USDA Forest Service
Global Change Research Program Highlights: 1991-95

Edited by

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PACIFIC GLOBAL CHANGE PROGRAM HIGHLIGHTS

Introduction

The Pacific Global Change Research Program (PacGCRP) has identified four high-priority ecosystems for its research: the boreal forest, the moist temperate conifer, the Mediterranean (chaparral) and the dry temperate forest (ponderosa pine) types. PacGCRP research emphasizes better understanding and management of the interactions between climate change, air chemistry, and ecosystem processes and productivity in these ecosystems. The focus is on integrating process and small-scale response research with watershed and landscape-level studies. Long-term, sustained environmental monitoring will utilize a "Pacific mega-transect" of linked monitoring and research sites extending from Alaska to California and from coastal to alpine sites. Modeling will be integral to the program in guiding specific research tasks, predicting ecosystem responses to climate changes, and improving the predictive capability of General Circulation Models.

Atmosphere/biosphere Gas and Energy Exchange

General Circulation Models need to be Localized for the Pacific Region

General circulation models (GCMs) are the basis for climate change predictions, but they operate at the 300- to 500-km spatial scale using a limited number of climate features. Ecosystems and the policy decisions for managing ecosystems operate on much smaller scales, and vegetation management involves micro-climatic effects of particular importance to plants, animals, and belowground processes. To accurately drive models that predict climate impacts on wildlands, the additional parameters not previously considered in GCMs are necessary, such as humidity, surface winds, and lightning. This information is crucial when considering the effects of fire on future forests and wildlife habitat. Another critical aspect of climate scenarios is a measure of the uncertainty of the predictions, and expressing it in ways that are meaningful to policymakers.

A fire and environmental research applications team has been examining climate scenarios around the world to take into account these additional parameters. The team has developed special methods to (1) localize climate-change predictions, (2) model surface winds and humidity that control the rate of moisture and energy exchange between plants and the atmosphere (Fig. 30), and (3) link spatial and temporal lightning strike patterns with general circulation flow regimes for better understanding of fire ignition potential in a changing climate.

The Climate of Mexico City as a Future Model for Southern California

The climate of southern California is characterized by mild winters and summer drought. During the dry period, high concentrations of tropospheric O_3 develop. In winter, the climate of the Mexico City area permits O_3 concentrations to be higher than they are in Southern California. Ozone in the Mexico City region might be higher in summer; however, tropical storms and associated cloudiness limit O_3 formation from precursor air pollutants even though pollutants and incident solar radiation remain high (Fig. 31). With global warming, southern California summer and winter temperatures are expected to increase. In effect the O_3 "season" may be extended earlier in the spring and later in the fall. Thus, studying the interaction of climate, O_3, and forests in Mexico and southern California may allow managers to predict the future damage to forests in a warming climate.

Climate, O_3 and tree injury data have been gathered in forest stands near Los Angeles and Mexico City (Miller et al. 1992). A persistent drought in southern California during the 1985-89 period limited stomatal uptake of O_3 and tree injury. The return of adequate moisture levels increased O_3 uptake and tree injury. The continuation of the mesic climate and high emission levels of pollutants in the Mexico City region contributed to a more constant level of tree injury.

Burning the Tropical Forests—How Much C is Added to the Atmosphere?

Wildland and agricultural fires may be contributing to climate change, varying in the extent and strength of their emissions. Best estimates show that biomass combustion is an important global source of atmospheric aerosols and trace gases that affect the earth's radiation balance.

We have participated in an international Working Group on Fire and Environmental Change in Tropical Ecosystems to assess the continental-scale impacts of fire and fire emissions on climate, human health, and ecosystems. The group has characterized fire emissions and developed statistical models of the emission rates of CH_4 and hydrocarbons. They have shown that the processes underlying combustion are the same in Brazilian savanna and forests as they are in the United States. Thus, the results are applicable to fire management on our forests and rangeland. Because of the high frequency of fires in Brazil, results were obtained at a fraction of the cost and time required to make the same measurements in the United States.

Ecosystem Dynamics

Increased Soil Temperature and Elevated Atmospheric CO_2 Affect C Balance in a Simple, "Model" Boreal Ecosystem

The boreal forest biome contains approximately 13 percent of all terrestrial organic C, and much of this is belowground. Conifers exposed to elevated atmospheric CO_2 allocate more C to roots which results in greater soil C as roots die. Changes in canopy structure in CO_2-enriched environments also have

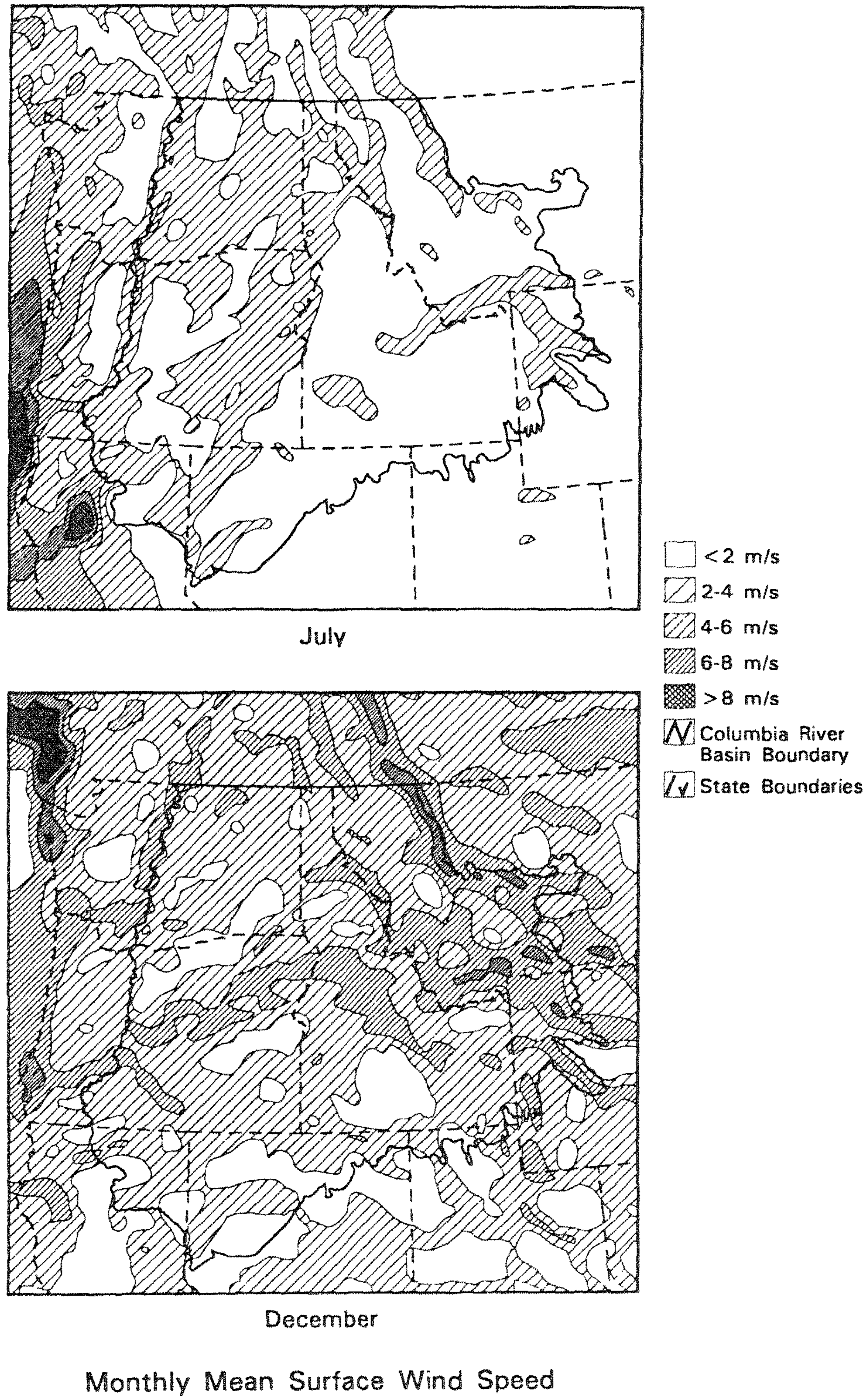

Figure 30.—Monthly mean surface wind speed for the Pacific Northwest region (Ferguson, personal communication).

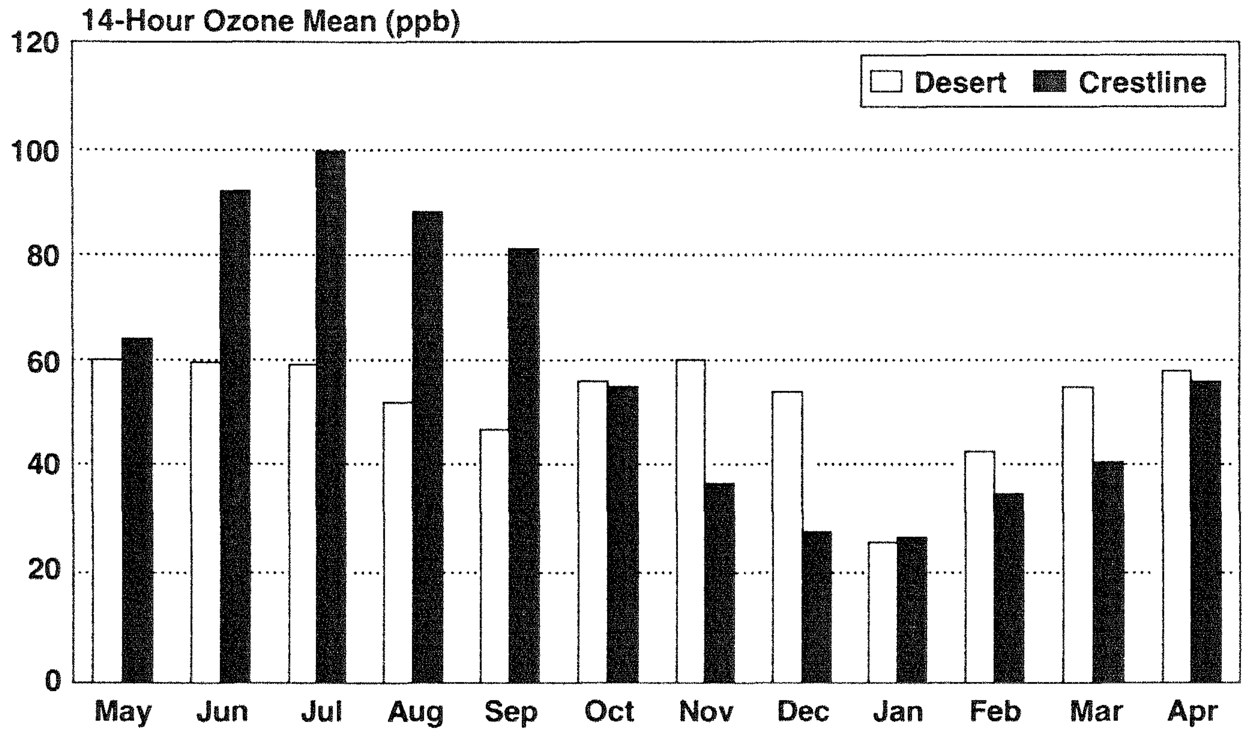

Figure 31.—Ozone levels are lower in summer at Mexico City because of cloudiness and rain, but during the dry winter O_3 can remain as high as summer values; the summer dry climate of Los Angeles and warmer temperatures contribute to high O_3 levels (Miller et al. 1992).

been found. In the boreal forest, presence or maintenance of permafrost is significantly affected by canopy cover, landscape albedo, and surface energy budgets. Increased soil temperature increases both root and microbial activity. Increased atmospheric CO_2 availability in the future will thus affect soil C balance in a complex web of interactions. Prediction of the changes in boreal forests due to increased atmospheric CO_2 and accompanying global warming will allow progressive management of an enormous soil C reservoir.

We are conducting an experiment on a model ecosystem by exposing plants to ambient CO_2, double ambient CO_2 levels, +4°C soil temperatures, and both elevated CO_2 and soil temperature. This experiment was designed to quantify C and nutrient allocation within the plant and soil at 1-year intervals over 3 years. Preliminary data indicate that white spruce seedlings grown in CO_2-rich air assimilated CO_2 more quickly in the first month, but that in the following months this rate slowed. In the second growing season, spruce in the CO_2-rich air had faster assimilation rates but acclimated within 2 weeks. At the end of the first year of exposure to CO_2-enrichment, seedlings increased in stem diameter (4 percent) and height (9 percent), and produced 35 percent more buds. Soil C was detectably enriched in the first year of exposure.

Permafrost of Alaska—C Sink or Source?

Global warming is expected to be observed first, and with devastating effects, at high latitudes. The boreal forest biome is underlain by permafrost rich in C that was trapped over the last 8,000 years during a cooler period. Global warming threatens to melt the permafrost and release this stored C into the atmosphere. Increased C released into the atmosphere will further exacerbate global warming.

To improve our understanding of the functioning of permafrost zones, we are gathering data critical to a model that will predict the effect of permafrost loss on ecosystem water and C balance (Irons et al. 1992). Dissolved organic C constitutes 90 to 95 percent of the total stream-borne C (particulates constitute 5 to 10 percent), and total stream-transported C is high in the boreal forest relative to temperate environments. Dissolved organic C in stream water is proportional to the percentage of the watershed underlain by permafrost. Increased melting of permafrost due to global warming will directly release CO_2 to the atmosphere and increase C lost through runoff. The role of microbes in using stream-dissolved organic C is currently being investigated.

Excess N in Vegetated Watersheds—How Plants Respond

Northern temperate forests have long been considered to be N-limited. However, there is a growing concern that chronic N deposition near urban areas can lead to the contrasting condition of excess N, with undesirable effects on water quality. A N-saturated forest is one that no longer exhibits a positive growth response nor retains additional inputs of N.

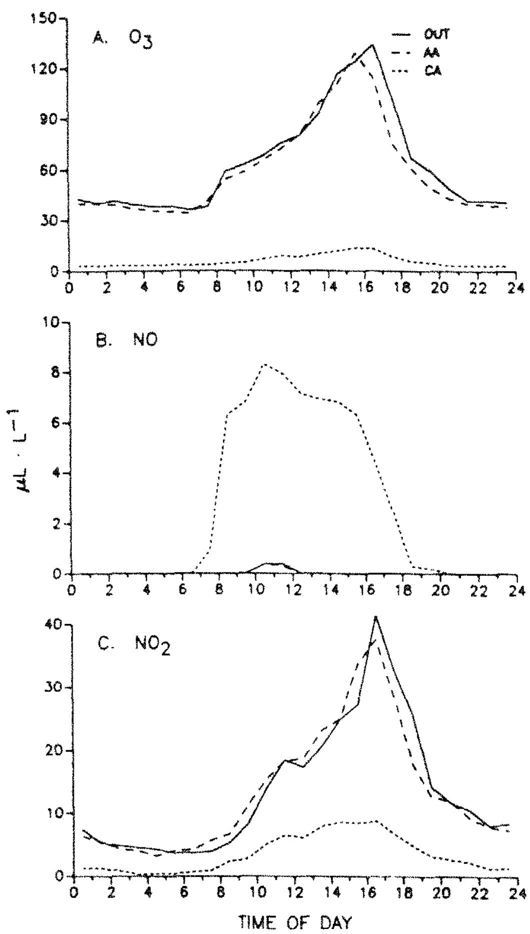

Figure 32.—Concentrations of air pollutants for different exposure regimes expressed as hourly means for 30 September 1987 through 11 October 1987 period (Bytnerowicz et al. 1990). "Out", outside chamberless plots; "AA", ambient air open-top chambers; "CA", clean air open top chambers.

Nitrogen-saturated forests have a persistent loss of N either as NO_3^- in solution into groundwater, or as NO_x release from the soil surface, further exacerbating global atmosphere concentration of this trace gas.

Nitrogen saturation in western forests can occur from natural sources such as N-fixation by red alder or by weathering from ammonia-rich rock. However, excess N deposition to ecosystems in the dry form (mainly NO_2, NH_3 and particulate NO_3^- and NH_4^+), and NO_3^- and NH_4^+ in precipitation in the southern California air basin and the western slope of the southern Sierra Nevada ecosystems, are of concern. A team of scientists has been investigating atmospheric deposition in western forests by attempting to quantify the amount and rates of exogenous N deposition in the mixed-conifer zone of Central and Southern California (Fig. 32). Fires in N-saturated coniferous and chaparral ecosystems induce high pulses of NO_3^- in streamwater. We anticipate problems in the next 20 to 50 years in Pacific forests near the Seattle-Tacoma area in Washington, and near Portland, Oregon.

Predicting Changes in the Distribution of Ecosystems

More than half of the world's major biomes will be converted to a different biome (e.g., temperate grassland to temperate deciduous woodland) in response to a doubling of CO_2, according to the evaluation of climate change scenarios by leading biogeography simulation models. Anticipating where these changes will occur, and the rate of conversion (whether gradual succession or rapid deforestation as results from fire or other catastrophic disturbance) are key questions for policymakers. The volume, area, and location of forest types are of particular interest to both the forest products industry and conservation leaders. Predicting these changes will prove invaluable in managing the transition to new forest types.

A model of location, volume and area of forest types under the climate that might be produced under a doubling of CO_2 concentration has been developed by Neilson and others (1995). The Mapped Atmosphere-Plant-Soil System (MAPSS) is a biogeography model that calculates the potential natural vegetation that can be supported under a steady state climate (Fig. 33). The model also provides an essential link to other models that predict changes in regional forest products and economics. The MAPSS model is useful in scales from landscape to global.

Human Activities and Natural Resource Interactions

How Important is Climate Change?

The importance of climate change and its effects on ecosystems can only be defined in terms of the human values that are affected. Our tolerance for change, the rate of change society will accept, and the characteristics of ecosystems most important to protect are not well understood. Answers to these questions will guide future Forest Service research and development efforts to focus on the most important ecological changes.

We led a 3-day workshop entitled "Breaking the Mold: Global Change, Social Responsibility, and Natural Resource Policy" in May of 1994 that began to define the scope and purpose of the Forest Service Human Dimensions of Global Change Program (Geyer and Schindler 1994). It was organized jointly with Oregon State University, Consortium for Social Values and Natural Resources, and Battelle Pacific Northwest Laboratory. The workshop included national and international participation and was one of a series of regional and national workshops on the subject.

Problems and issues, research and management questions, and 29 recommendations were defined in each of four areas: governance, values and perceptions, local practices, and sustainability. For example, the Forest Service needs to work cooperatively with other agencies on a fully integrated global change agenda, focus on community-scale vulnerability to

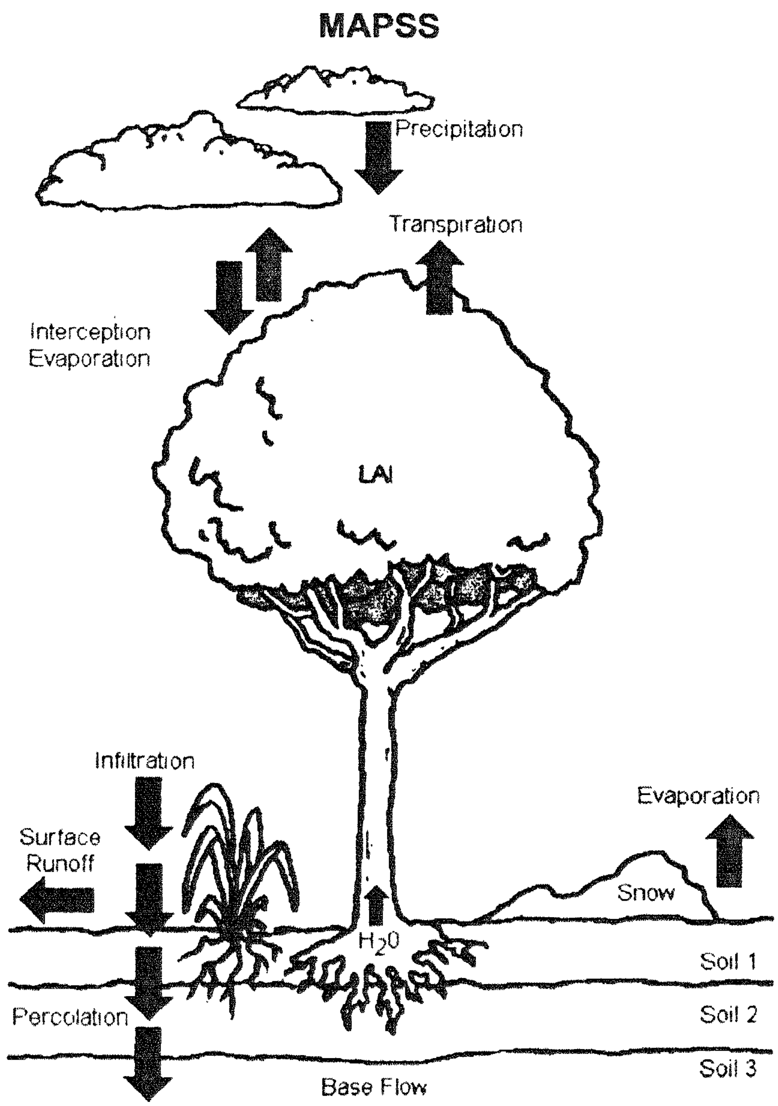

Figure 33.—Conceptual model of the water balance processes incorporated in MAPSS (Neilson 1995).

global changes, and link global change programs with ecosystem management planning and policy.

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FOREST PRODUCTS LABORATORY GLOBAL CHANGE PROGRAM HIGHLIGHTS

Introduction

The Forest Service's Forest Products Laboratory (FPL)—located in Madison, Wisconsin—conducts research aimed at enhancing the effective use of forest products and publishes its findings for government, industry, and the consumer. By developing techniques that increase the use and longevity of wood products, reducing negative environmental impacts associated with their production, improving energy conservation, and strengthening the forest products and construction industries, FPL contributes both to reducing the impact of global change and improving the economy. FPL's global change research program concentrates primarily on the Atmosphere/Biosphere Gas and Energy Exchange and Human Interactions elements of the national program.

