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Concentrations of Ozone in National Park Service Class I Areas and Effects on Sensitive Biological Resources

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INTRODUCTION

Ozone is a phytotoxic gas in the troposphere that can be transported over long distances to National Parks in the U.S. and, at sufficiently high levels, can alter morphological, physiological, and phenological processes of sensitive biological resources. Under the Prevention of Significant Deterioration provisions of the Clean Air Act Amendments of 1977 the National Park Service (NPS) is directed to protect the air quality related values, such as biological and cultural resources, visibility, and odor, in parks designated as class I from degradation due to air pollution. To accomplish this goal the NPS has instituted national programs of ambient monitoring of air pollutants and biological monitoring of natural resources in NPS class I areas. The NPS conducts ambient monitoring primarily for ozone, sulfur dioxide, and fine particulates in national parks throughout the United States, many of which are designated as class I areas. In conjunction with this ambient monitoring, NPS conducts research to determine the sensitivity and variability in response of native plant species to air pollutants and institutes long-term biological monitoring of these species. The information generated by these programs are used to comment on Prevention of Significant Deterioration permits, to review Environmental Protection Agency (EPA) criteria documents, and to prepare testimony on the effects of air pollution on national parks for Congressional committees.

There is increasing interest in coupling ambient air measurements with biological monitoring of forest and arid land species to improve our understanding of exposure-response relationships under field conditions. Ambient monitoring results can trigger the need for some level of biological monitoring in ecosystems. Conversely, the quantification of pollutant injury on known sensitive species can indicate the need for instrument monitoring, can suggest sites where ozone exposures may be highest, and indicate the spatial distribution of ambient ozone over large areas where conventional instrument monitoring would be difficult or nearly impossible. The evaluation of the severity of ozone injury in stands of sensitive conifer species with ambient monitoring data collected near these stands is necessary to determine ozone exposure thresholds that begin to stress forest ecosystems and to elucidate the effectiveness of the current National Ambient Air Quality Standard (NAAQS) of 120 ppb to protect sensitive resources.

This paper examines several statistics to describe and compare ozone levels in several class I national parks and examines the relationship between ozone exposure and observed ozone injury on ponderosa (Pinus ponderosa Laws.) and Jeffrey (Pinus Jeffreyi Grev. and Balf.) pines in the California Sierra Nevada. The monthly and annual statistics chosen for this comparison are: (1) daily one-hour maximum; (2) the number of hours equal to or exceeding 60, 80, and 100 ppb; and, (3) the cumulative ozone exposure equal to or exceeding 60 and 80 ppb. Six national parks in the western U.S. where ponderosa and/or Jeffrey pines are known to grow were chosen for this study (Saguaro National Monument, Arizona; Rocky Mountain National Park, Colorado; Great Sand Dunes National Monument, Colorado; Sequoia National Park, California; Kings Canyon National Park, California; and Yosemite National Park, California). To make a very general comparison between ozone levels measured in western U.S. national parks with those measured in the eastern U. S., one eastern U. S. park (Great Smoky Mountains National Park, Tennessee) was selected. A brief synopsis of the biological effects occurring in these parks as a consequence of ambient ozone pollution is presented. A more detailed evaluation of ozone injury on ponderosa pine and Jeffrey pines in three California parks is reviewed. The ozone sensitivity of ponderosa pines in the western United States, particularly California, has been well documented[1,2,3,4,5]. Ponderosa pine and Jeffrey pine (yellow pines) occur from 900 - 2800 meters and, depending on location, can be subjected to elevated exposures of anthropogenic ozone. Since biological monitoring of ozone injury on yellow pines was initiated in these parks prior to most of the ambient monitoring, we examined the relationship between the ozone injury observed in 1986 at various sites within these parks and the ozone exposures measured at these sites during the period 1987 to 1990. The modifying influences of temperature, precipitation, and relative humidity, that are known to determine internal foliar ozone dose, relative to ambient ozone exposures, are not addressed in this paper[6].

