

## Preface

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The Sierra Nevada is the second largest and the most elevated mountain range in the United States south of Alaska with its highest peak, Mount Whitney, reaching 4418 m (Fig. 1). The Sierra Nevada is very important, both ecologically and economically, for the state of California and the entire United States. These mountains contain geological and biological resources of exceptional value and beauty including many threatened and endangered species. Areas such as the Lassen Volcanic, Yosemite, Sequoia & Kings Canyon National Parks, and the Lake Tahoe Basin are nationally and internationally recognized natural wonders (Fig. 2). Preservation of these resources is one of the top priorities for US federal agencies, state authorities, environmental groups and the general public.

The Sierra Nevada is also located near some of the most populous urban areas in the US. Many of California's population of over 36 million people use the Sierra Nevada for recreation, hunting, and vacations. In addition, millions of people visit these mountains each year from other states and countries. Air pollution generated from urban areas and traffic corridors has pronounced effects on forests and other ecosystems of the Sierra Nevada. Regional haze resulting from anthropogenic activities and natural processes affects visibility of many national parks and Wilderness Class I Areas and has become a great concern for land managers. Air quality is also a very important feature for the health of the inhabitants of many foothill and mountain communities and the millions of visitors to the Sierra Nevada national parks and forests.

Other factors, especially changes of climate (Field et al., 1999) and management practices (Procter et al., Chapter 15, this volume), have long term impacts on Sierra Nevada ecosystems. Among these, increases in ambient temperatures, changes in water availability patterns, higher occurrence of wild fires, or outbreaks of insect populations are most important. It is difficult to quantify the effects of each of these factors separately because they occur simultaneously, but it is expected that changes of forest health, species diversity and quality of ground and stream water may occur.

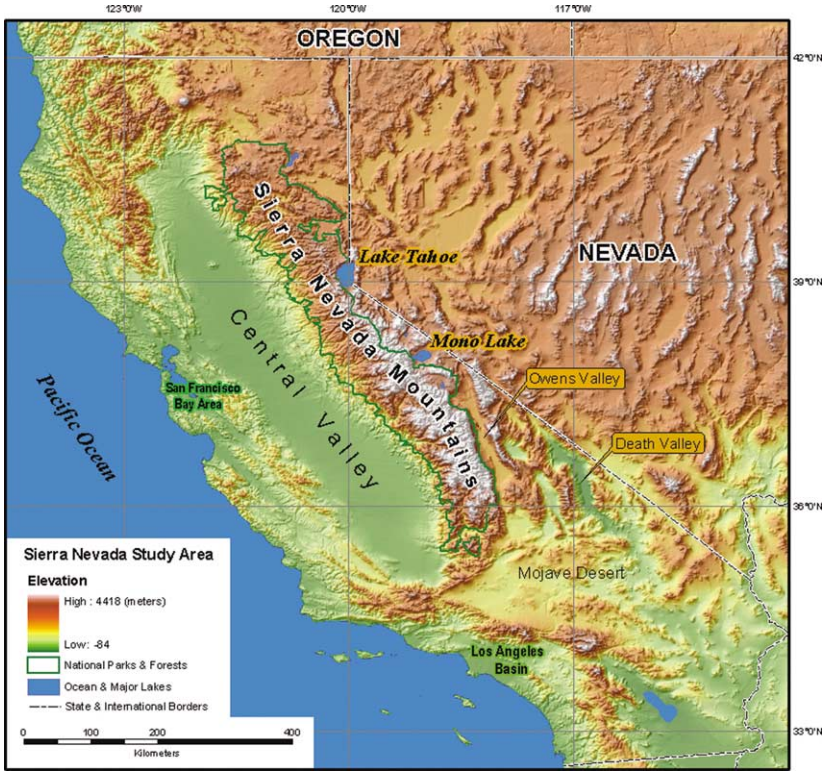


Figure 1. Locations of the Sierra Nevada, California, and borders of the study area.

