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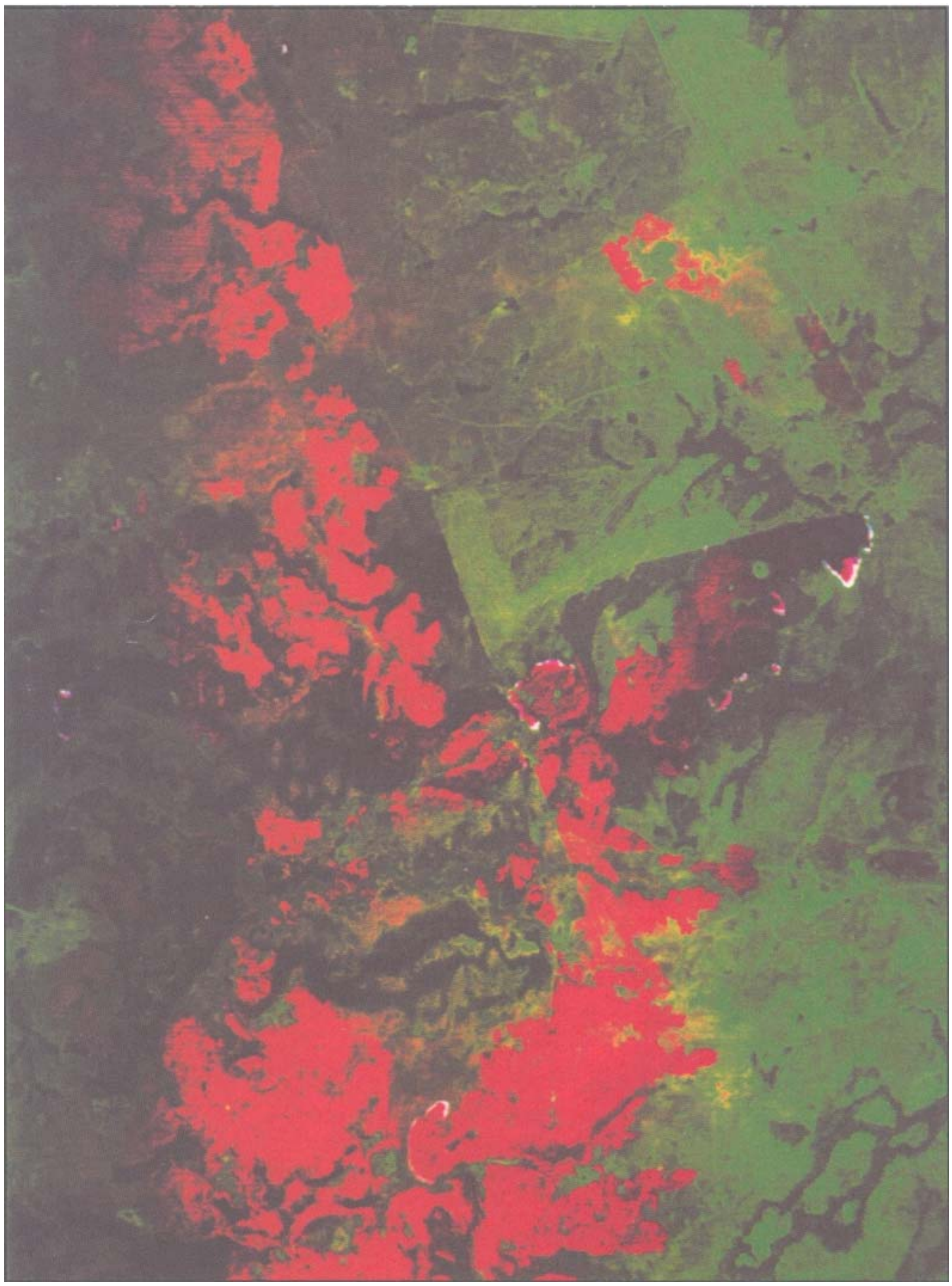
Forest Service

**Pacific Southwest
Research Station**

General Technical Report
PSW-GTR- 161

Atmospheric and Biospheric Interactions of Gases and Energy in the Pacific Region of the United States, Mexico, and Brazil



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Abstract

Bytnerowicz, Andrzej, technical coordinator. 1997. **Atmospheric and biospheric interactions of gases and energy in the Pacific region of the United States, Mexico, and Brazil.** Gen. Tech. Rep. PSW-GTR-161 Albany, CA: Pacific Southwest Research Station, Forest Service, U.S. Department of Agriculture; 42 p.

Anthropogenic activities of the past century have caused a dramatic increase in global air pollution. This process has accelerated in the past few decades, and emissions of carbon dioxide, nitrogen oxides, or chlorofluorocarbons caused serious changes in the earth's climate, e.g., increased temperatures or elevated ultraviolet-B radiation. These changes, together with more severe droughts, forest fires, and air pollution (ozone, nitrogen or sulfur compounds), may have pronounced effects on terrestrial ecosystems. Changes in global and regional carbon and nitrogen cycles as well as changes in water resources and cycling have also taken place. The current and predicted atmospheric and biospheric interactions of gases and energy in the Pacific Region of the United States, Mexico, and Brazil are described in this document. The role and status of simulation modeling for weather predictions, production and transport of smoke from biomass burning, and air pollution uptake by forest canopies are discussed. To meet growing needs for environmentally sound forest management, priorities for research on air pollution, forest fire effects, nutrient cycling, water resources, and development of models are listed.

Retrieval Terms: air pollution, climate change, forests, nutrient cycles, plant responses, simulation modeling

Technical Coordinator

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Acknowledgments

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Atmospheric and Biospheric Interactions of Gases and Energy in the Pacific Region of the United States, Mexico, and Brazil

Andrzej Bytnerowicz, *Technical Coordinator*

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In Brief...

Bytnerowicz, Andrzej, technical coordinator. 1997. **Atmospheric and biospheric interactions of gases and energy in the Pacific region of the United States, Mexico, and Brazil:** Gen. Tech. Rep. PSW-GTR-161. Albany, CA: Pacific Southwest Research Station, Forest Service, U.S. Department of Agriculture; 42 p.

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Increased concentrations of air pollutants or "greenhouse" gases (carbon dioxide, methane, chlorofluorocarbons, nitrous oxide, and others) in the earth's atmosphere increase air temperature as well as deplete the stratospheric ozone layer causing elevated ultraviolet-B radiation-which may be deleterious to sensitive plants, animals, and humans. Anthropogenic activities, such as human-caused forest fires, are major sources of greenhouse gases, as well as the use of fossil fuels that cause increased emissions of air pollutants such as nitrogen and sulfur oxides and ozone formation which may be toxic to various forms of life.

Elevated emissions of carbon dioxide, methane, and nitrogen oxides affect global cycles and pools of two elements of major biological importance: carbon and nitrogen. However, other human activities, especially harvesting of old-growth forests in the Pacific Northwest of the United States or in the Brazilian Amazon, may affect global carbon resources even more. Whether boreal forests will continue to be a carbon sink (an absorber of increasing amounts of carbon dioxide) will depend on the extent of land use conversion from forests to other uses, as well as the degree of global warming and the soil temperature and moisture status of these forests. Elevated nitrogen deposition, among other effects, may lead to shifts in species composition in severely affected ecosystems. For instance, grasses may expand to other species' habitats in various ecosystems worldwide. Increased emissions of nitrogen may also cause some beneficial effects, but only in the short term. More available nitrogen in soil may initially improve vegetation growth and increase the capability of forests and other ecosystems to sequester increasing amounts of carbon dioxide.

Climatic changes may also affect water availability in the Pacific region of the United States. Increased temperatures could cause a significant reduction in snow cover, melting of glaciers and permafrost, and changes in stream flow. As a consequence of these changes various effects can be predicted, such as increased surface warming (less solar energy reflected from the snow-covered earth surface) or reduction of water availability during the vegetation growing season. These effects may cause major changes in western ecosystems and agricultural activities in the west.

Interactions between atmospheric and biospheric processes are very complex, and various responses of ecosystems to the occurring changes can be expected. Some of the expected changes due to elevated concentrations of carbon dioxide could be increased yields of some plant species, altered susceptibility of plants to drought, and shifts in species composition of natural ecosystems. Some of the effects of the increasing nitrogen emissions and deposition may include changes in plant growth rates and susceptibility to air pollutants and other environmental stresses.

To predict the effects of air pollutants on forest ecosystems, simulation modeling plays a key role. Although the absolute results of these models (i.e., geographically specific "predictions" or "forecasts") should be viewed with great caution, they are one of the few tools available for assessing the most sensitive components of the environment. Some models that have provided the most useful results include regional scale weather models, models simulating production and transport of smoke pollutants from biomass burning, models simulating uptake of gaseous pollutants by forest canopies, and terrestrial ecosystem biogeochemical models. By using these models, forest managers can be provided with useful data to help them implement the best environmental policy decisions, such as regimes of prescribed burning, fertilization, or timber harvesting. Future research needs will include assessment of emissions of trace gases from forests, better understanding of a relationship between nitrogen and carbon global and regional cycles, evaluation of nitrogen deposition to forests, etc., which will also provide new information to help managers with revising environmental policy.

Introduction

Andrzej Bytnerowicz,[1] Sue Ferguson,[2] and Mark Poth[1]

Because of human activities, such as the use of fossil fuels and prescribed forest fires that cause unprecedented rates of global climate change, the earth's average surface temperatures are expected to increase from 1.5 to 4.5°C before the end of the 21st century. Although the magnitude and rate of expected climate change will not be steady, this continued warming by increased concentrations of air pollutants or "greenhouse" gases (carbon dioxide, methane, chlorofluorocarbons, nitrous oxide, and others) will be enhanced because of cold periods caused by a number of internal and external climate forcings. These should be short-lived, however, compared to the greenhouse gas contribution to warming (Intergovernmental Panel on Climate Change 1990, 1992).

Cess and others (1995) found disagreement between the measured and predicted absorption of solar radiation by clouds, indicating a very high degree of uncertainty in predicting the rate of the expected warming. Clouds have been shown to reduce net solar radiation at the sea surface more efficiently than previously believed-much higher amounts of radiation are trapped by water contained in clouds than current models would predict (Ramanathan and others 1995). On the basis of revised simulation models, future climate changes may be less dramatic than previously thought. However, research has shown that the future climate should be warmer, with less precipitation and slower surface winds (Kerr 1995).

Because of this inability to predict the exact rate of change, precisely how regional climates will change is unknown. However, studies have shown that due to a consistent poleward migration of atmospheric moisture, and the normal latitudinal distribution of incoming solar radiation, most regional changes in climate are expected to occur first over land areas in the northern latitudes (Ferguson 1995, Hare 1988, McBeath 1984, Weller 1993). This means that most climate change in the Pacific states of the United States is expected to occur first in interior Alaska, with less change elsewhere. Small changes in climate, however, can cause dramatic biological responses in areas with steep elevation gradients, like the mountainous western United States (Barbour and others 1991).

Interactions between climate/ atmospheric chemistry and ecosystems in the United States Pacific region determine if current natural landscapes will remain intact (U.S. Congress 1993). Unlike farm land or other areas in which management can radically and quickly adapt to changing conditions, natural landscapes cannot be managed (Intergovernmental Panel on Climate Change 1990). For instance, climate and atmospheric deposition are important variables that affect ecosystem processes such as primary production or decomposition. These processes directly affect climate and atmospheric systems by modifying fluxes of water and various greenhouse gases. Such effects may result in immediate changes in climatic properties. This difficulty is because of the complexity of interactions between atmospheric and biospheric processes as a result of various time and spatial scales of their individual components *(fig. 1, Intro)* (Ojima and others 1991).

