60 stations, selected by probability, ranging from the Upper Keys to the Dry Tortugas (Fig. 4). Each colony in a radial belt transect (113 m²) is examined, counted and identified (Fig. 5); fifteen coral species and eleven disease syndromes are documented. Results show that up to 28% of the coral populations near Key West are affected by disease (Santavy et al. 2001). Corals in this area do not appear to be recovering and, in the case of elkhorn coral, there has been nearly complete destruction (Patterson et al. 2002). NHEERL collaborative research with the University of Georgia has shown that elkhorn corals are susceptible to white pox disease caused by *Serratia marcescens*, a common soil and enteric microorganism (Patterson et al. 2002). Yet, across the Florida Keys reef tract the prevalence of disease is considerably less (Santavy et al. 2004). In August, 2002, the greatest prevalence (percentage of diseased corals at any site) was 13%, but this occurred in only 2.2% of the sampling area (Fig. 6). Seventy-nine percent of the area had less than 6% disease prevalence.

The annual field surveys were initiated and performed in response to the emergence of several diseases that were unknown prior to 1970. With continued declines in South

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Florida corals, the NHEERL research effort has expanded to characterize coral condition. New measurements are being introduced to evaluate the cumulative consequences of bleaching and disease, as well as other stressors, on coral individuals and populations. Reef-to-reef comparisons of disease prevalence are sometimes confounded by different taxonomic composition (e.g., some sites do not have susceptible host species); the new condition measures are unrelated to taxonomic composition and allow direct comparisons across reefs and geographic areas. Three condition endpoints have been added to the disease survey that estimate total coral surface area, the percent of living coral, and the living coral surface area of each coral encountered in the transect. Total surface area (TSA) serves as a surrogate for reef structural complexity and the habitat value associated with high complexity. It also supplies a record of the cumulative, or historical, capacity of the habitat to grow and sustain corals. Percent living coral (%LC) can be used to examine potential associations of adverse effects from diseases or other stressors. Living surface area (LSA) is an indicator of the more recent capacity of the environment to support corals; LSA also represents the amount of coral with potential to grow and reproduce.

A pilot project was conducted in 2003 to investigate the feasibility of acquiring these data in combination with bleaching and disease surveys. Five stations at two study areas, Key West and Dry Tortugas, were surveyed. The Key West area has high human density relative to the remote Dry Tortugas. Comparison of data demonstrated wide differences in species composition, abundance, TSA and %LC (Table 1), but the actual living coral (LSA) was nearly identical at both study areas. One promising tool is the comparison of %LC among species (Fig. 7), which will indicate whether one species has lost more tissue than other species in the same area, and whether the same species has lost more tissue in one study area over another. It is anticipated that these measures of coral condition will ultimately be integrated into a condition index for comparison of reefs and geographic areas over time. Until then, the bleaching, disease and condition information provided by the field surveys is directly useful in the management of the Florida Keys National Marine Sanctuary and the Dry Tortugas National Park.

Although condition indicators can provide useful insight to status and trend of coral populations, it is imperative for future management that declining condition is ultimately linked to a cause. Condition indicators can be used to compare reefs with putative coral stressors. To this end, NHEERL scientists are investigating chemical contaminants in coral reef areas, and collaborate both with Florida International University to measure nutrients and chlorophyll and with NERL scientists to measure temperature and UV-B at coral reefs. Any associations of these factors with declining coral condition can be investigated in the laboratory, as described below.

Characterization of Stressor-Response Patterns.

Relating coral decline to global change stressors requires knowledge of the thresholds

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at which changing environmental conditions create adverse effects. NHEERL has developed unique laboratory facilities and expertise to expand this knowledge. Two 'solar simulator' systems have been constructed to expose corals and algal symbionts to varying levels of both photosynthetically-active radiation and UV-B. In addition, NHEERL scientists retain in culture over 15 reef-building coral species and 28 algal symbiont (*Symbiodinium* spp.) isolates for controlled laboratory experiments (Figs. 8 and 9). Research using algal symbionts is particularly promising because the interaction of temperature and UV-B very likely affect the photosynthetic processes of symbionts. Also, results of experiments have potential worldwide application because corals have established symbioses with relatively few algal symbiont groups (clades). Early studies in the solar simulators validated that different coral species exhibited different bleaching responses to elevated UV-B radiation. During these early studies, methods for documenting changes in zooxanthellae number, photopigments, mycosporine-like amino acids, and photosynthetic efficiency were validated and improved. Temperature studies on algal symbionts have documented lethal thresholds (35° C) and declining growth rates at temperatures above 31°C during short-duration exposures. Studies on the interactions of UV-B and temperature have confirmed, for the first time in a laboratory system, that elevated UV-B exposure exacerbates the adverse effects of high temperature (Fig. 10).

Several physiological mechanisms are being investigated to understand the interactive effects elevated temperature and UV-B and to develop biomarkers able to distinguish susceptible corals in the field. Corals are experimentally bleached in the solar simulators and both corals and algal symbionts are examined for changes that could be used as biomarkers of susceptibility. For example, it is expected that changes in photopigment concentrations will be an early response to elevated UV-B. To refine current methods, an efficient methanol extraction process was developed to quantify changes in the symbiotic algae photopigments (Rogers and Marcovich 2004). The technique is much improved over previous techniques, yielding greater than 95% recovery of pigments in less than half the time. Another technique requires pulse-amplitude modulated fluorometry to examine photosynthetic efficiency of the symbiotic algae and may help to determine how photosynthesis is affected by temperature and UV-B. An immunoassay technique has been adapted in collaboration with the University of California to detect thymine dimer formation in coral DNA (Fig. 11; Anderson et al. 2001, 2004); these specific mutations are characteristically formed only by UV-B exposure. As they are generated, biomarkers will be tested in the field to determine their ability to predict species at risk to both global change and local stresses.

Main Conclusions

Coral health in the Florida Keys is deteriorating at unprecedented levels. Tools to evaluate coral reef condition are needed to assess potential consequences of this decline and to guide management options. Field surveys that estimate prevalence and distribution of coral bleaching and disease, using a probability-based sampling design

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and a radial belt transect (113 m²), have been validated and applied at 60 sampling stations across the Keys (41 km²). Bleaching and disease prevalence in the Lower Keys was particularly high in 1998 relative to other years (1998-2002), and was higher than comparison sites in the Dry Tortugas. A pilot project, comparing only five sites in the Lower Keys with five sites in the Dry Tortugas, demonstrated a greater percentage of dead coral in the Lower Keys area.

Various endpoints are being validated to document coral condition. When combined, these endpoints must reflect the growth, survival, health and reproduction of corals; identify at-risk species; be comparable across stations, reefs and regions; and identify associations of condition with disease prevalence and other putative stressors. To achieve this goal, bleaching and disease surveys are being supplemented with three estimates made for each coral colony in the survey — total surface area, percent living coral tissue, and total living coral surface area. Results from a pilot project have demonstrated that these measures can be combined to indicate coral population health, survival and capacity to reproduce. Continued surveys of coral populations in the Florida Keys is expected to lend insight to the species, reefs and regions that are most valuable, most at risk, and potentially most responsive to management action.