Air quality in the Sierra Nevada is highly variable: excellent much of the time and in many places and seriously degraded at other times and places. Even prior to Euro-American colonization of the Sierra Nevada, summers were typically quite smoky as many small fires burned for months until the rain extinguished them in the fall (SNEP, 1996). It has been known for about 30 years that air pollution originating in the California Central Valley, the San Francisco Bay Area, or even the Los Angeles Basin, drifts into parts of the Sierra Nevada (Miller *et al.*, 1972). In 2001, the San Joaquin Valley recorded 101 violations of the federal eight-hour ozone ( $O_3$ ) standard, which exceeded those recorded in the South Coast Air Basin of Los Angeles, which has had the nation's worst air quality for decades. Elevated concentrations of  $O_3$  have been responsible for foliar injury to ponderosa and Jeffrey pines (Stolte *et al.*, 1992). There have been concerns that other tree species, including the giant sequoia, may be affected by elevated levels of  $O_3$  (Grulke and Miller, 1994; Grulke *et al.*, 1996).

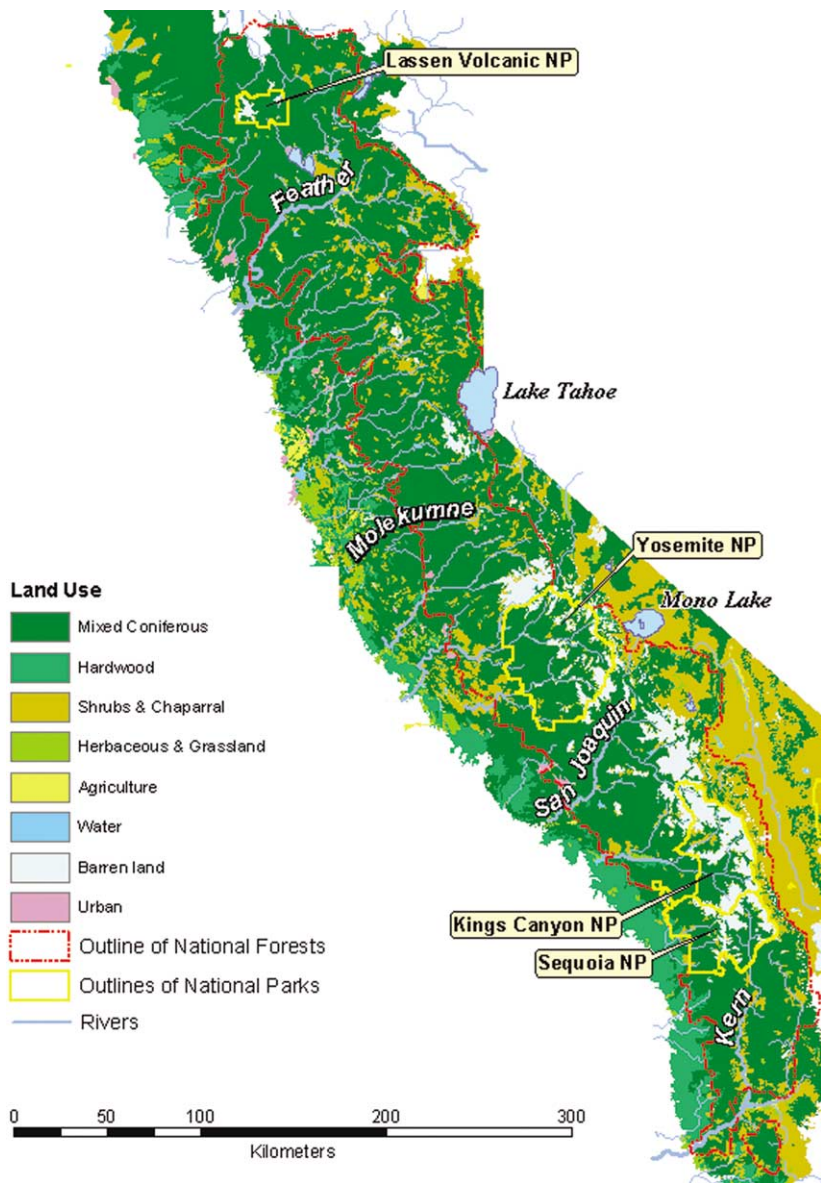


Figure 2. Land use and the most characteristic geographic features of the Sierra Nevada.