METHODS

Ambient Ozone Monitoring

The National Park Service operates and maintains extensive national networks of air pollution monitors. Continuous measurements of ozone using ultraviolet photometric analyzers are currently being performed at 40 national parks throughout the United States. The monitoring methods and quality assurance procedures employed in the NPS network meet the EPA's requirements of 40 CFR Part 58. Each monitoring station is equipped with a data logger that automatically calculates one-hour ozone averages. Stations are periodically queried on a daily or weekly basis, depending on whether or not telephone service is available at the station, by a minicomputer located in Lakewood, Colorado, and stored in a centralized data base for further processing and validation. Once validated the data are then entered into the EPA's Aerometric Information Retrieval System (AIRS) database.

Ambient Ozone Exposures

In this study we have selected three statistics, on a monthly and annual basis, to describe ozone exposure levels in national parks: (1) the daily one-hour maximum; (2) the number of hours equal to or exceeding 60, 80, and 100 ppb; and, (3) the cumulative monthly and annual ozone exposure equal to or exceeding 60 and 80 ppb. The cumulative ozone exposure is defined as the sum of the excess concentration of each hourly observation above a given threshold over a specified period of time, as given by:

$$E_t=\sum_{i=1}^{N}(x_i-t),x_i\geq t$$

where E_t = cumulative exposure equal to or above threshold, t,
x_i = observed hourly concentration
N = total number of observations in day, month, season, etc.

Exposure statistics as described above and by equation (1) are affected by the amount of data capture achieved at a monitoring location. Less than 100% data capture during months having concentrations above a selected threshold will always result in the underestimation of these statistics. The use of observed statistics will yield errors in any comparisons between exposures and could mask any relationship that may exist between exposure and other variables, such as observed ozone injury to pines. It is necessary to use some type of estimation technique that accounts for missing data. We have chosen an estimation approach similar to that used by EPA in determining the expected number of exceedances of the ozone standard as described in 40 CFR Part 50, Appendix H. The estimated annual cumulative exposure, $\hat{E}_t$, is defined as the sum of the estimated monthly exposures as given by:

$$\hat{E}_t=\sum_{i=1}^{12}E_{t_i}\frac{N_i-z_i}{n_i}$$

where:

$\hat{E}_t$ - Total estimated annual exposure over a threshold, t,
E_{ti} - Observed exposure over a threshold, t, for month i,
N_i - Total number of hours for month i,
n_i - Total number of hours measured for month i, and
z_i - Number of hours assumed to be below the threshold, t, in month i.

Since we have not studied the effects of extremely poor data capture on this estimation method, we have confined the application of this method to data captures of at least 25% on a monthly basis. The properties of the above estimate require further study.

Comparison of ozone levels for the period 1987-1990 were made for Sequoia NP (period of record is 1982-1990), Kings Canyon NP (1990), Yosemite NP (1987-1990), Great Sand Dunes NM (1988-1990), Rocky Mountain NP (1987-1990), Great Smoky Mountains NP (1988-1990) and the desert parks Guadalupe Mountains NP (1987-1990) and Saguaro NM (1982-1990) (Table 1). Within Sequoia NP, Kings Canyon NP, and Yosemite NP comparison of ozone levels using the above statistics were made for the period 1987-1990 at the following sites, with the period of monitoring record given in parenthesis following the name of each site: Lower Kaweah (1984-1990), Grant Grove (1990), Wawona Valley 1987-1990), Yosemite Valley (1990), and Camp Mather (1988-1990). At the Lower Kaweah site precipitation monitoring was conducted at a nearby site. The three years preceding the 1986 tree injury survey (1984-1986) were analyzed for ozone exposure and precipitation amounts to aid in the interpretation of severity of observed injury in 1986. Ozone monitoring was conducted seasonally (June-October) from 1984-1986 and annually from 1986-1990.