Atmosphere/biosphere Gas and Energy Exchange

Fuel Alcohol from Wood

The goal of this research is to improve technology for producing alternative liquid fuels such as ethanol from renewable resources to replace fossil fuels and thereby reduce atmospheric CO_2 accumulation.

Xylose and arabinose are five-carbon sugars found in the hemicellulose of fast-growing hardwoods and other angiosperms. Xylose is the second-most abundant sugar found in terrestrial biomass, and its utilization is essential for the economic conversion of lignocellulose into ethanol. One way to more efficiently convert wood to ethanol is through fermentation, and we have applied for a patent on one transformation process to enhance use of xylose and arabinose fermentation as an adjunct to glucose fermentation. Only a few yeasts transform xylose and arabinose effectively. We are also continuing work on other yeast species. Mutant strains of some of our yeasts produce up to 55 percent more ethanol than the parent generation and exhibit higher fermentation rates (Amartey and Jeffries 1994).

Waste products such as grain hulls are potentially important to ethanol production. Grain hulls from corn wet milling are a major byproduct that has a limited market both here and abroad, but grain hulls consist largely of xylose and arabinose. These sugars can be recovered by acid hydrolysis, but their fermentation is very difficult. If we can solve the problem of xylose and arabinose fermentation, scientists in the grain processing industry estimate that the potential exists to produce almost 500 million gallons of ethanol annually from this byproduct. Scientists have identified *Pichia stipitis* and *Candida shehatae* as two of the best yeasts available for the fermentation of xylose (Amartey and Jeffries 1994). In a fed-batch fermentation, *C. shehatae* will produce up to 56 grams of ethanol per liter within 48 hours. This is one of the highest ethanol concentrations reported for xylose fermentation. Studies in other laboratories show that *P. stipitis* is an equally good fermenter, and is capable of producing even higher yields than *C. shehatae*.

Our research has shown that by selecting organisms for rapid growth on a number of slowly metabolized pentose sugars in the presence of respiratory inhibitors, we are able to increase ethanol production by 50 to 100 percent.

In addition to these traditional methods for strain improvement, our laboratory has developed a powerful genetic transformation system for *P. stipitis* (Jeffries et al. 1994). We have cloned one of the critical genes for nucleic acid biosynthesis, URA3, along with an autonomous replication sequence (ARS) that enables the URA3 gene to be maintained as an extrachromosomal element. We have also obtained a number of URA3 deficient recipient strains that can be transformed by the *P. stipitis* URA3 ARS-based vectors. By combining strain selection for improved fermentative mutants with genetic engineering to introduce and overexpress rate-limiting enzymes, we are able to increase ethanol production on these sugars (Fig. 34).

Reducing Volatile Organic Chemicals in Wood Finishes

To achieve the air standards required under the New Clean Air Act, widespread changes in the paint industry will be necessary. Many paint and stain manufacturers will have to change formulations to meet the required decreases in VOC content in wood finishes. These new formulations need to be evaluated.

We improved technology to permit decreased levels of volatile organic compounds (VOC's) in finishes for wood (Williams 1995). During the last 3 years, all studies initiated within our Wood Surface Chemistry and Preservation Research Work Unit have included VOC compliant finishes.

The studies have included but are not limited to the following:
—Cooperative study on low VOC finishes on decks constructed with western wood species.
—Effects of surface roughness on finish performance.
—Effects of back-priming on finish performance.
—Interaction of finishes, fasteners and substrate on a test house.
—Comparison of VOC compliant coatings with non-compliant coatings.
—Evaluation of moisture movement through coatings.

Forest Products Laboratory scientists participated in the Regulation-Negotiation Committee convened by EPA who is writing a regulation to control the emissions of VOC's from architectural and industrial finishes under provisions of the new Clean Air Act.

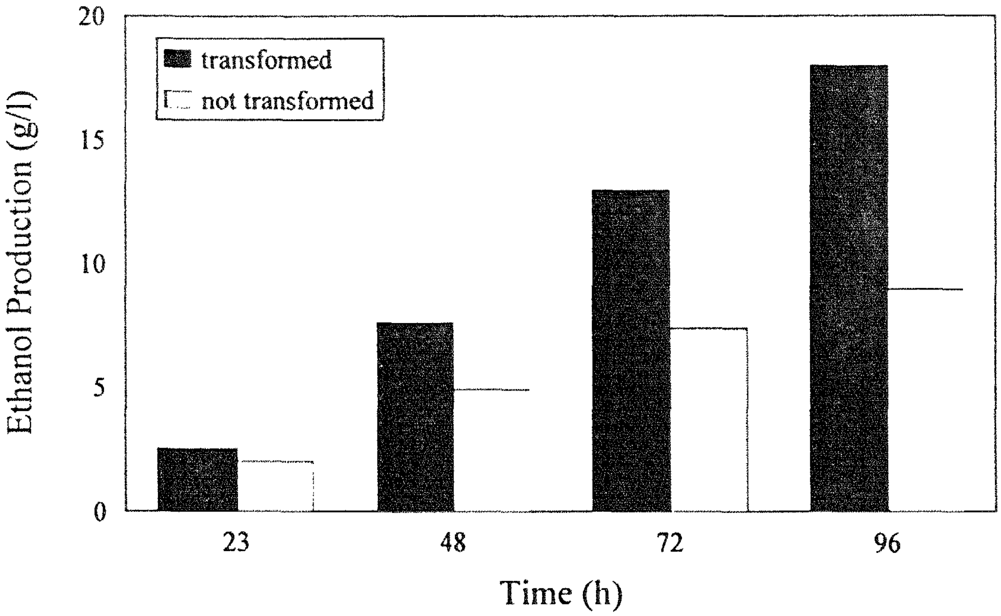

Figure 34.—Genetic transformation of yeast *Pichia stipitis* increases ethanol production from xylose (Amartey 1994).

Recycled Material for Light-frame Construction

Research on the recovery of low-quality unsorted fiber from wastepaper and wood—major components of municipal solid waste—is another way of conserving resources, energy, and fossil fuel use.

An alternative use for recovered fibers is FPL Spaceboard, a value-added product (Gaumnitz 1994). Performance of Spaceboard panels for use in light-frame construction was evaluated. Tests of panels and materials in the wet- and dry-formed products resulted in a range of ratios from 2.0 to 3.5:1 (ratios of stiffness, tensile strength, and compression strength based on wet- vs dry-forming). Puncture load tests indicated the panels were capable of meeting industry-acccepted performance standards for single-layer flooring. These test results will provide incentive for the structural panel industry to adopt molded fiber (Spaceboard) technology as a means for utilizing recycled paper fiber from mixed waste streams.

Fuelwood Issues: Increasing Recycling, Reducing Emissions, and Improving Efficiency

An engineering economic analysis on producing fuel from used pallets compared the capital and operating costs of four methods of pallet breakdown. The analysis included six sizes of facilities ranging from 900 to more than 100,000 tons per year[1]. The study included an existing pallet repair facility and a new breakdown-only facility. Capital and operating costs also were developed for burning this fuel at six different new wood-burning facilities and two retrofitted coal/wood-burning facilities.

Research on combustion of manufactured products such as particleboards and wood/plastic boards is funded by the Center for Clean Industrial and Treatment Technologies. The study measures the emissions of CO, aldehydes, organic C, polynuclear aromatic hydrocarbons, sodium, and potassium from a laboratory scale combustor (Baker 1991). The high and low molecular weight hydrocarbon emissions can be correlated with the emission of CO. These studies indicate minimum acceptable combustion conditions of various products.

We also developed a pressurized down-draft combustor for use with a gas turbine (Baker et al. 1991). Direct burning of wood in a turbine is among the most efficient ways to generate electricity.

Another study for the National Science Foundation analyzed the effect of reducing conditions on ash composition at various temperatures (Mahendra et al. 1992)

Human Activities and Natural Resource Interactions

The FPL has studied mitigation measures to combat adverse effects of global change. Studies focused on conserving energy, reducing volatile organic compound content in wood finishes, using biomass fuel as an alternative to fossil fuels, and sequestering C in wood products (Zerbe 1993).

[1]MLSE & Associates. 1993. Report on engineering and economic analysis on processing used wood pallets, etc. to fuel. Final Report. FPL Contract No. 53-5680-3-440. Lockport, Illinois: M.L. Smith Environmental, Inc.

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GREENHOUSE GASES, CLIMATE, AND THE GLOBAL CARBON CYCLE

Richard A. Birdsey[1]

GREENHOUSE GASES, AEROSOLS, AND CLIMATE CHANGE

Some gases in the atmosphere absorb heat radiated from the earth and cause a warming or greenhouse effect. Besides water vapor, the most radiatively-active gases are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and the clorofluorocarbons (CFCs). Table 1 lists some important greenhouse gases, their global warming potential (relative to CO_2), and their relative effect on warming.

Table 1.—Greenhouse gases and relative contribution to global warming over 100 years.

Gas	Global warming potential (relative to CO_2)	Relative contribution to "greenhouse effect" (%)	Rate of concentration change during 1980's (%/yr)
Carbon dioxide	1	61	+ 0.4
Methane	21	15	+ 0.8
Nitrous oxide	270	4	+ 0.25
CFCs	3500-7300	11	+ 4
Other gases	...	9	...

Sources: Houghton et al. 1990; 1995.

The atmospheric concentration of most of the greenhouse gases is rising. The Intergovernmental Panel on Climate Change (IPCC) projects increases in atmospheric concentrations of most of the greenhouse gases because of continuing increases in emissions (Houghton et al. 1996). Exceptions are CFCs and halocarbons, whose emissions are declining. Widespread concern about reductions in stratospheric ozone has led to international efforts to phase out their production.

Recent global assessments give more weight to the role of aerosols in climate. Aerosols tend to cool the climate because the small particles absorb and reflect radiation, and change cloud properties. Aerosols enter the atmosphere from volcanoes and from industrial emissions of sulfates. The combined effects of greenhouse gases and aerosols are integrated into projections of probable warming by the IPCC in the most recent global assessment (Houghton et al. 1996). Over the next 100 years, the average global temperature is expected to increase from 1°C to 3.5°C, a significant reduction below previous estimates that ranged from 1.5°C to 4.5°C (Houghton et al. 1995).

Changes in atmospheric gas concentrations and consequent climate changes could have a significant impact on forests. Solar radiation, temperature, precipitation, humidity, and atmospheric CO_2 are among the most important factors affecting ecosystem processes. Because CO_2 has strong direct and indirect effects on forests, and because forest processes affect the global carbon cycle, the buildup of CO_2 is of great interest for forest policy and forest management. Forests of the globe, including forest soils, store approximately 987 Pg C[2], and on balance are emitting an estimated 0.9 Pg C/yr to the atmosphere (Brown et al. 1996). Although the evidence is incomplete, it is estimated that emissions from deforestation (about 1.65 Pg C/yr) are partially offset by additions to C storage in regrowing temperate forests.

Methane (CH_4) is another natural greenhouse gas whose concentration in the atmosphere is increasing (Houghton et al.1995). Methane emissions from natural sources (including northern forested wetlands) comprise about 30 percent of all methane emissions. Methane emissions from wetlands are very sensitive to changes in temperature or precipitation, indicating the potential for significant positive or negative feedbacks with the climate system.

THE GLOBAL CARBON CYCLE

The atmosphere, ocean, and land contain major reservoirs of C exchanged through regular cycles of varying length. On a daily basis during the growing season, land and ocean plants take up C through photosynthesis during the day, and release C through respiration both day and night. Daily and weather-related fluctuations are evident in measurements of atmospheric CO_2 taken at a tower in a forest canopy (Fig. 1). On a yearly cycle, the average global concentration of atmospheric CO_2 is lower in the North during the summer months because plants on the large land area of the Northern Hemisphere take up more C through photosynthesis than they respire, producing a net gain of C in biomass. Respiration in the North continues during the winter, while photosynthesis nearly stops, producing a net release of CO_2 from the land to the atmosphere. The yearly cycle is evident in measurements of atmospheric CO_2 from Mauna Loa, Hawaii (Fig. 2). Interannual variation is due to processes such as the well known El Nino/Southern Oscillation events (Francey et al. 1995), and may occasionally involve spectacular global events such as the recent eruption of Mt. Pinatubo.

[1]USDA Forest Service, Northeastern Forest Experiment Station, Radnor, PA 19087.

[2]One petagram (Pg) = 10^{15} grams = one gigaton (Gt) = one billion metric tons

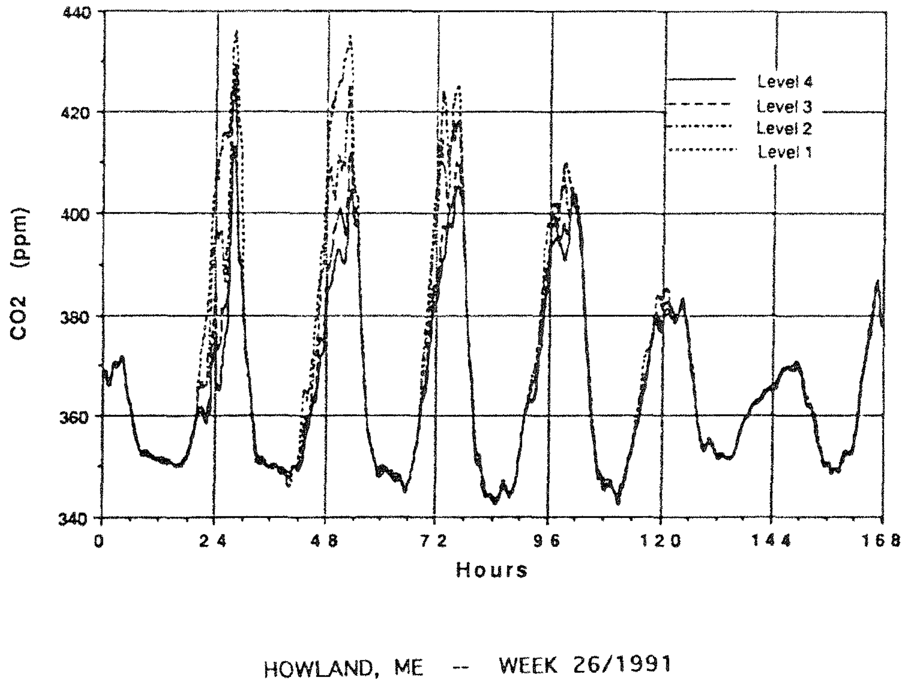

Figure 1.—A week of CO_2 profile data taken at four levels in and above the forest canopy at Howland, Maine. During this summer week the weather changed from sunny and moderately windy to cloudy with higher nighttime winds (Goltz 1993).

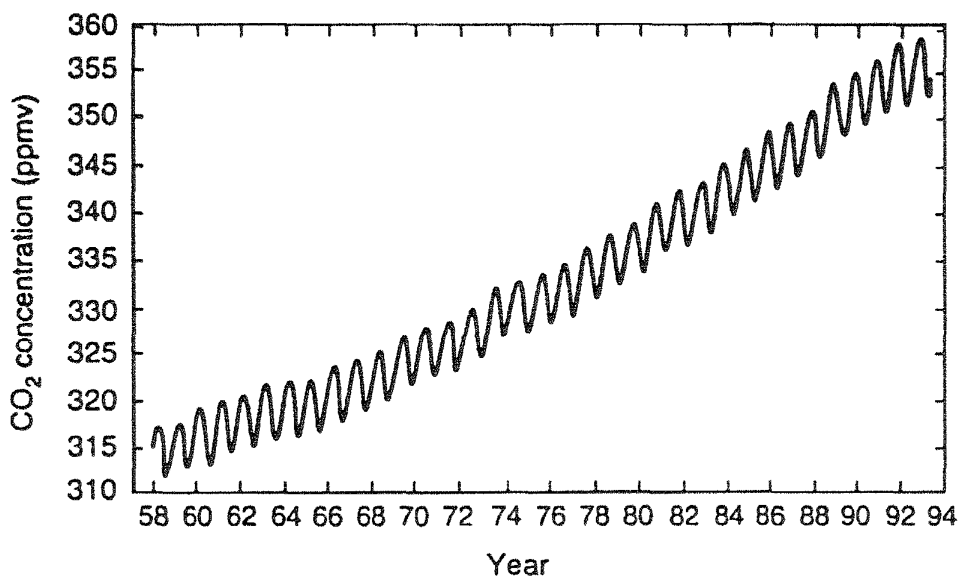

Figure 2.—CO_2 concentrations measured at Mauna Loa, Hawaii since 1958 showing trends and seasonal cycle (Houghton et al. 1995).

The atmospheric record shows that CO_2 has been increasing for the last 40 years, and when the contemporary record is supplemented by measurements of CO_2 in air bubbles trapped in ice cores, the combined record shows a continual increase for several hundred years (Fig. 3). Part of the increase is due to long-term natural cycles of radiation and temperature that influence other earth processes such as glaciation. According to the most recent Intergovernmental Panel on Climate Change consensus report (Houghton et al. 1996), human activity (primarily land use change and fossil fuel use) is causing some of the recent observed increase in atmospheric CO_2. Projections based largely on expected economic activity and demographic changes show atmospheric CO_2 increasing at a rate that could double pre-industrial levels during the next 100 years.

Despite systematic measurements of atmospheric CO_2, and terrestrial and ocean reservoirs, the exact size of the various reservoirs and the fluxes between reservoirs are only partially known. Schimel (1995) summarized the current state of knowledge of the global C cycle, with particular reference to the role of terrestrial ecosystems (Fig. 4). Fluxes

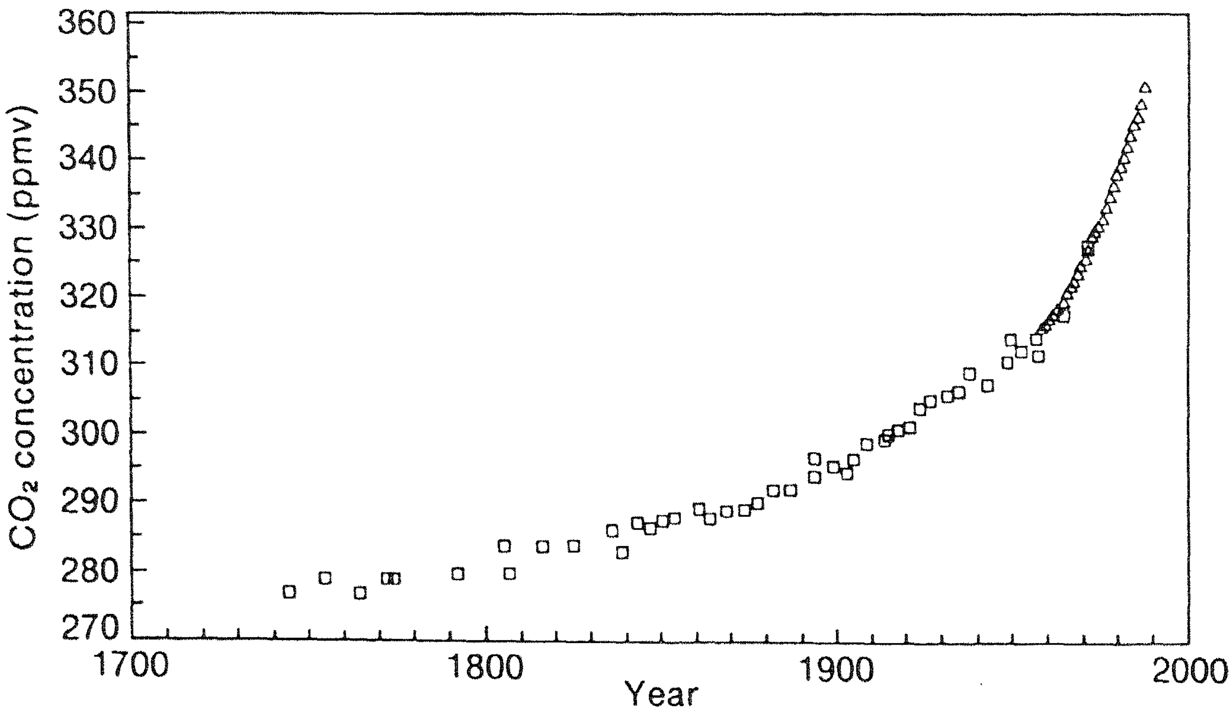

Figure 3.—Atmospheric CO_2 increase in the past 250 years, as measured from air trapped in ice (squares) and by direct atmospheric measurements (triangles) (Houghton et al. 1990).

among the four major reservoirs—fossil C, the atmosphere, the oceans, and the terrestrial biosphere—should be in balance, but our best estimates produce an imbalance or "missing sink" of approximately 1.4 Pg C/yr. Evidence from atmospheric measurements suggests that the missing sink is located in the Northern Hemisphere (Ciais et al. 1995). It is thought that inaccurate accounting for additions to C storage in regrowing forests, CO_2 fertilization of plant growth, and Nitrogen (N) deposition may all be contributing to the imbalance (Schimel 1995).

The evidence supporting the hypothesis that regrowing forests are a large C sink comes from three sources: periodic forest inventories, direct flux measurements above forest canopies, and measurements of the atmospheric concentrations of isotopes of C and oxygen.

Periodic inventories of timber volume in Europe and the U.S., when converted to estimates of C, show increasing C storage in forest ecosystems over the last 40 years (Birdsey 1993; Kauppi et al.1992). These inventories are based on statistical sampling designs that provide representative data for large geographic areas. There is considerable uncertainty in estimating the non-timber components of ecosystem C (C in soils, litter, coarse woody debris, understory vegetation) that comprise the bulk of the total C (about 85 percent) in the ecosystem. Estimates from successive inventories can be compared to estimate average CO_2 flux over long periods.

Direct measurements of CO_2 flux at towers in the forest canopy are more precise over short periods and when meteorological conditions are favorable. However, the few active measurement sites represent only limited areas of the landscape, and also have limited capability to specify the allocation of C to specific ecosystem components (e.g. Wofsy et al. 1993). A much larger network of sites is required to make statistical estimates for large regions of the globe.

Measurements of the concentrations of C isotopes at a global nework of sites can quantify the net removal of CO_2 from the atmosphere by the oceans and terrestrial plants (Ciais et al. 1995). Analysis of this data shows strong evidence of a northern temperate C sink in 1992 and 1993.