In addition to O<sub>3</sub>, elevated concentrations of other components of urban and agricultural air pollution, especially nitrogenous (N) compounds, may impact forests and other Sierra Nevada ecosystems. Among those, ammonia (NH<sub>3</sub>), nitrogen oxides (NO<sub>x</sub>), nitric acid vapor (HNO<sub>3</sub>), and particulate nitrate (NO<sub>3</sub><sup>-</sup>) and ammonium (NH<sub>4</sub><sup>+</sup>) are of the greatest importance (Bytnerowicz and Fenn, 1996). With the projected twofold increase of California's population by the year 2040 (State of California, Department of Finance, 1998) and rapid development of the California Central Valley, higher emissions of air pollutants and even more severe effects of air pollution on the natural ecosystems of the Sierra Nevada are expected.

Although it is well known that the air pollution impacting the Sierra Nevada originates in the California Central Valley and the San Francisco Bay Area, there is little information about O<sub>3</sub> distribution in the Sierra Nevada forests. In 1990–1991 a regional program was initiated—the Sierra Cooperative Ozone Impact Assessment Study (SCOIAS)—to monitor ambient O<sub>3</sub> and meteorological variables at six Sierra Nevada sites (Van Ooy and Carroll, 1995). Yosemite, Sequoia & Kings Canyon, and Lassen Volcanic National Parks, joined SCOIAS by contributing ambient O<sub>3</sub> data at three locations within each Park, and the USDA Forest Service's Pacific Southwest Research Station, provided 4 years (1992–1995) of ambient O<sub>3</sub> data from a site in the San Bernardino Mountains. In addition to SCOIAS sites, there are a number of other O<sub>3</sub> monitoring stations in the San Joaquin Valley Air Basin located in the mountain counties on the eastern side of the Basin. Ozone data from stations in this region are available from the California Air Resources Board as printed summaries, on compact disk, and from their web site (<http://www.arb.ca.gov/aqd.htm>). The National Park Service maintains both active and passive O<sub>3</sub> monitors at Sequoia & Kings Canyon, and Yosemite National Parks. Printed reports are available and the latest information can be obtained from the National Park Service web site (<http://www.aqd.nps.gov/ard1/gas>). The rapid increase occurred in the last years in the use of passive samplers for quantifying ambient concentrations of air pollutants is allowing to extend the continuous monitoring networks and perform exploratory studies in remote areas where active monitors are not available.

Diurnal patterns of O<sub>3</sub> concentrations vary considerably between sites and depend primarily on distance from sources, elevation, and airflow patterns. Van Ooy and Carroll (1995) examined patterns at six SCOIAS sites along the western Sierra Nevada and observed that some sites had strong diurnal patterns, and other sites had little diurnal variation. Differences in diurnal O<sub>3</sub> patterns were not linked to forest tree injury in three subsequent studies (Miller *et al.*, 1996; Salardino, 1996; Arbaugh *et al.*, 1998).

Reports of O<sub>3</sub>-caused injury to ponderosa and Jeffrey pines in the 1970s (Miller and Millecan, 1971) and subsequent surveys using 10-tree trend plots (Pronos and Vogler, 1981) are among the earliest accounts describing the extent and severity of O<sub>3</sub> injury in the region. For example, Pronos and Vogler (1981) reported that between 1977–1980, the general trend was an increase in the amount of O<sub>3</sub> injury present on pine foliage in the southern Sierra Nevada. Peterson et al. (1991) evaluated crown condition and derived basal area growth trends from cores collected from ponderosa pines in seven federal administrative units in the Sierra Nevada. From north to south, samples were collected in the Tahoe National Forest, Eldorado National Forest, Stanislaus National Forest, Yosemite National Park, Sierra National Forest, Sequoia & Kings Canyon National Parks, and Sequoia National Forest. From July through August 1987, four symptomatic and four asymptomatic sites were visited in each unit, and only sites with ponderosa pines greater than 50 years old were selected for sampling. The symptomatic plots generally indicated increasing levels of chronic O<sub>3</sub> injury (reduced numbers of annual needle whorls retained, and chlorotic mottle symptoms on younger age classes of needles) from north to south. Overall, the results of this study documented the regional nature of the O<sub>3</sub> pollution problem originating primarily in the San Joaquin Valley Air Basin as well as east of the San Francisco Bay Area. The study found no evidence of recent large-scale growth changes in ponderosa pine in the Sierra Nevada; however, the frequency of trees with recent declines of growth was higher in the southernmost units. Because these units had the highest levels of O<sub>3</sub> exposure (and more chlorotic mottle symptoms on needles of younger age classes), it is likely that O<sub>3</sub> is one of the factors contributing to the decline in pine basal area. Other factors limiting tree growth in this region include periodic drought, brush competition, and high levels of tree stocking.