Various responses of ecosystems to these changes and interactions may be expected. In many cases the strategy of the key ecosystem components is endurance (plant surviving a drought) or avoidance (wildlife leaves for better areas). Because of the very complex interactions between all facets of ecosystems over very long time scales, the ability to manage physically and biologically complex natural landscapes is limited for typical successional time scales (50 to 300 years for ecosystems that include woody plants).

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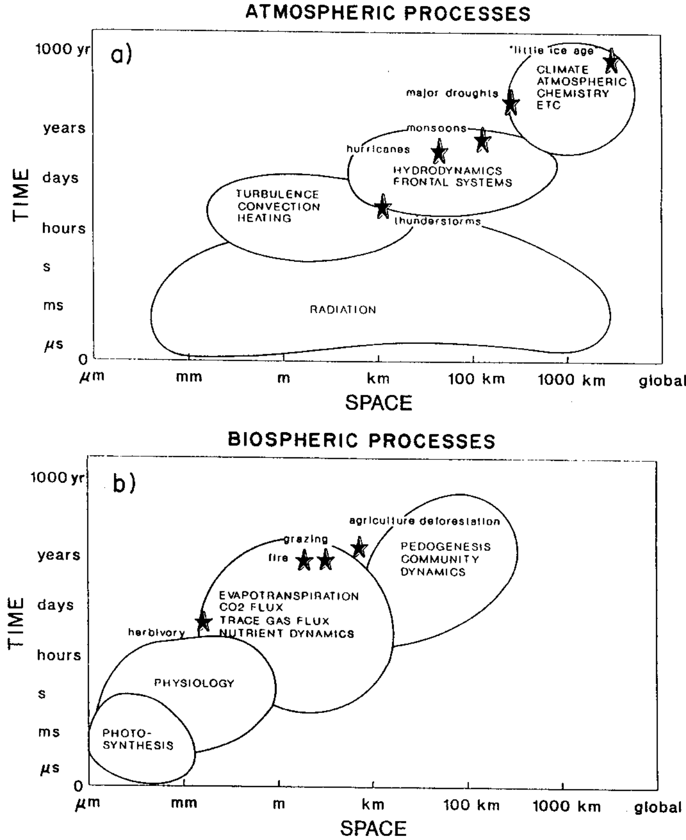

Figure 1-Spatial and temporal representation of (a) major climatic processes and (b) biospheric processes (Ojima and others 1991). Reprinted with permission from D.S. Ojima and others: Critical issues for understanding global change effects on terrestrial ecosystems. Ecological Applications 1(3), p. 319. Copyright 1991, Ecological Applications.

Given the expected changes, the future of natural areas and forests may be at stake. Hence the scope of our work is both geographically and biologically wide ranging. Our region, which reaches from the tundra to the tropics, includes unique biological resources. Many species such as giant sequoia and bristle cone pine hold special ecological value. Other large areas hold both ecological and economic importance, such as the commercial forests of the Pacific Northwest.

This report describes the state-of-the-science studies of the Pacific Global Change Research Program of the Pacific Southwest Research Station on the effectiveness of ecosystem management practices and simulation models to monitor greenhouse gases, nutrient cycles, carbon cycles, and energy flows in the atmospheres and biospheres of the Pacific region of the United States, Mexico, and Brazil.

Part I

Synthesis of the Current State of Knowledge about Atmospheric and Biospheric Interactions

Exchanges of Gases and Aerosols Between Atmosphere and Terrestrial Ecosystems

Nancy Grulke,[1] Paul Miller,[1] Roger Ottmar,[2] Mark Poth,[1] and Philip Riggan[1]

Emissions of certain air pollutants (often called "greenhouse gases and aerosols") have pronounced effects on global temperatures, the amount of ultraviolet (UV-B) radiation reaching the earth, and the cycles of carbon and nitrogen. Forests and other terrestrial ecosystems may serve as sources and sinks for these pollutants. Rates of exchange of gases and aerosols between atmosphere and terrestrial ecosystems depend on many biotic and abiotic factors. Climate warming, forest fires, nutritional status of soil, or application of various management practices may be listed as some of the most important factors in this regard. Primary air pollutants, such as hydrocarbons and nitrogen oxides, can serve as precursors for formation of secondary pollutants, such as ozone, peroxyacetyl nitrate, nitric acid or nitrate aerosols. These secondary pollutants may have direct toxic effects on plants, animals, and humans, or may significantly affect forest health and productivity.

Key Greenhouse Gas and Aerosol Emissions

Although consequences of increasing greenhouse gases on the terrestrial ecosystems are still not very well-defined, there is no doubt that their concentrations in the atmosphere are increasing. In the atmosphere, the major carbon constituents that contribute to greenhouse warming are, among others, carbon dioxide (CO_2), methane (CH_4), and chlorofluorocarbons (CFCs) *(fig. 1, Chapter 1).* These gases have an important role in global carbon cycle and can be of natural and anthropogenic origin.

From pre-industrial times to 1990, the atmospheric CO_2 concentration has increased 26 percent (Watson and others 1990), and currently this gas contributes

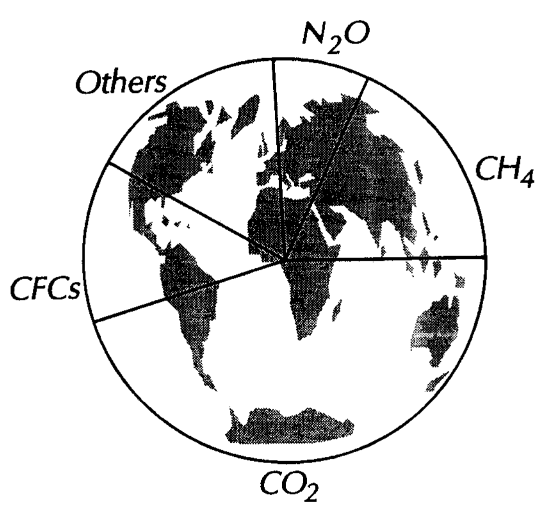

Figure 1 -The relative contribution of the major greenhouse gases to global warming during the 1990's (Ashmore 1990).

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to about 50 percent of the warming. The effect of individual gases on radiation balance may by calculated from a knowledge of the atmospheric concentrations of the gas and its rate of increase, the relationship between concentrations and radiation absorption of that gas, and the extent to which its absorption bands overlap those of other gases. However, it should be emphasized that the presented values of contribution of individual gases to global warming are only estimates (Ashmore 1990).

Concentrations of atmospheric CO_2 measured at the Mauna Loa observatory in Hawaii from the late 1950's to 1990 reflect these changes *(fig. 2, Chapter 1).* Similar trends of increasing CO_2 concentrations are predicted for

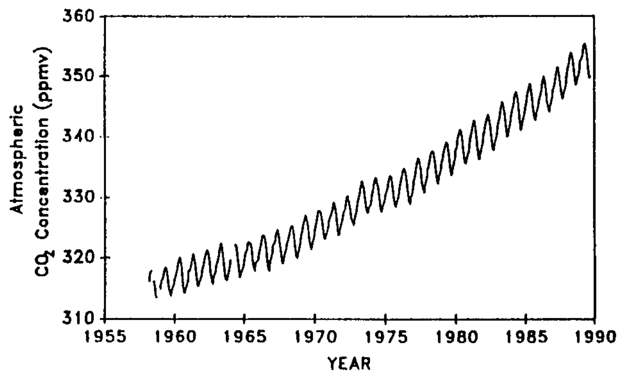

Figure 2-Concentrations of atmospheric CO_2 measured from the Mauna Loa observatory, Hawaii. Reprinted with permission from L.G. Simpson and D. B. Botkin: Vegetation, the Global Carbon Cycle, and Global Measures. In: Dunnette, David A.; O'Brien, Robert J., eds. The Science of Global Change: The Impact of Human Activity on the Environment. ACS Symposium Series 483. Washington, DC: American Chemical Society. Copyright 1992, American Chemical Society.

the near future. However, the carbon-to-nitrogen ratio (C:N) is expected to vary throughout the next century depending on the mix of energy source chosen. More nitrogen in the emissions can produce a cofertilization effect in the terrestrial biomes, which would lead to sequestration of additional carbon. The uncertainty in the C:N ratio will create uncertainty in the measurements of atmospheric concentrations of CO_2 as high as 20 ppm (Keller and Goldstein 1994). The major natural sources of CO_2 are decomposition, respiration, wildfires initiated by lightning, volcanic emissions, as well as inorganic sources such as exchanges between substrates rich in carbonates and water (Solomon and others 1985). Anthropogenic sources of CO_2 include fossil fuel burning, changes in land use (high C density ecosystems converted to urban or agricultural uses with lower C density, low or no C storage, and net C loss to the atmosphere) (Kurtz and Apps 1992), and slash pile and field burning (very rapid carbon release back into the atmosphere, but short-term increase in nutrient status) (Ashmore 1990). The major sinks for CO_2 are photosynthetic uptake by plants and CO_2 absorption within oceans (about 17 percent and 15 percent, respectively, of the atmospheric pool). Atmospheric residence time is about 50 to 230 years (Bolin 1986), and the rate of increase is 0.4 percent or 1.5 ppm per year (Keeling 1983). One-sixth of the increase of atmospheric CO_2 concentrations is attributable to deforestation (Anderson 1992). The more recent estimates show 7.3 to 9.2 Gt C yr^{-1} as a sum of global emissions. Out of that figure, 5.8 to 6.2 Gt C yr^{-1} is attributed to fossil fuel burning and 1.5 to 3.0 Gt C yr^{-1} to tropical deforestation (Gifford 1994).

Methane is the most abundant, reactive trace greenhouse gas (Ehhalt 1985, Khalil and Rasmussen 1990). The major biogenic sources include wetlands and tundra ecosystems, termites, and by-products of digestion. Anthropogenic sources include various agricultural practices such as formation and maintenance of rice paddies, domestic ruminants, biomass burning, natural gas exploitation, and landfills (Ashmore 1990, Ehhalt 1985). The major sink for methane is atmospheric reaction with hydroxy (OH) radicals. The atmospheric residence time of methane is 10 years, and the current rate of increase is 0.9 percent or 0.015 ppm per year (Blake and Rowland 1988, Ehhalt and others 1983).

One of the largest globally significant ecosystem sources of methane are rice paddies (70-170 x 10^9 kg CH_4/yr). The Sacramento River Delta in California is one of the largest centers of rice production in the United States. However, the boreal and arctic biomes are other wet ecosystems that contribute globally significant sources of methane (40-110 x 10^9 kg CH_4/yr). Cattle alone contribute 49-70 x 10^9 kg CH_4/yr. Biomass burning contributes 20-110 x 10^9 kg CH_4/yr, and methane emissions from wildfires in the subpolar regions, Pacific Northwest of the United States, and the tropical savannas are also likely to contribute at a globally significant level (Ehhalt 1985). Emissions of methane may increase because of increases in isoprene emissions. According to the doubling of the CO_2 scenario, the isoprene emissions would be about 25 percent higher than the current emissions mainly because of the expansion of tropical humid forests that have the highest annual emission rates (Turner and others 1991).

Chlorofluorocarbons (CFCs) are the most rapidly increasing greenhouse gas compounds (Prinn 1988). They are important because they react with and destroy stratospheric ozone. Some of the species of CFCs are stable long enough to act as global atmospheric tracers. Most of the CFCs are anthropogenic in origin and include aerosols, refrigerants, and foam packaging (the exception is methyl chloride). After release into the atmosphere, there is a 1- to 3-year delay for net transfer to the stratosphere where CFCs are chemically broken down (Rowland and Molina 1975). The residence time varies for different species, but is in the range of 6 to 170 years (Prinn 1988). The current rate of increase is 4 percent, or 0.015 ppb per year (Ashmore 1990).