CO_2 fertilization effects are thought to be significant because the many experiments conducted with individual plant species show typical increases in photosynthesis and growth of about 20 to 40 percent or more with doubling of CO_2 (Bazzaz et al. 1990). However, most studies have been short-term and involved immature plants in isolation from other ecosystem factors that may limit the plant response to increased CO_2. The effect of plant acclimation as well as the effects at the whole ecosystem level can only be inferred from incomplete evidence. It is thought that nutrient and water limitations reduce the magnitude of the CO_2 fertilization effect, but the interactions of C, N, and water are complex and can only be partially understood at the ecosystem level by using models. Only a few ecosystem-level experiments have been initiated and these studies tended to involve short-stature, non-tree vegetation. Direct observations of natural ecosystems cannot attribute responses to specific causes even if the measurement

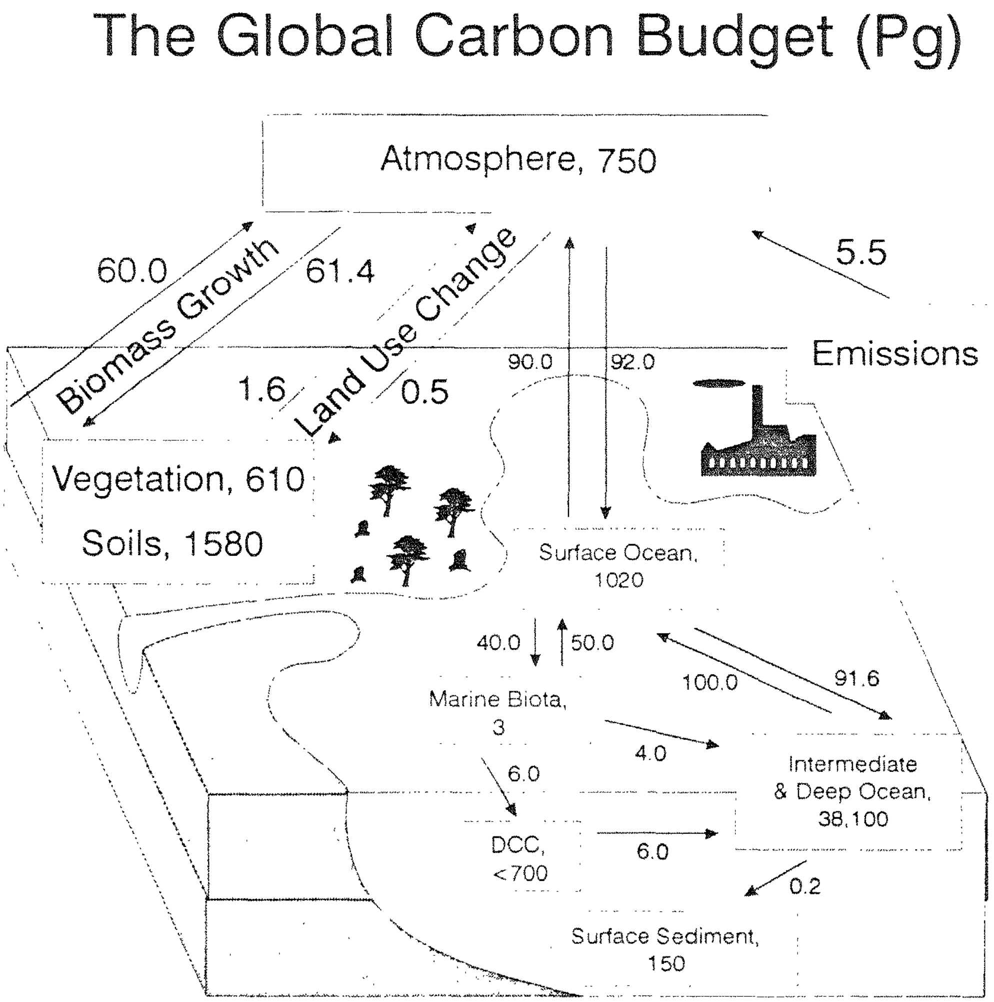

Figure 4.—The global carbon budget (Pg) (Schimel 1995).

difficulties could be overcome (e.g., measurement of root growth changes or changes in foliar biomass), because ecosystem responses integrate many different factors such as light, moisture, temperature, successional status, and nutrient availability, as well as a complex of atmospheric influences such as ozone and CO_2.

Nitrogen deposition is thought to increase C storage because most ecosystems respond positively to added N (Schindler and Bailey 1993). However, as with the C cycle, there are limited measurements available as well as a lack of understanding of some key processes that make the model estimates unreliable. There is also increasing evidence that some ecosystems can become saturated with N. Excess N may reduce growth and cause losses of N to water systems (Aber et al. 1989).

If northern forests are sequestering more C than expected, there remains a significant question about where that C is located. Harrison and Broecker (1993) calculated that a 1.1 Pg C/yr increase in the inventory of C should be found in the following pools: 0.5 Pg C in the soil; 0.1 Pg C in litter, and 0.5 Pg C in vegetation. However there is great uncertainty in these estimates, and refinement would offer managers and policy makers better choices in their attempts to mitigate atmospheric increases in CO_2.

CONCLUSIONS

Reducing the uncertainty about feedbacks between the biosphere and the atmosphere is essential to improving our simulations of future atmospheric CO_2 and potential greenhouse warming. This knowledge also helps us understand and anticipate the effects on forest ecosystems so that managers may know how their actions could help mitigate the causes of warming, and how they could adapt to expected changes in the physical and chemical environment.

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CLIMATE SCENARIOS

Sue Ferguson[1]

A climate scenario is a description of a possible condition. Usually scenarios are based on assumptions about the future and may be limited in scientific knowledge and certainty. Because there is no assigned probability of occurrence, scenarios are not forecasts. Most available climate scenarios are at relatively coarse spatial and temporal scales (several hundred kilometers and monthly to seasonal), which are above the resolution of typical hydro-ecological processes. Table 1 summarizes the climate inputs required by models supported in the Forest Service Global Change Research Program. Note that modeling hydro-ecological processes usually requires less than 100 km spatial scales and monthly or less temporal scales.

Assessing the impact of global change on ecosystem dynamics in the United States has required the specialized development of techniques to down-scale output from global and regional climate models. The following sections describe methods for generating baseline scenarios, from which the degree of possible future change can be determined, and possible future scenarios. Although methods to down-scale scenarios are becoming increasingly sophisticated, adequately representing climate variables that control disturbance (e.g., flood, fire, drought, insect infestation, blow-down, etc.) is difficult. Also, influences of complex topography and surface roughness (variable vegetation and water surfaces), which are common in wildland areas of North America, are poorly handled in many down-scaling methodologies. Some of the special methods that have been developed to incorporate climate scenarios into assessments of hydro-ecological responses are described.

BASELINE CLIMATE

To help understand the magnitude and rate of change in a possible future condition, baseline conditions usually are described from a database of historical information. If instrument data are used, empirical methods are required to spatially or temporally interpolate between observation sites and times, or to estimate climate variables that were not directly measured. Available global data sets range from 1/2° to 5° latitude-longitude resolution (e.g., Trenberth and Olson 1988a, 1988b; Shea 1986; Legates and Willmott 1990a and 1990b; Leemans and Cramer 1991; Hurrell and Campbell 1992; Warren and others 1986). Within the contiguous United States domain, the Historical Climatology Network (HCN) data provide high quality, long-period records (most greater than 70 years) of monthly mean, maximum, and minimum temperature, and monthly total precipitation. A subset of these stations have available daily data. Most HCN sites were established at early centers of population, preferentially located in river valleys or other low elevation sites. Observations are unevenly spaced (not in a grid-point format) about 1° latitude-longitude in the eastern United States and about 2° latitude-longitude in the western United States (Hughes and others 1992). The HCN data are a subset of the National Weather Service Cooperative Observer network (NOAA 1988), which offers the highest spatial resolution of daily data throughout the nation. The highest temporal resolution historical data that are most easily available are in the National Solar Radiation Data Base (NSRDB) developed by the National Renewable Energy Laboratory (1992) with 30 years (1961-1990) of hourly data from National Weather Service primary stations. Observed and derived values of temperature, wind, radiation, snow depth, cloud cover, dew point, precipitation, and relative humidity are included. Climatological winds were derived by Elliot and others (1987) at 1.4° latitude by 1.3° longitude spatial resolution and seasonal temporal resolution. Various regional data sets provide added spatial and temporal resolution.

Several methods have been applied to the instrument and proxy data to generate long-term means of historical records. For example, Daly and others (1994) developed a Precipitation-elevation Regressions on Independent Slopes Model (PRISM) to distribute precipitation observations. PRISM is a statistical-analytical model that uses point data and a digital elevation model (DEM) to generate gridded estimates of monthly precipitation. It is well suited to regions with mountainous terrain, because it incorporates a conceptual framework that addresses the spatial scale and pattern of orographic precipitation. A database of long-term monthly mean precipitation has been generated at 5 minute (about 10 km) grid-cell resolution for the contiguous United States (Daly and others 1994).

To generate a climate database at 1/2° latitude-longitude spatial resolution for the contiguous United States, Kittel and others (1995, 1996) used PRISM-generated monthly precipitation data and applied an adiabatic adjustment to spatially interpolate monthly temperature observations (Marks 1990). A stochastic weather generator, WGEN (Richardson 1981; Richardson and Wright 1984), was used to generate daily mean data from these monthly statistics. Daily vapor pressure deficit and solar radiation was then estimated from WGEN temperature and precipitation by applying CLIMSUM (Running and others 1987; Glassy and Running 1994).

Regional daily scenarios include those in the Northwest and Southeast United States. Running and Thornton (1996) generated 2.5-km grid-cell scenarios for 3 characteristic years in the Columbia River Basin. A cool, wet year (1982), warm, dry year (1988), and a normal year (1989) were chosen to take advantage of more numerous mountain observation data that became available in the late 1970's. They used elevation-regression techniques to distribute daily data from over 400 stations within the region. Cooter and others (In press) used the Richman-Lamb 1° historical database (Richman and Lamb 1985; Richman and Montroy

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Table 1.—Climate input variables required for hydro-ecological models. Results of a 1994 survey of Forest Service Global Change Research Program modelers.

Model	Resolution		Climate Input Variables
	Temporal	Spatial	
TEM	monthly	n/a	temperature
			precipitation
			cloudiness
MAPSS	monthly	10km to 1 deg. lat/lon	temperature
			precipitation
			vapor pressure
			windspeed
BIOMASS	daily	1 km to 1 deg. lat/lon	temperature
			precipitation
			cloudiness
PnET	monthly	1 km	temperature
			precipitation
			solar radiation
			vapor pressure
MAESTRO	hourly	n/a	temperature
			precipitation
			relative humidity
			windspeed
MHMS	daily	.5 km2 to 75 km2	temperature
			precipitation
			solar radiation
Tree Regeneration	weekly or monthly	1 km	windspeed
			potential evapo-transpiration
Gap-phase	monthly	1 km	temperature
			precipitation

1986), of proxy data and known physical and statistical relationships, to form a 45-year (1949-1993) daily baseline scenario for the southeastern United States, which includes maximum and minimum temperature, precipitation, net radiation, and vapor pressure deficit.

Monthly time step scenarios are more common than daily. For example, Neilson (1993), Neilson and Marks (1994), and Monserud and others (1993) used various forms of the IIASA climate database (Leemans and Cramer 1991) for their global baseline scenarios at 1/2° latitude-longitude grid resolution. Ollinger and others (1993, 1995) used multiple-regression techniques to spatially distribute observations from 164 stations in the northeastern United States. A database of long-term (1951-1980) monthly mean precipitation, humidity, radiation, and minimum and maximum temperatures was generated at 30" (about 0.8 km) latitude-longitude spatial resolution.

Unfortunately, data sets built on monthly means do not easily represent extreme events that cause ecological disturbances (e.g., flood, fire, drought, insect infestation, blow-down, etc.). Neilson (1995) compensated for this deficiency by assuming that summer precipitation occurs during similar atmospheric instability that causes lightning in the central United States. Therefore, he turned on and off a fire rule depending upon summer precipitation occurrence. The coarse resolution of wind climatology (Elliott and others 1987), however, prevents application to other ecological disturbances like blow-down, fire spread, and pollution trajectories.

CLIMATE CHANGE SCENARIOS

Output from general circulation models (GCMs) are the most commonly available climate change scenarios. These models have been used to test the atmosphere's sensitivity to increasing greenhouse gases. Quasi-steady state, or equilibrium, model runs typically have a dynamic atmosphere with simple approximations for hydrosphere, biosphere, and cryosphere. Currently available transient model runs couple dynamic atmosphere general circulation models (AGCMs) with dynamic ocean general circulation models (OGCMs).

These often are referred to as coupled (ocean-atmosphere) general circulation models (CGCMs). Recently, special emphasis has been directed toward improving dynamic sea-ice modeling (e.g., Lynch and others 1995; Wehner and others 1995) and dynamic vegetation modeling (e.g., Chase and others 1996; Neilson and Running 1996).

Equilibrium GCM experiments most commonly simulate the response of general circulation patterns to doubling the amount of current atmospheric concentrations of carbon dioxide (2 x CO_2), or its greenhouse gas equivalent. There are baseline (1 x CO_2) and 2 x CO_2 scenarios available from each model. USDA Forest Service researchers commonly use model output data that have been generated by modeling groups at: Oregon State University (OSU, Schlesinger and Zhao 1989), Geophysical Fluid Dynamics Laboratory (GFDL, Gordon and Stern 1982), United Kingdom Meteorological Office (UKMO, Slingo 1985), Goddard Institute for Space Sciences (GISS, Hansen and others 1983), and Canadian Climate Center (GCMII, Boer and others 1992; McFarlane and others 1992). Model output from the Max Planck Institute (MPI) also is available (ECHAM, Rockner and others 1992). The International Society of Biometeorology recently established a study group to evaluate scenarios of possible global warming and made available several climate scenarios from MPI's ECHAM GCM, including one high resolution (about 100 km by 100 km) 2 x CO_2 scenario (Auliciems and von Storch 1994).

Because of the global scale of these GCMs, grid resolutions are from 4° latitude by 5° longitude to 8° latitude by 10° longitude. The temporal resolution of most available output data are monthly to seasonal. The models reasonably simulate large-scale flow patterns that are controlled by continentality, or the contrast between land and sea (IPCC 1990, 1992). Down-scaling techniques are required to determine local and regional climate responses to increasing greenhouse gases from global model output (Giorgi and Mearns 1991).

Mesoscale or regional climate models can be nested within GCMs to obtain higher spatial resolutions and evaluate regional responses to changes in global circulation. Currently, output from only one nested model is available for the contiguous United States. It was developed by Giorgi and others (1993a, 1993b, 1994) at the National Center for Atmospheric Research (NCAR). The model, RegCM, nests the NCAR and Pennsylvania State University mesoscale model, MM4 (Anthes and others 1987), with the NCAR Community Climate Model, CCM (Thompson and Pollard 1995a and 1995b). The spatial resolution of RegCM output is 60 km x 60 km. Two continuous 3.5-year-long climate simulations over the continental United States are available, one for present-day conditions and one for conditions under double CO_2 concentration (Giorgi and others 1994). Output from RegCM shows reasonable representation of topographically controlled climate in the Pacific Northwest (Giorgi and others 1993a; Giorgi and others 1994). For this reason it was used to help generate a climate change scenario for the Columbia River Basin Assessment and Eastside Ecosystem Management Project (Ferguson, in press).

McCorcle and others (1993) used the Mesoscale Atmospheric Simulation System, MASS (Zack and Caplan 1987; Cram and others 1991) with GFDL's 1xCO_2 and 2xCO_2 output to demonstrate the importance of mesoscale climate features in the eastern United States. In particular, mesoscale soil-moisture and lake-land variations significantly affected temperatures, cloud cover, and precipitation in the midwestern United States. Work now is underway to develop MASS-GFDL generated data at 25-km x 25-km spatial resolution in the eastern United States for characteristic climate years (e.g., 1988 Great Plains drought and 1993 Midwest flooding)[2].

Equilibrium model runs have limited application for assessing disturbance because the models do not adequately simulate daily through decadal patterns of variability (Mearns and Rosenzweig 1994; Campell and others 1995). Also, extreme values typically are not reported. The physical models do calculate instability, humidity, incoming radiation, and winds, however, that are missing from most observation data. Therefore, if appropriate output formats can be acquired, they may provide useful tools for generating some types of climate disturbance scenarios.

Time-series scenarios can be generated by using output from CGCMs or by selecting a function (e.g., linear or exponential) of change from current to 2 x CO_2 using equilibrium GCM output. Model output from transient (time series) CGCMs are becoming more available. Descriptions and comparisons of output from the NCAR (Washington and Meehl 1989), MPI (Cubasch and others 1992), GFDL (Stouffer and others 1989), and UKMO (Cullen 1993) coupled ocean-atmosphere runs also are available (IPCC 1992; World Climate Research Programme 1992; Kattenberg and others, in press). Most commonly, simulations of the dynamic response of oceans and atmospheres assume 1% per year increases in CO_2 concentration, or its greenhouse gas equivalent. Available output includes monthly values for periods averaging around baseline (current) and the time of 2 x CO_2 (about 70 years from baseline).

The spatial resolution of the atmospheric component in CGCMs is similar to GCMs (from 4° latitude by 5° longitude to 8° latitude by 10° longitude). A high resolution (60km by 60km), 10-year (1979-1988) baseline simulation of monthly mean and daily time-series values from RegCM is available (Giorgi and others 1993a) for the contiguous United States. Bowles and others (1994) are working to extend this baseline scenario to 15 years for the western States.

LINKAGE

Available process-modeled climate scenarios exist at large spatial scales, short time periods, or small domains. Therefore, empirically generated scenarios most commonly are used to represent current (baseline) climate for hydro-ecological applications. The baseline climate scenarios are

[2]Personal communication. 1996. Warren Heilman. North Central Forest Experiment Station, 1407 South Harrison Road, Room 220, East Lansing, MI 48823.

then linked to process-modeled change scenarios. One way of creating this linkage is to apply the change calculated between model control runs and model 2 x CO_2 runs onto the empirical baseline scenarios (Neilson 1993; Monserud and others 1993; Kittel and others in press; Cooter 1996; Cooter and others, in press; Running and Thornton 1996). This method preserves spatial variability that is inherent in the baseline scenarios.

Most often equilibrium change scenarios are applied to a baseline of long-period means (20 to 50 years). Output from several GCMs are used in order to illustrate a range of possible change. Running and Thornton (1996) applied a "best guess" regional change scenario (Ferguson 1997) to a "normal" year (1989) baseline for the Columbia River Basin; a limited, but effective way of illustrating spatial variability in daily climate patterns.

Scenarios based on surprise alternatives or historical analogues are scarce. The "MINK" study used a "dustbowl" scenario for the central United States based upon 1930-1939 observations of temperature and precipitation (Crosson and Rosenberg 1993). Some researchers select an unusual year of observation data and then hold that year's weather constant for 10 to 20 years to simulate surprise scenarios.

Linking empirical and process-modeled scenarios with time series is more difficult but still desirable to preserve the spatial and temporal variability best represented by observations. Efforts to model the transient response of vegetation to climate change have been hampered by the lack of high temporal resolution climate scenarios (Mearns and Rosenzweig 1994). Recent efforts have begun to generate long-period, high temporal resolution, transient scenarios for the contiguous United States at 1/2° spatial resolution by VEMAP and for the state of Oregon at 2.5' resolution (Ferguson and others, in preparation)[3]. The effect of changes in climate variability at daily to decadal scales is an important uncertainty. Therefore, the scenarios generated by these projects will be of great value for future global change assessments.

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MULTIPLE STRESS STUDIES ON FOREST TREE SPECIES

John Hom[1]

Plants are subjected to environmental factors that reduce their potential for growth, including limitations of water, light, and nutrients. Plants, especially long-lived trees, must endure simultaneous and sequential environmental stresses to survive and maximize productivity. Forest ecosystems currently face a new suite of stresses in the chemical and physical environment that are increasing at unprecedented rates: ozone, atmospheric deposition, and elevated carbon dioxide. These anthropogenic stresses impose new conflicting demands on plant resources as they modify natural environments, and result in conditions that the plant has not adapted to and may exceed its genetic ability for compensation.

Adaptation to stress is an integrated, whole plant process. Biochemical and physical adjustments, occurring over different time scales, compensate for environmental changes. However, most physiological studies on plant stress usually focus on a single process over a short period of time. The results are extrapolated to predict losses in long-term yield. This approach can be equivocal as it does not consider interactive effects with other stresses or long term adaptation to stress.

Our program emphasizes physiological research on the effects of multiple, interactive stresses of major air pollutants, greenhouse gases, and environmental stresses, individually and in combination, on the growth and carbon allocation of important timber tree species.

CO_2, WATER, AND NUTRIENTS

Elevated CO_2 has been shown to increase photosynthesis and growth in plants, increase water use and transpirational efficiency, and decrease dark respiration. Thus, elevated CO_2 is normally not considered a stressor. However, some plants under high CO_2 may initially increase their photosynthetic rate but readjust to ambient conditions after a short acclimation period. Limited nutrient resources may reduce net photosynthesis under elevated CO_2.

Forest productivity in the South is limited by water stress and soil nutrient status. Field studies on the effects of elevated CO_2 with water and nitrogen fertilization showed that net photosynthesis for loblolly pine increased 32 to 91 percent compared with ambient controls in branch chamber studies (Fig. 1). Fertilization produced a 20 to 24 percent increase in net photosynthesis in elevated and ambient CO_2 treatments, while irrigation increased net photosynthesis 5 percent in both CO_2 treatments (Dougherty and Allen 1994; Murthy et al. 1995; Allen et al. 1995). Elevated CO_2 may increase the growth potential of these southern pine forests on sites not limited by nutrients and water.

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Elevated CO_2 was found to compensate for water stress in red oak in environmental chamber studies (Tomlinson and Anderson, 1995). Water stress decreased biomass, leaf area, leaf number, height, and stem diameter, while elevated CO_2 increased these growth parameters. Water stress also reduced chlorophyll content and increased the nitrogen concentration in seedlings. With elevated CO_2, photosynthetic rates and chlorophyll content appears to plateau between 530 and 700 ppm. The combined effects of elevated CO_2 and water stress showed that CO_2 may offset the effects of water stress on growth and biomass production.