Ozone Injury on Sensitive Conifers

Ozone injury in the Sierra Nevada was first documented by Miller and Millecan[7] and led to the establishment of long-term pine monitoring plots in Sequoia NP and Kings Canyon NP by park staff[8]. In order to evaluate the spatial extent of injury throughout Sequoia NP, Kings Canyon NP, and Yosemite NP Eridanus Research Associates[9] conducted geographically extensive surveys in 1986 of Jeffrey and ponderosa pine at 98 points in Sequoia and Kings Canyon NPs, treated as one unit in the 1986 survey, and 110 points in Yosemite NP. The survey points were located by using a stratified random sampling design with grid squares of 3.2 km. Each survey point was characterized by slope, elevation, and aspect. Relationships between severity of injury and elevation at the survey point were evaluated. At each point 3 branches on each of 15 trees were evaluated for number of whorls, severity of ozone foliar injury, and diameter at breast height. Severity of ozone injury was evaluated by determining the percent surface area discolored with chlorotic mottle, using four classes (0-3) of injury severity (0=0; 1=1-10%; 2=11-30%; and 3=31-100%). Severity of chlorotic mottle was evaluated on each age of needle whorls on each branch. This method of evaluating the severity of injury allows for several approaches of quantifying the injury at the tree level in subsequent data analyses. One approach is to take the mean of the 0-3 injury classes averaged over all whorls and branches. Another approach is to use the Forest Pest Management (FPM) score, that evaluates the number of needle whorls that are free of ozone injury[10], e.g., a score of 2 represents trees that have 2 whorls of needles (the current and 1-year-old needle whorls) that are free of any chlorotic mottle symptoms. The FPM scores are an inverted index where higher numbers equal less ozone foliar injury. A third approach is to use an injury index (0-10 index) that weights the severity of foliar injury by the age of the needle whorl on which it occurs. High index scores represent trees that have high percentages of chlorotic mottle on relatively young whorls of needles.

From this larger data base we examined the severity of ozone injury at survey points within 8 km of current ambient monitoring sites in Sequoia NP (Lower Kaweah), Kings Canyon NP (Grant Grove) and three monitoring sites in Yosemite NP (Wawona Valley, Yosemite Valley, Camp Mather). A nested analysis of variance was used to determine whether statistically significant differences in ozone injury existed between parks, sites within parks, and survey points within sites. Student-Neuman-Keuls (SNK) mean separation tests were performed on the 0-10 injury index to identify site and point means that were statistically different from each other. At the Lower Kaweah site severity of ozone injury observed in 1986 was compared to ozone concentrations, cumulative ozone exposures, and precipitation measured during the preceding period 1984 to 1986.

Ozone Exposure and Response of Sensitive Species

Ozone injury on ponderosa and Jeffrey pines in 1986 at the Lower Kaweah site in Sequoia NP, the Grant Grove site in Kings Canyon NP, and three sites in Yosemite NP (Wawona Valley, Yosemite Valley, and Camp Mather) was compared with annual cumulative ozone exposures ≥ 60 ppb for these sites from 1987-1990 (varying period of record for each site). The amount of injury observed at each site in 1986 was used to characterize the sites as slightly, moderately, or severely impacted by ozone. At the Lower Kaweah site in Sequoia NP the ozone exposure/tree response relationship was examined further by comparing the ozone exposures in 1984, 1985, and 1986 with the amount of ozone injury recorded in 1986. Ozone exposure is the external ozone concentration available for plant uptake, and is not intended to represent the internal dose experienced within the plant foliage. The potential phytotoxicity of the ozone exposures (potential dose) was considered by evaluating the amount of rain and snow (25.4 cm of snow = 2.54 cm of rain) that fell near the site in 1984-1986 and 1987-1990 with the 58 year averages of rain and snow for that site.