The best estimates of all the sources and sinks of nitrous oxide (N_20), a long-lived greenhouse gas, leaves about 30 percent of the observed increase unaccounted for (Keller and others 1986, Khalil and Rasmussen 1992, Matson and Vitousek 1990). The global budget for nitric oxide (NO), a more reactive gas important in tropospheric photochemistry and ozone formation, is similarly out of balance (Davidson 1991). Forest soil may be the origin of some of the N trace gases; according to Anderson and others (1993), forest soil microbes responsible for the production of nitrous oxide produce at a much higher rate than their agricultural soil counterparts *(fig. 3, Chapter 1)* We know that ecosystem soils can respond to disturbance (fire, N additions) by increasing nitric oxide and nitrous oxide emissions (Anderson and Poth 1989, Castro and others 1993). This suggests that emissions from forest soils may be significant and that proper management practices should be applied to minimize these emissions.

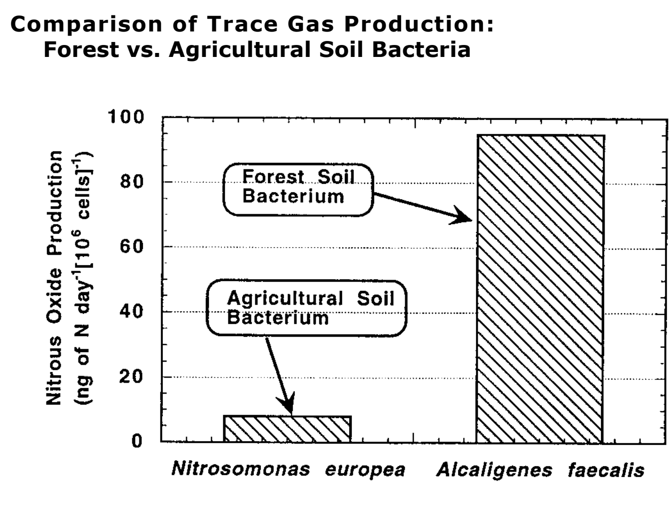

Figure 3-Nitrous oxide production by microorganisms in forest soils and agricultural soils (Anderson and others 1993).

Forests and wildlands can serve as sources and sinks for N_2O, CO_2, and CH_4 depending on how these lands are managed. The Pacific Global Change Research Program (PGCRP) at the Pacific Southwest Research Station, USDA Forest Service, has been gathering baseline data on current rates of exchange in undisturbed forests and related ecosystems; this information is a reference point for future comparisons. In addition, for ecosystems that have demonstrated regional as well as potentially significant global contributions of trace gases, researchers in the PGCRP have begun to evaluate the influence of management on trace gas exchange. Typical forest management practices such as timber harvesting (Anderson and others 1993) and forest fertilization (Matson and others 1992) directly influence carbon storage and cycling, as well as the emissions of greenhouse gases from forest soils, as a result of stimulating nitrogen availability or physically changing soil water availability or temperature regimes. Thus, the choice of land management practices determines the amount of emissions. In some cases, offsite, long-term storage in forest products can offset the C loss from forest ecosystems. This effect is greatest when the forest products are long-lasting and forest regeneration rates are fast (Kurtz and Apps 1992).

Forest Fire Emissions of Radiatively Important Trace Gases and Aerosols

The emitted greenhouse gases affect the earth's radiation balance. Wildland and agricultural fires may now be contributing to climate change depending on their global extent and the strength of their emissions. Best available estimates are considerably uncertain but do show that biomass combustion is likely a primary anthropogenic source of atmospheric aerosols, methane, carbon monoxide, carbon dioxide, and some nitrogen oxides (Crutzen and Andreae 1990, Radke and others 1991). Yet fire is a natural process in many of the world's terrestrial biomes, and thus only a portion of contemporary emissions can contribute to climate change. Fires of human origin could be important in the net flux of radiation-absorbing trace gases if, over the long term, they reduce the amount of carbon accumulated in standing biomass or soils or if they emit a higher proportion of CH_4, CO, or N_2O than would alternative processes of organic matter decomposition. Anderson and Poth (1989) found that burning increases production of CO_2, NO, and N_2O from ponderosa pine, chaparral soils, and tropical savanna. Trace gas flux is a function of soil mineralization and other processes that respond to fire intensity and frequency (Dunn and others 1979, Fenn and others 1993, Poth and others 1995). Various aspects of the effects of fires have to be considered when the budget of emissions of radiatively important gases is calculated. However, forest fires may reduce net production of these gases if total emissions resulting from fires are lower than emissions from natural decomposition processes in forests.

Emissions of particles higher than those found in natural fire regimes could well dominate and compensate for the radiative effects. A high proportion of smoke particles are active as cloud condensation nuclei (CCN) (Hobbs and Radke 1969, Radke 1989, Radke and others 1991, Rogers and others 1991), and their entrainment in clouds can produce more numerous droplets of smaller diameter, thereby increasing cloud albedo and possibly liquid water content and cloudiness. Combined with their direct radiative effects, aerosols from biomass combustion could be responsible for a global cooling as high as 2 watts m^{-2}, comparable in magnitude and opposite in sign to the radiative effects expected from increases of greenhouse gases during the 20th century (Penner and others 1991, 1992).

Current estimates of global fire extent, and thereby emissions, are inexact and come from uneven reporting of fire occurrence and from calculations based on growth of the human population and land use (Seiler and Crutzen 1980). They do show that tropical savanna and deforestation of primary tropical forests are likely the greatest global sources of fire emissions (Crutzen and others 1985, Seiler and Conrad 1987).

Emission rates of NO_x, HCN (hydrogen cyanide), and CH_3CN (acetonitrile) from biomass burning are sufficient to contribute significantly to the global budgets of carbon and nitrogen. Possibly, half of the biomass nitrogen can be converted to molecular nitrogen, N_2, leading to an estimated annual loss of 12-28 x 10^{12} g of biomass N (pyrodenitrification) equal to 9 to 20 percent of the estimated global rate of terrestrial nitrogen fixation (Lobert and others 1990). Cicerone (1994) has also shown that NO, NO_2, and CO can produce ozone in troposphere downwind from burning sites, which is also found in polluted urban air after a series of photochemical reactions. We have found that tropical fires are a strong source of methyl bromide, which is important in the destruction of stratospheric ozone, and have made the first quantitative, synoptic measurements of radiant energy release from wildland fires (Riggan and others 1993).

The PGCRP is supporting an assessment of the role of tropical fires in global change through a cooperative program with the government of Brazil *(figs. 4, 5, Chapter 1).* The scientists of the Pacific Southwest Research Station, USDA Forest Service, and the National Aeronautics and Space Administration (NASA) Ames Research Center in California are working with the government of Brazil and other United States agencies to assess the extent and global environmental impacts of widespread burning in central Brazil.

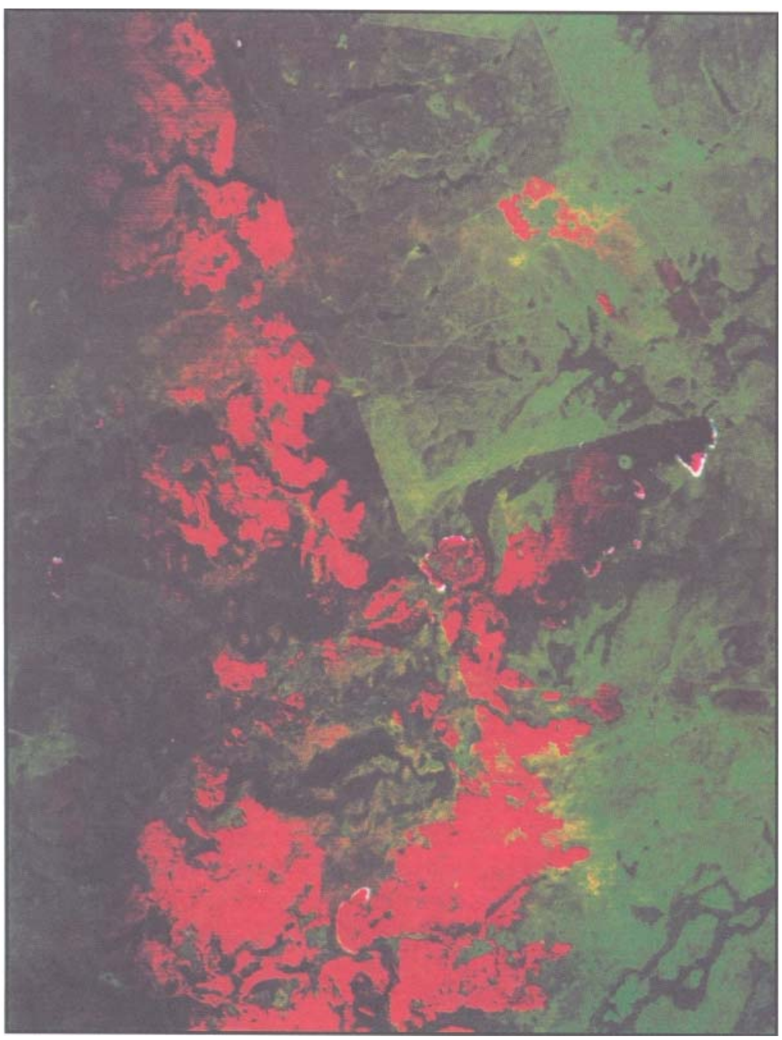

Figure 4-By using a specialized fire remote sensing system, fire spread can be mapped and emissions of greenhouse gases and smoke particles important in climate change can be estimated. Recent fire scars are in red and several active fire fronts are shown in white in a portion of Pantanal, Brazil, one of the world's largest wetlands.

Figure 5-The USDA Forest Service is working with Brazilian scientists and fire fighters to improve and demonstrate techniques in fire management and to restore a more natural role for fire in Brazilian national conservation areas (photograph by Philip Riggan).

Emissions of Other Anthropogenic Air Pollutants

Climate warming is expected to have an influence on the natural and anthropogenic emissions of primary air pollutants including nitrogen oxides (NO_x), non-methane volatile organic compounds (NMVOC), and sulfur oxides (SO_x) (Melillo and others 1993). NO_x and SO_x emissions may result from the fuel combustion associated with increased energy needs for air conditioning and refrigeration if current energy-producing technologies are continued. NMVOC's will increase because of more rapid volatilization of petroleum fuel and solvents, as well as from increased emissions of isoprene and terpenes from vegetation (Knox and Scheuring 1991).

The formation of secondary pollutants, including ozone and the peroxyacyl nitrates, is temperature dependent (Smith and Tirpak 1990). Currently, a correlation can be observed between air temperature and ozone concentration particularly in urban or near-urban atmospheres (Kuntasal and Chang 1987). Most forested areas where sensitive species now show symptoms of ozone injury are influenced by near-urban atmospheres. The enlargement of urban centers expected with population growth will probably exacerbate the problem. In the western United States, examples of rapid growth and accelerated air pollution problems can be found in Seattle, Washington, and the California Central Valley (Bakersfield, Fresno, and Sacramento). The forests in the adjacent mountain ranges (Cascades, western Sierra Nevada) are predicted to experience negative effects of that growth.

The climatic feature most associated with prolonged pollution episodes is the formation and persistence of the high pressure systems, including the Pacific High affecting the west coast of the United States in summer and the Subtropical High Pressure Belt influencing central Mexico in winter. These systems will be more frequent and persistent, particularly in coastal areas because temperature contrast will be higher between the near-surface stable marine layer and warm overlying continental air. Recent comparisons of the annual cycle of ozone formation near Los Angeles and Mexico City have shown that warmer winters near Mexico City result in higher winter-month ozone levels. Conversely, the hotter, rain-free summer months near Los Angeles result in ozone concentrations higher than those seen near Mexico City in the wet summer season *(fig. 6, Chapter 1)* (Miller and others 1994).