CO_2 AND TEMPERATURE

The Southern region is predicted to increase in temperature under global change scenarios. Temperature stress is a limiting factor in the productivity and regeneration of southern forests. A study of the effects of CO_2 and elevated temperature on carbon fixation of mature field-grown loblolly pine (Teskey 1995; Liu and Teskey 1995) indicated that long-term exposure to elevated CO_2 in branch chamber increased net photosynthesis 40 to 100 percent, increased leaf area 33 percent, and decreased dark respiration 10 percent when compared with foliage exposed to ambient CO_2. There was no downward acclimation in photosynthesis in the long term response to elevated CO_2. Increasing the air temperature by +2 °C had a slightly negative effect on photosynthesis, which is minor compared with the large CO_2 effect.

The direct effects of elevated CO_2 may change the cold hardiness of some economically important tree species and consequently change tree productivity and distribution. Seedlings of three conifers were cold-hardened in growth rooms under ambient levels of CO_2 (350 ppm) or 2X ambient levels (700 ppm). High CO_2 had little effect on cold hardiness of radiata pine, but increased the fall and spring hardiness of Douglas-fir. High CO_2 increased hardiness of ponderosa pine in autumn and decreased it in the spring. This preliminary study suggests that Douglas-fir is well adapted at its present upper elevational limit and may increase its distribution to higher elevations with elevated CO_2 and a warmer climate (Tinus et al. 1995).

OZONE AND WATER STRESS

Ozone is a potent phytotoxin that causes significant growth reduction and damage to sensitive tree species. Ozone accelerates foliar senescence, decreases leaf area and growth, and generally lowers the photosynthetic capacity and carbon accumulation through damage to the photosynthetic machinery. Generally, plants with higher rates of photosynthesis are more susceptible to ozone damage (Reich 1987), as ozone damage is cumulative. Water stress and low stomatal conductance will decrease plant growth and the interaction of water stress and ozone may decrease ozone injury by reducing the cumulative uptake of ozone through the stomates.

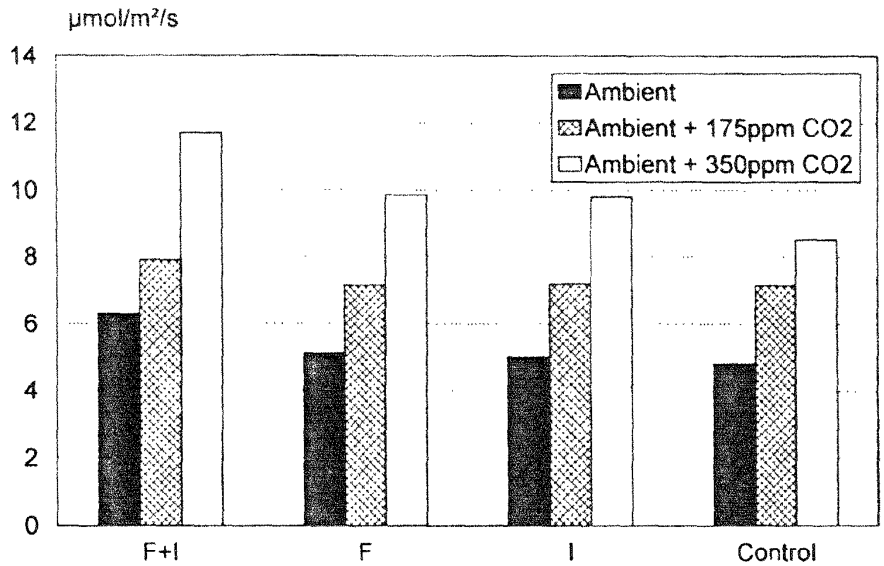

Figure 1.—Maximum photosynthetic rates of loblolly pine under elevated CO_2, irrigation (I), and fertilization (F), Dougherty and Allen, 1994.

Peak ozone concentrations as well as water stress occurs during the summer months in southern California. A long, persistent drought during 1985 to 1989 reduced the uptake of ozone and limited tree injury. A return to adequate precipitation increased plant gas exchange, resulting in greater ozone uptake and tree injury (Miller et al. 1994).

Water stress is recognized as the most limiting factor to growth in southern forests. However, significant ozone damage occurred in shortleaf pine in open-top exposure chambers (Flagler et al. 1993) even at severe water deficit conditions, resulting in accelerated senescence of foliage and decreased biomass, chlorophyll and nitrogen content, photosynthesis and stomatal conductance. Ozone has been implicated as the causal agent for a 5 percent reduction in the annual growth of southern commercial pines (Teskey 1995b). This annual, compounding loss in productivity is expected to increase under scenarios of increased drought and regional ozone exposure. The interaction of ozone and drought stresses under existing ambient conditions may cause greater growth reduction than either stress alone (McLaughlin and Downing, 1995a). This analysis is currently being debated (see Reams, et. al., 1995, McLaughlin and Downing, 1995b)

CO_2 AND OZONE

Elevated levels of atmospheric carbon dioxide are generally thought to ameliorate the detrimental effects of ozone. The higher concentration gradient of CO_2 from leaf interior to exterior would decrease stomatal aperture, yet maintain equivalent photosynthetic rates while limiting ozone uptake into the leaf interior. Increased carbon assimilation and reserves would support additional carbon requirements to repair ozone damage to membranes and biochemical constituents in the leaf.

Long term exposure of yellow-poplar to ozone and elevated carbon dioxide showed compensatory growth (Rebbeck 1993, 1994, 1995; Fig. 2) when the plants were exposed to two times ambient levels of O_3 and 700 ppm CO_2 (2X+CO_2). However, eastern white pine initially showed no response or a small decrease in stem height with increasing O_3, with the largest growth reductions in trees grown at 2X+CO_2. White pine photosynthetic rates for 2X+CO_2 increased substantially in the second year of treatment, but greater whole tree growth was not observed. The interaction of ozone and CO_2 in pines showed less compensatory response to elevated CO_2 than yellow-poplar, demonstrating that it is difficult to generalize or predict a species response to ozone, alone and in combination with elevated CO_2.

Clones of trembling aspen, grown in open-top chambers, responded very differently to elevated ozone, alone or in combination with CO_2 after two years of exposure (Kull et al. 1996; Coleman et al. 1995, 1996). Physiological and biomass measures for ozone-sensitive clones of trembling aspen showed a significant negative response to O_3. The negative impact of O_3 was not compensated by the simultaneous addition of 150 ppm CO_2 above ambient levels, resulting in significant negative interaction of O_3 and CO_2 on photosynthesis, biomass, stomatal conductance, chlorophyll content, leaf abscission, and leaf area (Fig. 3). These experiments show that different plant species and even clonal varieties within a species may respond differently to greenhouse gases individually and in combination. These are exceptions to the generalization that elevated CO_2 will compensate for ozone stress, emphasizing the importance of multiple stress studies on different species. For some clonal species such as aspen, land managers may wish to select for resistant stock.

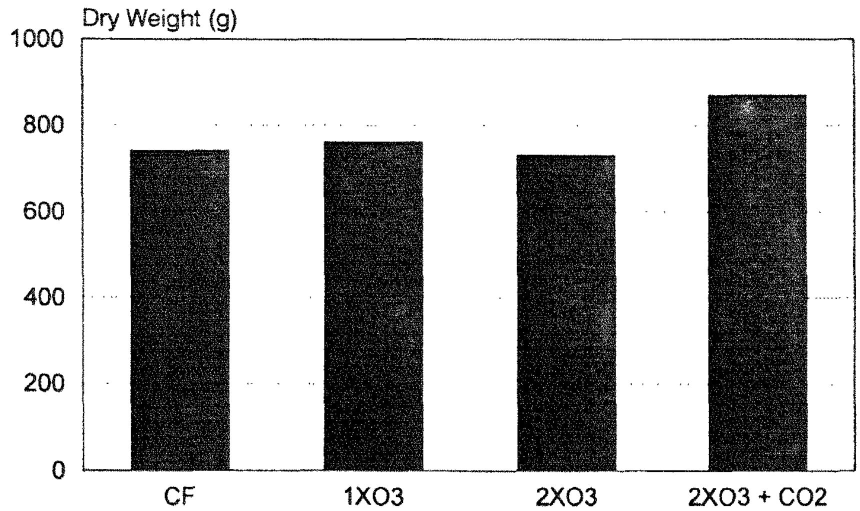

Figure 2.—Total biomass of yellow-poplar grown under charcoal filtered (CF), ozone and elevated CO_2 treatments (from Rebbeck, 1995).

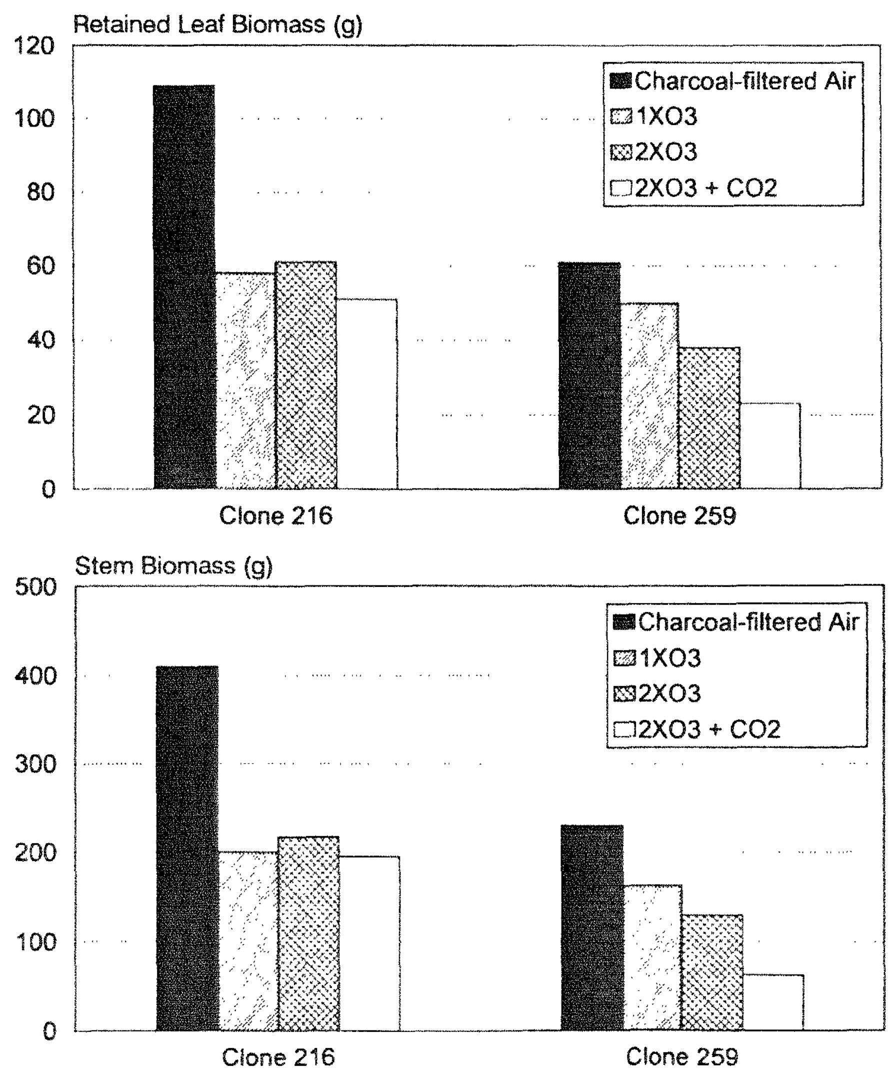

Figure 3.—Response of ozone tolerant (216) and ozone sensitive (259) aspen clones to elevated CO_2 and ozone treatments, (D. Karnosky, personal communicatons).

CLIMATIC AND POLLUTION GRADIENT STUDIES

Controlled experiments utilize step increases in treatment dosage above ambient levels (2XCO_2, 2XO_3) to emphasize the treatment effect while controlling confounding factors. However, this does not address how environmental stresses influence ecosystem processes, nor does it address realistic rates of increase for climatic factors and greenhouse gases (i.e., 0.4 percent per annum for CO_2). Studies along climate and pollution gradients address ecosystem processes but encounter difficulties with year to year climate variability and confounding factors such as geographic differences in climate, soils and plant compositions along the gradient.

Despite spatial and temporal variation, there is evidence that pollutant deposition has altered soil and vegetation processes in gradient studies. The Michigan Gradient was established to examine the effects of climate and atmospheric deposition on forest productivity and ecosystem processes. Leaching of calcium (Ca) and magnesium (Mg) from foliage and soil solution at sites receiving high levels of acidic deposition was a consequence of the pollution deposition. Higher foliar biomass in the southern sites may be a consequence of higher temperature and longer growing season, but is also consistent with the effects of chronic nitrogen (N) deposition in this region.

The San Bernardino Mountains in Southern California represent a west-to-east air pollution gradient for high-to-low ozone and nitrogen deposition from anthropogenic emissions (Riggan et al. 1985; Fenn and Bytnerowicz, 1993). The use of fossil fuels releases nitrogen pollutants, typically nitric oxide (NO). In the presence of photooxidants, ozone, and with sufficiently warm temperatures, the NO is rapidly oxidized to NO_2 and subsequently to nitric acid (HNO_3) vapor by gas phase reactions. Daily peak concentrations of nitric acid and ozone occur at the same time in the mountains of the South Coast Air Basin. Exposed plants may be predisposed to phytotoxic effects of other pollutants. However, forests may benefit from the fertilizer effect of nitrogen deposition to compensate for ozone damage with higher foliar N concentrations and carbon assimilation rates (Pell et al. 1994).

PRIMARY AND SECONDARY STRESSES

The timing and intensity of multiple stresses may determine how a tree responds to environmental change. An initial stress such as acidic deposition predisposes red spruce to freezing damage. Several studies have shown that acid mist, common in high elevation red spruce, lowers the cold tolerance of red spruce foliage by 3 to 5 °C, predisposing it to winter injury (Strimbeck et al. 1995).

The sequence of environmental stress, along with phenological stage of the plant, may allocate limited carbon resources to leaves, roots, plant secondary compounds, or antioxidants and lower the plant's resistance to secondary stresses. Hypothetically, a plant that may be tolerant to ozone may shift its carbon and nitrogen resources to antioxidants instead of secondary compounds, and therefore may be susceptible to insect vectors.

PRIMARY AND SECONDARY EFFECTS

Environmental stress directly affects plant productivity and survival, and secondarily affects ecosystem processes, which in turn affect forest health and productivity. For example, elevated CO_2 can increase the photosynthetic rate at a lower nitrogen content, increasing the photosynthetic efficiency per unit nitrogen, and reducing the respirational requirements to maintain photosynthetic enzymes. However, the lower nitrogen content will eventually change the quality of the leaf and litter. This feedback would increase C:N ratios in the soil, lower decomposition rates, and affect nutrient cycling. A greater proportion of carbon may be required for new roots to acquire limited nutrients, changing plant productivity.

A change in leaf quality was seen with insect herbivory studies on plants grown under CO_2 and ozone (Herms et al. 1995). Growth rates of insects decreased when fed leaf tissue grown under elevated CO_2, whereas ozone-fumigated foliage increased insect growth rate over ambient controls.

FUTURE RESEARCH

Without multiple stress studies, we cannot develop a comprehensive understanding of how plants respond to interactive stress. The results of multi-factor experiments show the difficulty in generalizing the response of complex ecosystems from single factor experiments on a limited number of species. The challenge is to design integrated studies, at larger scales, to address multiple stress interaction on forest ecosystem processes, such as the Free Air Carbon Dioxide Enrichment (FACE) studies at Duke University, and the large ecosystem-scale exposure facility under construction at the USDA Forest Service Laboratory at Rhinelander, WI. Stand-level process models parameterized for important forest species should be developed in parallel with field experimentation to integrate across scales. Managers and policy analysts need to know these outcomes and should carefully evaluate broad conclusions based on numerous small-scale experiments, many of which involve immature trees in short term studies.

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POTENTIAL CHANGES IN THE VEGETATION DISTRIBUTION IN THE UNITED STATES

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INTRODUCTION/APPROACH

The potential impacts on U.S. vegetation of CO_2-induced global warming were analyzed for sufficient effects, either positive or negative, that might require dramatic shifts in forest management policies. The Mapped Atmosphere-Plant-Soil System (MAPSS) was used to simulate vegetation distributions, and the results were compared with other ecological models to explore uncertainties.

The point of departure for the analysis was the Resources Planning Act (RPA) Assessment *Forest Resources of the United States, 1992* (Powell et al. 1993). Tables in the 1992 RPA assessment present the area of each forest type as determined from forest survey data. The data selected for this analysis are for all forests in the conterminous U.S., including forest reserves. The 1992 survey also includes a forest type map produced as a remote sensing product. The map has a spatial resolution of 1 km and, when incorporated in a Geographic Information System (GIS), allows an independent estimate of forest area by type. The GRASS GIS was used for these analyses (USA-CERL 1993).

Potential future forest distribution under global change was determined in two separate projects, a USFS-sponsored project and a consortium-sponsored project (USFS, NASA, NSF, EPRI). The MAPSS project is an ecosystem distribution simulation project with a spatial resolution of 10 km over the conterminous U.S. and 0.5° latitude-longitude over the globe (Neilson and Marks, 1994; Neilson 1995). The Vegetation/ Ecosystem Modeling and Analysis Project (VEMAP) is an IGBP core project (VEMAP members 1995) to compare three global biogeography models (MAPSS, DOLY (Woodward and Smith 1994) and BIOME2 (Haxeltine and Prentice in press)) and three global biogeochemistry models: TEM (McGuire et al. 1995; Raich et al. 1991), CENTURY (Parton et al. 1988), and BIOME-BGC (Running and Hunt 1994) under current and $2xCO_2$ climates. The advantage of the MAPSS project is the relatively high spatial resolution (10 km) and the greater number of climate scenarios, but the project is limited to the use of only one biogeography model. The advantage of the VEMAP project is the use of several different ecological models, but the project is limited by the coarse spatial resolution of 0.5° and fewer scenarios.

The MAPSS model (Neilson 1997, this volume), a process-based biogeography model, was implemented over the conterminous U.S. at a spatial resolution of 10 km. The model has been calibrated to current climate and the simulations compared to the RPA forest area data (Powell et al. 1993). Since MAPSS only simulates potential natural vegetation distribution, there is no facility for directly incorporating land use. Therefore, the 1992 remote sensing image of forest distribution and forest type (Powell et al. 1993) was used to develop a mask of the non-forest area. This mask was used in the GIS to limit analysis of the MAPSS output to those areas that are currently forested, as represented in the satellite image. The MAPSS model was then operated under several $2xCO_2$ climate scenarios produced by different General Circulation Models (GCM). The present-day, non-forest, mask was also used for all potential future forest distributions, imposing the unrealistic assumption that areas currently non-forested will remain non-forested, primarily due to agriculture.

Scenarios of double CO_2 climatic change were derived from six GCM $2xCO_2$ equilibrium simulations. Climate scenarios were supplied by the Data Support Section within the Scientific Computing Division of the National Center for Atmospheric Research (NCAR). Model outputs for current and $2xCO_2$ climates were obtained from the following models: GISS (Goddard Institute of Space Studies, Hansen et al. 1988); UKMO (United Kingdom Meteorological Office, Mitchell and Warrilow 1987); GFDL (Geophysical Fluid Dynamics Laboratory, Wetherald and Manabe 1988); and OSU (Oregon State University, Schlesinger and Zhao 1989). The GFDL-R15 (ca. 4° x 5° grid), R15 Q-flux and R30 (ca. 2° x 2.5° grid) versions were used. The Q-flux version of the GFDL model (GFDL-Q) includes a prescribed ocean-atmosphere coupling (Manabe et al. 1991). The coarse grid from each model was interpolated using a 4 point, inverse distance squared algorithm to a 10 km albers grid in a raster-based Geographic Information System (USA-CERL 1993). The scenarios were applied as recommended and calculated by the NCAR Data Support Section. Scenarios were constructed by applying ratios $((2xCO_2)/(1xCO_2))$ of all climate variables (except temperature) back to a baseline long-term average monthly climate dataset (NOAA-EPA 1993). Ratios were used to avoid negative numbers, but were not allowed to exceed 5, to prevent unrealistic changes in areas with normally low rainfall. Temperature scenarios were calculated as a difference $((2xCO_2) - (1xCO_2))$ and applied to the baseline dataset. The VEMAP project was limited to the UKMO, GFDL-R30 and OSU scenarios.

It is expected that elevated CO_2 concentration will produce global warming. However, elevated CO_2 concentration may also produce direct physiological effects on plants that could offset some of the negative effects of global warming on vegetation. The MAPSS model is capable of simulating the physiological effects of elevated CO_2 concentration by reducing the maximum stomatal conductance to confer an increased water use efficiency (WUE) (Eamus 1991). Since the "CO_2 effect" is not well understood and may not operate in complex ecosystems to the extent that it does in growth chambers (Eamus and Jarvis 1989), companion simulations with and without the WUE effect were completed.

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The MAPSS vegetation classification is based on physiognomic properties, such as leaf form (broadleaf or needleleaf), leaf phenology (evergreen or deciduous) and stand structure (closed forest or open woodland/savanna). Vegetation types were both geographically and logically translated into the forest type categories used in the RPA assessment (Powell et al. 1993). This required aggregation of some of the RPA forest types to be compatible with MAPSS types. Table 1 presents the classification strategy. Twenty of the 22 RPA forest types were aggregated into 9 groups. Pinyon-juniper and chaparral types were not calibrated in the MAPSS output.

Table 1.—Cross Classification between RPA forest types and MAPSS vegetation classes.