Relating coral decline to global change stressors requires knowledge of the thresholds at which changing environmental conditions create adverse effects. Controlled laboratory exposures, using novel solar simulator systems, have established temperature and UV thresholds for various coral species and algal symbionts. Early studies demonstrated that different coral species exhibited different bleaching responses upon exposure to UV radiation. Temperature studies have confirmed the adverse effects above 31°C for coral symbionts and the interactive effects of high temperature with elevated UV-B. Future laboratory studies will document differences in sensitivity among the various groups (clades) of algal symbionts to temperature and UV radiation, and will evaluate changes in sensitivity from short (acute) to long (chronic) exposures. Various biomarkers are being investigated to provide insight to the physiological mechanisms of bleaching and for indications of coral susceptibility to bleaching. Characterization of stressor-response patterns for different coral species and algal clades can be used interactively with field studies to identify which stressors are most affecting the various species, reefs and regions of the Florida Keys.

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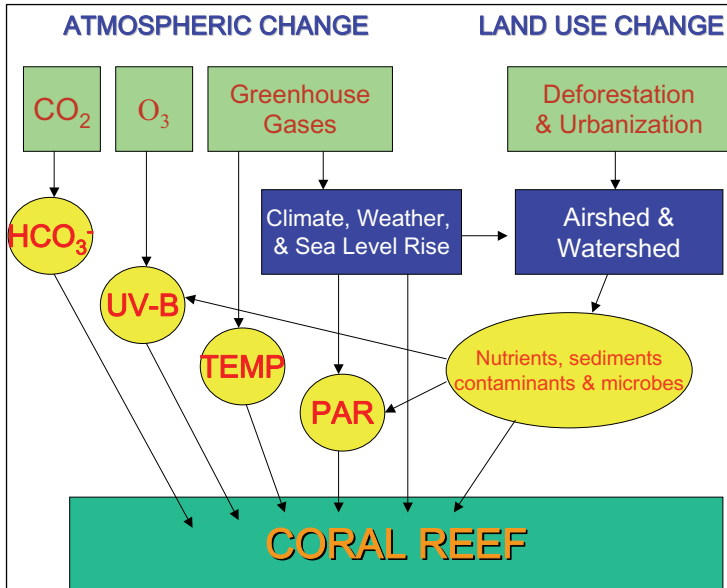


Figure 12-1. Coral reefs are affected by environmental changes in temperature, UV-B, photosynthetically-active radiation (PAR), carbonate (HCO_3^-) availability in sea water, nutrients, sediments, contaminants and microorganisms that fluctuate in relation to global atmospheric and land use changes.

Figure 12-2. Bleaching is a term used to describe the loss of pigmented symbiotic algae from coral tissue. Their loss leaves the coral with the stark white appearance of the coral skeleton. Coral tissue still covers the surface of the skeleton, but is transparent.

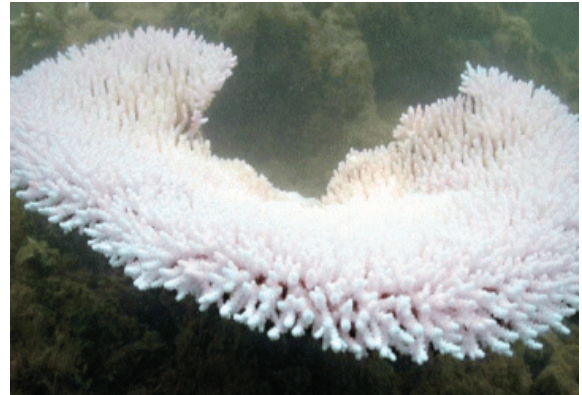
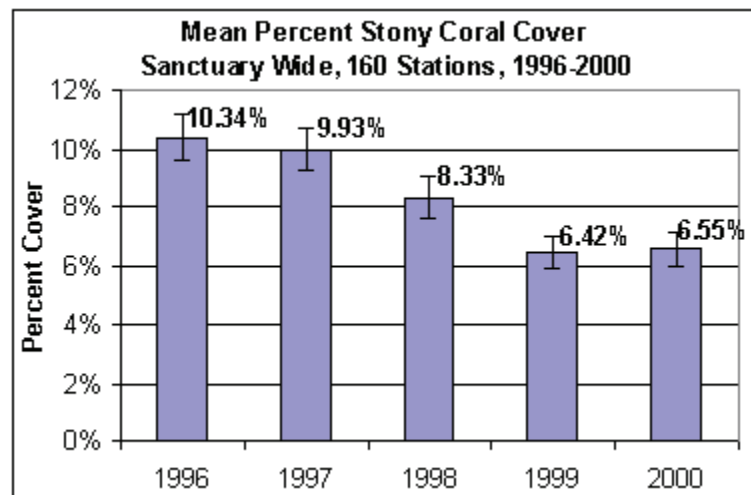


Figure 12-3. Mean percent coral cover declined over 160 stations in the FKNMS during 1996-2000 (from Wheaton et al. 2001). The 2000 coral cover represents a 38% decline from the 1996 coral cover



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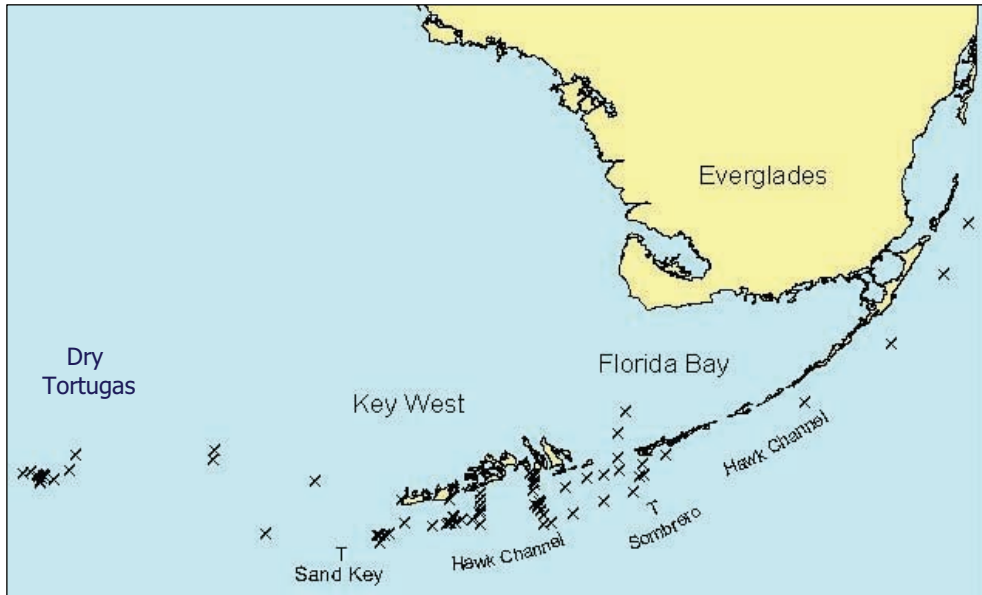
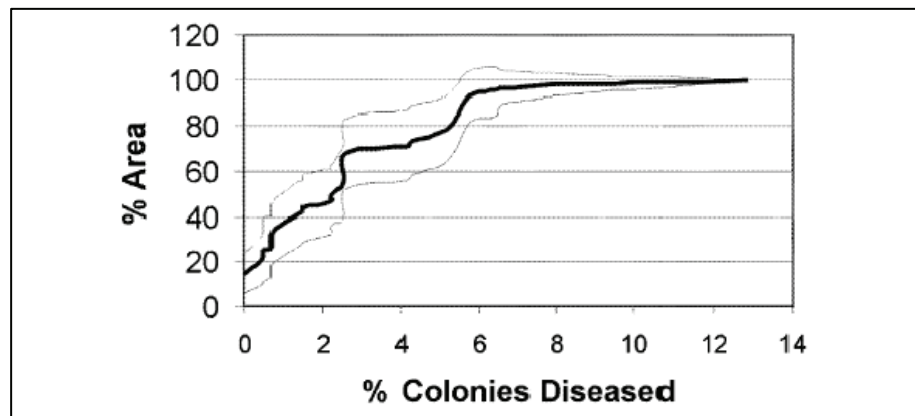


Figure 12-4. Coral Reef areas and NHEERL study sites in the Florida Keys and Dry Tortugas.