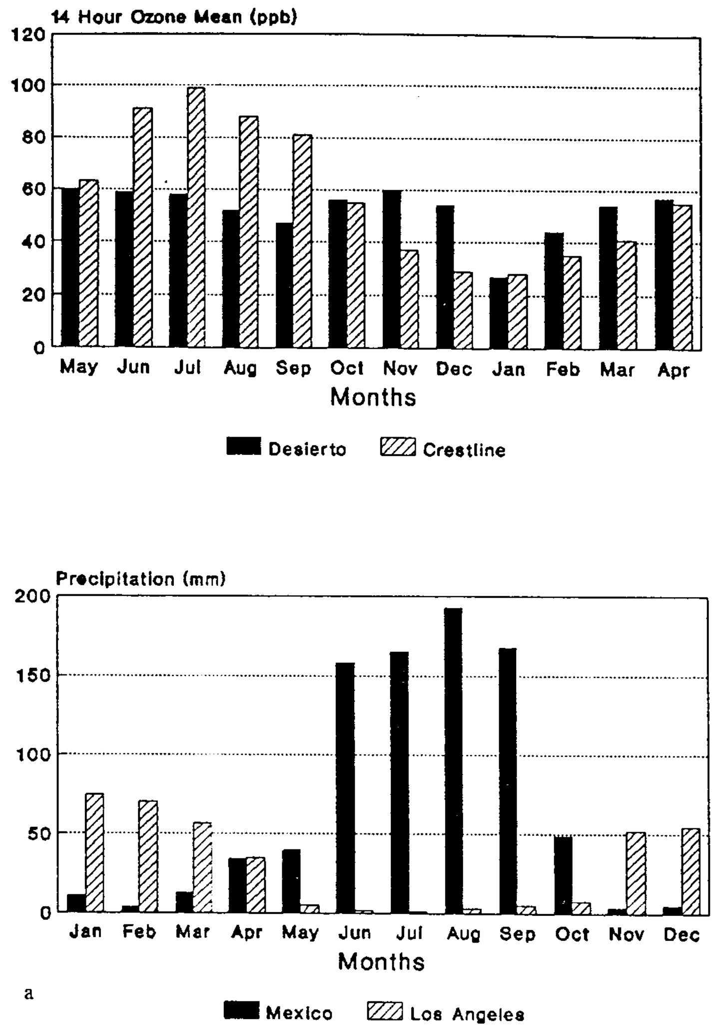

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Figure 6-Precipitation and ozone concentrations in two mountain locations: Desierto de los Leones near Mexico City, and Crestline, San Bernardino National Forest near Los Angeles (Miller and others 1994). "Precipitation" graph reprinted with permission from Atmospheric Environment, volume 28, Paul R. Miller, Maria de Lourdes de Bauer, Abel Quevado Nolasco, and Tomas Hernandez Tejeda, "Comparison of ozone exposure characteristics in forested regions near Mexico City and Los Angeles," pages 141-148, 1994, with kind permission from Elsevier Science Ltd, The Boulevard, Langford Lane, Kidlington 0X5 IGB, UK.

The change to warmer prevailing air temperatures and lower rainfall could lengthen the season during which severe episodes of photochemical smog may be expected. This may be partly caused by increasing emissions of isoprene from the forests (Turner and others 1991). A similar scenario has been presented for western Europe: large-scale, ground-level ozone concentrations could reach 0.10 ppm with a possibility of peak values exceeding 0.15 ppm (Feister and Warmbt 1987).

Warmer temperatures will also increase the oxidation rate of NO_2 and SO_2 to nitrate and sulfate forms; thus, dry deposition of aerosols to forest canopies may increase, which could significantly affect nutritional status of the forest plants. Low-volume rain events in air masses from heavily polluted airsheds will continue to result in hydrogen ion deposition causing immediate changes in the acidity of some alpine lakes and gradual changes in poorly buffered alpine soils (Brown and Lund 1991, Melack and Stoddard 1991). Furthermore, the increased amount of sulfate haze will further impair visibility in areas where scenic vistas are the major attraction. Sulfate haze from the troposphere may contribute to a layer of haze now being monitored in the upper atmosphere. This layer is believed to be transparent to incoming solar radiation but tends to inhibit night-time reradiation of long-wave radiation from the troposphere. This phenomenon may reinforce the greenhouse effect (Hofmann 1990).

Chapter 2

Nutrient Cycles and Energy Flows

Andrzej Bytnerowicz,[1] Mark Fenn,[1] Sue Ferguson,[2] and Nancy Grulke[1]

Carbon and nitrogen are the key elements for any form of life on the earth. These two elements are also essential constituents of various air pollutants affecting global climate. Better knowledge of carbon and nitrogen global cycles, including understanding of their mechanisms and quantification of their flows, is needed for proper planning of management practices in terrestrial ecosystems. For the same reason a sound knowledge of the climate-caused changes in distribution and rates of water resources, including streams, snow, and permafrost, is also critically needed.

Global Carbon Cycle and Carbon Resources of Western Forests

Carbon is an essential element for all living organisms. The fixations of carbon dioxide (CO_2) by plants through geologic time have resulted in the presence of oxygen in the earth's atmosphere that sets the oxidation potential for the entire planet. Through oxidation and reduction processes the cycles of other elements are closely tied to the global cycles of carbon (Schlesinger 1991). The largest fluxes of the current carbon cycle are those linking the atmospheric CO_2 to terrestrial vegetation and the oceans *(fig. 1, Chapter 2).* The carbon contained in forest ecosystems globally has been estimated to be equivalent to about one-half of

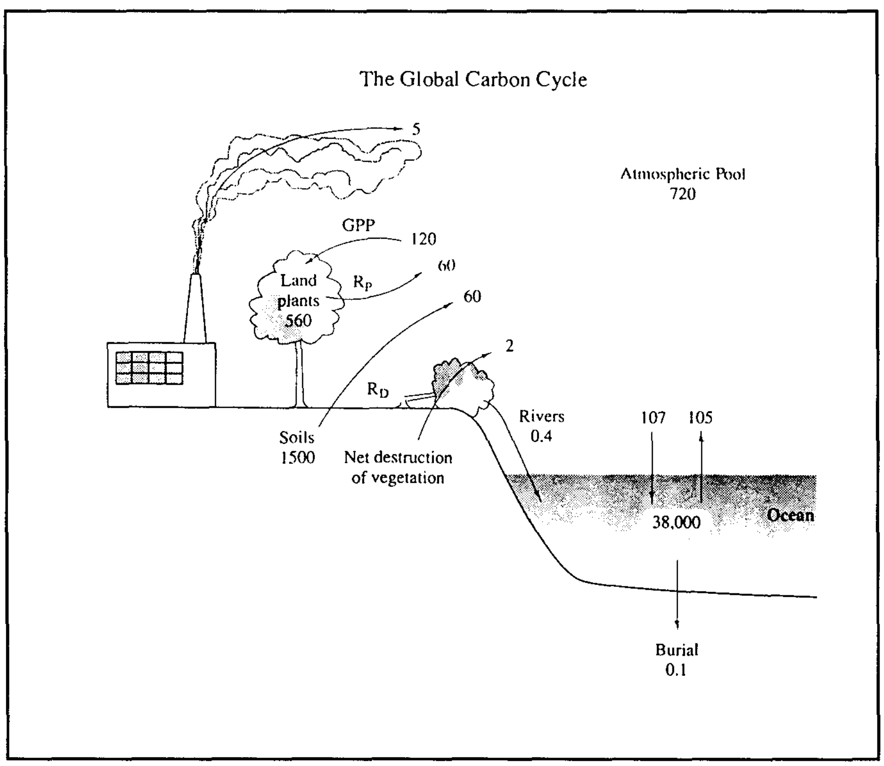

Figure 1-Current carbon cycle. All pools are expressed in units of 10^{15} g C and all annual fluxes in units of 10^{15} g C/yr (Schlesinger 1991). Reprinted with permission from William H. Schlesinger: Biogeochemistry-An Analysis of Global Change. San Diego, CA: Academic Press, Inc. Copyright 1991, Academic Press.

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(Simpson and Botkin 1992), two-thirds of (Jarvis 1989, Schlesinger 1991, Watson and others 1990), or even two times (Woodwell 1991) the carbon contained in the atmosphere. The predicted climate warming and the accompanying increase in mean soil temperature could accelerate terrestrial emissions of CO_2. Soil respiration and N mineralization have been shown to increase with soil temperature when adequate water is available (Alexander 1977). A 4 °C increase in air temperature increases the CO_2 efflux from upland tundra soil by 26 percent (Oberbauer and others 1986). Increased atmospheric CO_2 concentrations and higher air temperatures are expected to be accompanied by changes of summer soil wetness (Manabe and Wetherald 1986). Billings and others (1983) found that lowering the level of the water table alone changed the net carbon balance of a coastal wetland soil from a net sink (+119 g CO_2 m^{-2}) to a net source (-476 g CO_2 m^{-2}) during a growing season. Carbon budget response of forests to future global change scenarios is speculative because responses of mature trees to CO_2 enrichment and the effects of temperature on terrestrial sources and sinks of CO_2 have not been determined (Luxmore and others 1993).

Arctic tundra has changed from a sink to a source of CO_2. Approximately one-third of terrestrial organic carbon is stored in northern peatlands (boreal forests and Arctic tundra) (Post and others 1982). The large C stores are believed to have accumulated during the early Holocene (10,000 B.C.) when the climate was warmer than at present. Currently, net ecosystem CO_2 balance is negative in coastal wetlands, and increasingly positive with soil drainage (Oechel and others 1993). Increasingly drier soils are expected with global warming in these northern ecosystems (Manabe and Wetherald 1986), which could further exacerbate global warming (Billings and others 1983). Carbon is also being exported to aquatic ecosystems (Hobbie 1980): as the underlying permafrost melts, surface subsides, and water runoff increases, the areas of lower topography may accumulate water and thus become sources of methane. Modeling of soil chemical and physical properties will help to predict the extent that this biome will become a net emitter of greenhouse gases (Reynolds and Leadley 1992).

The estimate of the net flux between the biosphere and atmosphere is particularly uncertain and has been currently a matter of considerable controversy as to whether the biosphere is a source of CO_2 or a sink for CO_2 (Jarvis 1989). This controversy may not be resolved until the sizes of the vegetation carbon pools and associated carbon fluxes are better assessed. A proper actual and potential role of vegetation in the global carbon cycle requires accurate information about carbon storage and change over time (Simpson and Botkin 1992). Recent ecosystem-scale nutrient studies indicate that 1.0 to 2.3 Gt C yr^{-1} of carbon storage may be stimulated by anthropogenically caused increases in nitrogen deposition in the 20th century (Hudson and others 1994). Calculations suggest that northern continents are a major sink for carbon and that nitrogen-stimulated carbon uptake may more or less balance global carbon losses to the atmosphere from deforestation and agriculture (Schindler and Bayley 1993).

The most important factor affecting carbon resources of the Pacific states of the United States is harvesting of old-growth forests. Mass balance calculations indicate that the conversion of old-growth forests to second-growth plantations west of the Cascade Mountains in the past 100 years has added 1.5 to 1.8 x 10^{12} kg C to the atmosphere (Harmon and others 1990). Boreal forest ecosystems contain 13 percent of the terrestrial biomass (Whittaker and Likens 1975) and also 13 percent of the earth's terrestrial organic soil carbon (Post and others 1982). Whether boreal ecosystems will continue to be a carbon sink will depend on the degree of global warming and soil moisture changes (Oechel and Billings 1992), as well as the extent of harvesting and management practices in boreal ecosystems.