	MAPSS Assessment Classes	RPA Forest Type Groups	MAPSS Original Classes
Eastern Forests	1 NE Mixed Conifers and hardwoods	1 White-red-jack pine 2 Spruce-fir 10 Aspen-birch	Forest Mixed Cool
	2 NE Mixed Woodland (Boreal Woodland)		Tree Savanna Mixed Cool (Evergreen Needleleaf)
	3 Maple-beech-birch	9 Maple-beech-birch	Forest Hardwood Cool
	4 Oak-Hickory Forest	6 Oak-hickory 8 Elm-ash-cottonwood	Forest Temperate Deciduous
	5 SE Mixed Pines and Hardwoods	3 Longleaf-slash pine 4 Loblolly-shortleaf pine 5 Oak-pine 7 Oak-gum-cypress	Forest Mixed Warm Deciduous to Evergreen, Broadleaf to Needleleaf)
Western Forests	6 Western Fir-Spruce	17 Fir-spruce 22 Aspen-birch	Taiga/Tundra
	7 Douglas Fir	11 Douglas-fir 16 Larch	Forest Evergreen Needle
	8 Coastal Spruce-Hemlock Redwood	12 Hemlock-Sitka spruce 18 Redwood	Forest Mixed Warm (Evergreen Needle)
	9 Western Pines	13 Ponderosa pine 14 Western white pine 15 Lodgepole pine	Tree Savanna Evergreen Needle
	10 Western hardwoods	21 Western hardwoods	Tree Savanna Mixed Warm (Evergreen Needle)
Tropical	11 Moist Tropical Forest		Forest Evergreen Broadleaf Tropical
	12 Dry Tropical Forest		Forest Seasonal Tropical Evergreen to Deciduous
Arid Woodlands	13 Oak-Hickory Woodland		Savanna Temperate Deciduous
	14 SE Mixed Woodland		Savanna Mixed Warm (DEB)
		19 Chaparral	Not Calibrated
		20 Pinyon-juniper	Not Calibrated

FOREST DISTRIBUTION

Current Climate

The comparison between the MAPSS output under current climate, and the RPA forest area statistics from both survey data and the remote sensing forest map, is presented in Figures 1-3. Of the 562 million acres shown on the RPA forest map, (excluding pinyon-juniper and chaparral), MAPSS captures 503 million acres as forest (Figure 1). MAPSS-simulated non-forested areas tend to occur in the more arid interior regions and on high mountain tops where the model overestimates the area of alpine tundra and ice.

RPA forest classes do not recognize a distinction between closed forest and open woodland or savanna types containing the same species; whereas, the MAPSS model does make the distinction. For the comparison statistics in Figure 2, the MAPSS woodland/savanna classes have been aggregated with the closed forest classes in order to be consistent with the RPA data. That is, MAPSS types 13 and 14 (Table 1) have been aggregated with types 4 and 5, respectively. However, the two woodland types (13 and 14) are displayed separately in all maps. Geographic designations are misleading, but are retained to reflect the RPA nomenclature with the SE Mixed Forest type representing all warm mixed forests. and the NE Mixed Forest type representing cool mixed forests. These types occur in some MAPSS simulations in the western U.S. as minor elements.

The satellite data indicate too much western pine (Ponderosa, Lodgepole and Western White, Figs. 1-4) in comparison to the ground survey; although, it may in part be due to classification issues. The western pines are often successional to other conifers, such as Douglas-fir, true firs and spruce. It may be that some of these stands were classified differently, based on the successional data. Also, the MAPSS model clearly underestimated the distribution of pines over the Colorado Plateau and in the Sierra Mountains.

Western hardwoods are simulated by MAPSS as a warm, needleleaf woodland/savanna, which occurs as a nearly closed forest in the Willamette Valley and other western locales. Conifer forest is the natural climatic climax associated with the western oak woodlands in the absence of fire (Franklin and Dyrness 1973), a process not included in these simulations. The western hardwoods are underestimated by both MAPSS and the satellite data, likely, in part, due to the complex successional status and the small spatial scale of variation among the different successional states. Also, the western hardwoods class, as defined in the RPA data is not a pure class. The survey data for western hardwoods include Alder, Oaks and Aspen-Birch. The Alder-Oak combination in the western hardwoods cannot be specifically simulated by MAPSS, since the two genera occur at opposite ends of the moisture spectrum in succession toward conifer forests, primarily Douglas fir with respect to oaks and Douglas fir-hemlock or hemlock-cedar-spruce with respect to alder (Franklin and Dyrness 1973). Aspen-Birch is associated, in part, with succession to spruce-fir (Long 1995; Bartos et al. 1983). Also, the RPA databases are inconsistent, with Aspen-Birch being aggregated with western hardwoods in the survey statistics; while, the satellite map separates Aspen-Birch as a distinct type, which is also separate from eastern Aspen-Birch. Most of the simulated western hardwoods class in the Willamette Valley, Oregon is excluded by the non-forest mask and is not included in the analysis (Fig. 3).

The average simulated Leaf Area Index (LAI) is a relationship of the surface area of the leaves to the surface area of the ground (m^2/m^2). The LAI of the two woodland types ranges from about 2.5 to 3.0 (all-sided) while that of the two forest types ranges from 6.6 to 7.4. Thus, foliar density in the closed forests is about 2.5 times greater than in the woodlands. If the two types are aggregated in the analysis of global warming impacts, then large changes in the areas of woodland relative to forest are not well represented. The aggregated results may indicate that total forest area changes very little; while, in fact total forest biomass could change considerably. Changes in LAI are used as an index of change in forest density or basal area. Although the relationship is not strictly linear, foliage volume will be used as a rough index of biomass or timber volume. The foliar volume is calculated as the density (in units of LAI) times the area. Percent change in foliar volume is calculated as foliar volume of the future scenario minus the volume of the control simulation, divided by the volume of the control simulation.

2xCO_2 Climate

Three criteria of change are examined; changes in forest area, changes in foliar density (LAI), and changes in foliar volume (LAI x Area). Foliar density is used as a coarse index of basal (stem) area per unit land area; while foliar volume will be used as a coarse index of biomass or timber volume over the entire forest area. Since the relationship between LAI and basal area or biomass is not strictly linear, these indices are only intended as coarse metrics of direction and general magnitude of change. These analyses are comparisons of the steady-state statistical properties of the forests under current and "future" climate conditions and do not consider the relocation of the forests to new sites via dieback, regeneration, dispersal, establishment and growth.

Potential changes in the area and volume of forests are presented in Figures 4-5. Maps of these future scenarios are shown in Figures 6-8. The area changes are presented in two forms: 1) the two eastern forest woodland types (Table 1, types 13 and 14) aggregated with their respective forest types (4, 5) and 2) woodlands tabulated separately. Each bar-graph figure (4,5) contains four panels, with and without aggregation of woodlands and with and without a WUE effect. Since woodlands and tropical types are of little importance today, but increase dramatically under some of the climate scenarios, the percent changes in these types dominate the overall changes. The maps (Figs. 6-8) are

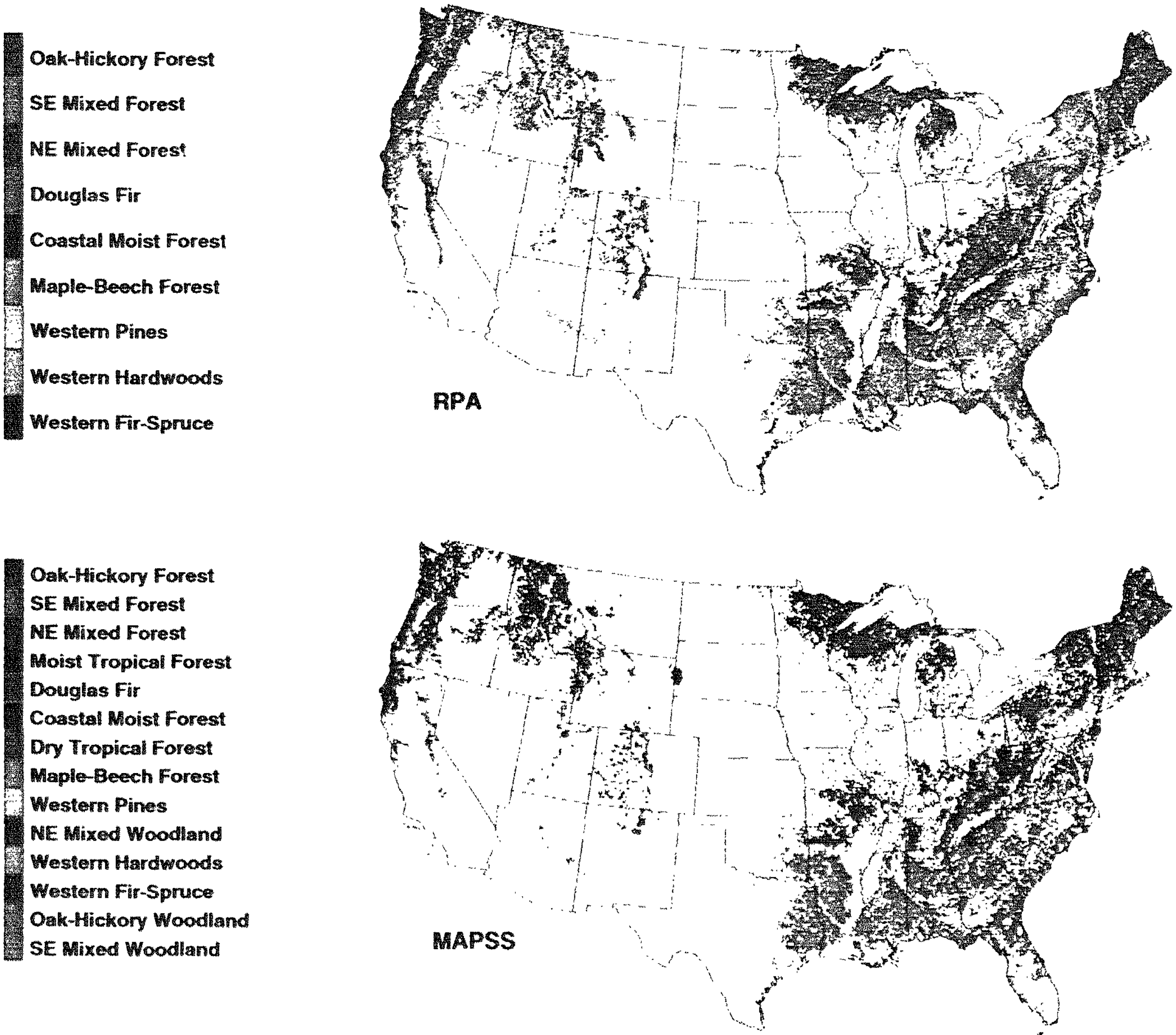

Figure 1.—Maps of United States forests based on (a) RPA satellite analysis (1-km resolution) and (b) MAPSS simulation (10-km resolution).

presented with woodlands disaggregated from forest classes.

Eastern Forests. In general there are northward and elevational shifts in all forest types, whether there are increases or decreases in total area and volume. The cold forest types (types 1-3) tend to show large decreases (average area loss over 6 scenarios, no WUE effect, 32 percent-100 percent). Since most of these forest types are constrained by temperature, there is a great deal of consistency in their loss among the different climate scenarios. However, increased water use efficiency confers a benefit to the cool hardwood forests in the NE, showing increases under GISS (48 percent) and OSU (6 percent) scenarios, but at the expense of oak-hickory forests (Figs. 4-8). Even so, the average across all six scenarios, with a WUE effect, indicates losses ranging from 37 percent to 100 percent. Without a WUE effect the average losses of the cold forest types across the six scenarios ranges from 74 percent to 91 percent.

If the eastern woodlands (Table 1, types 13 and 14) are aggregated with true closed forest, then, in the absence of a WUE effect, oak-hickory forests (type 4) change little (7 percent loss) or expand (up to 50 percent) in area under all scenarios (average 29 percent increase across 6 scenarios) Increased WUE (with aggregated woodlands) results in a

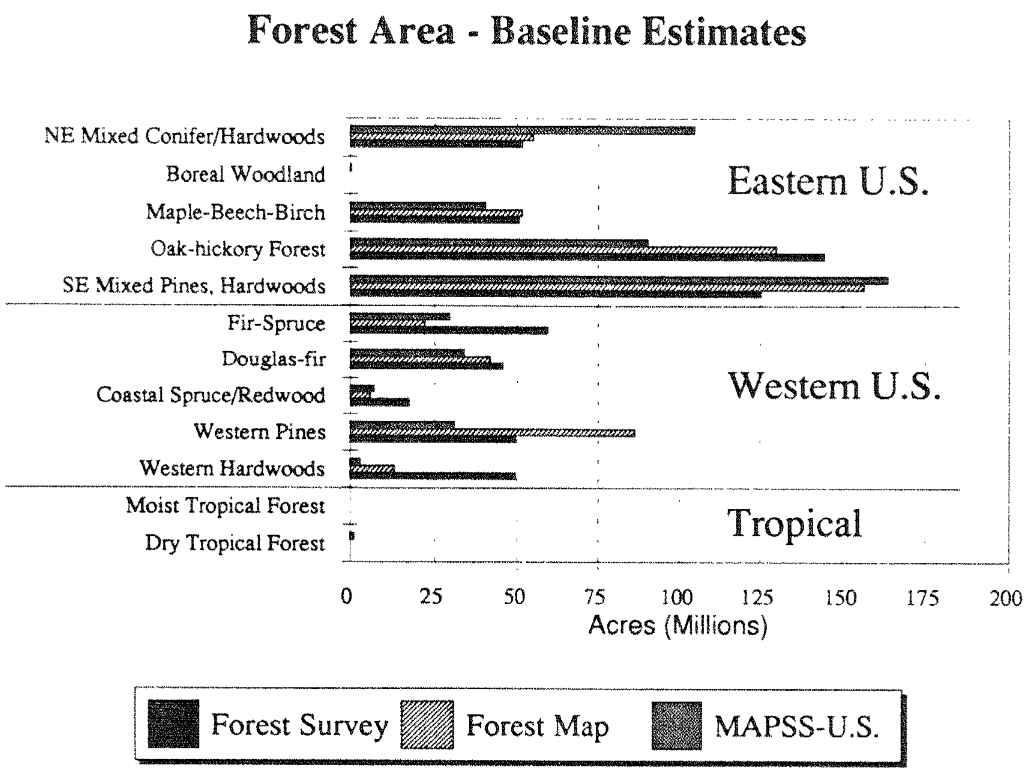

Figure 2.—Comparison of forest area as estimated from 3 separate approaches: ground survey, satellite analysis, and MAPSS simulation.

more modest increase in area (average 7 percent across 6 scenarios) due to encroachment by the southeastern pines and hardwoods and to a less detrimental effect on cool hardwoods (Fig. 4-8, types 1 and 3). The cooler and wetter scenarios with a WUE effect tend to favor beech-maple in the NE (type 3) while allowing the SE mixed forests to move north due to warming. The combination then produces the most severe losses of oak-hickory forest area through displacement, e.g. a 47 percent loss under the GISS scenario.

The SE pines and hardwoods increase in area (up to 42 percent) in all scenarios, with (average 30 percent) or without (average 25 percent) a WUE effect, except the non-WUE UKMO scenario which shows a minor decrease (7 percent) in area. However, these modest losses to large gains in area in these two forest types (4, 5) with woodlands aggregated obscure the large shifts in forest type from high density forest, to low density woodland (Fig. 4-8).

If woodlands are tabulated separately, then the oak-hickory (Table 1, type 4) and the SE mixed forests (type 5) demonstrate significant losses under most scenarios without a WUE effect, averaging losses of 31 percent (oak-hickory, range -82 percent to +29 percent) and 53 percent (SE forests, range -97 percent to 0 percent), respectively. Oak-hickory increases in area under GISS (21 percent) and OSU (29 percent) scenarios as it displaces northern cool forests (types 1-3). As before, with increased WUE, the gains in oak-hickory are reversed by shifting dominance toward the beech-maple in the north; while being displaced by SE forests from the south, averaging losses of 6 percent (range -47 percent to +24 percent). With a WUE effect, the SE forests average a 9 percent gain in area, even with woodlands tabulated separately (range -53 percent to +37 percent), although they may no longer be centered in the southeast.

Comparing the average foliar density (LAI), as an index of basal area, of each type in its current location with the average foliar density for that type in its new location, in most scenarios there is a reduction in the average density of all U.S. forests of 15 percent (woodlands aggregated) or 11 percent (woodlands separate, no WUE effect, based on the mean across all forest types of the mean LAI change of each forest type). The numbers are slightly reduced with a WUE effect. Most of the density change occurs in the eastern forests with average losses of 35 percent and 51 percent for oak-hickory and SE mixed forests, respectively, without a WUE effect, or 10 percent and 17 percent, respectively with a WUE effect (woodlands aggregated). These numbers are considerably reduced if woodlands are considered separately, but still indicate density losses.

Examination of the foliar volume change plots (Fig. 5), as an index of change in total wood volume, indicates large volume losses in all eastern forest types, especially when woodlands are aggregated. Area-weighted foliar volume losses over the conterminous U.S. averaged over the six scenarios are 57

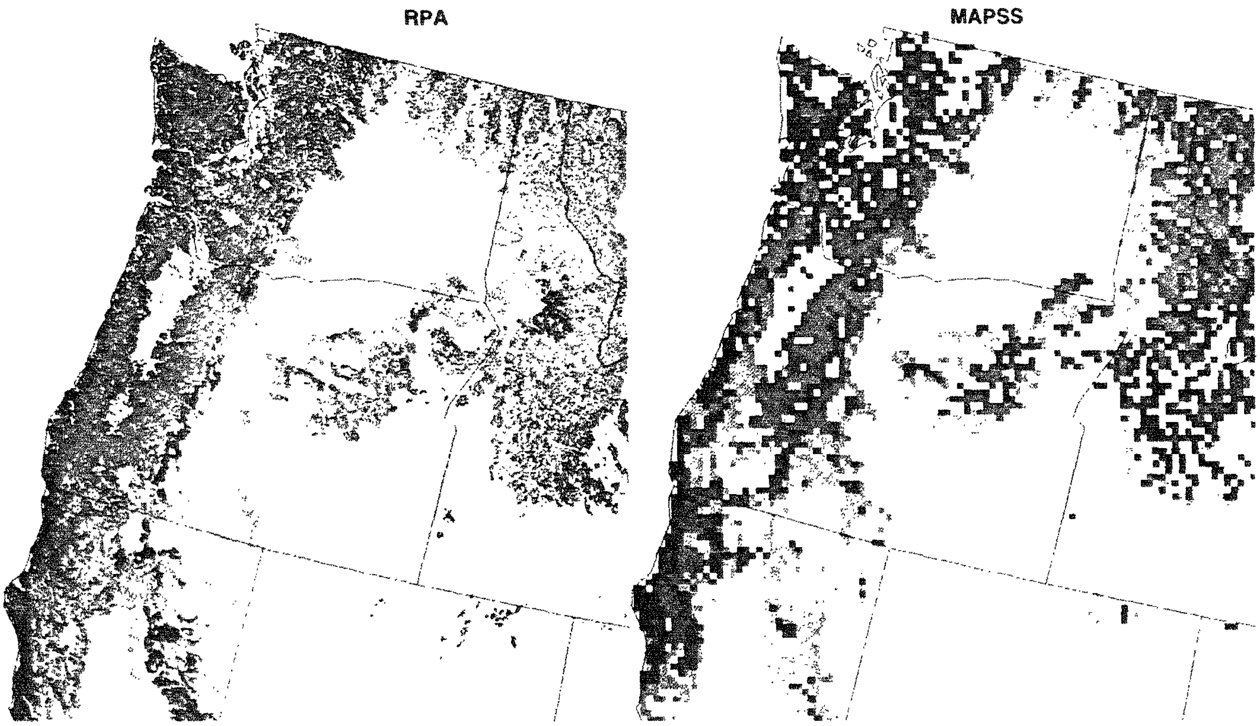

Figure 3.—Maps of forest distribution as estimated by (a) RPA satellite analysis (1-km resolution), and (b) MAPSS simulation (10-km resolution), Pacific Northwest Region.

percent without a WUE effect or 26 percent with a WUE effect. The GISS scenario with a WUE effect is the only scenario that shows an overall increase in foliar volume across all the forests.

In a few simulations there is a very small increase in the foliar volumes of oak-hickory and SE mixed forests (GISS and OSU scenarios), due to a shift into more northern lands and only when a direct CO_2 effect (WUE) is incorporated. These increases in foliar volume under a WUE effect occur whether woodlands are considered separately or not. There is a large effect of increased water use efficiency on both forest types (4, 5), offsetting the large losses that occur without a WUE effect, and producing a mix of scenarios with both increased and decreased volume, usually accompanied by an increase in the area of the type. Dry tropical forests (type 12) and to a lesser extent moist tropical forest (type 11) increase in the Gulf states area, but the dry tropical forests are not very dense, being similar to open woodlands.

Western Forests. Fir-spruce forests (type 6) in the western U.S. decrease in area and foliar volume in all scenarios (average 76 percent loss, range -91 percent to -53 percent), largely a result of being pushed off the top of the mountains (Figs. 6-8). Douglas-fir (type 7) shows quite mixed results, depending on the presence or absence of a WUE effect. In the absence of a WUE effect the Douglas-fir forests decrease in all scenarios in area (average loss 47 percent, range -76 percent to -15 percent) and total volume (average loss 52 percent, range -83 percent to -19 percent). The volume losses incorporate an average 13 percent loss in foliar density (LAI), an index of basal area. In the presence of a WUE effect there are increases in area in all scenarios except UKMO and GFDL (average gain 26 percent, range -26 percent to +73 percent). Foliar volume changes with a WUE effect are similarly mixed with average gains of 18 percent (range -40 percent to +63 percent). The increased volume of Douglas-fir under a WUE effect occurs primarily through increases in area, since the foliar density (LAI), i.e., basal area, actually decreases (average -8 percent, range -19 percent to +6 percent) with the only increased density occurring under GISS and OSU scenarios. Range contractions of Douglas-fir and related types occur in the southern Cascades and Coast Ranges. Expansions bring Douglas-fir into the higher elevations of the Cascades, Sierras, Blue Mountains and northern and central Rocky Mountains (Figs. 6-8). Other range expansions extend into the Pine zone under increased WUE.

