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Chapter 2

Historical perspectives on ambient ozone and its effects on the Sierra Nevada

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Abstract

An overview of summer wind flow climatology as it relates to the transport of ozone (O_3) to the Sierra Nevada is presented. We also review a representative sample of studies documenting the occurrence of ozone injury symptoms in the forests of the western Sierra and in the Lake Tahoe Basin. We conclude that ozone is negatively impacting existing forest flora and that current trends in regional O_3 concentrations imply continued and possibly increasing injury to these plants. All field studies to date examine the relationships between exposure and injury, not dose. The lack of concurrent stomatal conductance and ozone concentration measurements precludes determination of dose, adding considerable uncertainty to determination of ozone injury thresholds. Given the diurnal variation in stomatal conductance and the frequent diurnal variation in local ozone concentrations, monitoring systems need temporal resolutions not greater than several hours.

1. Introduction

During the afternoon and evening hours of the warm season, the predominant, low-altitude, regional wind-flow pattern in Central California is the inflow of marine air through various gaps in the coastal mountains to the Central Valley and eventually up the slopes of the mountains bounding this valley

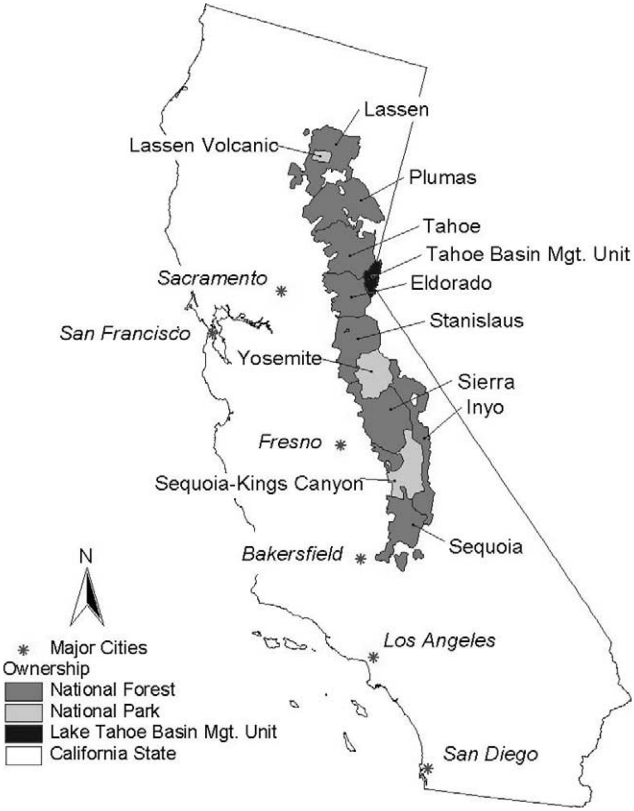


Figure 1. Map of California showing major cities and national forests.

(Fosberg and Schroeder, 1966; Zaremba and Carroll, 1999). This pattern occurs on 72% of the warm season days (Hayes et al., 1984). A strong diurnal wind reversal, with midday and afternoon upslope flow and nighttime down slope flow characteristic of mountain-valley wind regimes, occurs over the western slope of the Sierra Nevada (Fig. 1) located east of the Central Valley. Various agricultural, urban, and transportation sources emit air pollutants and their precursors into these air streams, which result in significant concentrations of primary and secondary air pollutants being transported into forested areas of the Sierra Nevada (Miller and Millecan, 1971; Van Ooy and Carroll, 1995; Bytnerowicz et al., 2000). Many of the forest flora are sensitive to oxidants (Miller et al., 1983; Salardino and Carroll, 1998; Miller et al., 2000). In addition, many organic and inorganic nitrogen species formed from anthropogenic sources can negatively affect aquatic ecosystems (Jassby et al., 1994; Asman and Larsen, 1996). Although this warm season airflow climatology has existed for centuries, it is only in the past five or six decades that these flows have transported enough pollutants to potentially affect the ecosystems in the Sierra. This chapter focuses on the general history of ambient ozone (O_3) concentrations in selected areas of the Sierra and the effects of O_3 exposure on sensitive forest species.

Ozone is found naturally in the troposphere and has two primary sources: downward mixing from the stratosphere and formation in the troposphere due to photochemical reactions. The latter is the major source in the summer when warm temperatures, increased biogenic emissions of precursors, and ample sunshine all favor O_3 formation. In simplistic terms, tropospheric O_3 forms when nitrogen dioxide is photo-dissociated by sunlight to form atomic oxygen and nitric oxide. The atomic oxygen collides almost instantaneously with an oxygen molecule to form O_3. This reaction is reversible in that the O_3 so formed can then react with the nitric oxide to reform nitrogen dioxide and oxygen. In the presence of reactive hydrocarbons (i.e., volatile organic compounds (VOCs)), there are additional pathways for converting the nitric oxide back to nitrogen dioxide that do not consume O_3, allowing the concentrations of O_3 to increase to levels significantly higher than if these hydrocarbons were absent. Oxides of nitrogen are produced by microorganisms and are emitted naturally from soils, among other biological sources. Reactive hydrocarbons, such as isoprene, are emitted by plants. Hence, plant communities emit O_3 precursors contributing to the natural background concentrations of O_3 in the troposphere. Natural selection has resulted in modern plants that are able to generate antioxidants to protect themselves from background O_3 concentrations. Although there is considerable disagreement about levels of pre-industrial background O_3 concentrations, pre-1960 measurements in remote, “pristine” areas were typically between 20 and 30 parts per billion by volume (ppbv). Post-1988 concentrations at the same (or nearby) locations show values between 35 and 55 ppbv (NARSTO, 2000).