Both permanent plots and cruise surveys have been employed in Sequoia & Kings Canyon and Yosemite National Parks, to determine the spatial distribution and temporal changes in injury to ponderosa and Jeffrey pine (Duriscoe and Stolte, 1989). Comparisons of the same trees in 28 plots between 1980 and 1982 and between 1984 and 1985 in Sequoia & Kings Canyon National Park showed increases in O<sub>3</sub> injury severity and increases in the total number of trees with O<sub>3</sub>-type injury. The highest levels of tree injury occurred at approximately 1800 m elevation in the Marble Fork drainage of the Kaweah River, and were associated with peak hourly O<sub>3</sub> concentrations of ~ 80–100 ppb that only occasionally reached 120 ppb.

In 1986, about 3120 ponderosa or Jeffrey pines were examined in a cruise survey conducted in Sequoia & Kings Canyon and Yosemite National Parks (Duriscoe and Stolte, 1989). More than one-third of these trees exhibited chlorotic mottle. At Sequoia & Kings Canyon National Park, symptomatic trees comprised 39 percent of the sample, and at Yosemite National Park they

comprised 29 percent. Ponderosa pines were generally more severely injured than Jeffrey pines (Pronos *et al.*, 1978). These cruise surveys characterized the spatial distribution of injury in Sequoia & Kings Canyon and Yosemite National Parks, and indicated that trees in drainages nearest the San Joaquin Valley experienced the most O<sub>3</sub> injury.

The Lake Tahoe Basin has distinct air quality problems resulting from a combination of local and remote pollution sources. This is in contrast to most other Sierra Nevada sites where pollution results only from long-range transport. In 1987, a survey of 24 randomly selected plots in the Basin found foliar O<sub>3</sub>-type injury on 29.2% of trees; while at 16 plots to the east of the Basin, injury was lower than within the basin, as only 21.6% of trees were injured (Pedersen, 1989).

In 1990–1991, the Forest Ozone REsponse STudy (FOREST) was initiated to link injury information with the SCOIAS. The two parallel projects were conducted at the same locations in the Sierra Nevada from 1991 to 1994. The FOREST project was developed to examine tree injury through an agreement between the California Air Resources Board and the Air Resource Management Program of the Forest Service's Pacific Southwest Region. This agreement led to the establishment of forest vegetation plots in the vicinity of SCOIAS monitoring stations, for the purpose of annual assessments of O<sub>3</sub> injury to ponderosa and Jeffrey pine populations. Other participants, including Yosemite, Sequoia & Kings Canyon and Lassen Volcanic National Parks, joined FOREST by establishing and assessing tree conditions at three plots in each park; and the Forest Service's Pacific Southwest Research Station joined by including 4 years (1992–1995) of ozone injury index (OII) evaluations from three sites at Barton Flats in the San Bernardino Mountains. Since 1992, Project FOREST has monitored the condition of pines and O<sub>3</sub> air quality at 10 locations in the Sierra Nevada, from Lassen Volcanic National Park in the north to Sequoia National Park in the south. One additional site is located in the San Bernardino Mountains in southern California. High positive correlation between injury of ponderosa and Jeffrey pines and cumulative O<sub>3</sub> exposure over four summer seasons has been reported (Arbaugh *et al.*, 1998). Injury amounts in the Sierra Nevada range from almost no crown injury in the north to moderate crown injury in the south. At the site in the San Bernardino Mountains, located about midway along a west-to-east gradient of ozone exposure, the amount of crown injury is moderate.