Coastal spruce-hemlock and redwood forests (type 8) show mixed responses without a WUE effect with large increases in area under the GFDL-R30 and GISS scenarios (up to 133 percent), but large losses under the other scenarios (to -71 percent under UKMO). The differences arise from large differences among the scenarios in regional precipitation changes. However, with a WUE effect the coastal humid forests increase significantly in area and total foliar volume in all scenarios (average 158 percent, range 21 percent to 550

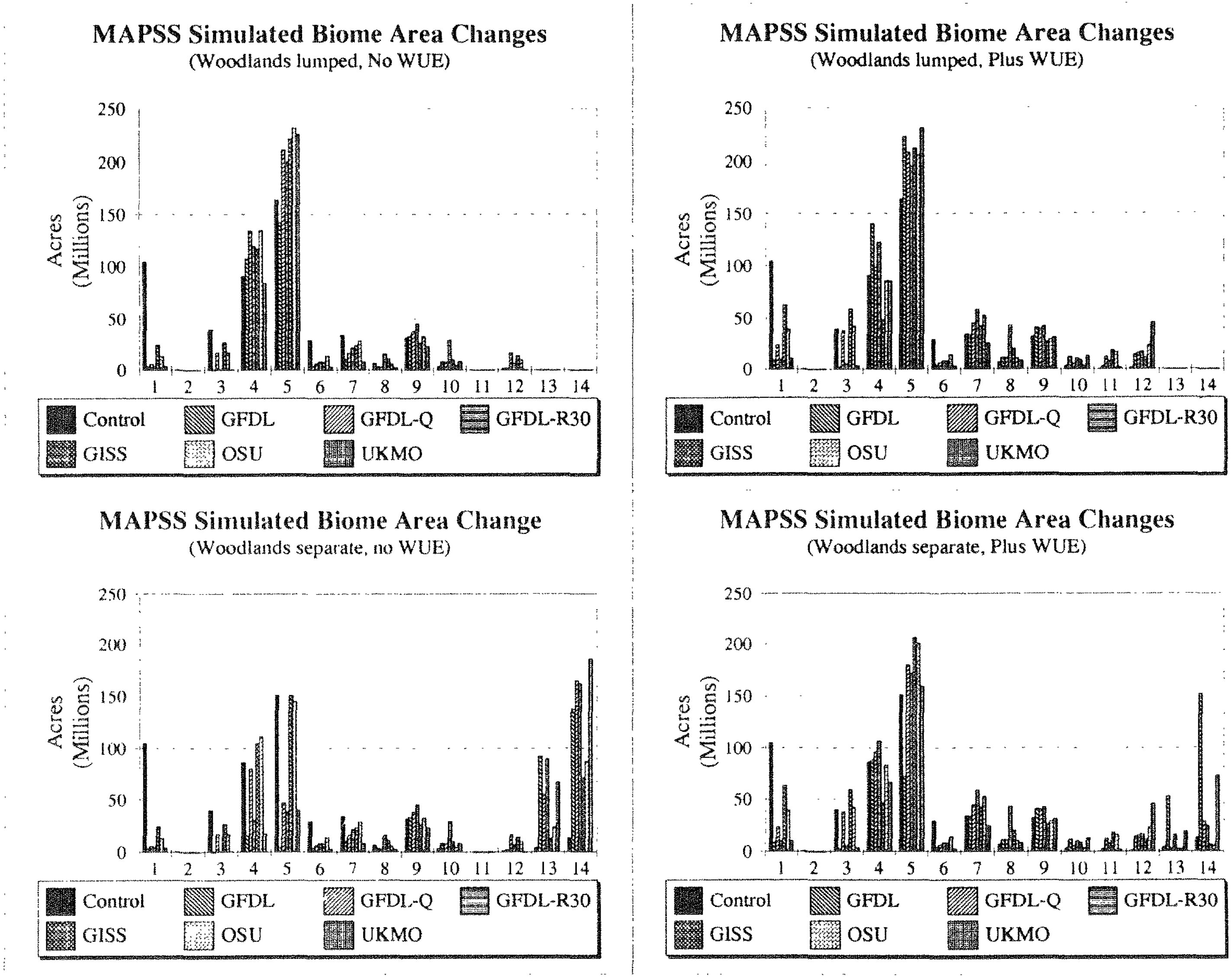

Figure 4.—Estimates of change in forest area by type under $2xCO_2$ climate.

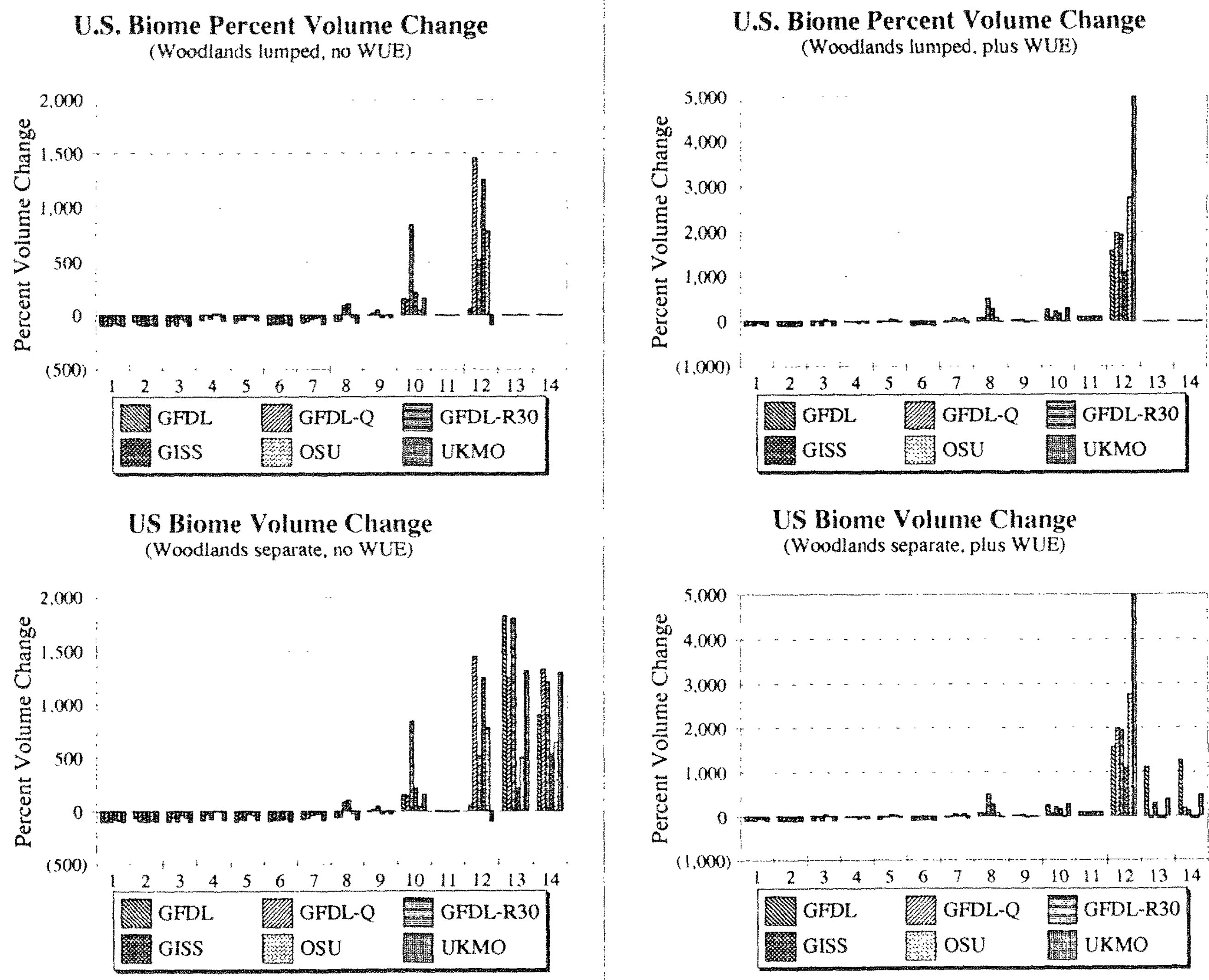

Figure 5.—Estimates of percent change in forest volume by type under $2xCO_2$ climate (note different scales).

percent), although they are displaced northward in some scenarios. The foliar volume changes are of a similar magnitude, but also incorporate some increases or decreases in average foliar density (LAI). Range contractions occur in the central and southern Coast Range forests of Oregon; while, extreme range contractions extend declines into the coastal Redwood zones of California (Fig. 6-8). Range expansions bring the mesic coastal forests into the east side of the Coast Range and into the Willamette Valley and the lower reaches of the west slope of the Cascades.

Western pines (ponderosa, lodgepole and western white, type 9) show variable responses with some increases and decreases in area under all scenarios and water use efficiencies (average +6 percent, range -26 percent to +44 percent, non-WUE, average +11 percent, range -15 percent to +34 percent, with a WUE effect). Foliar density changes are slight within this type. The increases are larger and the decreases smaller with increased water use efficiency under the various scenarios. The pines tend to disappear from their southern and lower elevational limits being replaced by more xeric, non-forest vegetation. The most consistent losses across all the scenarios occur in the Southern Rockies and Colorado Plateau, especially the Mogollon Rim. Under situations where Douglas-fir contracts from the Cascade Range and other locales, they are generally displaced by the pines (Fig. 6-8).

Western hardwoods (type 10) show increases in area under all scenarios and water use efficiencies (average non-WUE increase 274 percent, range 42 percent to 870 percent). The increases under increased WUE are smaller than the non-WUE simulations (average 125 percent, range 0 percent to 320 percent). The smaller expansion of western hardwoods with a WUE effect occurs because of the retention of closed forests in potential expansion zones. The large percentage changes occur, of course, because of the relatively small amount of the forests in the control simulation. Western oaks, in particular, increase in area and volume as they replace the lower elevation Douglas-fir and mesic spruce-hemlock-redwood forests. These forests would be converted to a western hardwood type as they open up due to temperature-induced drought and as fire becomes more prevalent.

MODEL COMPARISONS

Under VEMAP, three biogeography models (MAPSS, DOLY, and BIOME2) were compared under current and altered climate, as were three biogeochemistry models (TEM, CENTURY, and BIOME-BGC). The 2xCO_2 climate scenarios were derived from the UKMO, GFDL-R30 and OSU simulations. These results are summarized (VEMAP members 1995).

The six models were parameterized to simulate 21 different vegetation types, aggregated from Küchler (Küchler 1964). No attempt was made to mask out current land use from the analyses. Under control climate all three biogeography models exhibit nearly identical statistical skill in simulating the aggregated Küchler map. However, each model exhibited its own unique signature. Likewise, the three biogeochemistry models exhibited nearly equal skill in simulating the net primary productivity and carbon pools of the different vegetation types. All models in both groups exhibited very different levels of sensitivity to global warming, even given their similarity under current climates.

Of the three biogeography models, MAPSS was found to be the most sensitive with respect to temperature induced drought stress effects on forests, while BIOME2 was the least sensitive. DOLY was intermediate. The MAPSS results at the 0.5° resolution used in VEMAP are quite similar to those described above, although the western U.S. forests are not well resolved at the coarse resolution and results are more questionable. BIOME2 in contrast to MAPSS shows substantial increases in forest area under most scenarios and with or without a CO_2 effect. MAPSS also has the most sensitive CO_2 response of the three models, BIOME2 the least and DOLY is intermediate. Thus, simulations incorporating the direct effects of CO_2 were more similar among the three models than were those without the CO_2 effects. The range of simulations presented above for MAPSS encompasses most of the range of forest responses encompassed by all three models, except that BIOME2 would extend the range of forest expansions a bit.

One of the primary reasons for the differences among the three biogeography models appears to be in the assumptions made with respect to mass and energy coupling of the canopy to the atmosphere. MAPSS assumes strong coupling such that transpired water is easily mixed, through turbulence, to the atmosphere and carried away from the region, thus producing little negative feedback on the demand for moisture from the vegetation. BIOME2 is configured such that transpiration produces a strong negative feedback on further moisture demand. Strong negative feedback occurs if transpiration from the canopy is not well mixed through turbulence to the general atmosphere. DOLY is intermediate in these processes.

At the opposite end of the vegetation gradient, semi-arid land (southwestern deserts), DOLY was the most sensitive, showing substantial increases in desertification under most scenarios. MAPSS and BIOME2 were similar and produced rather mild increases in desertification. It is not yet clear why DOLY is more sensitive to desertification potential than MAPSS and BIOME2, but again may involve canopy-atmosphere coupling with respect to water balance.

The biogeochemistry models produced a similar range of disparity among the 2xCO_2 simulations. TEM was the most conservative, producing significant increases in forest productivity both with and without a CO_2 effect under most 2xCO_2 scenarios. BIOME-BGC was the most sensitive to temperature induced water stress and produced results similar to MAPSS. CENTURY was intermediate. TEM and BIOME2 are relatively consistent in terms of combined biogeochemistry and biogeography results, both showing relatively small decreases in productivity and forest area, and potentially much gain from global warming. BIOME-BGC and MAPSS are, likewise, consistent with each other, both indicating significant water-balance sensitivity of U.S. forests to global warming.

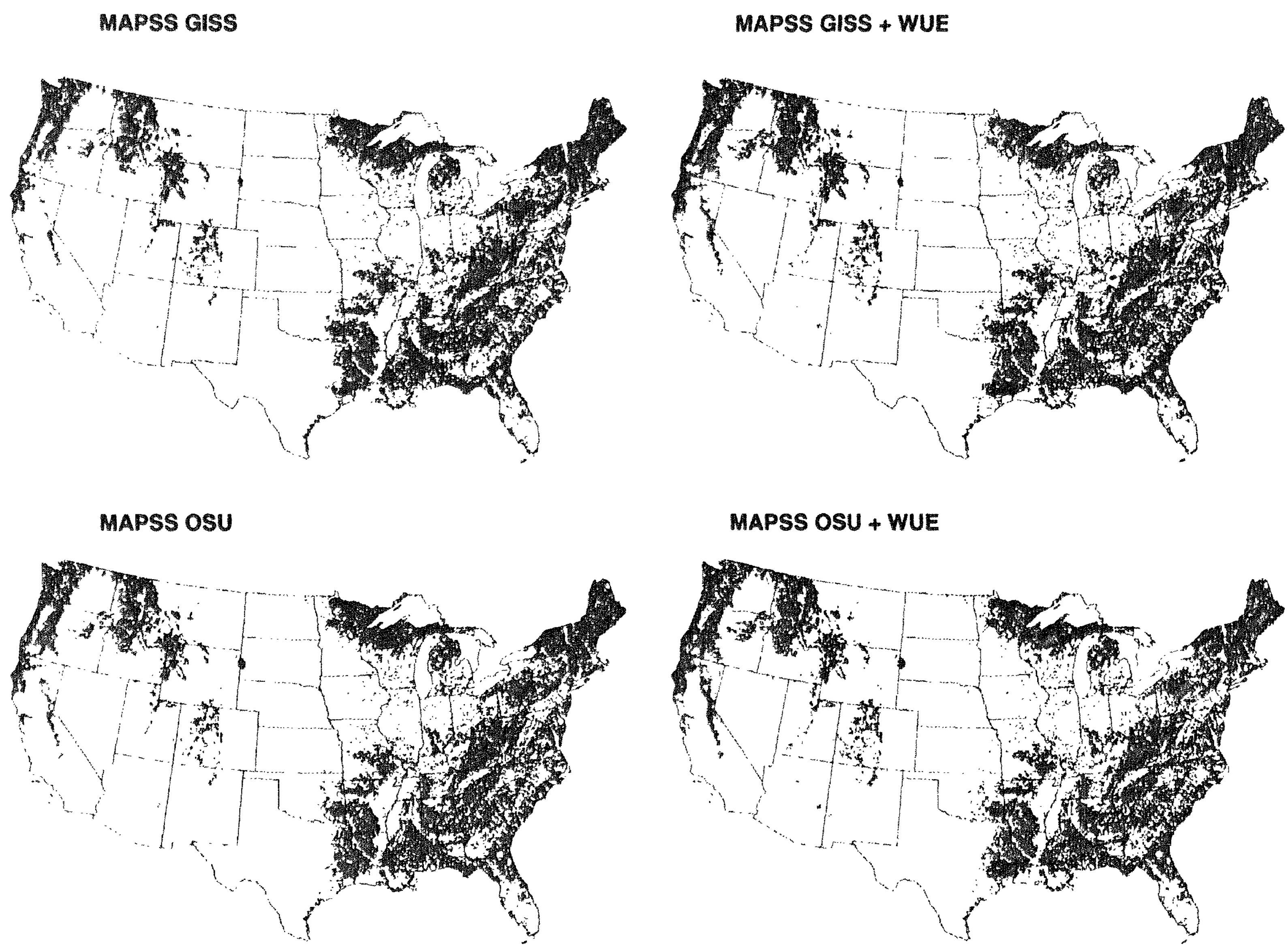

Figure 6.—Maps of potential future forest distribution under $2xCO_2$ climate, with and without a CO_2-altered water use efficiency effect (WUE), GISS and OSU scenarios.

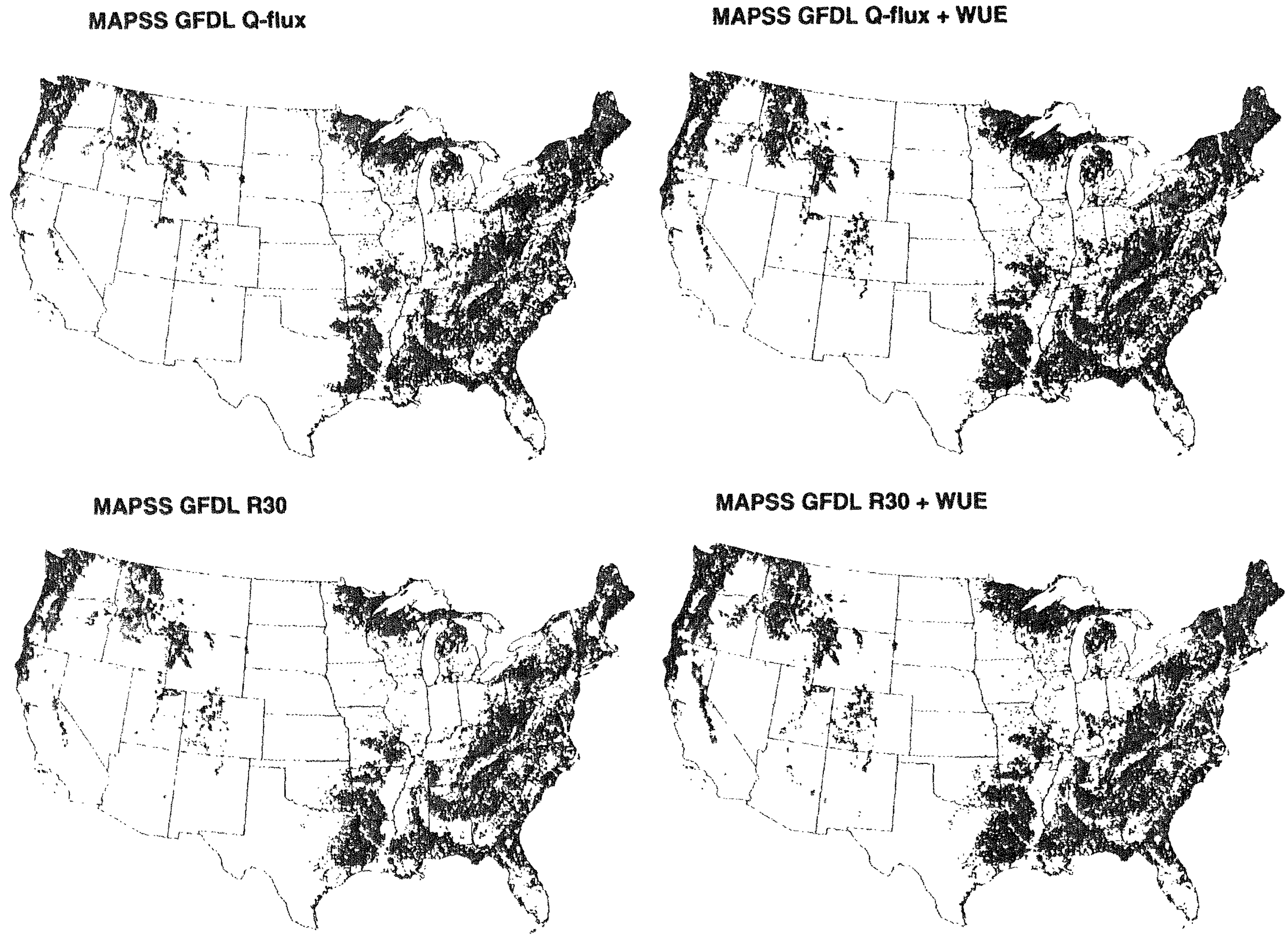

Figure 7.—Maps of potential future forest distribution under 2xCO_2 climate, with and without a CO_2-altered water use efficiency effect (WUE), GFDL-Q and GFDL-R30 scenarios.