2. Ozone climatology of the Western Sierra

2.1. California ozone history

Ozone, first discovered in the 1840s, was shown to be toxic to animals in the 1870s and to cause crop damage in the 1940s (Middleton et al., 1950). The tropospheric photochemical formation mechanisms, including the role of hydrocarbons, were elucidated in the 1950s (Haagen-Smit, 1952; Leighton, 1961). The primary source of pollutant O_3 is combustion. Nitrogen is present in air and in many fuels (coal, oil, biomass) and at high combustion temperatures is converted to oxides of nitrogen (NO_x) emitted to the atmosphere. Industrialized societies also emit large quantities of hydrocarbons. These anthropogenic

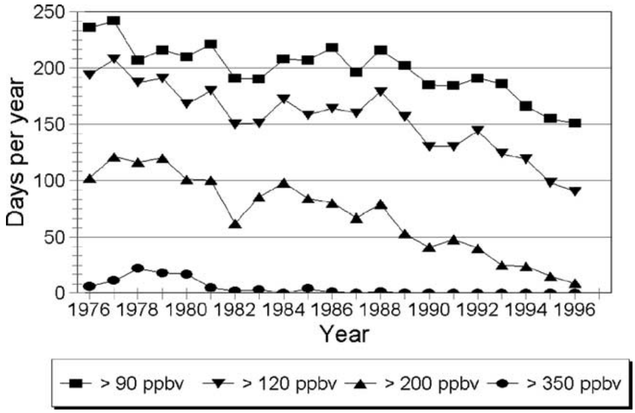


Figure 2. Number of days in the Los Angeles Basin during which ozone exceeded the indicated threshold concentrations during the calendar years 1976 through 1996.

emissions react to form pollutant O_3. During the 1960s and 1970s ambient O_3 concentrations within and downwind of highly populated areas reached many times the natural background values—especially in areas like southern California where low mixing depths, light winds, and basin-like topography limit dispersion of pollutants and warm temperatures and sunny skies favor O_3 formation.

In some areas O_3 concentrations have been greatly reduced. Emission controls on gasoline powered vehicles have been especially significant. For example, a well-tuned 1996 model automobile emits 1.9% of the VOCs, 11% of the NO_x, and 3.9% of the CO, compared to what a well-tuned 1966 model car emitted. Although the nationwide number of vehicle miles driven has increased by more than 130% since 1970, total emissions have decreased (USEPA, 1999).

Since 1980, implementation of emissions controls has reduced O_3 formation in many coastal urban areas of California. For example, the number of occurrences (Fig. 2) of very high O_3 concentrations has decreased substantially in the South Coast Air Basin (Fig. 3). Clearly, even though the population there has increased from about 13 million people to about 16 million, the O_3 concentrations have decreased dramatically. However, the California primary O_3 standard (90 ppbv for 1 hour) was still violated about 111 days during 1999 in the South Coast Air Basin.

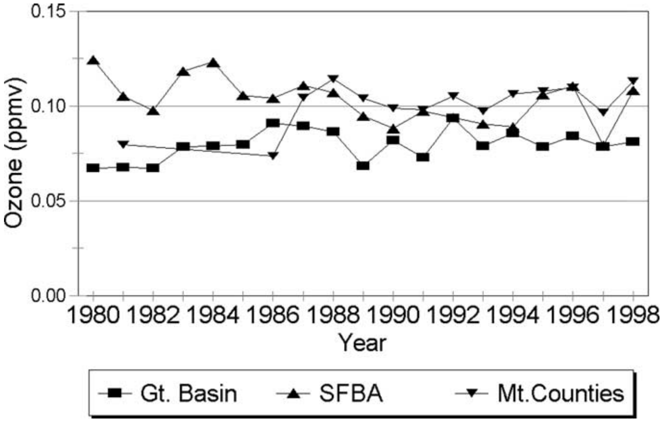
Time plots show the average of the 30 highest daily 1-hour values for several regions throughout California (Fig. 4). There is a downward trend in the coastal air basins, but not for the inland valleys. Currently, the southern San Joaquin Valley is one of the highest O_3 impacted areas in the country. It appears that

Figure 3. Map of California showing the locations of the designated air basins.

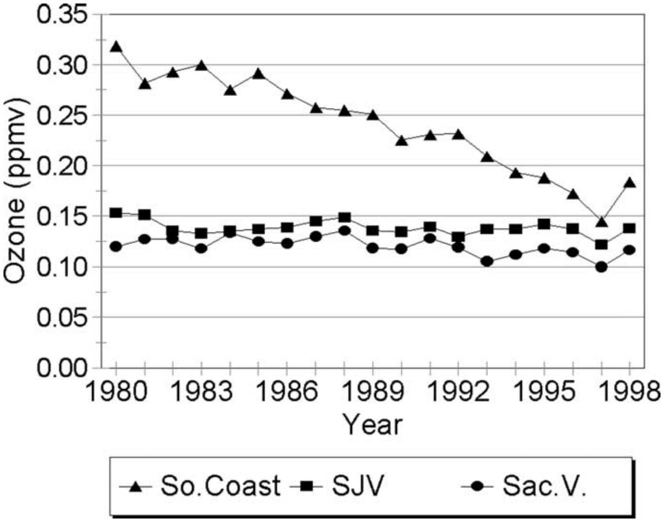
the cumulative emissions into the air masses traveling from the coast to the inland valleys, coupled with the rapid population growth in these valleys, has offset the reduction of emissions per source. Given the typical daytime upslope flow from the valley toward the southern Sierra, high O_3 concentrations are expected over the western slopes of the southern Sierra as well.