Based on the FOREST sites, Forest Service scientists monitored O<sub>3</sub> concentrations at 89 sites in the mixed conifer zone of the entire range of the Sierra Nevada over the summer of 1999 by using passive monitors. At 9 sites active O<sub>3</sub> monitors were co-located with the passive samplers for calibration of the passive sampling devices, and at 25 sites O<sub>3</sub> injury to ponderosa and Jeffrey pines was evaluated. Data from these measurements were made available

to several groups of scientists who had expressed interest in this study. This resulted in the development of three models of spatial and temporal O<sub>3</sub> distribution in the Sierra Nevada range, estimates of distribution of diurnal O<sub>3</sub> concentrations at a large landscape level, and evaluation of risks to sensitive species of pines from O<sub>3</sub> exposures.

An intention of the editors of this book is to publish in a single volume the results of monitoring and modeling from this unique study instead of individual papers appearing in different outlets. By including different modeling approaches with a unifying goal of landscape-level evaluation of O<sub>3</sub> distribution and biological effects, this book will be valuable to anyone interested in regional scale assessments and modeling O<sub>3</sub> distribution and effects. Although the primary objective of this book is to present integrated results of the air quality and forest heath monitoring and modeling efforts, other topics are also covered. In order to better understand complex responses of forests to air pollution, the effects of other stresses, such as climate change, fire, and pathogen infestations on the mixed-conifer forests, are discussed. In addition, information on the past O<sub>3</sub> effects on the Sierra Nevada forests provides a historical perspective for the presented findings. Discussion of management options for the pollution-affected forests and research and technology transfer needs related to long-term effects of ambient air pollution and other factors on the Sierra Nevada forests are also offered.

Section I, "Ozone and its Effects on Sierra Nevada Ecosystems," consists of five chapters and provides background information needed for understanding air pollution problems and potential effects of O<sub>3</sub> and other stresses on the Sierra Nevada ecosystems. Minnich and Padgett (Chapter 1) give a general overview of the Sierra Nevada natural resources. Special emphasis is placed on mixed-conifer forest ecosystems, but other adjacent ecosystems are discussed as well. Information on climate and fire status provides background information needed for better understanding of major forces of nature that may directly influence forests and other ecosystems and modify responses of vegetation to the air pollution stress. Carroll et al. (Chapter 2) review history of O<sub>3</sub> measurements and monitoring efforts in the Sierra Nevada and compare those with other areas in California. The authors also give an overview of O<sub>3</sub>-caused pine injury monitoring efforts within the Sierra Nevada from the early 1970s until the present by using three different methodologies. Grulke (Chapter 3) discusses how the O<sub>3</sub> effects differ between coniferous trees and other plants. The author gives a physiologically based assessment of O<sub>3</sub> injury indices for the conifers that consist of combinations of injury index scores most characteristic of O<sub>3</sub> effects (foliar chlorotic mottle, needle retention, and needle length). The information is based on both controlled experiments and field observations that relate the effective uptake of O<sub>3</sub> to individual components and total scores of the injury-evaluation system for pines used in the Forest Pest Management,

Forest Health Monitoring, and Ozone Injury Index systems. Goldstein et al. (Chapter 4) describe recent accomplishments of research on O<sub>3</sub> uptake at several different scales from the leaf level to the whole ecosystem. Factors controlling O<sub>3</sub> stomatal uptake, especially phenological status of plants, availability of water, and diurnal distribution of O<sub>3</sub> concentrations, are discussed. This chapter also provides the basis for understanding processes controlling biologically relevant O<sub>3</sub> uptake and discusses needs for the development of biophysical models that would estimate O<sub>3</sub> uptake at large scales of complex mountain landscapes of the Sierra Nevada. Fenn et al. (Chapter 5) discuss interactive effects of O<sub>3</sub>, N deposition, and other stresses on Sierra Nevada forests and other ecosystems. The authors emphasize that O<sub>3</sub> does not act on trees and natural ecosystems alone. Nitrogen deposition and other environmental stresses, especially drought, may seriously modify O<sub>3</sub> effects on trees and other plants. Ozone and N deposition effects are discussed at the tree, forest canopy, watershed, and entire ecosystem levels. An overview of the Sierra Nevada research results, that are still very limited, is complemented with results from studies on the interactive effects of these stresses on mixed conifer and chaparral ecosystems in the San Bernardino and San Gabriel Mountains in southern California.