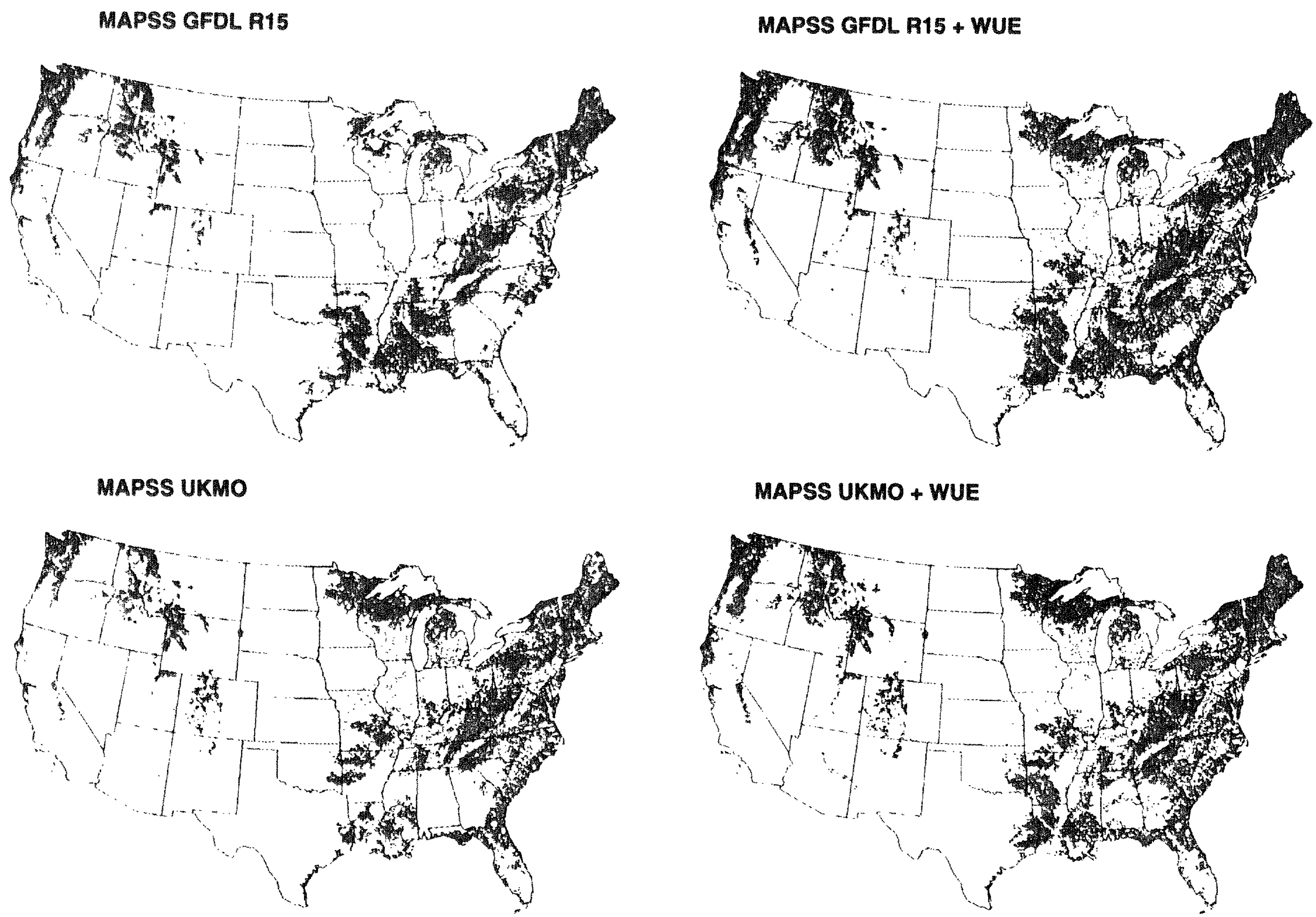

Figure 8.—Maps of potential future forest distribution under $2xCO_2$ climate, with and without a CO_2-altered water use efficiency effect (WUE), GFDL-R15 and UKMO scenarios.

CONCLUSIONS

There is no clear agreement among the different scenarios and vegetation models with respect to the potential responses of U.S. forests to global warming. However, given the variety of ecological and atmospheric models the possible range of future forest responses has likely been bracketed by these results. One thing seems certain; change is likely. Also, there are several relatively consistent patterns.

Forests that are constrained to cool climates, such as northeastern hardwoods and high altitude forests, will likely be lost or reduced significantly in size. High latitude forests, however, would shift north. Soil characteristics at high altitudes and latitudes may restrict expansion of forests into those regions.

Forests that occur in warm regions are potentially sensitive to increased drought stress. Notable among these are the southeastern mixed pines and hardwoods and the western Douglas-fir regions. The southern Coast and Cascade Ranges are particularly sensitive in this regard. These closed forests could be replaced by woodlands or savannas, possibly with similar species composition. In the West the forest classification acknowledges differences between closed forests and open woodlands and savannas. To some extent this occurs because there is a species replacement. For example, when Douglas-fir forests occur in drier climes, they tend to exist with a fire regime that promotes the establishment of pines or oaks. However, in the Eastern U.S. the companion woodlands to the closed oak-hickory and SE mixed forests are not explicitly recognized in the classification. This presents difficulties in defining or interpreting the potential impacts of global warming.

The three most important uncertainties contributing to the wide range of these results are: differences among the GCM scenarios, the direct effects of elevated CO_2, and the mechanisms and degree of coupling between the canopy and the atmosphere. The uncertainties with GCM scenarios are covered elsewhere.

Most of the increase in forest volume and area under these global change scenarios occurs when the direct effects of elevated CO_2 are explicitly simulated. However, there are numerous uncertainties with these results. None of the six models in the VEMAP exercise incorporated CO_2 effects in the same way. Some imparted an increased productivity, others an increased water use efficiency and others included both effects. It is not yet clear how to incorporate these physiological effects. Even more uncertain, is how CO_2 effects will be manifest under complex ecosystem constraints, as distinct from growth chamber studies. For example, the CO_2 sensitivity in the MAPSS model may be too high and that in the BIOME2 model may be too low.

The problem of atmospheric coupling has several components. The quantitative aspects of canopy roughness are not well understood yet are the dominant controls on turbulent mixing processes between the canopy and the atmosphere. The relative importance of stomatal control on stand water balance can only be understood in the larger context of the importance of turbulence in the canopy. Above the canopy the boundary layer gradually mixes with the upper atmospheric layers. How well this canopy boundary layer mixes with upper layers is also not well understood, nor well measured; although new syntheses of existing data are clarifying this coupling somewhat and indicate a relatively large degree of coupling between forest canopies and the atmosphere (Hollinger et al. 1994; Schulze et al. 1994). These canopy-atmosphere coupling processes may not be well simulated until vegetation models and GCMs are dynamically coupled to fully express all energy, mass and momentum feedbacks in a fully closed Earth System Model.

Other issues not dealt with in this assessment include: dynamic land-use simulation, dispersal and succession. As forests are forced to move around, some areas will experience dieback, possibly catastrophic with severe drought death, infestation and fire (King and Neilson 1992; Neilson and King 1992; Overpeck et al. 1990; Smith and Shugart 1993; Neilson et al. 1994; Neilson 1993a; Neilson 1993b; Franklin et al. 1991). Establishment in new locations may be difficult due to dispersal and soil constraints. Even if dispersal constraints produce lags in the colonization of an area by new species, there will usually be other species already present that will be able to live in those regions. For example, if the eastern hardwoods are not able to colonize northern boreal forest regions very rapidly, the boreal species may still survive but at a different density, if their reproduction is not constrained to certain cooling requirements.

The fixed land-use map used for the MAPSS analysis is a severe and unrealistic constraint, particularly in those scenarios that portend significant expansion of forests. A deterministic land use model is required that will allow conversions of forest to agriculture and vice versa as a function of the population density, supply and demand economics, and cultural status. Such models are only now being constructed.

The potentially catastrophic conclusions presented here are consistent with other studies of the potential impacts of global warming on U.S. forests (Franklin et al. 1991; Winjum and Neilson 1990). The potential changes are of sufficient magnitude, either positive or negative, that dramatic shifts in forest management policies may be required. These results present a broad spectrum of possible futures, and should ac as a catalyst to the formation of alternative policy options.

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THE FOREST CARBON BUDGET OF THE UNITED STATES

Richard A. Birdsey and Linda S. Heath[1]

SUMMARY

An ongoing synthesis of basic forest statistics and development of carbon (C) accounting models have highlighted the past and prospective role of U.S. forests in the global C cycle. We have shown that increases in biomass and organic matter on U.S. forest lands over the last 40 years have added 281Tg/yr[2] of stored C, enough to offset 25 percent of U.S. emissions for the period. When added to estimates of C increases in other northern temperate forests, there is sufficient C to account for a significant portion of the "missing" C in evaluations of the global C cycle. Projections show additional increases of approximately 177 Tg/yr through 2040. Increasing amounts of C in harvested wood, the effects of increasing atmospheric CO_2 on ecosystem productivity, and large reforestation programs all substantially effect the rate of C sequestration.

Results from the U.S. Carbon Budget Model (FORCARB) have helped quantify the effects of alternative policies for offsetting greenhouse gas emissions through forestry actions under the President's Climate Change Action Plan. Basic information about C changes over time for different forest management intensities, and for converting agricultural land to forest, can account for 10 percent of the needed reductions in the President's Plan. Estimates of C accumulation by region for different forest types are used by individuals and companies who plant trees and then report the results of these voluntary actions to the Department of Energy as an offset of CO_2 emissions. Planting trees to offset CO_2 emissions is becoming popular among companies that generate electrical power by burning fossil fuel.

FORCARB is one component of a national integrated model of global change effects on forests. This integrated modeling system allows us to simulate the effects of environmental changes on productivity, natural forest succession, harvesting, natural disturbance, timber production, and carbon storage. The integrated model includes socioeconomic models used to conduct national assessments required by the Resources Planning Act (RPA). The socioeconomic models provide estimates and projections of human activities such as land use change and timber harvest that have major impacts on the status of forest vegetation. The integrated modeling system has been used in the 1993 RPA Assessment update. Current efforts focus on improving projections of potential forest vegetation distribution, forest ecosystem composition, forest growth, and the national C budget.

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[2]One teragram (Tg) = 10^{12} grams = one million metric tons

APPLICATIONS OF THE U.S. CARBON BUDGET MODEL

Initial Estimates for the U.S.

Although estimates of C in U.S. and global forests have been made for decades, the initiation of the U.S. Global Change Program in the late 1980's focused scientific attention on the accelerating buildup of CO_2 in the atmosphere. The Program generated global interest in exploring options for reducing emissions and increasing terrestrial C sinks. Tans et al. (1990) attempted to account for all of the C exchange between the atmosphere, the oceans, and the terrestrial biosphere, and restarted a worldwide effort to find the "missing" C, suspected to reside somewhere in the Northern Hemisphere.

We began our efforts to estimate carbon in 1989 using the most current compilation of national inventory statistics (Waddell et al. 1989) and biomass statistics (Cost et al. 1990). Initial baseline estimates were reported in 1990 at the IUFRO World Congress (Birdsey 1990a). It was estimated that U.S. forests contained 52.5 Pg C, 4 percent of all the C stored in the world's forests. About 32 percent was estimated to be in live vegetation, 9 percent in dead organic material, and 59 percent in the soil. Detailed estimates of C storage and accumulation for states, forest types, and several land classifications were published in 1992 (Birdsey 1992a). At that time the rate of C accumulation in U.S. forests (trees only) was estimated to be 106 Tg/year, equivalent to about 9 percent of annual U.S. emissions of CO_2. Periodic refinements to these initial estimates using updated methodology and newer inventory statistics have not changed the baseline estimates significantly. A similar methodology produced equivalent estimates for C in major forest ecosystem components except for coarse woody debris which differed significantly (Turner et al. 1995).

Offsetting CO_2 Emissions by Tree Planting and Forest Management

Concurrent with developing the national baseline, we attempted to quantify the impacts of U.S. forest management policies on the C cycle (Birdsey 1990b, 1992b). Using estimates of C storage by age class for different forest types and conditions, we estimated that converting 22 million acres of marginal cropland and pasture in the South to forest would increase C accumulation by about 32 Tg/year, enough to offset about 3 percent of U.S. emissions of CO_2. Other forest management practices such as increasing the density of trees on poorly stocked forest land did not appear to produce much gain in the rate of C accumulation compared with simply leaving the land alone to regenerate and grow. At the same time, Moulton and Richards (1990) estimated the costs of reforestation and forest management for various levels of investment. They concluded that a maximum program level of $20 billion could offset about 56 percent of U.S. emissions.

The cost/ton of C would be about $10 for a 5 percent offset and about $18 for a 30 percent offset.

A more thorough analysis included estimates for broad management practices by major region and forest type in the U.S. (Birdsey 1992c). Recommended management strategies to maximize C accumulation included: (1) increasing the area of forest land by planting trees or allowing natural regeneration, (2) converting poorly stocked forest land by clearing and regenerating only if current productivity is well below average, (3) applying intermediate stand treatments (thinning or timber stand improvement) only if the current stand is overstocked to the point of stagnation, (4) managing for longer rotation lengths.

A Carbon Budget Model for Trend Estimates and Projections

We became interested in developing a U.S. Carbon Budget Model (FORCARB) for making projections and investigating alternative policy scenarios. We chose to link FORCARB with the timber supply models used for RPA assessments. This enabled us to include the effects of C management on the supply and demand for timber products, which could affect harvested volume and the amount of C stored on the land at any time. The data for the C model was an aggregation of all of the data prepared for previous analyses, combined with additional data about timber growth and yield. The new model produced estimates of C in forest ecosystem components plus harvested wood products. The first application showed continued increases in carbon storage on private timberlands through 2020, with decreases thereafter as increasing timber removals outpaced growth (Plantinga and Birdsey 1993). Additions of C to forest product and landfill pools offset the projected decline on private timberland.

A subsequent analysis expanded the model to include public timberland (Birdsey et al. 1993). Expected gains in biomass on public lands due to reductions in mandated harvest levels were projected to offset the declines on private timberland. This study also included a retrospective look at changes in timber volume on U.S. timberland since 1952, and converted those estimates to carbon. Carbon storage in U.S. forests has increased by 38 percent since 1952, or 8.8 Pg, enough to account for 21 percent of the hypothesized carbon sink in northern temperate regions over that period (Birdsey et al. 1993).

Exploring Alternative Management and Modeling Options

We noted many uncertainties in the development of the initial estimates and projections. There were several international meetings to refine estimates for forests in major regions of the globe (tropical, temperate, boreal) in an attempt to better quantify the sources and sinks for C. There was a continual need for analysis of management options for the Presidential Initiative to reduce greenhouse gas emissions to 1990 levels, coordinated by the U.S. Department of Agriculture, the Environmental Protection Agency, and the Department of Energy (Clinton and Gore 1993).

We extended projections to 2070 and simulated the effect of a drastic "no harvest" scenario (Heath and Birdsey 1993a). Under baseline conditions, U.S. timberlands would be a net source of C by 2070, but would sequester an average of 328 TgC/year if all harvesting were stopped. In another study of management policy options, we showed that increased recycling would be as effective as a modest tree planting program of about 10 million acres, and that the disposition and storage of C after harvest is an important factor for determining effectiveness of strategies (Heath and Birdsey 1993b).

Because of the importance of the disposition of harvested C in evaluating alternatives, we did a special study to estimate the magnitude of this component of the total C pool (Heath et al. 1995). We showed that of the 10.7 PgC harvested in the U.S. since 1900, 35 percent remained in products and landfills, 35 percent was burned for energy, and 30 percent was emitted to the atmosphere without producing energy for consumption. The current average net flux of C into products and landfills is about 37 TgC/yr, with 50 TgC/yr burned for energy or emitted.

Estimates for the 1993 RPA Assessment Update

We have aggregated the previous work into a revision of the national C budget (Birdsey and Heath 1995). We updated estimates of C allocation among tree and ecosystem components and among regions of the U.S. (Figures 1, 2). We confirmed earlier estimates that U.S. forests have been a significant C sink since 1952, and that additional C will be sequestered through 2040 but at a slower rate (Figure 3). Between 1952 and 1992, C stored on forest land in the conterminous U.S. increased by 11.3 PgC, an average of 281 TgC for each year, enough to have offset about one quarter of U.S. emissions of CO_2 for the period. Most of the historical increase in C storage has been on private timberland. Base projections through 2040 show an additional increase in storage of 8.5 PgC, and average accumulation of 177 TgC/yr.

Most of the projected increase in C storage is expected on public forest land. The expected effects of increased atmospheric CO_2 on forest productivity, and alternative forest management strategies, could each result in additional C storage through 2040. The baseline estimates from Birdsey and Heath (1995) are used in preparing the forestry baseline for the President's "Climate Change Action Plan" (Clinton and Gore 1993).

Reporting and Information for Landowners

We have synthesized and expanded the estimates of C storage over time for the major forest types in the conterminous United States (Birdsey 1996). The estimates include the C stored in live trees, understory vegetation, litter and other organic matter on the forest floor, coarse woody debris, soil, and timber removed from the forest. The estimates cover 120 years beginning with the regeneration of clearcut timberland, cropland, or pasture. Birdsey (1996) includes C yield tables designed to represent the most common forest types and conditions in nine regions of the conterminous United States. Carbon yield tables are reported for natural

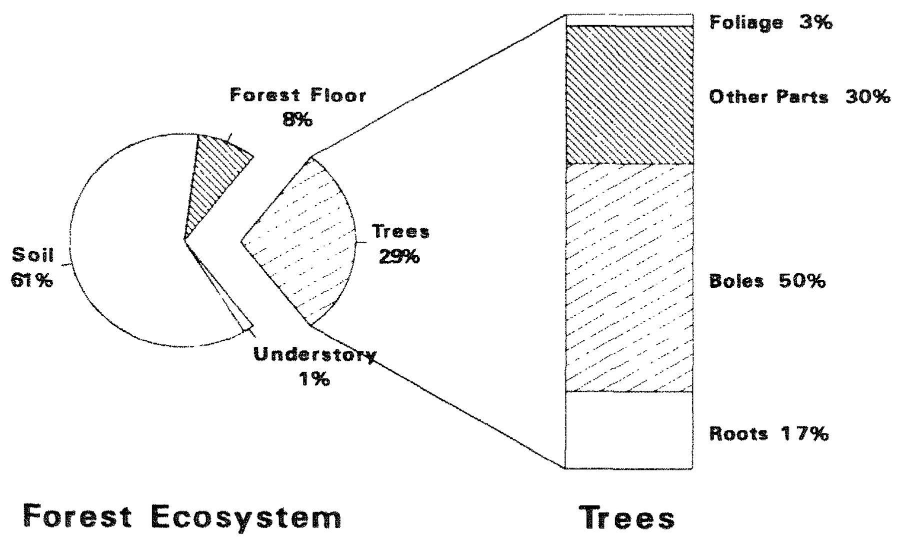

Figure 1.—Allocation of carbon in forest ecosystems and in trees, U.S. forests, 1992. Total storage in the U.S. is 54.6 Pg.

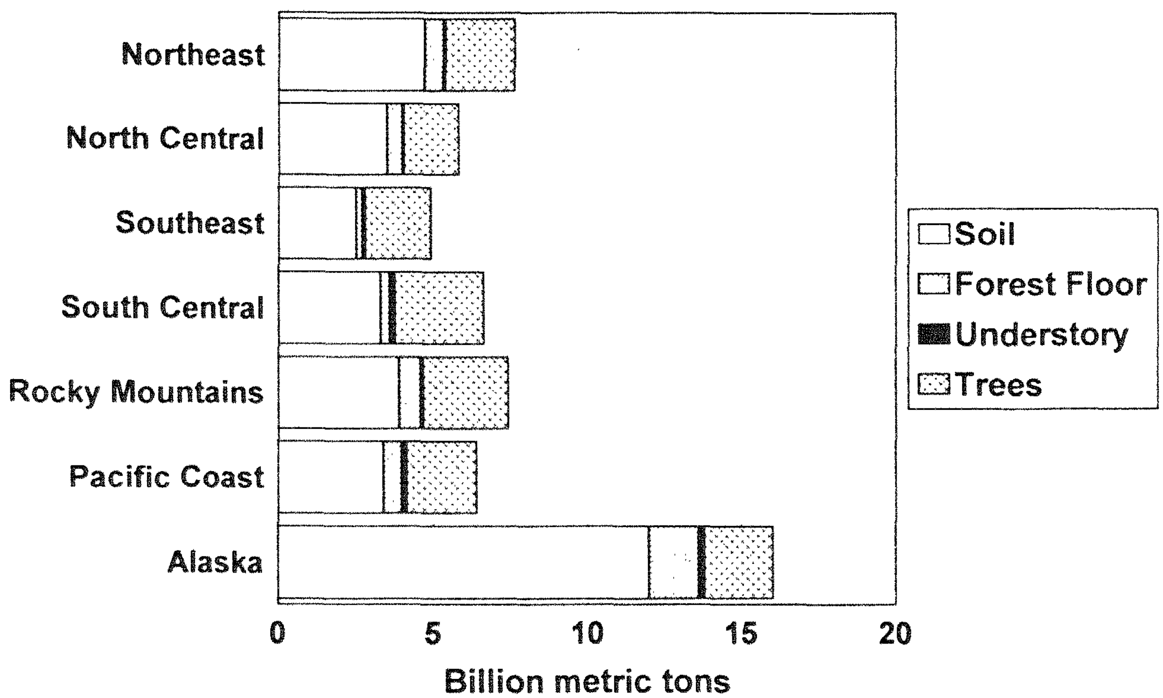

Figure 2.—Total carbon storage by region and ecosystem component, U.S. Forests, 1992.

forest types and plantation species that are harvested and regenerated, and for pasture or cropland that is planted with trees or allowed to revert naturally to forest. Different site productivity classes and management intensities are included for some regions. All of the estimates represent expected regional averages for different vegetation classes (e.g. by forest type and past land use), actual yields on specific tracts of land will be more or less than the regional averages.

Carbon yield tables can be used to analyze the effects of specific actions outside the context of economic or policy models. The tables provide the basis for estimates of C storage in forests that would result from reforesting marginal crop and pasture land and increasing timber growth on timberland. The impacts of two of the action items in the President's plan for reducing greenhouse emissions were estimated with C yield tables: reducing the depletion of nonindustrial private forests and accelerating tree planting in nonindustrial private forests (Clinton and Gore 1993). On the individual scale, guidelines for voluntary offsets proposed by the Department of Energy have adopted carbon yield tables (U.S. Department of Energy 1994).