2.2. Sierran ozone exposure

High levels of photochemical air pollutants have been measured in the Central Valley and southern Sierra since the early 1970s (Miller et al., 1972). Carroll and Baskett (1979) reported aircraft-measured O_3 concentration as high as 240 ppbv over the area west of Yosemite National Park. Ground-level measurements of O_3 in the southern Sierra between 1976 and 1981 showed frequent one-hour daily maximum O_3 concentrations in the 130 to 160 ppbv range (Vogler, 1982). Van Ooy and Carroll (1995) reported similarly high ground-level O_3 concentrations in the southern Sierra for 1992. Given these relatively



(a)



(b)

Figure 4. Annual average of the 30 daily ozone maxima for six air sheds: (a) Great Basin (east of the Sierra and north of the Mojave Desert), the San Francisco Bay Area (SFBA), and the alpine counties of the central Sierra (Mt. Counties); (b) The South Coast Air Basin, the San Joaquin Valley (SJV) and the Sacramento Valley (Sac.V.). Note the ozone concentration scale change.

high ambient O_3 concentrations, it is not surprising that O_3 specific, foliar injury was found on sensitive pine species in the Sierra (Miller and Millecan, 1971).

Actual exposure of forest individuals in the Sierra is not a simple function of latitude or altitude but is controlled by the upwind proximity to concentrated

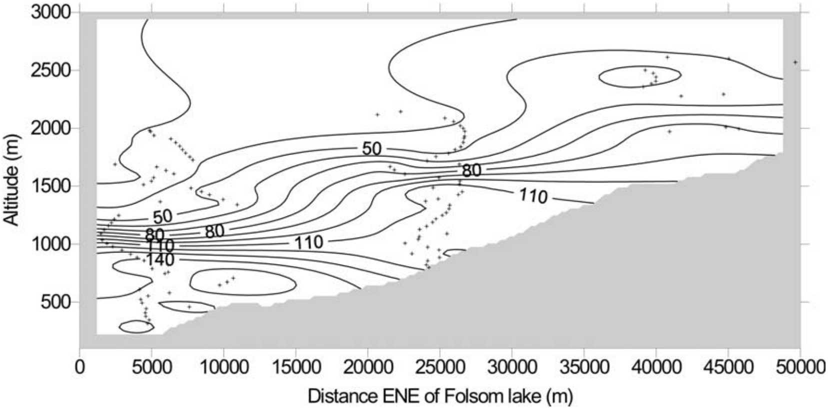


Figure 5. Vertical, east-west cross section showing aircraft-measured ozone concentrations (ppbv) east of Sacramento, California, on July 24, 1996 17:00 to 18:00 hours, PST. Lower shaded area represents topography; Plus signs indicate the aircraft sampling locations.

(i.e., urban) sources and by the nature of the terrain over which the air travels as it moves eastward. For example, the vertical distribution of O_3 downwind of Sacramento over the central Sierra on one afternoon in July illustrates this (Fig. 5), which is typical of the pattern of distribution seen over the Sierra: high concentrations at the lower elevations near the central valley, but with the eastward extent limited to elevations below about 1800 m (about 6000 ft) above mean sea level (MSL) in the central Sierra (Carroll and Dixon, 2002) and higher to the south.

This local exposure variability can be seen by examining details of exposure patterns measured at Project FOREST (Forest Ozone Response Study 1991–1994) sites (Fig. 6, Table 1). Project FOREST introduced a multi-parameter Ozone Injury Index (OII; described in more detail below) with values ranging from 0 indicating no symptoms to 100 indicating maximum possible symptoms. Three sites in closest proximity to each other (Jerseydale, Wawona, and Camp Mather) vary in average concentrations an amount almost equal to the range among all sites (Table 1). The airflow from the San Joaquin Valley to Jerseydale follows a uniformly rising slope to reach that site. However, just east of Jerseydale, the air must cross several ridges to reach the other sites. Crossing transverse ridges tends to enhance vertical mixing and dilute pollutants, and the sites downwind of such topographic features will experience lower 24-hour averaged concentrations, as do Camp Mather and Wawona. However, the latter sites experience greater variability, with their averaged maxima being nearly 45% higher than their means. The data on O_3 concentrations show a distinct increase in concentration from north to south, but the injury index is not well correlated with O_3 concentrations.

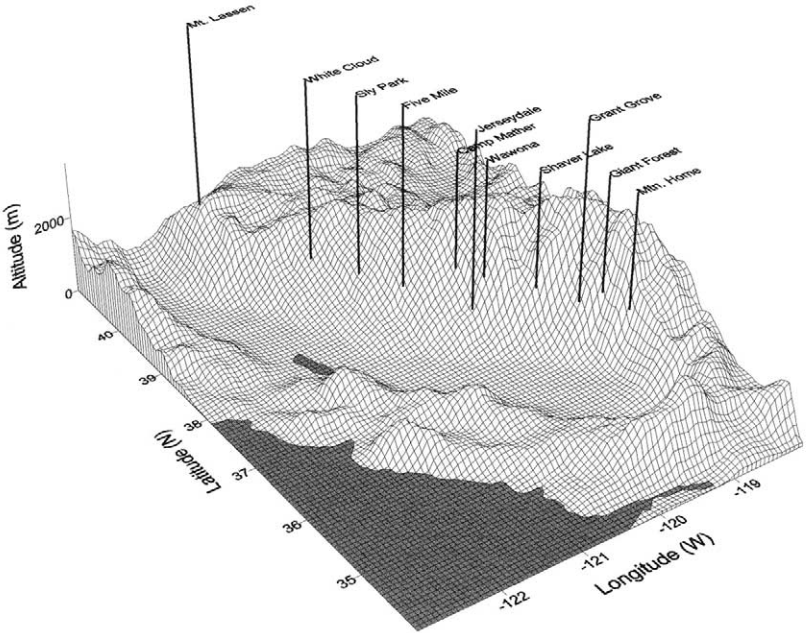


Figure 6. Perspective view of Project FOREST sites.