Figure 12-5. Using SCUBA, surveyors count and identify each colony in a 113m² radial belt transect and examine each for evidence of bleaching and disease.



Figure 12-6. Cumulative distribution function depicting overall area estimates associated with coral disease prevalence in South Florida (with 95% confidence intervals (Santavy et al. 2004).



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	Number of Colonies	TSA (m²)	LSA (m²)	%LC
Dry Tortugas				
BK06	178	42.4	32.4	76.4
BK07	94	33.1	26.7	80.8
LR05	149	33.4	26.2	78.6
LR06	165	38.1	32.0	84.1
<u>LR07</u>	<u>104</u>	<u>29.0</u>	<u>22.7</u>	<u>78.2</u>
Total	690	175.9	140.0	79.6
Key West				
SK01	240	73.8	44.4	60.1
SK02	350	85.1	41.8	49.2
SK03	162	26.5	17.7	66.8
ED01	155	25.8	15.5	59.8
<u>WS03</u>	<u>90</u>	<u>29.6</u>	<u>17.4</u>	<u>58.6</u>
Total	997	240.9	136.9	56.8

Table 12-1. Number of coral colonies, total estimated surface area (TSA), calculated surface area of living coral (LSA) and the estimated percent of living coral (%LC) for all colonies encountered within the transects at each of five stations in the Dry Tortugas and Key West study areas. Totals were determined from combined data of all stations in each study area.

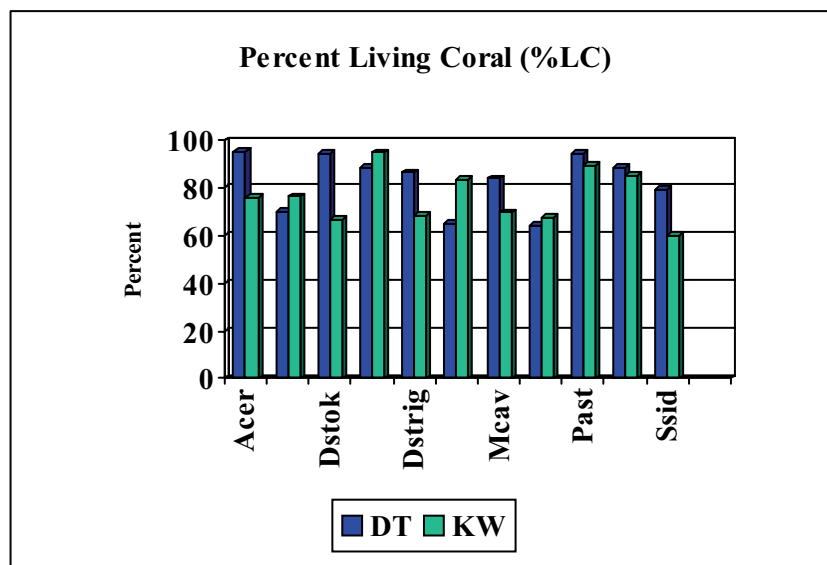


Figure 12-7. Percent living coral for several coral species that co-occurred at Dry Tortugas and Key West study areas. Corals, in order, are *Acropora cervicornis*, *Colpophyllia natans*, *Dichocoenia stokesii*, *Diploria clivosa*, *D. strigosa*, *Montastrea annularis*, *M. cavernosa*, *M. faveolata*, *Porites porites*, and *Siderastrea siderea*.

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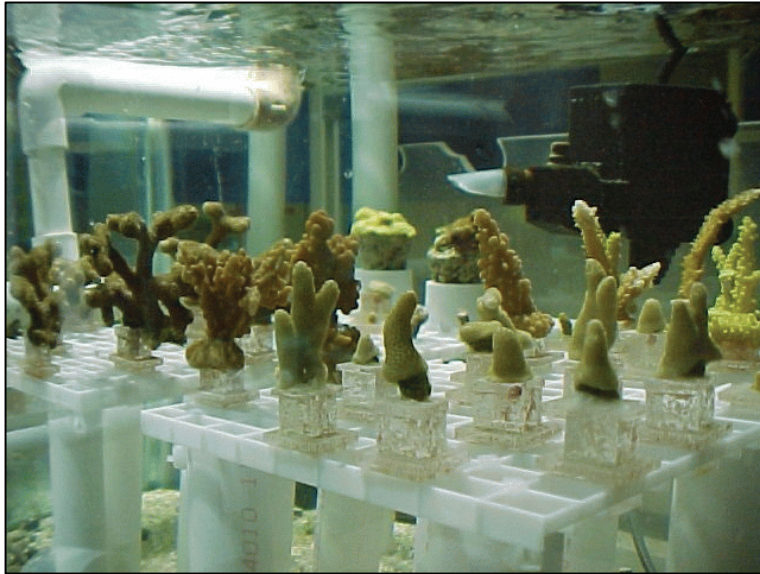
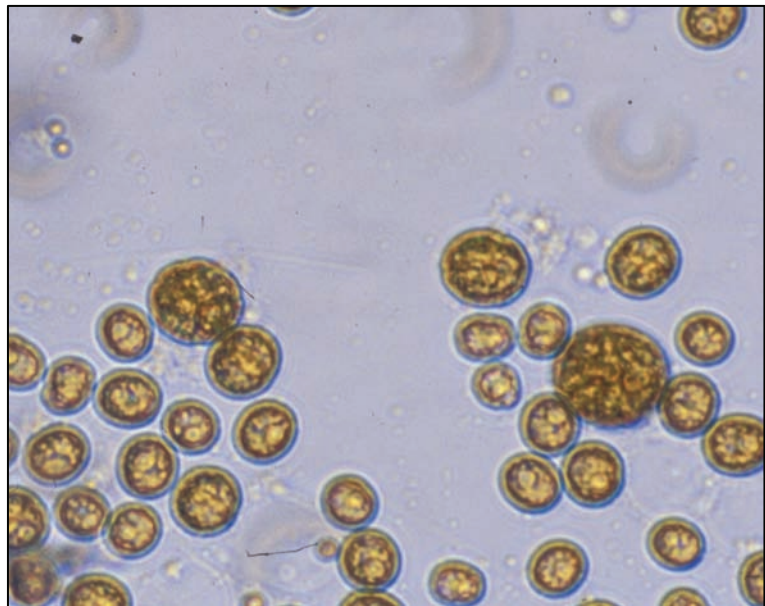


Figure 12-8. Laboratory culture of different coral species allows comparisons of susceptibility to varying levels of temperature and UV-B under controlled experimental conditions.

Figure 12-9. Laboratory culture of isolated algal symbionts (*Symbiodinium* sp.) allows a rapid examination of temperature and UV-B effects on the photosynthesis, pigment production, growth and survival.