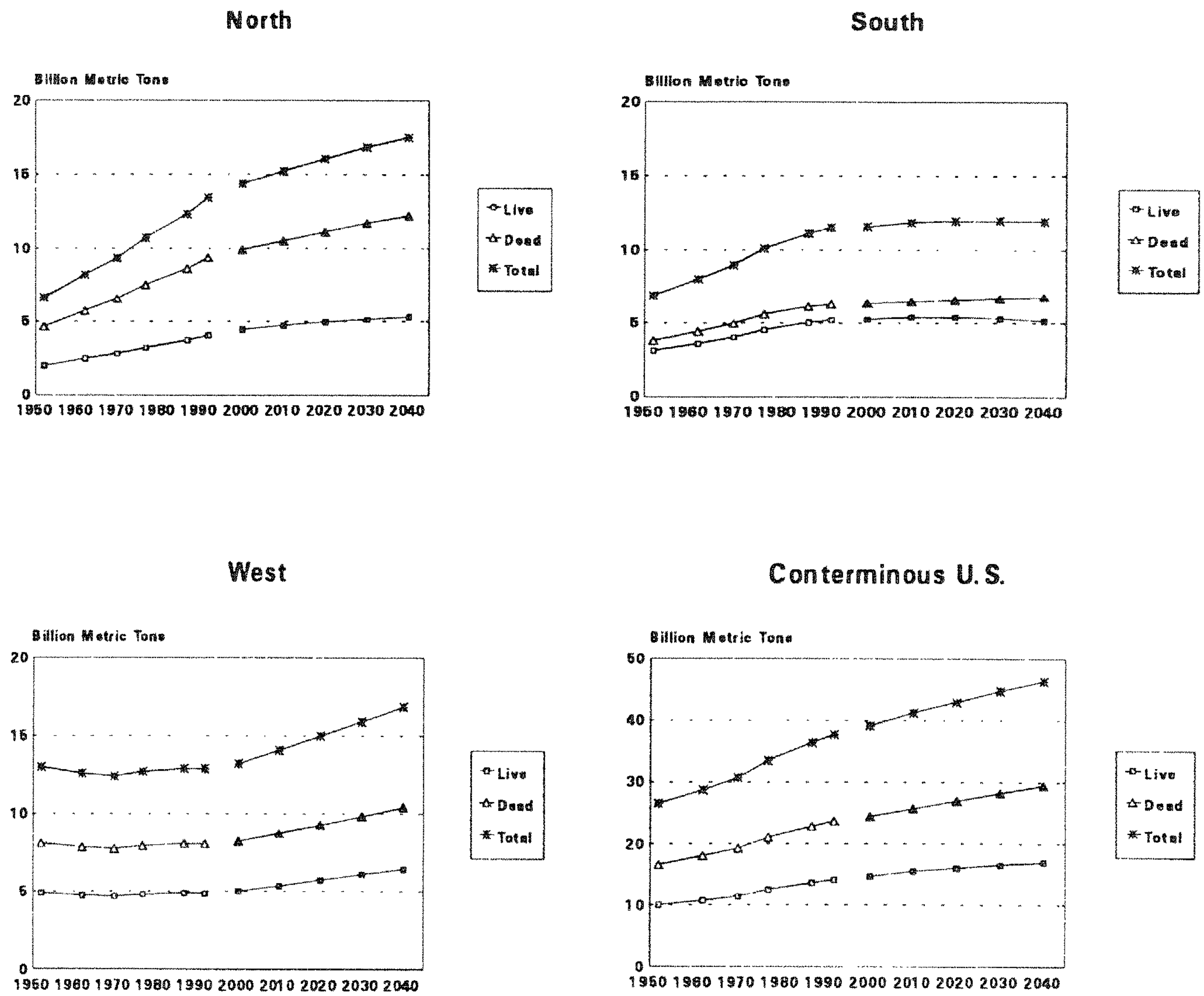

Figure 3.—Carbon storage in live (tree and understory) and dead (soil and forest floor) organic matter, conterminous U.S. forests, 1952-2040.

FUTURE ANALYSES

In looking ahead to the 1998 RPA Assessment, we are beginning a complete overhaul of the FORCARB model to reduce uncertainties in estimates of components of the C budget, expand the analysis capabilities for additional scenarios, improve the linkages with other models, and update the modeling techniques for public lands. A separate modeling effort will cover Alaska, which accounts for more than 1/4 of all C in U.S. forests and is a key component of the northern boreal forests of the world.

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HUMAN ACTIVITIES AND NATURAL RESOURCE INTERACTIONS: AN OVERVIEW OF THE *HUMANI* PROGRAM ELEMENT OF THE FOREST SERVICE'S GLOBAL CHANGE RESEARCH PROGRAM

Bernard J. Lewis[1] and Martin F. Price[2]

Since the 1970's, social scientists have been using the term 'global change' to refer to changes in international social, political, and economic systems, particularly in the context of concerns about international insecurity and decreases in the quality of life (Price 1989). In many ways, this anthropocentric use of global change anticipated the concept of sustainable development, first brought to international attention by the World Commission on Environment and Development in 1987 and subsequently adopted as a policy objective by governments and other institutions around the world.

The HUMANI element of the Forest Service Global Change Research Program (FSGCRP) is concerned with the interactions between human activities and global change, i.e., how these activities may both cause, and be affected by, global change. Three broad problem areas for research have been identified:

(a) Assessment of ecosystem change impacts: Identification and assessment of the effects of forest ecosystem responses to climate change on communities and society;
(b) Evaluation of forest policy options: Identification and evaluation of policy options in rural and urban forestry for mitigating and adapting to the effects of global change;
(c) Implications for forest management: Research on the integration of risks associated with potential climate change into rural and urban forest management decision processes.

This paper presents a brief overview of the context for HUMANI research, ongoing and planned HUMANI activities, and some suggestions for possible future HUMANI research directions.

THE HUMAN DIMENSION RESEARCH CONTEXT FOR *HUMANI* ACTIVITIES

A variety of organizations both in the United States and abroad are involved in conducting research on human dimensions of global change (HDGC). These groups provide a reservoir of knowledge relevant to HUMANI program activities. An awareness of the linkages among this web of knowledge and experience will be an important ingredient in the effectiveness of subsequent HUMANI research efforts. In the most general terms, the HD research context for HUMANI activities includes:

- Other elements of the FSGCRP
- The mission and programs of the U.S. Forest Service
- Global change research efforts within the United States
- International research on HDGC: International organizations and individual countries.

Research in HUMANI problem areas needs to complement and enrich that conducted within the other FSGCRP program elements, both via communication and the exchange of knowledge. This may frequently involve using models that include human, as well as geophysical and biophysical systems. The vast majority of the 191 million acres of forests and grasslands managed by the U.S. Forest Service are simultaneously natural and human settings; and understanding how human-ecosystem *interactions* shape present and future conditions of these settings is a task for natural and social scientists working together on different dimensions of the same phenomenon. In this regard, the National Forest System represents a wealth of empirical possibilities for accomplishing this task as part of the agency's mission (USDA Forest Service 1995).

This also points to the importance of the broader context of Forest Service priorities, programs, and capabilities. At the highest policy level, HDGC research themes are evident within the four priority research and management actions defined by the Chief in his "Course for the Future" speech during the 1994 Forest Service Leadership meeting in Houston, Texas. One major theme is to increase understanding of the human dimension of ecosystem management. This also was emphasized in the Forest Service's "Strategy for the 90's for Forest Service Research" and in the National Research Council's 1990 report "Forestry Research: A Mandate for Change." There are also important linkages between the FSGCRP and assessments conducted under the Resource Planning Act (RPA), with respect to which the Forest Service has played and will continue to play a major role. Specific areas of mutual interest relating to HDGC include:

- Estimation of expected changes in resource productivity and species composition
- Analysis of the economic impacts of global change and the effects of policies on atmospheric chemistry though linkage of global change models and RPA assessment models
- Identification and evaluation of policy options for mitigating or adapting to global change.

The US Global Change Research Program (USGCRP) was established in 1989 to combine and coordinate the research and policy development activities on global change of various federal departments and agencies. It is organized under the auspices of the Subcommittee on Global Change

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Research of the National Science and Technology Council's Committee on Environment and Natural Resources Research. The broad context and scope of the USGCRP is described in "Our Changing Planet", an annual report prepared by the Office of the USGCRP. The Office's research programs in the social, economic, and policy sciences are organized around the following themes: 1) International population trends and the human condition; 2) Patterns of trade and global economic activity; and 3) Adaptation and mitigation, including environmental resource use and management. The USGCRP is currently expanding its efforts with respect to two elements involving HDGC themes:

- Analyzing the impacts and consequences of global change on environment and society
- Developing tools for assessing national and international policies and options for responding to global change.[3]

Finally, there is also a growing body of HDGC research occurring as part of programs conducted at the national level within a number of countries, or under the auspices of a variety of international organizations. While it is not possible to summarize these efforts here, an overview of the organizations and countries involved—the latter including nine European countries plus Canada and the United States—as well as their HD-related foci of research, may be found in Price and Lewis (1995). All of the above suggests that those engaged in HUMANI research have a wealth of resources from which to draw, including the communicative links with those thinking about and working on various aspects of human-nature interactions and linkages of the latter to global environmental change.

ONGOING AND PLANNED *HUMANI* ACTIVITIES AND ACCOMPLISHMENTS

In the 1992 FSGCRP Plan Update, a number of broad objectives were identified for the HUMANI element for the period of 1992-1996. These included:

- Linkage of econometric forest sector models with carbon budget models, to allow analysis of changes in commodity and non-commodity resource outputs and values, and evaluation of alternative policies for mitigating or adapting to global change;
- Development of an integrated model, linking an econometric model of potential land use changes resulting from climate change scenarios with a forest sector model, to evaluate land use and vegetation interactions;
- Identification of communities and social groups at risk from changing urban and rural forest conditions, based on sociological case studies of analogous situations;
- Identification of historical (and archaeological) relationships between climate change, ecosystem conditions, and society;
- Identification of changes in resource outputs and values likely to result from changes in forest health and productivity, as a basis for policy and management planning;
- Identification and evaluation of national and international forestry strategies for mitigating and adapting to global change.

During this period, HUMANI activities in the Southern Region have focused on the socioeconomic impacts of global change on forests, especially potential impacts in the southern pine timber market, with research in the following areas:

- Comparison of models of the economic impacts of potential climate change scenarios on southern commercial forest inventories;
- Examination of the effects of global change on aesthetic forest resources in the southern Appalachians;
- Exploration of the utility of existing biological data and impact information for economic modeling;
- Exploration of the suitability of existing economic criteria for assessing global change damage to forests;
- Examination of the economics of cost-share tree planting for sequestering carbon emissions.

In the Northern Region, attention has centered on understanding the effects of historical and current land use and management intensity on regional carbon dynamics, and this has included the modeling of carbon dynamics in contrasting environments along an urban/rural gradient. Among the activities of the TERRA Laboratory is included a HUMANI-related project designed to:

- Develop an initial understanding of the social forces affecting landowners' land use decisions in northeastern Colorado;
- Determine the relative significance of enterprise, socio-cultural, and political-economic factors needed for an economic model linked to an ecological model.

In the Interior West Region, activities during 1992-1996 have been concerned with assessing the impacts of humans on ecosystems and landscapes and evaluating management options from ecological, economic and social perspectives to enhance the sustainability of human populations and ecosystems. Current HUMANI research foci include:

- Assessing the impacts of ecosystem management policies and practices on economic stability and development
- Improving understanding of the environmental history of the Rio Grande Basin, the historic and contemporary human role in basin ecosystems, the nature and extent of anthropogenic disturbances to the basin, and the sustainability of cultural diversity
- Synthesizing literature on suburban and rural land use change in a wildland setting to produce a scheme for classifying human development near forests based on density and type of development.

[3]More details on the variety of agencies and organizations participating in the USGCRP and their HD-related research may be found in Price and Lewis (1995).

The Pacific Region has to date sponsored a workshop focused on defining parameters of the human dimension (see following section) and provided support for several integrative reports on the status of HDGC research in the Forest Service and elsewhere (Price and Lewis 1995).

On an overall basis, future goals (from 1997 onwards) in the HUMANI element have been anticipated to include:

- Improvement of integrated forest sector and carbon budget models, to incorporate the effects of climate change on local economies and evaluate the cumulative effects of local management decisions on gas exchanges with the atmosphere;
- Projections of the likely effects on forest ecosystems of expected changes in land use;
- Research and analysis of public perceptions of, and responses to, global change.

These objectives were identified in 1992. Subsequently, it has been recognized that it may be desirable to define other research priorities for the HUMANI program element.

MAPPING THE TERRITORY: RECENT FOREST SERVICE WORKSHOPS ON HDGC

Both the scope and the relatively recent origin of the FSGCRP—along with the equally recent emergence of attention to the human dimensions of natural resource management in ways that explicitly link natural and social processes at varying scales—have required a great deal of effort by those involved at "getting a handle on what we are dealing with," both conceptually and in terms of practical implications for policy and management. In response to this, the Pacific, Northern, and Interior West regions each sponsored a workshop in 1994-1995 to review progress and map out future program directions. The Pacific and Northern region workshops focused exclusively on the HUMANI program element, while the Interior West workshop involved all four program elements, with two topics devoted to HUMANI components. This section presents a brief overview of conclusions and recommendations emanating from each of these workshops.

The objective of the Pacific Region Workshop (Geyer and Shindler 1994) was "to explore the link between human activities, ecosystems, and global change and lay the groundwork for a meaningful program of cooperative interdisciplinary research". The participants agreed that four principles should guide the definition of future HUMANI activities:

- Questions addressed should be relevant to the USDA Forest Service.
- Research should be integrated with other FSGCRP program elements.
- Research should emphasize linkages between national policy decisions, regional ecosystem management, and local level stewardship.
- Research strategies and management implementation should incorporate opportunities for social learning.

Recommendations for future HUMANI activities were divided into four thematic areas. These may be found in Table 1, along with research and management topics identified as important research concerns.

A first set of topics centered on institutional and organizational structures and processes that would be efficient and flexible in defining and addressing problems and opportunities related to human and environmental dimensions of global change. The need for understanding the nature and interrelationships of human perceptions, values, and behaviors related to global change formed a second broad topic of concern. A key aspect of this concerned how perceptual and objective aspects of risk and uncertainty regarding the nature and scope of the phenomena contribute to shaping human actions. The importance of assessing not only the nature and intensity of values, but also perceived tradeoffs among them, was also stressed; as were mechanisms for effectively conveying information conducive to responsible public judgements on the part of stakeholders and the broader populace. Key behavioral manifestations of values and perceptions, as reflected both in household consumption patterns and in relation to broader social and biophysical carrying capacities, were other key topics of concern.

A third key theme focused on local communities and the role of agency-public interactions in enhancing understanding of the significance of global change processes for both short and long term community growth and stability. This will require recognizing the limits to sustainability of ecological and human systems, including societal thresholds for assessing tradeoffs. Such a shared understanding can only be achieved via communication networks in which public decision makers, resource users, agency administrators and managers, and the broader public are active participants. A fourth set of topics was concerned with operationalizing the concept of sustainability with respect to both ecological and human systems. Reliable estimates of biophysical and social carrying capacities, economic and social costs of achieving levels of sustainability, impacts of changes in land use, and the ability to learn from past land use practices and resource consumption patterns were all identified as important priorities.

The objective of the Northern Region workshop (Emery and Paananen 1995) was "to identify critical social science issues where human needs, expectations, and values meet forest ecosystems and natural resource policy". The participants at this workshop developed six broad categories of research foci. These were recast and prioritized at a subsequent meeting. Participants at the latter meeting stressed the need for baseline social science data that integrates information on social, physical, and biological systems. Their suggestions for research at a variety of social scales involving both rural and urban forests may be found in Table 2.

Table 1.—Themes & related topics for HUMANI research identified at the Pacific Region workshop (May 1994).

1) *Governance: Policy processes and institutional behavior*
- Institutional structures: Role in contributing to undesirable change and acting as barriers to program goals
- Organizational structures: Incorporating common focus for GC research
- Criteria and protocols to guide decisions for allocating scarce resources
- Organizational adaptive capacity: Flexible mechanisms for responding to surprise events or unexpected outcomes

2) *Values and perceptions: Human behavior and public understanding*
- Public's current understanding of GC, including factors influencing risks and uncertainties
- Social science information: Values and desires as distinct from tradeoff assessments
- Social acceptability vs. biophysical system capabilities: Perception and reality
- Information for responsible public choices: Nature and mechanisms for conveyance
- Green practices and household economics: Impact on consumption patterns

3) *Local practices: Effects on communities and agency-public relationships*
- GC impacts most significant for growth/atrophy of communities in short and long run
- Criteria for defining local limits of biophysical and social sustainability
- Public thresholds relevant to assessing resource tradeoffs
- Value and potential application of community case studies for assessing GC and agency response
- Local communication networks, including key decision makers, for access, use and control of resources
- Social, political, and organizational mechanisms to enhance agency-public interaction

4) *Sustainability: Ecosystem management (EM) and scales*
- Degrees of sustainability for natural and social systems: Economic, social & environmental costs
- Social vs. biophysical carrying capacities: Definition and assessment; Locations and circumstances where we are at or beyond carrying capacities
- Historic human consumption and land use patterns: Learning potential for future options
- Land use scenarios: Effects on ecosystem management
- Ecosystem Management: Local and national sustainability, and relevance on a global scale

Source: Geyer and Shindler (1994) Slightly modified from original phrasing

Table 2.—Prioritized topics for HUMANI research resulting from the Northern Region workshop (1995).

A. *Behaviors and demography*
- How do trends in human uses of forests affect the ecosystem/s?
- How do demographic trends affect forest use?
- What are the impacts of human actions on forested ecosystems?

B. *Social impacts of forest ecosystem management and policy*
- What are the intended and unintended consequences of management and policy?
- What are the differential effects of forest management actions and environmental changes across social groups and time?
- How can risk assessment techniques be used to evaluate social impacts of changes in forested ecosystems?

C. *Technology*
- How do various technologies affect the ways people use forests?
- How will changes in forested ecosystems affect technologies?

D. *Human response thresholds to environmental changes*
- What triggers human responses to changes in forested ecosystems?
- How do people respond to changes in forested ecosystems?

E. *Stakes and stakeholders*
- What methods can be used to identify stakeholders and communities of interest at various scales?
- Who are the relevant stakeholders and communities of interest at various scales?
- What methodologies can be used to identify and evaluate tradeoffs among benefits and costs of management and policy options for various stakeholders?
- What are the tradeoffs among benefits and costs of management and policy options for various stakeholders?

F. *Values and social constructions*
- What are the sources of environmental values?
- What are the interactions between environmental values and changes in forested ecosystems?
- How do social constructions of the relationships between nature and humans affect options for responding to change in forested ecosystems and landscapes?
- What are the relationships among values, beliefs, perceptions, and behaviors?

Source: Emery and Paananen (1995)

Critical research foci included the interrelationship between human behaviors and the status of forested and other ecosystems, including the range of influences that may trigger changes in such actions and behaviors. The significance of demographic manifestations of these behaviors for ecosystem stability was also explicitly recognized. Another key concern involved social impacts of resource policy and management decisions, especially in terms of how both intended and unintended consequences are experienced by different individuals and groups. The importance of incorporating measures of risk in assessing social impacts was also stressed, as was the relationship between changing technologies and forest uses. Another high priority was the need for identifying stakeholders and communities of interest at varying social scales, as well as assessing tradeoffs among benefits and costs of management and policy options as both perceived and actually experienced by different stakeholders. The nature of environmental values and their relationship to ecosystem change was also emphasized, as was their interplay with other key psychological attributes and behaviors in forming social constructions of human-ecosystem interactions. The impacts of such constructions need to be considered as they are expressed in changing patterns of forest uses and their concurrent effects on ecosystem health.

In April 1995, the Interior West region sponsored a GC workshop for the purpose of reviewing accomplishments over the past five years, outlining the implications of research results for natural resource management, and identifying future research needs. The workshop encompassed all four elements of the Interior West GCRP and resulted in a document containing twenty-eight papers, two of which dealt explicitly with HUMANI-related subjects (Tinus 1995). These focused on:

- Historic interrelationships of humans and the ecosystems of the Middle Rio Grande Basin
- Collaborative decision process support tools from global change research.

An ongoing study of the environmental history of the Middle Rio Grande Basin in New Mexico examined the historic period from 1540 A.D. to the present (Scurlock 1995). Four spatial and temporal models sequentially encompassing the entire historic period were described, in which climatic data is integrated with extant and new historical and archaeological data to model long term ecological trends in terms of: a) historic stream hydrology-morphology; and b) river-floodplain biological/ecological components. Testing and revision of the model is expected to provide a context for improved bioremediation, evaluation of sustainability of land use practices, and development of appropriate management programs. Scientists are also reviewing recent advances in geographic information systems (GIS) that will enhance collaborative decision capabilities for land and resource management (Fox and Faber 1995). An application of collaborative GIS techniques in the Arapaho-Roosevelt National Forest is described, and potentials for further enhancement of this management tool are discussed.

DIRECTIONS FOR FUTURE RESEARCH IN THE *HUMANI* ELEMENT

The variety of ongoing GCRP activities, the wide array of themes suggested in regional workshops, and the range of projects being conducted by other organizations in the United States and elsewhere, provide a basis for future research within the HUMANI element of the FSGCRP. From the perspective of HUMANI researchers, this also includes how we identify topics of actual or potential importance to understanding GC processes; how we acquire and organize knowledge and information about these processes; and how we communicate and share this knowledge with fellow researchers, resource managers, and others in different socio-geographic settings and contexts. Table 3 contains the broad subject areas that were identified as important research concerns by participants in the workshops described earlier; these served as headings within which more specific topics were situated.

One way of conferring a degree of order to the topics depicted in Table 3 is by relating them to one or more ***levels of HD analysis***. When we consider the movements and characteristics of people "on or across the land," as do those topics in Table 3 related to demographics and population dynamics, this *biophysical* level may be re-characterized as the social-geographic level of analysis. A person, however, is not simply a bipophysical body, but someone to whom the natural and human worlds are significant in various ways. A number of topics in Table 3—i.e., those concerned with perceptions, values, attitudes, as well as individual behaviors either contributing or responding to GC processes—are focused at the level of the *person*. Persons, moreover, interact and form relations with one another; and characteristics of these *relations* bring us to the level of the group or *society*. A variety of topics in Table 3 address this level—e.g., understanding patterns of social relations (social structures); assessing social impacts on relations among individuals and groups; understanding institutions as relational patterns in which actors occupy particular roles that shape behavioral expectations; and the whole class of interactions and relations specifically concerned with policy and management activities related to human-nature interactions and their global manifestations. Finally, when beliefs, values, modes of perception, etc., come to be *shared* within a group or society and passed on from generation to generation, we are concerned with the level of *culture*. A society's cultural fabric gives meaning to its members' interactions with nature (the ecosystem) over time (this is the basis of the historical 'cultural landscape' research perspective), including the technologies they develop and employ in interacting with the natural world.

By relating the list of topics in Table 3 to levels of analysis for the human dimension—i.e., biophysical–personal–societal–cultural—we may begin to view the human dimension of global change systematically in terms of actors, relations, and processes that are manifest at different levels of social scale, including the biophysical level through which human actions and behaviors are directly linked to global environmental change. This requires not only recognizing