Table 1. Summary of data for Project FOREST sites averaged for June through September of 1992–1994

Site	Elevation (m)	Ozone injury index	Average daily max O_3 (ppbv)	24-hour mean O_3 (ppbv)
Mt. Lassen	1770	6	52	42
White Cloud	1325	27	68	62
Sly Park	1130	28	70	53
Five-Mile	1220	27	70	65
Wawona	1220	14	65	40
Camp Mather	1400	14	62	49
Jerseydale	1140	N/A	72	64
Shaver Lake	1830	16	88	55
Giant Forest	1920	38	80	66
Grant Grove	1980	41	84	64
Mountain Home	1890	28	95	71

If we assume that the threshold for injury to pines is about twice the pre-industrial background value of about 30 ppbv, then the 24-hour averaged values listed (Table 1) suggest that none of these sites should show significant injury, except perhaps Mountain Home. The literature for crops suggests that exposure to high concentrations for short durations is more likely to have serious consequences than continuous exposure to moderate concentrations. However, the data for the two sites with the highest 24-hour O_3 averages (Mountain Home with 71 and Shaver Lake with 66 ppbv) and averaged daily maxima (95 and 88) have relatively moderate to low injury index values (28 and 16) (Table 1). It is important to note that field data report continuous instrumental exposure, but not dosage, which is the appropriate measure of insult. For most plants, the primary pathway for O_3 absorption is through the stomata. Dosage is proportional to the time-integrated product of the stomatal conductance times the ambient concentration. The stomatal conductance and photosynthesis are closely linked and depend on a number of environmental and physiological parameters, such as solar radiation, ambient temperature, soil moisture, ambient relative humidity, vapor pressure deficit, plant nutrient status, leave/needle age, etc. These conditions vary diurnally and seasonally. For example, in Sierra pines, stomatal conductances are generally highest in the pre-noon hours and in the early half of the growing season (Grulke, 1999). We expect that the scatter and frequent apparent contradictions in the data comparing exposure and injury would be greatly reduced if dose could be measured or estimated accurately. Hence, we caution against the use of data in the form of multi-day averages. We expect high O_3 concentrations are most likely to occur at sites with strong diurnal signals; hence, averaging over multiple days—as with the use of passive samplers for example—will mask these events and the time of their occurrence vis-a-vis the temporal cycles of stomatal conductances.

The frequency distribution of O_3 concentration was determined for six of the FOREST sites (Fig. 7). White Cloud has a higher 24-hour mean O_3 concentration than Shaver Lake, the latter has a much broader frequency distribution, including hourly averaged concentrations over 130 ppbv. The diurnal pattern of exposure is also quite different among sites (Fig. 8). Mountain Home, Shaver Lake and Sly Park show strong diurnal variations, with high concentrations during the afternoon, while Jerseydale, Five-Mile, and White Cloud show relatively flat variations with the higher concentrations continuing into the night. If the primary pathway for O_3 absorption and injury is through the stomata, then being exposed to high concentrations during the daytime should be more significant than nighttime exposures. The data show that when concentrations exceed 90 ppbv at White Cloud, it is frequently after sunset. In contrast, Shaver Lake experiences frequent occurrences of O_3 greater than 90 ppbv, which almost always occur between noon and sunset. However, it appears that conditions at Shaver Lake cause stomatal conductances to be small when O_3 concentrations are high, thus reducing dosage and impact there. At White Cloud, the post-dawn O_3 concentrations are moderate (O_3 about 65 ppbv) but higher

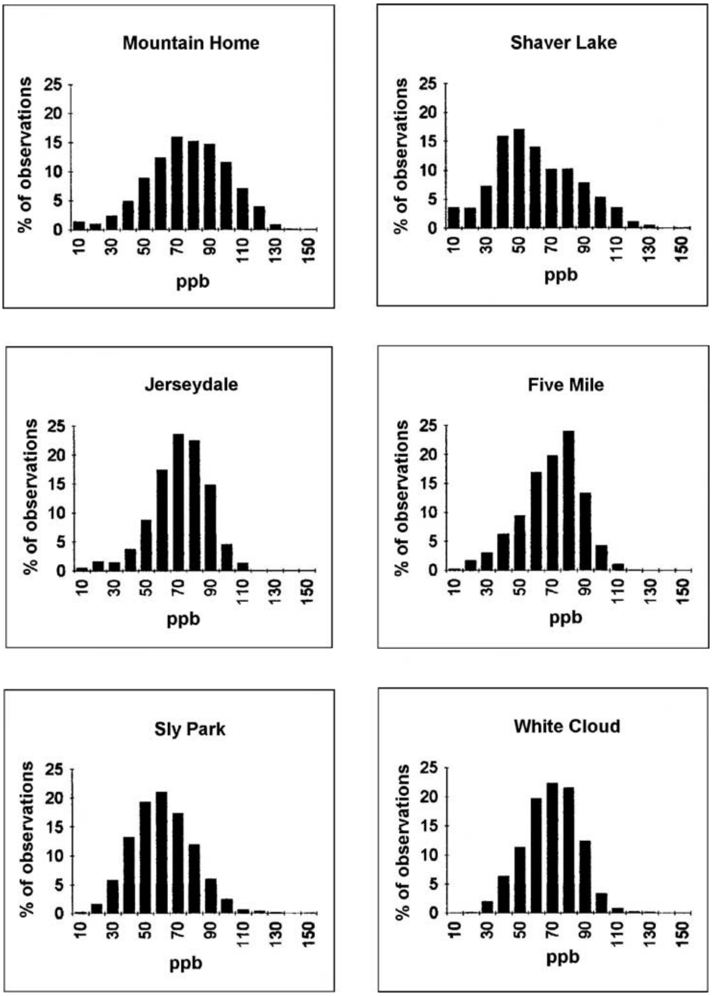

Mountain Home
Shaver Lake
Jerseydale
Five Mile
Sly Park
White Cloud

Figure 7. Frequency of occurrence of hourly averaged ozone concentrations by 10 ppbv ranges at six of the Project FOREST sites.