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13. Synthesis

Introduction

The Global Change Research Program's mission is to improve the scientific basis for evaluating effects of global change in the contexts of other stressors and human dimensions, to assess the consequences of global environmental change, and to improve society's ability to effectively respond to the risks and opportunities presented by global change as they emerge. NHEERL's role within this program has evolved over the years as the program's emphasis shifted from research on carbon cycling and terrestrial ecosystems to research on and assessment of impacts on aquatic ecosystems, including coral reefs.

As the global climate change debate was heating up in the late 1980's and early 1990's the United States Environmental Protection Agency (EPA) was rethinking its approach to environmental protection. After two decades of "end-of-pipe" regulation, and faced with non-point sources of pollution like agricultural runoff, serious questions were being raised about the cost-effectiveness of environmental policy. The EPA's Science Advisory Board (SAB) was convened to develop recommendations for guiding the agency's policy and research for the 1990's and into the 21st century (SAB 1990). The board recommended targeting research on problems with the greatest risk while exploring new regulatory processes such as market incentives and public education. The high-risk ecological problems identified by the SAB were (1) global climate change, (2) stratospheric ozone depletion, (3) habitat alteration and destruction, and (4) loss of biodiversity. These four issues are not mutually exclusive but interrelated in mechanism and mitigation.

In 1988 at the request of Congress, EPA initiated the first national-scale assessment of potential global climate change effects (Smith and Tirpak 1989). Research within EPA's Office of Research and Development (ORD) supported that Report to Congress and became part of the United States Global Change Research Program (USGCRP). Started as a Presidential initiative in 1989, the USGCRP was codified by Congress in the Global Change Research Act of 1990 (P.L. 101-606). The act established a research program "aimed at understanding and responding to global change, including the cumulative effects of human activities and natural processes on the environment, [and] to promote discussions toward international protocols in global change research..." Initially, the ORD research addressed stratospheric ozone depletion and global climate change to support international treaty negotiations—the Montreal Protocol and the United Nations Framework Convention on Climate Change (UNEP 2000, UNFCCC 2002).

Today, the USGCRP climate change research is managed within the US Climate Change Science Program along with the Climate Change Research Initiative (CCSP 2003). The latter is a Presidential initiative which establishes near-term

priorities for climate change research focusing on scientific information that can be used to address global change risks, including: the role of aerosols in climate forcing, inventorying carbon sources and sinks, improved climate modeling, risk management, and improved observation and monitoring of the earth's climate system.

Early research at EPA was geared toward evaluating potential global impacts that could most seriously affect humans and the ecosystems on which they depend. As part of a larger EPA program addressing potential impacts to agriculture, natural resources and human welfare, scientists at ORD's National Health and Environmental Effects Research Laboratory (NHEERL)—and its predecessor organizations—addressed potential changes to regional vegetation, impacts to rice production in Asia, and the effects on North American freshwater fish. The loss of forests, desertification and movement of major biomes with global warming were effects that the general public could envision.

As the world became more aware of the potential seriousness of climate change, an interest was stimulated in control technologies to reduce the accumulation of greenhouse gases in the atmosphere. The EPA initiated projects on efficient use of fossil fuels, accounting for emissions of greenhouse gases country by country, and the ecological sources and sinks of carbon compounds. NHEERL scientists focused on the terrestrial carbon cycle. A key issue in international negotiations was whether or not forests could sequester carbon from the atmosphere in amounts that might offset emissions.

These two policy drivers—demonstrating environmental effects of such scale as to warrant international attention, and the ability of forests to sequester carbon and offset emissions—triggered a long-term research effort at NHEERL to understand the interactions between ecosystems and human-caused climate change. Throughout the 1990's this research contributed to the scientific underpinnings of mitigation strategies for sequestering atmospheric carbon using forests and agriculture. Moreover, this research supported assessments of potential ecological effects resulting from climate change both in the US and abroad. NHEERL scientists were prominent in assessments of ecological vulnerabilities in conjunction with the national assessment process (National Assessment Synthesis Team 2000), and contributions to the assessments of the International Panel on Climate Change (IPCC 1995, 2001a).

Here, we review the research accomplishments of NHEERL scientists in light of changing policy issues, past, present and future. The intent is to show how the laboratory's scientists responded to changing policy needs as the issue of global climate change grew from a scientific curiosity to a major worldwide concern. We conclude with a discussion that provides a view of emerging scientific issues related to effects of global climate change that may impact the EPA's mission.

Humans and ecosystems

Climate change has affected human populations throughout history—indeed, our evolution as a species. Dramatic societal changes have resulted from past climate change. Climate change could affect the human condition directly as a result of extreme temperatures, sea level rise, and catastrophic storms and, perhaps more profoundly, indirectly through ecological change (Watson and McMichael 2001). The potential impact of global climate change to world food production was a major focus of EPA research

Food production is already a critical issue in light of expanding human populations worldwide. Potential impacts of climate change on are, therefore, of great importance. Whereas carbon conservation and fuel use are the primary concerns associated with global climate change in industrialized countries, sustainable production of major food crops and drinking water are major issues facing non-industrialized countries throughout much of the world (Speidel 2000). An early issue raised by the USGCRP was whether or not changing climate could compromise food production needed to support the world's growing human population. Assessing the impacts of global climate change on major crop species and crop production systems was critical in international negotiations (UNFCCC 2002).

Rice is the most important source of calories in the world. It is the principle food source for approximately 1.6 billion people, and another 400 million are dependent on it for a quarter to half of their caloric intake (Moya *et al.* 1998). To meet the demands of human population growth over the coming decades an estimated 70% increase in yield over 1990 levels is needed (IRRI 1993). Of the major cultivation practices, irrigated rice makes up 55% of the world's harvested rice area and 75% of world rice production (IRRI 2002).

NHEERL scientists conducted joint research with the International Rice Research Institute in The Philippines. In concert with broader EPA-funded research on how global climate change may affect the world's major crops, this research examined the effects of climate change and stratospheric ozone (O₃) depletion on rice production in Asia. Higher UV-B levels do not appear to affect irrigated rice production, however, elevated CO₂ and temperature can affect production both directly and indirectly through disease and pests. Elevated CO₂ enhances rice plant growth and grain yield if soil nitrogen is not limiting (Olszyk *et al.* 1999, Weerakoon *et al.* 1999, Ziska *et al.* 1996), but nitrogen is, generally, limiting and fertilizer is a major expense for farmers. In reality, the benefit of increased production from elevated atmospheric CO₂ may not be realized throughout much of the world. Additionally, higher temperatures can result in increased sterility in rice leading to reduced grain yield (Moya *et al.* 1998). Regional analyses for Asia predict a nearly 4% decrease in rice yield across south and Southeast Asia with projected changes in temperature and precipitation associated with a doubling of atmospheric CO₂ concentrations over 1990 levels (Matthews *et al.* 1995).

As part of the larger EPA crop assessment program, NHEERL scientists determined that for US Corn Belt, soil erosion is likely to increase with increasing frequency and intensity of precipitation, and wind erosion will increase with increasing temperature (Phillips *et al.* 1993, Lee *et al.* 1996). These losses will contribute to pollution and affect the sustainable yield of crops.