Section II, "Analysis of Spatial Patterns of Urban Transported Ozone in the Sierra Nevada," is central to this book and consists of six chapters. This section presents results of three different models of O<sub>3</sub> concentrations distribution and the results of pine crown injury evaluation in the Sierra Nevada during the 1999 study. Arbaugh and Bytnerowicz (Chapter 6) describe the 1999 O<sub>3</sub> passive samplers monitoring network, pollutant measurements done with active monitors, as well as data collected from the meteorological monitoring network. The authors describe principles of passive samplers performance, their calibration, chemical analysis, and calculation of O<sub>3</sub> ambient concentrations. To estimate surface O<sub>3</sub> distribution patterns in the Sierra Nevada, Lee (Chapter 7) uses auxiliary data for spatial interpolation, Preisler and Schilling (Chapter 8) use nonparametric local regression while Frączek et al. (Chapter 9) use the Environmental Systems Research Institute (ESRI) Geostatistical Analyst. Maps of temporal and spatial distribution of the pollutant in these chapters allow a reader to visually evaluate an extent of the O<sub>3</sub> problem in the Sierra Nevada bioregion. Arbaugh and Bytnerowicz (Chapter 10) provide a review of the three modeling chapters and discussion of air quality on status of pines in the Sierra Nevada forests. Based on the results of these models and their comparison, as well as potential biological effects of ambient O<sub>3</sub> on forests, the implications for future air pollution research and monitoring needs in the Sierra Nevada are discussed.

Section III, "Research and Development Needs for the Sierra Nevada," consists of five chapters. Various aspects of future needs for better understanding of the air pollution status in complex terrain of the Sierra Nevada are pre-

sented. Bytnerowicz et al. (Chapter 11) describe methodological needs and perspectives for monitoring air pollution and regional haze in the Sierra Nevada and other mountain areas in California. Discussion of the need for improved exchange of information among the scientists, managers, and policy makers dealing with complex issues of understanding and monitoring the air pollution effects in mountain forest ecosystems is provided. This chapter is closely linked to the next by Plymale et al. (Chapter 12) in which needs for establishing the air pollution effects monitoring system for the Sierra Nevada mixed conifer forests are described. Tonnesen et al. (Chapter 13) introduce the readers to regional modeling efforts and address O<sub>3</sub> and N pollution scenarios developed with the US EPA's Community Multiscale Air Quality (CMAQ) "third generation" (Models-3) modeling system. Panek et al. (Chapter 14) discuss the need for applying modeling techniques to estimate O<sub>3</sub> deposition and effects in the Sierra Nevada forests. The authors explain the limitations of concentration-based approach and the advantages of addressing stomatal O<sub>3</sub> flux that depend on plant phenology and physiological activity as well as diurnal changes in O<sub>3</sub> concentrations. In addition, the authors describe various approaches to O<sub>3</sub> uptake models at the leaf and canopy levels, and they discuss possible effects of predicted climatic changes on O<sub>3</sub> uptake by trees and sensitivity of California mountain forests to that pollutant. Procter et al. (Chapter 15) present information on how past and current management of air pollution has affected forests of the Sierra Nevada. The authors discuss the difficulties in managing the impacts of air pollution in the Sierra Nevada; management involves complex ecological, political, and regulatory issues for both the National Park Service and the Forest Service. These two agencies manage the vast majority of the Sierra Nevada and together have developed a leadership role in research, monitoring, and development of management strategies to address the effects of air pollution on forest ecosystems. The chapter focuses on the concepts and strategies of the Forest Service's Air Resource Management Program in the Sierra Nevada.

The book is closing with Section IV, "International Perspective of the Sierra Nevada Research." In this section, Alonso and Bytnerowicz (Chapter 16) present the results of the 1999 Sierra Nevada study from a perspective of similar activities in the San Bernardino Mountains of southern California, selected national parks in California and the eastern United States, as well as forested areas in Central & Eastern Europe and the Mediterranean.

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