than at Shaver Lake ($O_3 < 40$ ppbv). Coupled with high early morning stomatal conductances, this apparently results in higher doses and greater injury at White Cloud. Hence, the correlation between ambient O_3 concentration and injury is poor, because the amplitude and phase of the local diurnal variations of O_3 concentrations and of stomatal conductances are more important than the average or peak daily values of O_3 alone.

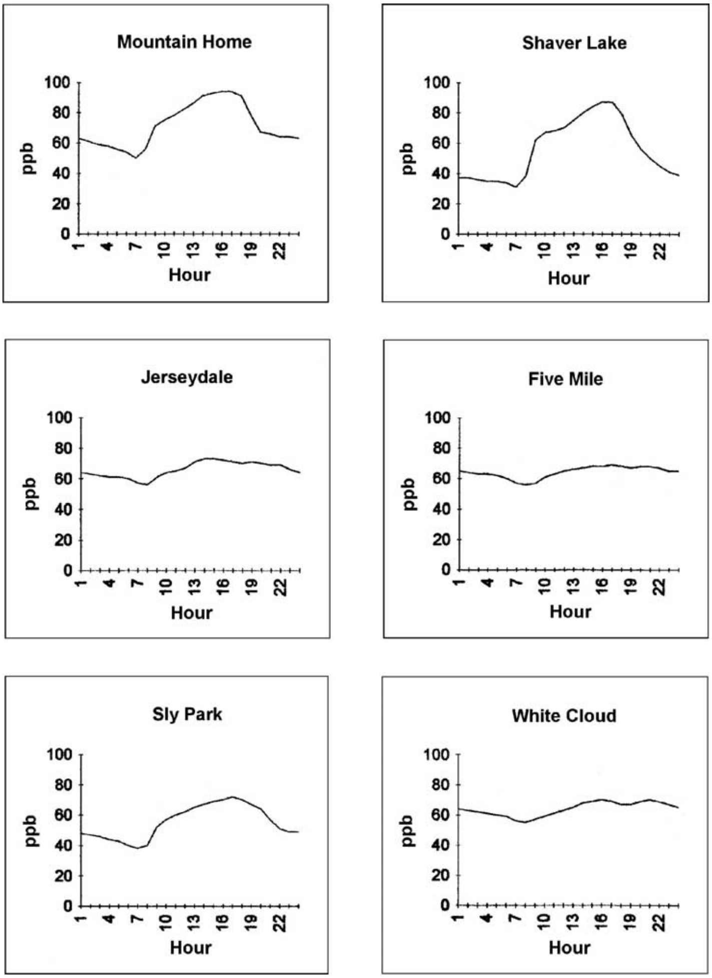


Figure 8. Diurnal distribution of hourly averaged ozone concentrations at six of the Project FOREST sites.

3. Effects

Ozone injury to pines in the Sierra Nevada was first reported in 1971 (Miller and Millecan, 1971) from an area east of Fresno, California, on the Hume Lake Ranger District, Sequoia National Forest, and in parts of Sequoia National Park near Grant Grove. This report came just 8 years after oxidant air pollution was

Table 2. Permanent plot O_3 surveys in the Sierra Nevada, 1977–1987

Survey dates	Area surveyed	No. plots	Trees/ plot	Total trees	% with injury	Reference
1977	Sierra, Sequoia NFs[a]	242	10	2420	19	Pronos et al., 1978
1980–1982	Sequoia–Kings Can. NPs	54	15	810	36	Warner et al., 1983
1981	Stanislaus NF	46	10	460	30	Allison, 1982
1982	Eldorado NF	30	10	300	14	Allison, 1984a
1983	Tahoe NF	37	10	370	17	Allison, 1984b
1985	Yosemite NP	20	15	300	58	Duriscoe, 1987a
1987	Lake Tahoe Basin MU	24	15	360	29	Pedersen, 1989

[a] NF = National Forest, NP = National Park, MU = Management Unit.

identified as the cause of X-disease on pines 200 miles to the south in the San Bernardino Mountains east of Los Angeles (Miller et al., 1963).

3.1. Permanent plot surveys

The responsibility for monitoring and evaluating the effects of agents like air pollution on Federal forest land lies with the Forest Pest Management (FPM) [now called Forest Health Protection (FHP)] staff of the USDA Forest Service. Results of surveys and data from permanent plots established within this area of known O_3 injury (chlorotic mottle) in 1974–1975 by the Forest Service documented that symptoms of O_3 injury were common and widespread (Williams et al., 1977). Severely affected pines with chlorotic mottle on needles in their second growing season were already present.