Another source of carbon resources are the tropical savannas. The conversion of these lands to agricultural fields and the frequency and extent of anthropogenic fires in this (Riggan and others 1993) and other ecosystems is a significant source of carbon release to the atmosphere. Olson (1981) summarized carbon release as a function of mean frequency of average fires per year for about 25 different ecosystems. If these estimates are correct, nonfossil carbon release by fires is at least slightly below the 5 x 10^{12} kg C yr^{-1} currently released by fossil fuel consumption. Chaparral, temperate marshes, boreal forest and mixed conifer forests all had comparable high carbon release (103 kg available carbon per square meter) with relatively low burn frequency (every 10-100 years). The ecosystem with one of the highest carbon release rates was the understory of giant sequoia, which also had one of the most frequent burn rates. However, this comparison did not differentiate wildfire from anthropogenically caused fires (Olson 1981).

Global Nitrogen Cycle and Nitrogen Deposition to Western Forests

The atmosphere is the largest pool (3.8 x 10^{21} g N) in the global nitrogen cycle and relatively small amounts of N are found in terrestrial biomass (3.5 X 10^{15} g) and soil organic matter (95 x 10^{15} g) *(fig. 2, Chapter 2).* The mean C:N ratios for terrestrial biomass and soil organic matter are about 160 and 15, respectively. The pool of inorganic N in the form of NH_4^+ and NO_3^- on land is very small. In general, the transformations of N in the soil and uptake of N by organisms are so rapid that little N remains in inorganic form, despite a large annual flux through this pool (Schlesinger 1991).

Concentrations of N air pollutants in a dry form (mainly as NO_2, HNO_3, NH_3, particulate NO_3^- and NH_4^+) and NO_3^- and NH_4^+ in wet precipitation in the Southern California Air Basin have been elevated (Blanchard and Tonnessen 1993, Brewer and others 1983, Grosjean 1983, Russell and others 1985) for at least 40 years. Although, in general, little is known of the concentrations of N pollutants in the mountains surrounding the Southern California Air Basin, recent studies suggest

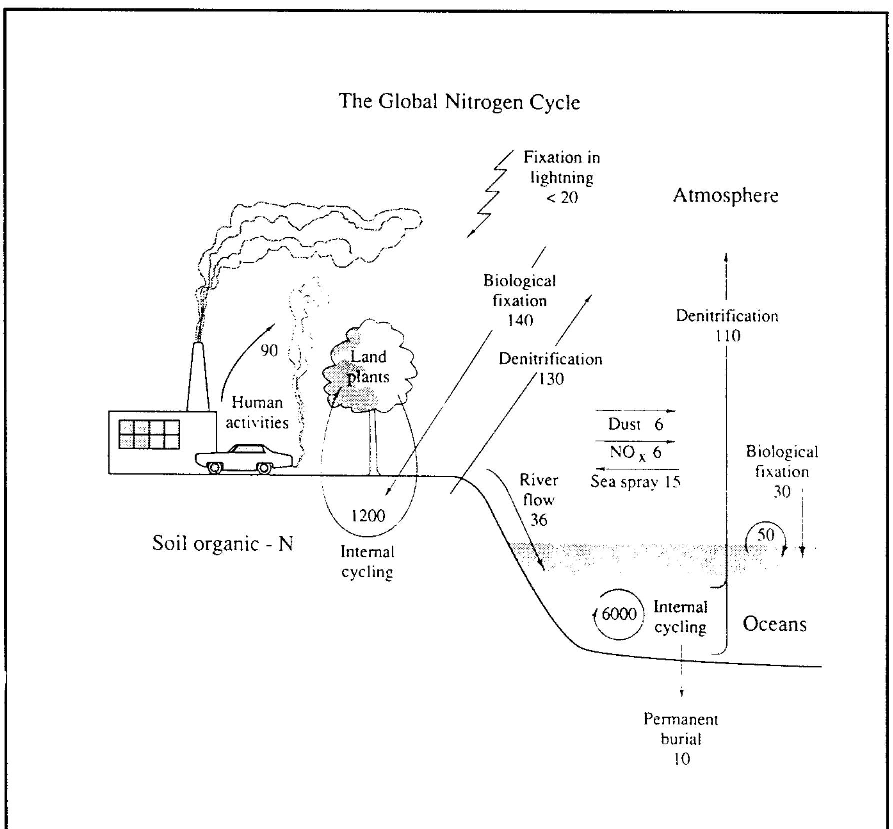

Figure 2-The global nitrogen cycle. Pools and annual fluxes are expressed in 10^{12} g N (Schlesinger 1991). Reprinted with permission from William H. Schelesinger: biogeo-chemistry-An Analysis of Global Change. San Diego, CA: Academic Press, Inc. Copyright 1992, Academic Press.

that some of the mixed coniferous forest locations in the San Bernardino Mountains (Fenn and Bytnerowicz 1993) as well as the chaparral stands of the San Gabriel Mountains (Bytnerowicz and others 1987a, 1987b, Grosjean and Bytnerowicz 1993) may receive as much as 30 kg N ha^{-1} yr^{-1}. These values are among the highest reported in North America and may lead to changes in internal cycling and export from the watershed.

Elevated levels of NO_3^- and NH_4^+ deposition also occur in western Sierra Nevada forests in California and are about six- and four-fold higher than in the eastern Sierra Nevada locations (*fig. 3, Chapter 2*) (Bytnerowicz and others 1991, 1992). Although the absolute values of dry deposition of N in the western Sierra Nevada were lower than in the Southern California Air Basin, the concentrations of reduced N compounds (NH_3, particulate NH_4^+) were higher in the Sierra Nevada sites (Bytnerowicz and Riechers 1995).

In recent years much has been learned about the chemistry of wet precipitation in California (Blanchard and Tonnessen 1993). Estimates of wet and dry N deposition for California based on the California Acid Deposition Monitoring Program network have also been attempted. Although estimates of

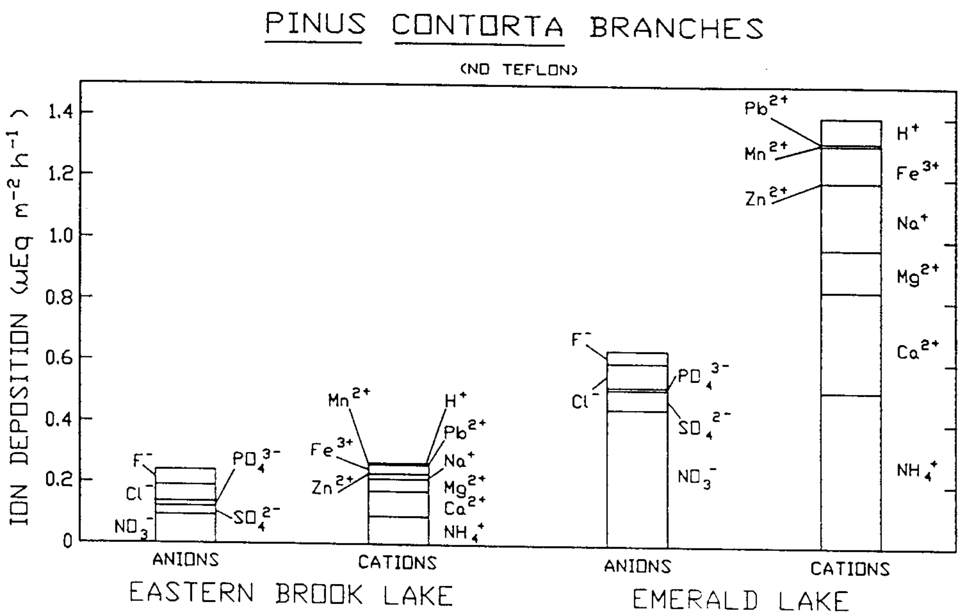

Figure 3-Atmospheric dry deposition of anions and cations, including NH_4^+ and NO_3^-, is much higher in the western (Emerald Lake) than in the eastern (Eastern Brook Lake) subalpine Sierra Nevada sites. Elevated levels of deposition in the western Sierras are caused by the long-range transport of the polluted air masses from the California Central Valley (Bytnerowicz and others 1991, 1992).

wet deposition in the Southern California Air Basin bear uncertainties of less than 20 percent, the estimates for the northern and southeastern portions of California are much less accurate (as high as 100 percent uncertainties). Estimates of dry deposition based on the California Acid Deposition Monitoring Program database are limited in many respects (mainly because of the limitation to only 10 sites in the network) and are subject to uncertainties as high as 50 percent (Blanchard and Michaels 1994). For other western states, only sparse results on wet and especially dry deposition are available.

Changes in Streams, Snow, and Permafrost Caused by Changing Climate

Most useable water in Pacific coastal regions of North America comes from the mountain snowpack. This important resource is strongly influenced by climate change. For example, a typical moist adiabatic lapse rate for mid-latitude winter

Figure 4-The snow line of the mountain near the Columbia River Basin (just above the central valley in early spring) could shift up near the ridge crest because of a minor degree of winter warming, causing a severe decrease in snow cover (photograph by Sue Ferguson).

is about 4 °C/km (Barry and Chorley 1987). This means that a 2 °C increase in winter-averaged temperature could raise the seasonal snow line by about 500 meters. According to current estimates of snow cover in the Columbia River Basin in the Cascade Mountains, a 500-meter rise in the snow line would cause a 44 percent reduction of snow cover (*fig. 4, Chapter 2*) (Fleagle 1991). This could cause a significant reduction in water resources and play a dramatic role in shifting ecological gradients in steep terrain, especially in the Sierra Nevada and Cascade mountains where the snow pack already shows a strong response to climate change (Cayan 1996).

Loss of snow cover not only reduces water supply, but produces a positive feedback to atmospheric warming. Seventy-five to 90 percent of incoming solar radiation is reflected back into the atmosphere by snow and ice. On the other hand, only 25 to 50 percent is reflected by soil and vegetation (Berry 1981). The rest is absorbed and re-radiated at longer wave-lengths, then trapped by the near-surface atmosphere. This feedback mechanism allows for small initial changes in snow cover to significantly increase land cover absorption of heat, which adds to the original heating. The most dramatic change in snow albedo feedback and subsequently greatest change in surface temperature is expected in central and northern Alaska where large areas of snow cover and sea ice could disappear completely (Ferguson 1995).

Large areas of the northern latitudes are covered by permafrost. In Alaska, north of the Brooks Range, some of the permafrost was formed thousands of years ago (Piexoto and Oort 1992). This is a region of continuous permafrost that is several tens to several hundreds meters deep. The top meter is an active layer that melts during the summer. Current winter temperatures in northern Alaska average between -20 °C and -30 °C, and continuous permafrost can persist at average annual temperatures as high as -7 °C (Ives 1974, Untersteiner 1984). Therefore, even the most substantial increase in global temperatures should cause little degradation in continuous permafrost (Osterkamp 1984). The active layer, however, may deepen (Maxwell 1992) and could refreeze more slowly during autumn and thaw more quickly during spring (Ferguson 1995).

Unlike continuous permafrost, regions of discontinuous permafrost, like interior Alaska, should be strongly affected by expected global warming (Osterkamp 1984). Melting permafrost in this region should cause dramatic increases in marsh and lake areas (Ferguson 1995).

The amount of water held in glacier ice in the Pacific region of North America equals or surpasses all the water in the lakes and streams. Nearly all glaciers in the United States exist in the Pacific region. Alaska is covered by 75,000 km^2 of glacier ice; 75 percent of glaciers in the contiguous United States are in Washington State; Oregon and California also have glaciers, mainly on the volcanic peaks (Ferguson 1991). Water flowing from Alaskan glaciers contributes more than 186,000 billion liters of water into the stream-flow system (Meier 1985).

Glacier-fed streams exhibit peak flows during mid-summer. This contrasts to snow-fed streams that usually peak during spring. The delayed discharge provides a more continuous and reliable water source in many coastal rivers (Fountain and Tangborn 1985).