Although plant productivity may rise with increases in atmospheric CO₂ and, consequently, offset some erosion, the overall effect of CO₂ increases in conjunction with changes in other stresses, including nutrients, temperature, and moisture availability, is uncertain and crop specific (Phillips *et al.* 1996). However, increases in plant production could increase soil carbon storage and ameliorate erosion losses to some degree so long as nutrients and water do not become limiting to crop growth. In fact, agricultural soils could become a small sink for atmospheric CO₂ if conservation tillage is practiced (Kern and Johnson 1993).

Ecological effects

EPA research on ecological effects was initiated in 1990 to assess the effects of global climate change on aquatic and terrestrial ecosystems as an integral part of the USGCRP. Early research at NHEERL assessed the impacts of climate change on fresh water fish and changes in the distribution of major vegetation types. In the early 1990's, policy makers became interested in the global carbon cycle, particularly in the sources and sinks of atmospheric carbon in the terrestrial biosphere. At that time, strategies were being formulated for removing carbon compounds from the atmosphere, and for managing the terrestrial biosphere to increase carbon sequestration. In particular, the large carbon pools in forests and soils were seen as potential sinks for atmospheric carbon. At NHEERL, research was initiated to assess forest management practices as a means to increase carbon sequestration. At the same time scientists were debating whether or not increased levels of atmospheric CO₂ would increase the productivity of crops and forests. In response, NHEERL scientists initiated long-term experimental research on the effects of increased temperature, elevated atmospheric CO₂, and air pollution on the carbon balance of forested ecosystems. In 1998, the USGCRP was refocused; ORD's primary ecological responsibility became watershed and aquatic ecosystem assessments. NHEERL research is currently addressing global change effects on coral reefs.

In the following sections, we summarize the research findings of the NHEERL scientists within the context of related research. While the research on thermal tolerance in freshwater fish, vegetation redistribution, and carbon sequestration has, largely, been completed and published, much of the experimental research on carbon cycling is not yet published. With the experiments completed and the data collected, scientists are in the process of analyzing and publishing their findings on multiple stress effects—publications will continue over the next several years. The research on coral reef decline was initiated in the late 1990's

and is continuing, consequently, the research plans and early findings are reported here.

Thermal tolerance in fish

Water temperature has long been recognized as one of the most important environmental variables influencing the distribution of fish species. NHEERL scientists have investigated the thermal requirements of freshwater organisms; especially fish, since the 1960's and 1970's when water quality research started to focus on requirements of aquatic organisms. NHEERL scientists provided some of the first assessments of climate change effects on North American fish species in support of the USGCRP. They assembled data on fish species, river characteristics (Poff and Allen 1995), and air-water temperature relationships (Stefan and Preud'homme 1993, Eaton and Scheller 1996) to predict the impacts of climate change on fish distributions (Eaton *et al.* 1995).

The effect of air temperatures on stream temperatures was determined based on field studies (Stefan and Preud'homme 1993, Eaton and Scheller 1996). The effect of climate warming was assessed for 57 North American fish species (Eaton *et al.* 1995). Results suggest that cold or cool water fish species could be lost from a large part of their range. Habitat losses were predicted to be greatest for species with limited distributions and in areas of the country anticipated to warm the most (e.g., the central Midwest). Results for warm water fish species were less certain because of a relative paucity of data on summer and winter thermal tolerances for species.

Effects of global warming on habitable stream reaches based on temperature changes can be modified near groundwater or tailwater discharges from reservoirs or lakes (Sinokrot *et al.* 1995). Empirical models were developed by NHEERL scientists to predict groundwater inputs to stream reaches based on watershed slope and hydraulic conductivity (Baker *et al.* 2001), and to predict modifications to stream thermal regimes based on stream shading from topography or riparian vegetation and groundwater inputs. These efforts will help fine-tune model predictions of the effects of global change on fish species distributions.

Global change effects on fish communities will depend not only on stream temperature, but also on flow regimes. Altered flow regimes resulting from climate change could be particularly pronounced in the western US. Research funded by NHEERL (Lettenmaier *et al.* 1992), and subsequent assessments (Gleick 2002) predict that the western US will experience a substantial reduction in the natural storage of water as snow pack with climate warming despite potential increases in precipitation. Loss of snowpack will result in higher stream flows in winter and lower water levels in summer (Lettenmaier and Sheer 1991). Consequently, aquatic ecosystems will experience substantial changes in flow

regimes and sediment loads in streams and rivers, which will impact fish species to varying degrees.

Global climate change could profoundly affect freshwater lakes because they are sensitive to a wide array of changes in climate. NHEERL research suggested that cold water fish are likely to disappear from southern Minnesota lakes, and experience habitat losses of 41% in northern Minnesota lakes. Largest gains in suitable habitat for cool and warm water species will occur in lakes with low production—oligotrophic (Stefan *et al.* 1996). The recent US National Assessment summarized possible climate change effects on water resources (Gleick 2002); the effects on lakes include:

- Small changes in climate can produce large changes in lake levels and salinity.
- With higher air temperatures, fewer lakes and streams in high-latitude areas will freeze to the bottom and the number of ice-free days will increase, leading to increases in nutrient cycling and productivity.
- Increased lake temperatures could result in higher thermal stress for cold-water fish, improved habitat for warm-water fish.
- Higher temperatures will increase lake productivity and lower dissolved oxygen, and degrade water quality.

Vegetation redistribution

Of the predicted global warming consequences, widespread changes in the distribution of forests, grasslands, and deserts are perhaps the most striking. The prospect of the pole-ward migration of temperate forests, the loss of tundra and boreal forests, and the desertification of grasslands could impact much of the world. The effects of world-wide changes in vegetation zones over a relatively short time period would have dramatic effects on fish and wildlife species, on forest health, on water quality, and on agriculture. Moreover, such changes in vegetation would have significant consequences for carbon storage and loss in the terrestrial biosphere.

The fundamental concept of vegetation redistribution is complex and occurs over time scales from years to centuries and at spatial scales from back yards to continents. Weeds can appear and spread in a new region within years or decades, but the climate-induced appearance of forest tree species new to a region requires centuries to millennia in the absence of human intervention. In contrast, the death of extant vegetation from climate stresses can occur relatively quickly, sometimes in only a few years or a decade.

NHEERL scientists conducted research to address vegetation redistribution using models which predict regional vegetation patterns. Precise data bases for climate and vegetation were critical to the modeling, and much of the early work was dedicated to their development (e.g., EPA/NOAA 1992, 1993). The modeling research followed two approaches. One used life form classifications (e.g., Sedjo and Solomon 1989, King and Neilson 1992) in conjunction with climate correlations to

define the climate space occupied by vegetation types (Neilson *et al.* 1992). A physiology model was then applied which calculated the uptake of CO₂ by photosynthesis and emission of CO₂ by respiration in each vegetation type (Neilson 1993a, 1995). The other approach used known climate thresholds to assemble different plant functional types in each ½ X ½ degree of latitude and longitude (Prentice *et al.* 1992). Both approaches used climate projections calculated by global climate models to define new vegetation distributions.

The redistribution of global vegetation in response to changing climate and land use remains a major uncertainty in predicting carbon sequestering in the terrestrial biosphere. Regional changes in temperature, precipitation, and consequently, soil moisture, are the driving forces that will alter the distribution of natural and managed vegetation as climate changes (Marks *et al.* 1993). The NHEERL modeling results indicated that the capacity of the terrestrial biosphere to remove and store atmospheric carbon would increase with a warmer global climate (Solomon *et al.* 1993, 1996; Solomon 1996, 1997). The direct effects of increasing atmospheric CO₂ on biomass were simulated at a global scale and found to increase carbon sequestration (Neilson 1993b, 1998; Neilson and Marks 1994). Subsequent work has suggested that increases in vegetation density and carbon storage will increase with climate warming to a threshold of approximately 4.5°C above which vegetation density and carbon storage will diminish (Bachelet *et al.* 2001).