After establishing that O_3 injury was common in certain locations in the mountains east of Fresno, the level of severity and extent of symptoms in other parts of the Sierra Nevada needed to be investigated. From 1977 to 1987, a series of O_3 injury plot networks were installed on National Forests and Parks throughout the Sierra (Table 2). All of these surveys attempted to document where injury symptoms were present, where they were absent, and how severe they were. Ponderosa and Jeffrey pine were the only plant bioindicator species used in all of the surveys. Survey protocols were developed for the Sierra Nevada by FPM and first used on the Sierra and Sequoia National Forests in 1977 (Pronos et al., 1978). Tree plots were selected where 1000 ft. contour lines between 1220 and 2440 m (4000 and 8000 ft.) intersected roads (and hiking trails in National Parks) in areas that had a component of ponderosa and/or Jeffrey pine. These networks were not designed to characterize O_3 injury to the southern Sierra pine population statistically, but rather to show the distribution and severity of injury. The number of trees evaluated per plot was either

Table 3. Rating system used in the FPM protocol

Individual tree score	Youngest needles with symptoms	Average plot score	Severity of injury
0	Current year	0–0.9	Very severe
1	Second year	1.0–1.9	Severe
2	Third year	2.0–2.9	Moderate
3	Fourth year	3.0–3.9	Slight
4	Fifth or older or none	4.0	No injury

10 or 15, which minimized the amount of time required to collect data at each plot and enabled crews to visit many plots in a large geographic area.

The numerical rating system used in the FPM protocol (Table 3), records only the first five of potentially more years of needle retention and which annual whorls have chlorotic mottle. The individual tree score value is the same as the number of healthy annual whorls, up to a maximum of 4. This means the lower the score, the greater the injury.

All of the data on the permanent plot O_3 surveys (Table 2) were collected using the FPM rating system, except for the 1985 Yosemite National Park survey. In the 1980s, the National Park Service was very active in refining the methods of evaluating the expression of injury in pine plots in order to increase the precision and accuracy of O_3 response estimates in the field. A new protocol and rating system that expanded the number of characteristics measured was developed (Stolte and Bennett, 1984). This was called the Air Quality Division (AQD) method, and it attempted to quantify the following parameters:

(1) Chlorotic mottle on foliage;
(2) Needle retention on each annual whorl;
(3) Number of annual whorls on each branch;
(4) Needle length of each annual whorl;
(5) Density of the upper and lower crown foliage;
(6) Abiotic and biotic agents affecting foliage on each annual whorl.

Eventually the AQD method lead to a standardized procedure that was designed to uniformly evaluate O_3 air pollution effects in the western United States (Miller et al., 1996). This method was called the O_3 Injury Index (OII) and it was used in a large scale monitoring effort called Project FOREST.

Because the permanent plot O_3 survey information was collected over a 10-year period, the data on percentage of trees with chlorotic mottle is not directly comparable (Table 2). Although knowing the proportion of pines affected by O_3 is helpful, the severity of injury is also important. For example, the 1987 survey of the Lake Tahoe Basin Management Unit (LTBMU) reported a fairly high percentage of affected trees at 29%. However, almost all of the pines with chlorotic mottle at Lake Tahoe were in the slight injury category. This is a limitation of the FPM method, namely that place to place comparisons may be difficult to establish. For example, the data collected 10 years earlier by surveys of the Sierra and Sequoia National Forests show only 19% of the pines with chlorotic mottle. However, on these two southern Sierra Nevada forests, many trees were in the severe and moderate categories, as well as the slight categories.

Because of limitations with the FPM sampling protocol, results from the ground plot surveys cannot be readily expanded to estimate the effects of O_3 on a forest-wide basis. The systematic method of selecting plot locations, restricted to those with road access, may introduce bias into the data. The number of trees per plot is too low, and the FPM rating system is not conducive to parametric statistical analysis nor is it well suited for place to place comparisons. However, it is appropriate to report information regarding the incidence and severity of O_3 symptoms that were found between 1977 and 1987, including the following:

- Symptoms of O_3 injury were found on all of the Sierra Nevada forests and parks surveyed;
- Chlorotic mottle was common in pine stands and was present on 20% or more of the trees sampled;
- Severity of injury increased from slight in the north to moderate/severe in the south;
- The worst injury occurred at elevations of 1800 m (5900 ft) or less;
- Injury decreased moving from west (low elevation) to east (higher elevation), as the distance from the source of O_3 (the Central Valley) increased.

3.2. Cruise surveys

In 1986, the National Park Service conducted “cruise” surveys in Yosemite and Sequoia–Kings Canyon National Parks (Duriscoe and Stolte, 1990). The intent of these surveys was to cover a much broader area in a manner as unbiased as possible given available resources, which would provide a more robust data base. The objectives were to randomly sample the entire geographic range of ponderosa and Jeffrey pines in both Parks and obtain an estimate of O_3 injury. A stratified-random design was used where hundreds of sites were visited and 15 trees at each site were evaluated. The cruise survey method does not establish permanent plots that can be relocated.

In Yosemite National Park, 29% of 1650 pines sampled at 110 points had chlorotic mottle, while at Sequoia–Kings Canyon National Parks, 39% of 1470 pines sampled at 98 points had chlorotic mottle. In both Parks, ponderosa pine made up about one-third of the sampled trees and the other two-thirds were

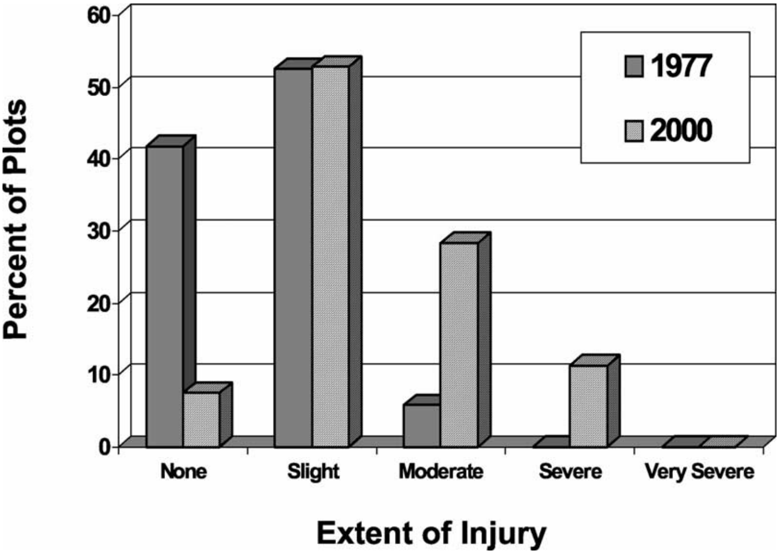


Figure 9. Changes in ozone injury on pine plots from 1977 to 2000, Sierra and Sequoia National Forests.