Advancing glaciers can choke rivers and streams with silt or glacier flour. This makes a rather inhospitable habitat for many plants and animals. Retreating glaciers, on the other hand, contribute little silt and have higher discharge rates (Ferguson 1991). Most mountain glaciers in the Pacific region have been retreating during the past 100 years and are expected to continue retreating during the next 100 years *(fig. 5, Chapter 2)* (National Research Council 1984). Many of the small glaciers, especially in California, could completely disappear. Larger glaciers that accelerate their retreat should produce greater stream discharges with less silt. Glacial retreat also may increase hazards in mountainous areas. Retreating ice may expose unstable slopes, increasing mass wasting from rock- and landslides and debris flows. Temporary dams formed by ice or moraines may fail, producing highly destructive debris-laden floods and flows with potential to travel long distances.

Changing climate can significantly affect both the seasonality (i.e., timing), total volume, and variability of runoff in streams. These effects can be quite pronounced and immediate where both rainfall and seasonal snowpacks contribute to runoff. Under these circumstances, relatively small changes in temperature or precipitation amount or type can dramatically influence the amount of water delivered to streams at different times of the year. For example, in the western Cascades, streams receive runoff from a rain-dominated zone below 400 m elevation, a "transient snow zone" between 400 and 1,400 m where snow falls but snowpacks tend to melt rather quickly during subsequent rainfall, and a seasonal snow zone above 1,400 m. With as little as a 2 °C warming, the lower boundary of the rain-on-snow zone may become as high as 1,000 m, effectively eliminating rain-on-snow events from some watersheds and changing the location and timing of melting of snowpacks in other basins (Swanson and others 1992). These changes will have consequence to the overall distribution of runoff within the year, such as reducing late-season low flows in basins where winter snowpacks have been depleted. Such changes may increase summer water temperatures, further stressing aquatic ecosystems (Hicks and others 1991). The central and northern Sierra Nevada, and south-central and south-east Alaskan mountains, where similar snowpack fluctuations exist, could experience similar effects.

In southern California, where a large percentage of streams currently are ephemeral, many streams could completely disappear if warmer temperatures and/or decreased precipitation were to occur. In addition, the currently perennial streams in this area may become ephemeral under a significant climate change (Peter Wohlgemuth, personal communication).

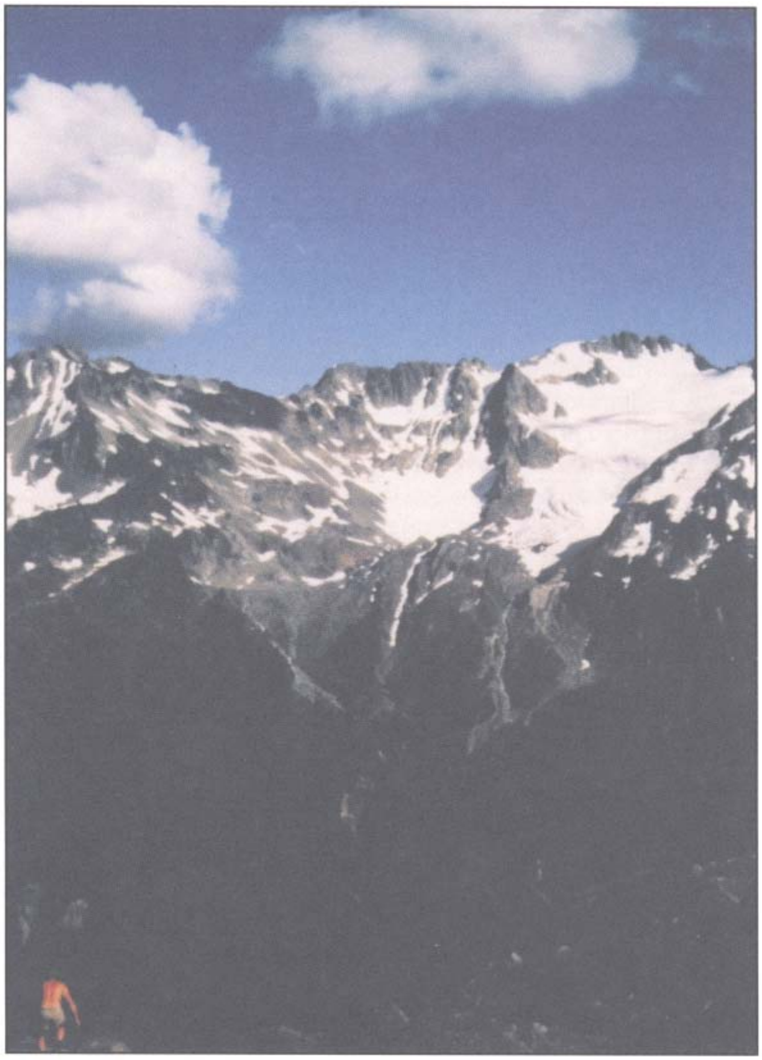

Figure 5-Most glaciers in the Pacific mountains of the Northwestern United States have been retreating over the last 100 years and are expected to continue retreating during the next 50 to 100 years. Small glaciers like these valley and cirque glaciers could disappear completely with continued global warming (photograph by Sue Ferguson).

Permafrost also affects streamflow. Permafrost-dominated catchments exhibit higher peak flows, lower base flows, and steeper recessions than adjacent permafrost-free basins (Hilgert and Slaughter 1987, Slaughter and others 1983). Therefore, decreasing permafrost areas could significantly alter streamflow regimes, especially in central Alaska where discontinuous permafrost areas could be disrupted significantly by changing climate.

Chapter 3

Plant Responses to Climate and Air Pollution Changes

Mark Fenn,[1] Nancy Grulke,[1] and Paul Miller[1]

Changing climate may have significant effects on terrestrial plants. Increasing levels of CO_2, elevated air and soil temperatures, diminished availability of water, elevated deposition of nitrogen, as well as direct phytotoxic effects of various air pollutants and UV-B radiation are the major factors in the presently observed and predicted changes in terrestrial ecosystems.

Changing CO_2 Levels

Kimball (1983) compiled data from 430 studies of different crops grown at ambient and twice ambient CO_2 levels and found that yields at elevated CO_2 concentrations were increased by an average of 30 percent. However, in natural ecosystems, response to elevated CO_2 atmospheres is much more variable than in the agricultural systems. An intact salt marsh community dominated by a sedge yielded a prolonged, net production increase of 88 percent in a doubled ambient CO_2 atmosphere (Drake and Leadley 1991). In contrast, exposure of intact tundra initially resulted in a net increase of 6 g C m^{-2} d^{-1}, which was lost by the third year of the exposures (Oechel and others 1994). Evidence of acclimation to elevated CO_2 was apparent within 3 weeks of the elevated CO_2 exposure in a separate experiment with intact tundra (Grulke and others 1990). Physiological down-regulation of photosynthetic capacity (acclimation) has been noted in a number of long-term CO_2 exposure studies (Cure and Acock 1986, Delucia and others 1985, Grulke and others 1993, Pearcy and Bjorkman 1983, Tissue and Oechel 1987). The capacity of some plants to acclimate to elevated CO_2 concentrations is an important factor to include in assessments of global carbon budgets because it may eliminate a source of buffering to the atmospheric increase. Elevated CO_2 is also known to reduce stomatal aperture of some species, but tends to provide beneficial effect to others by increasing water use efficiency in the warmer, less humid global climate that is expected (Bazazz and Fajer 1992). For instance, in at least one study, there was an apparent "acclimation" of stomatal conductance to an elevated CO_2 environment (Grulke and others 1993). If this study is correct and generalized, the findings will have significant repercussions for atmospheric water balance predictions. Ongoing research in the tropical rain forest is the only known study of elevated CO_2 exposure of an intact ecosystem (Charles Korner, personal communication).

Simulation models show that elevated CO_2 and the subsequent changes in plant transpiration and gas exchange will increase sensitivity of forest communities to climate change (Woodward 1990). Temperature extremes or extended droughts could induce widespread declines of some forest trees known as "lead species": these are the first to fail and drop out of the community because of expected perturbations caused by fire, insects, and diseases (Auclair and others 1992). One of the important mechanisms starting the decline of tree species is xylem cavitation injury resulting from fluctuations in water availability

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and temperature during the winter. Winter injury and weakening of trees by extended droughts makes them more susceptible to killing from insect pests like bark beetles. Furthermore, warmer temperatures are expected to increase the number of generations and spread of insect pests, especially herbivorous species, in a single year (Cammell and Knight 1992).

Elevated CO_2 concentrations may change leaf area of plants-some authors predict increase of leaf area index (LAI) (Taylor and others 1994), while others foresee an opposite trend (DeLucia and others 1994). Assuming the first scenario, for those pollutants that are conserved and for which continental landscapes are a sink (e.g. Hg°, N pollutants), increases in LAI would proportionally increase deposition at the forest stand and catchment level (this condition is especially true for the pollutants in which deposition is independent of stomatal conductance, e.g. gaseous HNO_3) (Taylor and others 1994).

Elevated levels of CO_2 can also have a positive feedback on soil C and N dynamics, producing greater N availability (Gifford 1994, Zak and others 1993). For instance, a buildup of non-structural carbohydrates in foliage (and litter), followed by increased C exudation from the roots can result in higher availability of easily metabolized C in the soil (stimulating faster rates of mineralization of "old" organic C) and hence increased soil N mineralization (Oechel and Strain 1985).

Increased Nitrogen Deposition

Northern temperate forests have been traditionally considered N-limited. However, recent studies in the eastern United States and Europe confirm the growing concern that chronic N deposition can lead to the contrasting condition of excess available N, with potentially undesirable effects on forest ecosystems (Aber and others 1989, Driscoll and Van Dreason 1993, Emmett and others 1993, Hultberg and others 1994, Kahl and others 1993, Stoddard 1994). Nitrogen saturation of a forest has been variously defined, but basically refers to an ecosystem that cannot retain and process additional inputs of N, or when vegetation no longer shows a positive growth response to further N additions. Nitrogen-saturated forests are characterized by persistent loss of excess N either as NO_3^- leached beyond the rooting zone or into streamwater, and/or as trace N gas emissions from soil denitrification and nitrification (Aber and others 1989, Stoddard 1994). Nitrogen saturation is of particular concern to ecosystem management because of the potential contamination of streamwater or groundwater with NO_3^-, and the possibility of increased emissions of trace N gases such as nitrous oxide (N_2O) and nitric oxide (NO). High concentrations of NO_3^- in soil are believed to greatly increase denitrification rates and emissions of N greenhouse gases (Aber 1992, Matson and others 1992, Melillo and others 1989).

Nitrogen saturation in forest ecosystems of the western United States can occur as a result of natural sources of excess N. Red alder *(Alnus rubra)* stands in Washington State are N saturated as a result of biological N fixation (Johnson and others 1991). Dahlgren (1994) also reported the occurrence of a naturally occurring N saturation in the Klamath Mountains in northern California as a result of weathering of ammonium from mica schist bedrock.

However, the main source of the increasing levels of available nitrogen in these forests is from anthropogenic emissions. For instance, some of the chaparral ecosystems in southern California appear to have developed N saturation, illustrated by the high concentrations and fluxes of NO_3^- in streamwater from grassland and chaparral watersheds exposed to high N deposition in the San Gabriel Mountains (Riggan and others 1985, 1994). Burning of chaparral stands exposed to chronic N deposition has mobilized N and resulted in NO_3^-

concentrations in streamwater as high as 69 mg L^{-1} (Riggan and others 1994). High NO_3^- efflux from chaparral watersheds does not appear to be typical, since burned and unburned chaparral watersheds in Arizona (Longstreth and Patten 1975), and in low-pollution areas of the Southern California Air Basin, did not have high NO_3^- concentrations in streamwater (Riggan and others 1985).