Climate-induced forest dieback and changes in the distribution of land used for agriculture could generate a pulse of CO₂ from the biosphere into the atmosphere lasting several decades (Neilson 1993b, 1998). The size of such a pulse could be 15-20% of that from anthropogenic emissions over the same time period (Solomon and Kirilenko 1997, Kirilenko and Solomon 1998). While not considered in recent estimates of future carbon releases from the biosphere (Falkowski *et al.* 2000; Hurtt *et al.* 2002), a carbon release of this magnitude would amplify any warming effect of anthropogenic emissions and limit the effectiveness of carbon sequestration efforts.

In an effort to refine estimates of CO₂ releases, forest gap models were used to estimate the dynamic responses of forests to rapid climate change. These models replicate the death, reproduction, growth, and maturity of trees, and the development of forest ecosystems (Solomon and Bartlein 1992, Solomon and West 1993, Bugmann and Solomon 1995, 2000). Although assessment exercises with these models (Solomon and Bartlein 1992, Bugmann *et al.* 2001) confirmed the potential for the long-term carbon pulse, the gap models have not yet been applied on the globally-comprehensive basis needed to thoroughly evaluate the carbon pulse phenomenon.

While the timing and magnitude remains uncertain, CO₂ emissions from vegetation redistribution will almost certainly occur and will affect greenhouse gas concentrations in the atmosphere (Solomon 1996, 1997). Human population

growth superimposed on climate related changes in human demographics and agricultural land use will have an effect on the size and timing of these releases. Analogously, Houghton *et al.* (1999) estimated that over the period 1700-1990, 25 petagrams (Pg) of carbon was released into the atmosphere from land use change in the US, largely from the conversion of forests to agricultural land and cultivation of prairie soils. In comparison, the US emission of CO₂ equivalents for the ten year period 1990-1999 was approximately 58 Pg (US Dept.of State 2002). In a warmer world, the intensity of agriculture is expected to increase at higher latitudes, thus reducing the capacity of the earth to store carbon and create potential sources of CO₂ through soil warming and land conversion (Cramer and Solomon 1993, Leemans and Solomon 1993, Solomon and Leemans 1997).

Vegetation zones are likely to shift as climate changes over the next century and beyond, but how they shift within regions and watersheds, over what time period, and with what ecological effects is still unclear. But that kind of information is necessary for developing adaptation strategies. Perhaps most limiting to vegetation modeling is the inability to predict regional precipitation and soil moisture. Current global and regional climate models cannot predict precipitation, soil moisture, and runoff on time scales beyond a few days (Hornberger *et al.* 2001). Adding to the uncertainty in predicting vegetation patterns, regional vegetation models are unable to simulate processes which control the redistribution of plant species—dieback, seed dispersal, and establishment. Global climate change involves rapidly changing climate, which may exceed the capacity of many plant species to adapt (Solomon *et al.* 1996, Etterson and Shaw 2001). Rapid loss of vegetation assemblages and slow, species-by-species establishment elsewhere is much more likely than a gradual process which delivers fully developed plant communities instantaneously. It is unlikely that new vegetation communities will contain the same species in the same abundances as old ones because migration and establishment requirements differ from species to species (Solomon and Kirilenko 1997, Kirilenko and Solomon 1998). Presently, the models do not account for factors controlling seed dispersal and species migration. Such improvements are needed before better predictions of species composition and carbon storage can be made.

Wildfires were not included in the NHEERL vegetation modeling, but they will affect future redistribution of vegetation and carbon loss from increasing climate stress. Large areas of essentially undisturbed forests in the US have been protected by fire suppression during the last century, permitting dangerous levels of fuels to accumulate and increasing the likelihood of severe, uncontrollable fires. Globally, the drought conditions over continental areas projected by most climate models (Solomon and Leemans 1997) will increase wildfire occurrences. Only recently have dynamic vegetation models included fire factors based on vegetation types, climatic conditions, and fuel characteristics (e.g., Bachelet *et al.* 2001). Currently, methods to include fire intensities and distributions in regional vegetation models based on wildfire characteristics, climate conditioning of vegetation, land use distributions, soils and topography are being developed by

EPA and USGS scientists. Once tested, these models will provide improved predictions of vegetation redistribution and carbon cycling. They will also be valuable in predicting health-related effects of wildfire emissions.

Carbon sequestration in forests

Sequestration of atmospheric carbon in soils and vegetation could play a key role in mitigating anthropogenic CO₂ emissions. Forest systems are a globally significant terrestrial carbon pool and play a major role in the Earth's carbon cycle through assimilation, storage, and emission of CO₂ (Dixon *et al.* 1994). The ability of forests to remove carbon from the atmosphere and store it for long time periods—carbon sequestration—is potentially important in mitigating anthropogenic emissions of carbon dioxide (Dixon *et al.* 1999, UNFCCC 2002).

The annual exchange of carbon between forests and the atmosphere, and the amount of carbon stored in forests, varies with the nature of forest cover, land use, and climatic constraints. Despite this variation NHEERL scientists showed that managing forests to maximize growth and biomass retention can significantly increase the long-term sequestration of atmospheric CO₂ (Dixon *et al.* 1994). Maintaining healthy forests was determined to be the most efficient way to store carbon, but uncertainties remain.

Most assumptions of how much carbon forests can sequester do not account for vegetation redistribution, land use change, or changes in human population density resulting from climate change. These factors can significantly affect estimates of carbon stored in forests. Changing land use is perhaps the greatest threat to sequestering carbon in forests (Dixon *et al.* 1999). Efforts aimed at storing carbon in the tropics—where the world's largest pools occur—are being countered by carbon emissions from forest destruction. Moreover, increasing agriculture in response to the growing human population is impacting forested regions world-wide. In fact, land use changes may have as large or larger effect on terrestrial carbon sequestration than direct climate change effects (Schimel *et al.* 2000).

Currently, the US is pursuing voluntary limitations on CO₂ emissions (EPA 2003), but should the US decide to pursue and implement strict limits in the future, EPA may be asked to regulate sources and sinks (Nature 2003, Samuelsohn 2003, Jeffords 2003). Moreover, many states within the US have passed or are developing legislation to limit CO₂ emissions that features sequestration in forests and agricultural soils (Murphy 2003). Participating countries under the Kyoto Protocol can receive credit for activities that increase carbon absorption such as planting forests, although how these credits will be assessed is still vague (Schiermeier 2002).

Carbon trading is being established under the auspices of the Kyoto Protocol in countries that have ratified the treaty. Among participating countries, large scale

reforestation projects are underway financed by the sale of carbon emission credits (e.g., Evolution Markets 2002). Driven partly by the expectation of some future, government-imposed emissions-reduction program, a number of large American corporations have banded together to make voluntary reductions in greenhouse gas emissions and trade carbon credits (Patrick 2003).

Despite all the interest and activity, there is no commonly accepted or scientifically verifiable way to measure carbon sequestration. Without such procedures, deciding how to calculate emissions and credits is problematical. Procedural uncertainties exist with the accounting and verification methods (e.g., Rypdal and Baritz 2002). Ecological uncertainties surround factors that limit ecosystem uptake and storage of carbon, particularly nutrient availability and elevated levels of atmospheric CO₂ (Pelley 2003, Scholes and Noble 2001).