RESULTS

Ozone Concentrations in NPS Units

Daily maximum one-hour ozone concentrations and estimated monthly cumulative exposures at the Lower Kaweah site in Sequoia NP were consistently higher than those measured at other NPS class I areas (Figure 1), although the daily maxima were occasionally greater at Guadalupe Mountains NP in September 1987 and at the Wawona Valley site in Yosemite NP in June 1987. Only in August 1987 did the Wawona Valley site have a high monthly cumulative exposure (4009 ppb-hr) similar to that recorded at Lower Kaweah (4446 ppb-hr). The monthly cumulative exposure at Lower Kaweah typically peaked in July between 6000 and 9000 ppb-hr substantially greater than the peak exposures measured at Guadalupe Mountains (1000 ppb-hr), Rocky Mountain NP (1500 ppb-hr), Saguaro NM (1500 ppb-hr), Wawona Valley in Yosemite NP (3000-4000 ppb-hr), and Look Rock in Great Smoky Mountains NP (1500-3000 ppb-hr). Monthly maximum cumulative exposures ≥ 60 ppb peaked from June-August at all locations, with July frequently the month of highest cumulative exposure for most parks. In Guadalupe Mountains NP monthly cumulative exposures ≥ 60 ppb from June 1988 through December 1990 were near zero, indicating that this park has long periods with little ozone contamination, similar to Great Sand Dunes NM. At Great Smoky Mountains NP, the only eastern U. S. park in this comparison, daily maximum ozone concentrations were similar to those measured in western parks. However, the cumulative exposure was greater at Great Smoky Mountains then at all western parks except for Sequoia, Kings Canyon, and Yosemite NPs.

Monthly patterns of ozone exposure among the seven park units were also evaluated by the total number of hours each month in 1990 when the hourly ozone average ≥ 60, 80, and 100 ppb. (Figure 2). The highest occurrences of elevated hourly ozone concentrations were observed in June-August in the more polluted NPS units. The greatest number of hours with ozone concentrations equal to, or above, these levels occurred at Lower Kaweah in Sequoia NP (420, 125, and 11 hours) and Wawona Valley in Yosemite NP (260, 95, and 10 hours). In contrast there were few hours when the hourly ozone averages equalled or exceeded these levels at Great Sand Dunes NM (80, 0, and 0) and Guadalupe Mountains NP (30, 0, and 0). As with the exposures, the number of hours above the indicated thresholds were estimated using a formula similar to the one used to estimate exposures.

A closer examination of ozone levels at the three California parks revealed that Ash Mountain and Lower Kaweah in Sequoia NP and Grant Grove in Kings Canyon NP had high hourly ozone averages and greater cumulative exposure ≥ 60 ppb for each month from 1987-1990 than Camp Mather, Yosemite Valley, and Wawona Valley in Yosemite NP (Figure 3). For most years all sites were relatively consistent in patterns and magnitude of cumulative exposures except for 1987 at Ash Mountain and Lower Kaweah and 1988 for Camp Mather. Percent data capture at Camp Mather for June and July in 1990 was relatively poor and the cumulative ozone exposure for these months was estimated from previous years data. Evaluation of the number of hourly ozone averages ≥ 60, 80, and 100 ppb in 1990 indicated that Sequoia NP (Ash Mountain and Lower Kaweah) and Kings Canyon NP (Grant Grove) were consistently higher in all months than at any of the monitoring sites in Yosemite NP (Wawona Valley, Camp Mather, or Yosemite Valley) (Figure 4). Grant Grove in Kings Canyon NP had the greatest number of hours of elevated hourly ozone averages (≥ 100 ppb) at all sites. There were 23 hours in August 1990 at Grant Grove when the hourly ozone average was ≥ 100 ppb, in contrast to 20 hours the same month for the Ash Mountain site. Integration of monthly cumulative ozone exposures into an annual 1990 cumulative exposure ≥ 60 ppb (Figure 5A) and 80 ppb (Figure 5B) for each site indicated that Ash Mountain in Sequoia NP received the most ozone compared to Lower Kaweah, Grant Grove, Camp Mather, Wawona Valley, and Yosemite Valley. Seasonal periodicity of peaks and troughs in ozone concentrations and cumulative exposure were similar at all sites. Diurnal patterns of maximum hourly ozone averages indicated peak concentrations occurred between 1200-1700 at all sites.