Similarly, a number of factors suggest that some mixed conifer stands in the western, highly polluted area of the San Bernardino Mountains are N saturated. Nitrate concentrations in soil solution were several-fold higher throughout the growing season in high deposition sites than in low deposition sites. High trace N gas emissions and high soil and foliar N concentrations, low C:N ratios in soil, high N:P (phosphorus) ratios in foliage, and a decreased foliar biomass in response to N fertilization have been observed at Camp Paivika, a high-pollution site in the San Bernardino Mountains (Fenn and others 1996). Furthermore, during the past 18 years C:N ratios and soil pH values have decreased considerably at Camp Paivika, but changed little or not at all at Camp Osceola, a low-pollution site in the San Bernardino Mountains (Fenn and others 1996). Although N saturation effects seem to be occurring in the highest N deposition sites, more widespread forested areas may benefit from a N fertilizer effect which is not visibly evident (Aber and others 1989). Critical loads of N for forest ecosystems are difficult to determine because they are highly site specific, varying on the basis of current and past forest and soil conditions (Cole and others 1992, Emmett and others 1993, Feger 1992). However, ecosystems in the Southern California Air Basin exposed to as much as about 20-30 kg N ha^{-1} yr^{-1} exhibit symptoms of N saturation based on loss of excess N from the ecosystem, suggesting that the critical load for these ecosystems may be <20 kg N ha^{-1} yr^{-1}.

Other Air Pollutants and UV-B Radiation

Air pollution potential effects in a changed global climate have been predicted to be higher if the increases in temperature materialize (Taylor and others 1994). Air pollution effects will be mixed with or modified to some extent by other co-occurring variables or stresses. The occurrence of stress agents in both time and space will exhibit considerable variability (Miller 1993). This variability will be manifested by stresses acting either simultaneously or sequentially and by a patchiness of stress effects on the landscape. Heterogeneity is further enhanced because of the vast latitudinal range over which stresses may interact including north of the Arctic Circle in Alaska (70° N) to parts of Brazil below the equator at 20° S. Temperature changes by year 2050 over this vast region may increase by an average 2.5°C over the Northern Hemisphere and from 6 to 10°C between 50° and 60° N (Manabe and Wetherald 1975, Mitchel 1983). If this scenario is valid, this temperature range introduces more uncertainty into the interaction among stresses.

The emphasis on single pollutants and acute effects has been replaced by recognition that most terrestrial ecosystems are not affected by one pollutant, that exposure and deposition are often chronic, and that effects in natural stands are largely the result of air pollution interactions with the suite of other environmental stresses (Taylor and others 1994). Plant species will be affected by a number of stresses either simultaneously or sequentially. Some of the more important stresses include effects of the higher CO_2 concentrations, increased UV-B radiation, extended droughts, temperature extremes, and increased damage from insects and diseases. For instance, for the past 40 years or so elevated concentrations of ozone (Miller and Ryan 1977) and increased deposition of nitrogen (Fenn and Bytnerowicz 1993) have interacted with changing climatic conditions in the San Bernardino Mountains in southern California, resulting in a combination of environmental stresses that are only partially understood.

UV-B radiation flux through the troposphere is increasing particularly at high elevations (Blumenthaler and Ambach 1990) because of the gradual decay of the stratospheric ozone shield by chlorofluorocarbons. This decay has caused a great potential for various biological effects of the increasing UV-B radiation and its interactions with the increasing levels of CO_2 and ozone (Krupa and Kickert 1993). However, the cuticles of conifers and other alpine species are not transparent to UV-B radiation (Day 1993, Sullivan and Teramura 1989), so effects would probably be seen first in species occupying lower elevations. In addition, because the tropospheric ozone acts as a shield for UV-B, ozone damage should not be expected to occur simultaneously. Therefore, no synergistic effects of ozone and increasing UV-B radiation levels on coniferous trees in the mountains of the western United States are expected.

Natural hydrocarbon emissions from plants can contribute to ozone formation, causing concentrations that exceed ozone standards (Chameides and others 1988). The rates of emission of isoprene (Tingey and others 1979) and monoterpenes (Tingey and others 1980) from vegetation increase as temperature increases. These are the most important natural hydrocarbons participating in ozone formation. Therefore, predicted increases in average temperatures could lead to higher emission rates of natural hydrocarbons and increase in ozone formation.

An important chemical outcome of the predicted climate changes will be an increase in trace gas levels through the lower atmosphere and the hydrosphere (Hansen and Lacis 1990, Mohnen and others 1993). Tropospheric O_3 has been building up in many regions of the Northern Hemisphere (Mohnen and others 1993), especially over Europe (Ashmore and others 1985). As a result of these changes, damage from gaseous pollutants could increase substantially, and the results may be non-additive if SO_2, O_3, and NO_x increase simultaneously. In particular, the vulnerability of vegetation to climate extremes may be enhanced by high pollutant concentrations (Oppenheimer 1989). Some of these pollutants contribute directly and indirectly with other stresses on ecosystems to cause acceleration of turnover rates of sulfur (S), N, and C. These changes may lead to the net transfer of nutrients from land to coastal ocean accompanied by forest decline and coastal eutrophication (Oppenheimer 1989).

The successful adaptation of individual species to new combinations of stresses will be the key process by which species may be perpetuated and move into new ranges where the general climate is most favorable to their needs.

Part II

Simulation Modeling: Role and Status

Simulation Modeling: Role and Status

Andrzej Bytnerowicz,[1] Sue Ferguson,[2] Francis Fujioka,[1] Roger Ottmar,[2] and Mark Poth[1]

Numerical model simulations can help to explain and summarize current information on atmosphere and biosphere interactions. However, absolute results (geographically specific "predictions" or "forecasts") are not possible because models have unknown errors both for spatial and temporal applications (Oreskes and others 1994), as well as limitations caused by variability and accuracy of input data. Thus, results of simulation models should be considered to be scenarios of possibilities rather than estimates of future conditions. Indeed, the general circulation models used for simulations of global climate cannot produce the common seasonal cycles of weather. Nevertheless, simulation models are valuable tools because they are designed on the basis of near-past and present conditions not future conditions, that are as yet unknown.

To assess the impact of global change on forest and natural resources the PGCRP developed models on two scales. The first scale is geographic, and the goal is to produce results and understanding that are relevant to particular sites and regions. The second scale is thematic and addresses the issues of importance to land managers and policy makers. For instance, in the Pacific region of the United States, the thematic range includes local weather, fire and smoke dispersal, air pollution uptake by forests, and terrestrial ecosystem simulations, among others.

Regional Scale Weather Models

Climate in the Pacific region depends highly on ocean currents. The temperature, strength, and seasonality of ocean currents significantly affect storm patterns (Wallace and Gutzler 1981). The California current and Alaskan gyre are predominantly surface currents strongly affected by river discharge. Small changes in regional air temperatures could cause large changes in snow melt, resulting in discharge patterns (Chapter 2, this volume). This process can alter coastal current patterns (Ebbesmeyer and Tangborn 1992) and create a significant feedback mechanism for regional climate patterns, but it has not yet been fully explored.

The Southern Oscillation (SO) is a phenomenon related to the displacement of warm water back and forth across the equatorial Pacific. Positive SO events (El Niño) have been correlated to warmer-than-normal temperatures and decreased snowfall in the Pacific northwest of the United States (Ferber and others 1992, Ferguson and others 1994) and wetter-than-normal conditions in the Pacific southwest (Schonher and Nicholson 1989). Negative SO events (La Niña) have been correlated to colder-than-normal temperatures and more snowfall in the Pacific northwest (Ferber and others 1992, Ferguson and others 1994).

Periods of strong SO fluctuations have occurred from 1880 to 1920 and since about 1950 with a quieter period in between (Intergovernmental Panel on Climate Change 1990). The SO creates a considerable amount of climatic noise that can dominate temperature records. Coupled ocean-atmosphere general circulation models are just beginning to simulate SO patterns, but a definite relationship between climate effects and increasing levels of CO_2 has not been observed.

The complex terrain of the Pacific region of the United States profoundly influences their climate. The complexity of the spatial distribution of climate variables also depends on the time scale in which climate is studied. For example,

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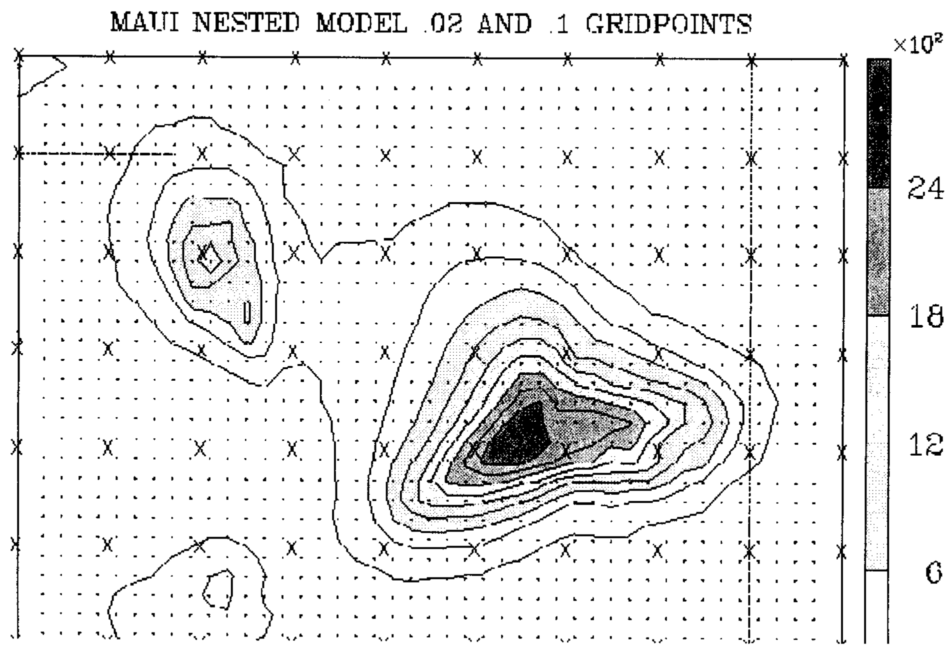
the spatial variability of temperature at a given hour will be different from the spatial variability of temperature for a given month. Greater variability implies greater uncertainty. Hence, any predictions based on climate scenarios include a margin of uncertainty proportionate to the inherent climate variability.

Models that incorporate varying spatial and temporal scales have been used to generate climate scenarios. The most descriptive are three-dimensional, mesoscale atmospheric models, that have been used for high-resolution reconstruction of regional weather and local climate conditions. Nesting a fine grid within a coarse grid is an economical method of obtaining spatially descriptive simulations.

- Regional Atmospheric Modeling System (RAMS) - Maui Island, Hawaii

A study of Maui fire climate used the RAMS (Pielke and others 1992) in a hierarchical grid structure (Ueyoshi and others 1996) with a coarse grid spacing of 250 km, and embedded grids with spacings of 50 km, 10 km, and 2 km *(fig. 1, Part II).*

Figure 1-An example of a nested grid scheme used in weather modeling to link large- and small-scale features. In this case, weather simulations for Maui, Hawaii, used grid spacing of 2 km (dots), 10 km (X's), 50 km and 250 km (not shown).



- Regional Spectral Model (RSM) - Los Angeles Basin, California

The RSM (Juang and Kanamitsu 1994) provided a simulation of repeated wind events (called Santa Anas) in southern California. The study used a nested grid structure with spacings ranging from 250 km to 25 km (Chen and others, 1996).

- MM5 - Cascade Mountains, Washington

The MM5 model, originally developed at Pennsylvania State University, was used in simulations with a coarse grid spacing of 250 km and hierarchical nesting to fine grid spacings of 27 km, 9 km, and 3 km (Steenburgh, in press).

Even with a nested grid structure, the computing costs of mesoscale models can be prohibitively expensive. More economical simulations are possible by reducing the model dimensions. A two-dimensional mesoscale model (WINFLO) has been used to simulate climate over the Columbia River Basin region at 10 km resolution (Hayes and Ferguson 1995).