Jeffrey pine. For comparison purposes, 36% of the pines in permanent plots installed using the FPM protocol in Sequoia–Kings Canyon Parks 4–6 years (1980–1982) prior to the cruise survey had O_3 injury. In Yosemite National Park, the system of 20 roadside plots established in 1985 yielded an incidence of 58%.

Of the 242 FPM plots established in 1977 on the Sierra and Sequoia National Forests, 53 were selected to act as "trend" plots and each forest was revisited in alternate years through 2000. In 1977, 21% of the pines evaluated had chlorotic mottle, and by 2000 this percentage had increased to 40. A comparison of injury severity, as reflected by the average O_3 plot score between 1977 and 2000, also illustrates the dramatic O_3 injury increase through the 23 years that this plot network was monitored (Fig. 9). In 1977 the majority of plots were in the "no injury" or "slight injury" categories, while by 2000 there had been a clear shift to the "moderate" and "severe" categories of the FPM method.

In general, the increase in O_3 injury between 1977 and 2000 was gradual. The most dramatic increase in symptoms occurred the first few years (1978–1981) after the plots were installed (Pronos and Vogler, 1981). These years represented a return to normal precipitation in northern California after 2 years (1975–1977) of extreme drought. Drought has been shown to reduce the amount of O_3 injury to crop plants (Tingey and Hogsett, 1985) and ponderosa pine seedlings (Temple et al., 1992) due to reduced stomatal conductance and

Table 4. Primary causes of tree death in Forest Pest Management (FPM) O_3 trend plots on the Sierra and Sequoia National Forests, 1977–2000

Primary cause of death	Number of dead trees	Percent of dead trees
Ozone	38	36.5
Bark beetles, wood borers	29	27.9
Fire damage	16	15.4
Broken top	10	9.6
Dwarf mistletoe	6	5.8
Cut	2	1.9
Logging damage	2	1.9
Windthrow	1	1.0
Total:	104	100

less O_3 uptake. Annual variations in precipitation can certainly influence the expression of O_3 symptoms in ponderosa and Jeffrey pine and help explain yearly changes in O_3 injury ratings. Although the Sierra Nevada experienced a more prolonged but less severe drought (compared to 1975–1977) between 1987 and 1993, the FPM O_3 plot network did not show any obvious widespread decrease in O_3 injury symptoms.

The FPM trend plot study is the only effort that documented the primary causes of tree mortality by year and cause of death (Table 4). During the lifetime of the FPM plots, 104 of the original 530 trees died. Possible contributors to tree mortality included: bark beetles and wood borers, mechanical injury, fire damage, dwarf mistletoe, logging, windthrow, and O_3. In many cases, two or more factors acted together to kill an individual tree, but we focused on only one agent that was considered to play the most active role in tree death. If a tree had an O_3 rating of 0 or 1 (very severe or severe injury) immediately preceding death, then O_3 was considered to play a direct role in the death of that tree. If a tree had an O_3 rating of 2 (moderate injury) immediately preceding death, then O_3 was considered a possible contributor to the mortality (but was not included in Table 4). O_3 was a direct contributor in 36.5% of the trees that died during the lifetime of the plots. This means that O_3 played a primary role in the death of 7.2% of the original population of trees between 1977 and 2000.

The Lake Tahoe Basin is located mid-way in the Sierra Nevada range, with the lake at an elevation of 1905 m (6250 ft). It has a different O_3 environment than does the western Sierra. Ozone within the Basin typically has concentrations well below ambient air quality standards and rarely reaches 90 ppbv for one hour. These concentrations are typical of those found in rural areas in the west remote from major source regions. Summer aircraft observations (an ongoing effort at the University of California, Davis) within the Basin show O_3

to be well mixed both vertically and horizontally (Carroll and Dixon, 2000), indicating local emissions play only a minor role in determining local O_3 concentrations. The 24 plots established within the Basin in 1987, using FPM protocols, were revisited in 1991. In the 4 years between visits, the percentage of trees showing injury symptoms increased from 29.2 to 39.8, and four of the plots showed statistically significant increases in FPM score (Holland, 1992). Most of the plots with injury adjacent to Lake Tahoe fall into the slight category, probably because they are located far inland from the Central Valley (primary source of O_3) and are all above 1900 m. Data from two visits to these plots do not establish a trend.

Of the 54 permanent plots, a subset of 28 established between 1980–1982 in Sequoia and Kings Canyon National Parks were revisited in 1985. Comparisons of the same trees showed increases in number of trees with symptoms and increased symptoms on individual trees. The percent of trees with chlorotic mottle increased from 47% to 79%, and the average FPM plot score changed from 2.8 to 2.4 (both in the moderate injury category). These revisited plots were those most readily accessible on the west slopes of the Park and were closest to the San Joaquin Valley, which is the primary source of atmospheric O_3 (Duriscoe, 1987b). Ozone injury was found to decrease with elevation, and the most injury was in the Marble Fork of the Kaweah River. Ozone concentrations tend to decrease with both the horizontal and vertical distances from the Central Valley. Conversely, the amount of annual precipitation increases with elevation along the western slopes of the Sierra Nevada.