Multiple stress effects

In conjunction with rising temperatures, the carbon dioxide concentration in the Earth's atmosphere is expected to double sometime during the second half of the 21st century (IPCC 2001a). Understanding the response of ecosystems to elevated atmospheric CO₂ is central to assessing the effects of global climate change on ecosystems as well as determining the capability of the biosphere to sequester anthropogenic carbon. Ecologists have been studying the effects of temperature and precipitation—the primary drivers of productivity—on ecosystems for many years. Atmospheric carbon dioxide while essential to ecosystem functioning has been viewed as a relative constant. The prospect of increasing levels of atmospheric CO₂ presents a new paradigm for ecologists trying to predict effects.

Elevated levels of CO₂ may increase primary productivity and water use efficiency in plants resulting in increased growth and carbon sequestration—the fertilization effect (Ceulemans and Mousseau 1994). Based on such experiments, it is commonly assumed that agriculture and forestry will benefit from future climate changes. Experimental studies have shown that elevated CO₂ increased plant height, stem diameter, leaf area index, and fine root biomass of *Pinus ponderosa* (Johnson *et al.* 1998, Tingey *et al.* 1996b) and increased *P. ponderosa* growth (Pushnik *et al.* 1995, Surano *et al.* 1986). Early results from a free air CO₂ enrichment (FACE) system in a young North Carolina forest show increased NPP during the first two years of exposure, however, this may be attributed to the young age of the trees, and may decline as the forest ages (DeLucia *et al.* 1999). Reviewing a number of studies, Morison and Lawlor (1999) and Norby *et al.* (1999) concluded that although elevated CO₂ increases the carbon assimilation rate, it does not mean that growth will be increased because of possible limiting factors in natural ecosystems.

In response to the uncertainties surrounding the fertilization effect of elevated levels of atmospheric CO₂ and the interacting effects of other stresses, NHEERL scientists conducted a series of experiments on intact and reconstructed natural

ecosystems to study the interactive effects of climate change, elevated CO₂, tropospheric ozone, and soil conditions on important tree species and ecosystems. A state-of-the-art, environmental exposure facility that controls and manipulates key climatic and edaphic factors was constructed at NHEERL's Western Ecology Division (Tingey *et al.* 1996a). Located in Corvallis, Oregon, this facility was used to study the interacting effects of atmospheric CO₂, tropospheric ozone, temperature, and soil moisture on forest ecosystem processes. Field exposure chambers in the Sierra Nevada Mountains near Placerville, California, were used to examine the effects of elevated CO₂ and soil nitrogen on the Ponderosa pine forests (Johnson *et al.* 2000). A Department of Energy FACE facility in the Mojave Desert on the Nevada Test Site allowed scientists to study the direct effects of elevated CO₂ on intact natural ecosystems (Phillips *et al.* 2002). Finally, a series of field sites were established in the western Cascade Mountains of Oregon to compare experimental research with actual field conditions and to provide a basis for modeling studies (McKane *et al.* 1997b).

Ecosystems respond to elevated atmospheric CO₂ and temperature in complex ways involving interactions between plants, soil processes, and the atmosphere. A fertilization response is uncertain, particularly in natural ecosystems. Research by NHEERL scientists (Johnson *et al.* 2000, Olszyk *et al.* 1998, Tingey *et al.* 1996b, 1997, Rygielwicz *et al.* 1997) suggests that the response to CO₂ can be limited by soil fertility—primarily nitrogen availability. Experiments in the NHEERL environmental exposure facility used a low nitrogen soil, but if the plants that were exposed to elevated levels of CO₂ were grown in a high nitrogen soil or otherwise fertilized, the results may have been different. A sufficient supply of nitrogen could increase growth until CO₂, water, or another resource became the primary limiting factor. This new level of plant productivity would be maintained to the extent that nitrogen supplies could be maintained.

Modeling studies support this pattern and further suggest that the commonly observed increase, and subsequent re-acclimation, of plant growth to elevated CO₂ is a consequence of nutrient limitation (e.g., Comins and McMurtrie 1993, McKane *et al.* 1997a). Applying the General Ecosystem Model (Rastetter *et al.* 1991) to various sites in the western Cascade Mountains of the Pacific Northwest led NHEERL scientists to suggest that soil nitrogen is a primary constraint on the ability of those forests to sequester carbon (McKane *et al.* 1997a). For a nitrogen-poor site, model results indicated that total ecosystem carbon storage will increase by less than 10% during the next 100 years in response to projected increases in atmospheric CO₂ and temperature. In contrast, carbon storage at a nitrogen-rich site was calculated to increase by over 25% during the same period.

Field studies in a variety of ecosystems also support the nutrient limitation concept. Orem *et al.* (2001) reported that mature pines grown on soil with poor fertility did not respond to elevated CO₂. In grassland ecosystems soil nitrogen availability appears to limit the capacity of plants to absorb expected increases in atmospheric CO₂. Recently published research on grasslands suggests that

there appears to be thresholds of atmospheric CO₂ above which ecosystems no longer respond (Gill *et al.* 2002). Moreover, increased concentrations of atmospheric CO₂ can actually reduce net primary productivity in nutrient-limited ecosystems (Shaw *et al.* 2002), hence the potential for biosphere sequestration of atmospheric CO₂ may be limited.

The response of desert ecosystems to elevated CO₂ is limited by water. NHEERL's collaborative research with the Desert Research Institute in the Mojave Desert showed a measurable CO₂ response only when adequate soil moisture was available (Smith *et al.* 2000). With adequate water, elevated CO₂ increased photosynthetic rates, water use efficiency, and above ground biomass of vegetation. However, root production and turnover were not affected (Phillips *et al.* 2002). Because water is the most limiting resource in this desert ecosystem, elevated atmospheric CO₂ increased production by increasing water use efficiency, but only when adequate water was available.

The fate of carbon in ecosystems that show no biomass increases to elevated levels of atmospheric CO₂ remains an enigma. In long term chamber experiments at NHEERL's Western Ecology Division, elevated levels of atmospheric CO₂ increased photosynthetic rates (Lewis *et al.* 1999, 2001), but tree biomass was not affected (Olszyk *et al.* 2003). The additional carbon assimilated by plants exposed to elevated CO₂ was allocated to the below ground biota. But the movement of carbon into long term storage as soil organic matter could not be detected as gross changes in total soil carbon. Similar findings were reported for a loblolly pine forest exposed to elevated CO₂ (Schlesinger and Lichter 2001). If plants are photosynthesizing more with increased concentrations of atmospheric CO₂, then where is this carbon going? Increases, if any, found in above ground or below ground carbon pools are too small to explain where the additionally-fixed carbon is being allocated—although accelerated rates of carbon cycling by increased respiration has been suggested by NHEERL scientists and their collaborators (Lin *et al.* 1999). It appears that biologically-mediated processes belowground that transform and acquire nutrients may ultimately determine how an ecosystem will respond to CO₂ fertilization.

Further analyses using stable isotope techniques detected a small increase in soil organic matter over several years (Lin *et al.* 2001). Although these results are preliminary, increased allocation of carbon to soil organic matter under elevated levels of atmospheric CO₂ could result in a substantial amount of sequestered carbon over decades to centuries, but it is uncertain if this will be a long term or transient process. The processing of atmospheric carbon through plants and soil biota to long term storage as soil organic matter, and how elevated temperature and CO₂ associated with global climate change affects this process remains a major scientific uncertainty.