Statistical atmospheric models generally require less computing than mesoscale models. A variety of statistical methods (e.g., MTCLIM [Running and others 1987] and PRISM [Daly and others 1994]) are being used to interpolate coarse-resolution (500-1000 km) GCM data to 10 km resolution over the contiguous United States. A set of regression equations was developed to estimate monthly mean surface temperature, dew point, wind speed and precipitation frequency at first-order National Weather Service stations in the contiguous United States, given the 700 mb height anomaly field over the Northern Hemisphere (Klein and Whistler 1991). No computing is necessary for qualitative descriptions of expected climate change (e.g., Ferguson 1995, for Alaska and northern Canada).

This section began with a caveat on accepting model outputs as predictions because of many and sometimes unknown factors that govern model performance. Whenever possible, model simulations should be verified by observations. The process of verification begins with comparison of observed and predicted fields (e.g., precipitation, as observed, then simulated by the Community Climate Model (CCM 1) *(fig. 2, Part II)*. It then proceeds to rigorous statistical analysis. The field of spatial statistics is itself rapidly evolving, but newer, potentially better methods for spatial analysis have already been applied in air pollution studies (Cressie 1990).

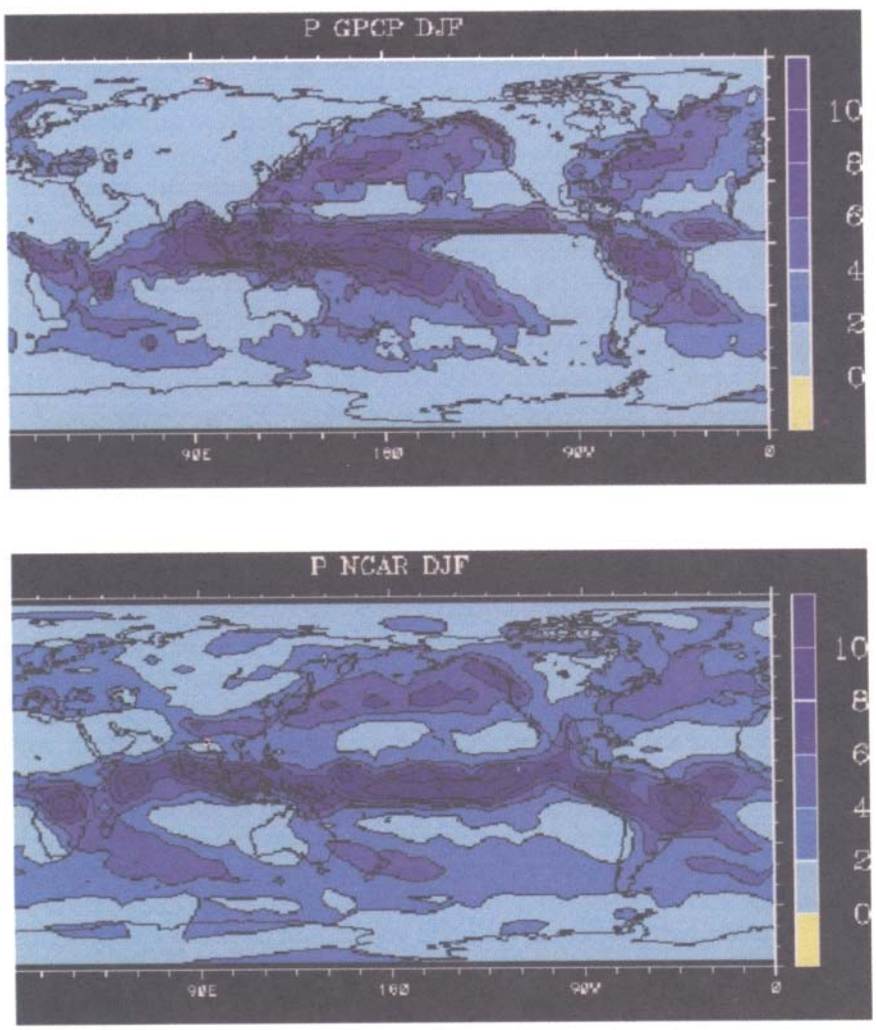


Figure 2-Global precipitation as analyzed by the Global Precipitation Climatology Project (top) and simulated (bottom) by the National Center for Atmospheric Research Community Climate Model CCMI (Roads and others 1996). Scale at right is in millimeters per day.

Production and Transport of Smoke Pollutants from Biomass Burning Models

Extensive research during the past several years has added considerably to the understanding of the production and transport of smoke pollutants from biomass burning. New fuel consumption models such as CONSUME (Ottmar and others 1993) and FOFEM (Keane and others 1994) have been developed to enable managers to estimate the amount of biomass consumed during fires. Emission characterization research (Ward and Hardy 1991) has focused on the development of emission factors and smoldering decay factors for biomass burning in temperate forests of the United States, tropical forests in South America, and grasslands of Africa. Several smoke dispersion models such as PUFF (Hardy and Ferguson 1993), CALPUFF (Scire 1990), V-Smoke (Harms and others 1994), and SASEM (Riebau and others 1988) have been developed and are being evaluated and modified for immediate burn decisions to reduce impacts on downwind communities. Emission inventory models (Peterson 1988, Peterson and Ward 1993) allow managers and regulatory agencies to estimate the total smoke produced.

Models Simulating Uptake of Gaseous Pollutants by Forest Canopies

Direct measurements of dry deposition of gaseous pollutants by plant canopies are difficult to make on a routine basis. Consequently, the use of models has been advocated as a means of deriving estimates of dry deposition fluxes (Hicks and others 1987). An example of such use is the "big leaf" multiple resistance model. The model is most applicable over relatively flat, horizontally homogenous terrain. The model is limited because of the omission of the within-canopy turbulent exchange process, its inherent inability to address questions about the flux of bi-directional pollutants such as NH_3, CH_4 and NO, and its lack of detail concerning transfer with soil, mesophyll, and cuticle (Baldocchi and others 1987, Hicks and others 1987). Various classes of models have been used in the past, including the "big leaf" multiple resistance model, and much more complex models such as the hybrid "big leaf"/ multi-layer model (Baldocchi and others 1987), K-theory model (Baldocchi 1988), and higher-order-closure model (Meyers 1987; Meyers and Paw U 1986). Their predictive capabilities were compared with direct eddy correlation measurements of SO_2 and O_3 fluxes to a deciduous forest for both well-watered and water-stressed conditions. By increasing the degree of detail of the exchange-governing processes from the more simple single layer model to the more detailed multi-layer models, the predictions of the deposition rates improved by 40-50 percent as determined from the root mean square error (RMSE). Also, by including the effect of water stress in the stomatal resistance formulations, the RMSE of the predictions was decreased by 50 percent for the models examined (Meyers and Baldocchi 1988).

However, use of the current models of dry deposition to forest canopies for conditions of the western United States is questionable. This difficulty is primarily because of the much higher complexity of the mountainous terrain, and the patchy character of vegetation cover (quite different from uniform canopies of forests in the eastern United States or agriculture crop canopies for which many deposition models have been developed). In addition, the available models are not designed for calculating deposition of particulate matter, which in dry conditions of the western United States accounts for substantial input of airborne nutrients to forests. And, the predictive ability of the multiple resistance "big leaf" models is limited in conditions when high concentrations of NH_3 are present, a situation quite typical for the western Sierra Nevada forests and other locations in California (Bytnerowicz and Riechers 1995).

Part III

Research Needs for the Pacific Region

Research Needs for the Pacific Region

Andrzej Bytnerowicz,[1] Paul Miller,[1] and Mark Poth[1]

Trace gas exchanges with terrestrial ecosystems and their potential effects on ecosystems are not well understood. For instance, more information on emissions of terpenes and isoprenes from forests and their potential for ozone formation, including mechanisms of these processes and their rates, are needed to develop reliable global atmospheric chemistry models. For the same reason, smoke impacts on atmospheric radiation, ecosystems, and human health require further investigations. Quantification of trace gas emissions in sites with chronic N deposition and high soil NO_3^- concentrations and the effects of different management practices (harvesting, prescribed fires, etc.) on these emissions is also required for a better understanding of N cycling and functioning of the terrestrial ecosystems.

Carbon and nitrogen emissions both increase on a global and regional scale, and their biogeochemical cycles are closely linked and mutually dependent. Therefore, the relationships between these two elements should be studied in various geographical and ecological scenarios to better understand mechanisms of their interrelations and to be able to develop more reliable regional and global scale models.

Increasing deposition of nitrogen seems to be one of the most obvious global changes affecting the Pacific region. Several research areas need further investigations. For instance, more field data should be collected to adequately characterize N deposition in the western United States. Although such monitoring efforts are very costly, they are essential in understanding regional distribution of dry and wet deposited nitrogen. In this regard, also understanding mechanisms of uptake and incorporation of various N pollutants by the terrestrial ecosystems is urgently needed to accurately estimate nitrogen cycling in various landscape forms (including forest stands). Available information in the literature on the subject is mostly from the eastern United States and Europe where climatic conditions are quite different from generally arid conditions of the western States. Accurate characterizing of nitrogen retention in terrestrial ecosystems is required for suggesting such management practices that could be consciously used in order to increase the capacity of sites to retain and use N from atmospheric deposition, N mineralization, or N fixation. Better understanding of the effects of chronic N deposition on sensitivity of important forest species, such as ponderosa pine, to ozone exposures is also needed.

A better understanding of the changes occurring in streams, snow, and permafrost is required. This includes a need to characterize changes in mountain snow cover and resulting impact on water resources and streamflow patterns, e.g., seasonal snow patterns in complex terrain, rain-on-snow flood potential, snow accumulation, and snow melt. In this regard a better characterization of elevation position of the rain/snow interface and a significance of its impact on slope stability and certain elevation-specific vegetation species is also needed. It is also important to find ways to parameterize mountain snow cover patterns in relation to large-scale climate patterns to estimate mountain snow from general circulation models. In addition, methods should be developed for spatial interpolation of sparse ground observations and/or techniques to couple vegetation cover with snow cover for remote sensing applications (current remote monitoring techniques of snow cover from satellite imagery have failed in forested and mountainous environments and there is no quantitative information on snow cover distribution in most wildland areas of the Pacific region).

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More reliable predictions of climate change both on a global scale and for the Pacific coast are urgently needed. Because building climate scenarios in complex terrain is compounded by the lack of observation data, the installation of a long-term, high-density array of year-round remote meteorological stations is needed. To account for cold-air pooling and drainage patterns in complex terrain, we must increase efforts to spatially interpolate relative humidity and temperature. To build long-term and/or large-domain climate scenarios with 10 km or less spatial resolution, techniques for interpolating wind and precipitation should be developed.

Studies across latitudinal gradients should be undertaken to predict possible changes related to warming of the climate. Present air pollution/climate scenarios from Mexico City may indicate possible future scenarios for other areas (e.g., the Los Angeles Basin). Changes occurring in Alaska, where temperature increases are hypothesized to be the greatest, could serve as an early warning system for the possible changes in lower latitudes.

Because very little is known on levels and biological effects of UV-B radiation, which has the potential to affect some sensitive components of western terrestrial ecosystems (including the effects on forest ecosystems), it seems necessary to establish the UV-B monitoring network in the western United States.

Because of great uncertainties in the present climate change models, especially in regard to the expected temperature increases, future biological effects research should focus on those changes that contain a relatively high degree of certainty (such as increasing concentrations of CO_2, elevated N deposition, increasing UV-B radiation). Such studies should consider effects of other modifying factors, e.g., changing temperatures or soil moisture deficit. Model simulations and regional estimates research should focus on application of micrometeorological methods to estimate net primary production in the tropical savanna in Brazil; development of regional estimates of biomass consumption by fire; development of models for nitrogen deposition estimates which would take into account the patchy and mountainous landscape of the western forests; and establishment of a linkage between the Global Circulation Models and landscape level ecosystem models (e.g., ZELIG, TreeGro) that would be critical for understanding landscape level changes.

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