4. Project FOREST

The Forest Ozone Response Study (Project FOREST) was a multi-agency effort that began in 1990 and was designed to look at O_3 effects on both Federal and private forest land throughout the Sierra Nevada. The data summarized in Table 1 are from project FOREST. A part of this project was a reconciliation between the two major methods for describing crown injury: the simple, long standing Forest Pest Management (FPM) method (which is expressed simply as the age of the youngest needle whorl with chlorotic mottle) and the newer, more complex Ozone Injury Index (OII). The OII is similar to the FPM but uses a more complete crown description. Project FOREST was designed to find the relationships between the distribution of pine foliar injury and O_3 concentration by co-locating active O_3 monitoring instruments and tree plots (Miller et al., 2000). By using up to 50 trees in each of three replicate plots at each site and a statistically robust means of synthesizing O_3 injury at the tree level (the OII), place-to-place and time-to-time comparisons could be made (Arbaugh et al., 1998). Although the issues surrounding the relationship of exposure to dose complicate the analysis, ultimately it was possible to use tree injury and static monitor response to establish a general increase in OII with increased O_3 exposure across the north-to-south extent of the Sierra by using GIS techniques (Rechel et al., 2001). The data also suggested that dominant and open grown ponderosa or Jeffrey pines were generally less injured than codominant, intermediate, or suppressed crown classes (Miller et al., 2000).

4.1. Dendroecology

The first tree ring analysis and crown injury study focused on Jeffrey pines in the Sequoia–Kings Canyon National Parks (Peterson et al., 1987). This study suggested that large, dominant trees on severe sites (thin soils with low moisture holding capacity) and exposed to direct upslope transport of O_3 showed as much as 11 percent ring growth decline in recent years, compared to adjacent trees without symptoms. In a second study, Peterson et al. (1991) sampled ponderosa pines over a wider area, including seven federally administered units in the Sierra Nevada. Four symptomatic and four asymptomatic sites were visited in each unit, including only trees that were greater than 50 years old. The symptomatic plots indicated an increase in crown injury from north to south, but corresponding tree ring growth declines were not identified.

4.2. Research with seedlings and mature trees

The effect of O_3 on both giant sequoia and pine seedlings has received attention. In Sequoia National Park, seedling health and mortality in natural stands beginning in 1983 showed that emergent sequoia seedlings in moist microhabitats had O_3-induced foliar symptoms. After fumigation *in situ,* to ambient or 1.5 times ambient O_3 concentrations in open-top chambers for 8–10 weeks after emergence, chlorotic mottle appeared (Miller et al., 1996). Significant differences were found in light compensation point, assimilation at light saturation, and dark respiration between charcoal-filtered air and 1.5 O_3 treatments (Grulke et al., 1989). Ozone exposure could accelerate the mortality of some seedlings. Studies with adult giant sequoias in branch chambers revealed a much lower sensitivity compared to seedlings (Grulke and Miller, 1994).

The principal study with families of Sierran ponderosa pine seedlings was carried out at Whittaker Forest (a University of California at Berkeley facility near Sequoia National Park) (Temple and Miller, 1994). Essentially, symptoms were produced at ambient concentrations in open-top chambers. Another critical finding was that drought stress limited O_3 injury. In a study conducted in Sequoia National Park, Patterson and Rundel (1990) measured the considerable impact of O_3 on the photosynthetic capacity of different ages of needle whorls of Jeffrey pines in native stands. An open-top chamber exposure of seedling ponderosa pines at Shirley Meadow at the southern tip of the Sierras generally required 2 years of twice the ambient O_3 to show these effects (Takemoto et al., 1997).

5. Summary and conclusions

Symptoms of O_3 injury have been found on pines in all of the Sierra Nevada National Forests and Parks. The amount of injury generally increases from north to south. Tree mortality due to O_3 has been documented, and one trend plot network in the southern Sierra Nevada recorded 7% mortality of plot trees due to severe O_3 injury over a 23-year period. Attempts to measure the effects of O_3 on tree growth have had limited success, and the general consensus is that over the life of a forest stand, periodic droughts and competition between trees and brush for soil moisture have a greater influence on growth and plant vigor than O_3. The overall effects of oxidant air pollution on conifers in the Sierra Nevada is much less than that which has occurred in the San Bernardino Mountains of southern California.

Given the continuing high O_3 concentrations in the Central Valley and the meteorological conditions that transport polluted air into the Sierra, exposure of forests to O_3 will continue and may become worse with time. Ozone remains a recurrent and persistent forest stressor, and sensitive plant species will continue to decline and die. Although emissions controls have significantly reduced per capita emissions of O_3 precursors, population increases in the Central Valley and many foothill areas has resulted in little change in peak O_3 concentrations in these inland areas. Unfortunately, because routine air quality monitoring has not been conducted in most of the Sierra, current conditions and recent trends are not known at most locations.

The penetration of highly polluted air eastward into the Sierra Nevada is limited by atmospheric stability and by increased mixing, as the polluted air moves to high elevations. The available evidence indicates that the near ground concentrations decrease significantly at elevations above 1800 m MSL over the central Sierra and increase with distance to the south. However, some systematic monitoring of conditions at potentially high impact sites should be initiated. Because dose is determined by O_3 concentration and stomatal conductance and the former often and the latter always have diurnal patterns, measuring daily or weekly averaged concentrations and environmental conditions are not sufficient to resolve local diurnal patterns. Hence, dose estimates will not be possible from such data.

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