How ecosystems respond to elevated temperatures and increased levels of atmospheric CO₂ is becoming clearer. It is safe to say that the fertilization effect

of CO₂ is not universal. In fact, it may be rare among unmanaged ecosystems. Forests, grasslands, and deserts can be expected to respond differently to climate change. Limiting resources seem to play an important, but uncertain role in this response. Perhaps the most challenging aspect of predicting how specific ecosystems respond to climate change is deciphering how multiple, interacting stress factors— temperature, moisture, elevated CO₂, air pollution, and nutrients—combine to affect ecosystem structure and functioning.

In addition to increased temperature and CO₂, ecosystems will be exposed to increased air pollution resulting from warmer climates and increases in human population. The primary cause of air pollution damage to vegetation is tropospheric ozone (O₃). Damaging O₃ concentrations currently occur over 29% of the world's temperate and sub-polar forests but are predicted to affect fully 60% by 2100 (Fowler *et al.* 1999). In multiple stress experiments, elevated levels of tropospheric ozone tend to cancel the stimulatory effect of CO₂ on plant growth (U of Wisconsin 2002, Felzer *et al.* 2002, Percy *et al.* 2002). Research in NHEERL's sunlit, controlled environment chambers suggests that increased levels of CO₂ may moderate the detrimental effects of O₃ on primary production (Olszyk *et al.* 2001). In conjunction with the NHEERL chamber research, Tingey *et al.* (2001) used a process-based whole-tree growth model to study the interactions of CO₂, temperature, and O₃. They found that increasing CO₂ can reduce, but not eliminate the O₃ impact. However, elevated O₃ also reduced the stimulant effect of CO₂ on plant growth and would be expected to limit carbon sequestration. Moreover, the interacting effects of O₃ and CO₂ on below-ground processes are poorly understood, but those processes are critical in determining the responses of ecosystems to those stresses (Andersen 2003).

With global climate change, ecosystems will be subjected to a changing milieu of stresses. Elevated CO₂, higher temperatures and changes in precipitation patterns combined with the effects of increased air pollution—nitrogen deposition and increased levels of tropospheric O₃—will produce a range of effects on natural and managed ecosystems. Ollinger *et al.* (2002) indicate that O₃ may counteract the increases in productivity afforded by elevated CO₂ and nitrogen deposition in the northeastern US resulting in little or no altered growth over the long term. Indirect effects and natural ecosystem processes can also limit the ability of plants to sequester CO₂. Changing climatic patterns can alter net ecosystem productivity (Knapp *et al.* 2002). The ability of forests to sequester carbon decreases as they age (Finzi *et al.* 2002, Schimel *et al.* 2001). The interacting effects of CO₂ and air pollution can alter the susceptibility of plants to pest damage and diseases (Percy *et al.* 2002). Ultimately, separating climate change effects from land management and invasive species effects on ecosystems is an obstacle to developing adaptation and mitigation plans.

Global change research has led us to appreciate the ramifications of multiple stresses acting in concert, and helped us realize that controlling single pollutants is not likely to achieve the desired results. While the NHEERL research provided

insights on the interaction between, climate, CO₂, and air pollution, the effects of multiple stresses simultaneously interacting on ecosystems are still major uncertainty. Comprehensive assessments of climate change effects on ecosystems need to consider multiple stresses, and projects intended to mitigate or adapt to climate change should factor in multiple stress effects.

Coral reef ecosystems

Coral reef ecosystems throughout the world are deteriorating at an accelerating rate. This decline is attributed to multiple stress factors, which include global changes in atmospheric gases and land use patterns. In the Florida Keys, coral health is deteriorating at unprecedented levels. The focus of current NHEERL research is to evaluate coral reef condition, to assess potential consequences of this decline, and to guide management options.

Bleaching and disease prevalence in the Lower Keys was particularly high in 1998 relative to other years (1998-2002), and was higher than comparison sites in the Dry Tortugas. A pilot project, comparing only five sites in the Lower Keys with five sites in the Dry Tortugas, demonstrated a greater percentage of dead coral in the Lower Keys area. Continued surveys of coral populations in the Florida Keys will provide information on the species, reefs and regions that are most at risk, as well as management recommendations.

Controlled laboratory experiments have established temperature and UV thresholds for important coral species and algal symbionts. Results of early research suggest that different coral species exhibit different bleaching responses with exposure to UV radiation. Temperature experiments have confirmed the adverse effects above 31°C for coral symbionts. Also, the interactive effects of high temperature with elevated UV-B have been quantified. Future research will determine differences in sensitivity among the various groups (clades) of algal symbionts to temperature and UV radiation, and will evaluate changes in sensitivity from short (acute) to long (chronic) exposures.

Biomarkers are being developed to aid in determining the physiological mechanisms underlying the bleaching process, and to determine coral susceptibility to bleaching. Once the mechanisms are understood, stressor-response patterns for different coral species and algal clades can then be used interactively with field studies to identify which stressors are most affecting the various species, reefs and regions of the Florida Keys.

Better tools for environmental assessments

NHEERL's climate change research program has evolved to meet changing policy needs. Along with ongoing research, the results of past research, both published and forthcoming, will continue to support critical policy decisions, but future assessments may need different analytical tools. The dynamic interactions

between humans and ecosystems require study because climate change interacts with other forms of human-induced change including land use change, air and water pollution, and invasive species. Assessments conducted at the sub-regional and watershed levels can inform the implementation of adaptation and mitigation strategies by state and local governments.

After more than a decade of assessing the impacts of global climate change in one manner or another, the basic conclusions and uncertainties about potential ecological effects remain much the same. We continue to refine our predictions, but the models and databases needed to make assessments for manageable parcels of land are still lacking. To some extent this is a result of the relatively coarse resolution of global climate models from which future patterns of temperature and precipitation are derived. But from an ecological perspective we still lack the ability to resolve ecosystem responses to multiple stresses at an ecologically reasonable scale.

To date, the USGCRP National Assessment has considered effects at national and regional levels. Comprehensive assessments of the effects of CO₂ and temperature changes on ecosystems at a “management” level are needed to plan mitigation projects and guide land use decisions. Planners in both the public and private sector will need information at the level of forest stands or watersheds in order to fully assess effects or to implement adaptation actions. Carbon sequestration projects will need to be designed at the scale of local land holders, not regions.

Should CO₂ controls become mandatory, managing natural ecosystems to maximize carbon sequestration will require a detailed knowledge of past, present and future land use, and how those practices affect carbon sources and sinks. Major questions remain about carbon uptake, translocation, and storage above and below ground. Social, political, and economic influences on land use and resource management, and how these forces affect the carbon storage must be resolved. Ultimately, the data and assessment tools to evaluate actions at the scale of projects—watersheds, forest plots, and specific crops—will be required.

To address these needs, assessment tools to evaluate land management options in conjunction with pollution and climate effects at the scale of forest stands, or sub-watersheds, will be critical. Ecosystem process models working at the watershed scale will be needed to assess climate change effects on both terrestrial and aquatic ecosystems. Continued development of spatially distributed ecosystem models capable of accounting for the interacting effects of elevated CO₂, climate change, pollution, and land use along with the supporting data bases is clearly warranted.

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