Monthly variation in ozone exposures (≥ 60 ppb) at Lower Kaweah indicated periods of relatively high exposures in July-August from 1984-1986, with a maximum 12,617 ppb-hr in August 1985 (Figure 6A). Monthly ozone exposures in July-August from 1987-1990 peaked at 8308 ppb-hr in July 1988. The cumulative annual exposures ≥ 60 ppb ozone exposures ranged from a high of 37,791 ppb-hr in 1985 to a low of 18,222 ppb-hr in 1987, indicating a maximum twofold differences in ozone at this site between years. The 1985 exposure is especially impressive since there was no monitoring of ozone in March-May in 1985 to add to the cumulative annual exposure. No appreciable accumulation of ozone ≥ 60 ppb occurred in any year from October-February (Figure 6B). Annual precipitation (rain and snow) records indicate that 1984-1986 were relatively wet years and 1987-1989 were relatively dry, with the exception of a heavy snowfall in the winter of 1988-1989.

Response of Sensitive Species to Ambient Ozone Concentrations

In all of the NPS units reported in this study some form of biological monitoring of ozone-sensitive species has occurred (biomonitoring gardens, spatially limited to spatially broad surveys, plot assessments, or radial ring growth studies). In Saguaro NM current ozone levels were high enough to injure a desert shrub (<u>Rhus</u> <u>trilobata</u> Nutt.) at lower elevations (938-1219 m)[11] and ponderosa pine (vars. scopulorum and Arizonica) at higher elevations (above 2000 m)[9]. In Great Sand Dunes NM[12], Rocky Mountain NP[12], and Guadalupe Mountains NP[11] injury surveys, plots, or growth studies indicated that current ambient ozone concentrations have not caused foliar injury to ponderosa pine (var. scopulorum). In Great Smoky Mountains NP ozone has caused foliar injury on a variety of tree, shrub, and herb species throughout a broad elevational range[13].

Ozone injury was found on Ponderosa and Jeffrey pines in Sequoia NP, Kings Canyon NP, and Yosemite NP in California in 1986 throughout most of the extent of their geographical and elevational distribution (Figure 7A, B)[9,14]. There were distinct differences in injury in different watersheds. Only the upper Kern Canyon in Sequoia NP was free of ozone injury symptoms (Figure 7C). Throughout Sequoia and Kings Canyon NP, 39% of 1490 trees had some degree of ozone injury, usually slight. The mean severity of injury throughout these parks was 0.28 (0-3 injury class). In Yosemite NP 29% of 1625 trees had some degree of injury. The mean severity of injury in this park was 0.18. There was a trend of decreasing injury with increasing elevation in Sequoia and Kings Canyon NPs and in Yosemite NP, with the more severe injury occurring near 1500 m. The relationship between injury and elevation was more pronounced ($r = .71$) within individual river drainages like the Kaweah Basin, with the most severe ozone injury occurring again near 1500 m[9].

Analysis of the severity of ozone injury in a subsample of the 1986 survey point, those found within 8 km of the current ozone monitoring sites, indicates a wide range in tree response between parks, at monitoring sites within parks, and at survey points within monitoring sites (Figures 8 and 9). At the Yosemite Valley site and Camp Mather site there was relatively low injury (Figure 9A, B). As the severity of injury within an area increased, the variability in injury between survey points increased also, as was observed at Grant Grove and Lower Kaweah (Figures 8A, B) and Wawona Valley (Figure 9C). The nested analysis of variance indicated that parks, sites within parks, and survey points within sites were significantly different (p-values between .0001 and .0113) for the variables number of whorls, 0-3 injury class, FPM score, 0-10 injury index, and dbh (Table 2). The coefficients of variation were much greater for the 0-3 injury class (130.4%), injury index (112.5%), and dbh (83.3%) than for number of whorls (21.8%) and FPM score (31.0%). The SNK mean separation test indicated that for all variables Sequoia and Kings Canyon NPs were significantly different from Yosemite NP ($\alpha = 0.05$). Sequoia-Kings Canyon NPs had a smaller mean numbers of needle whorls, higher mean 0-3 injury class, a lower FPM score (fewer whorls of needles free of ozone injury), a higher 0-10 injury index, and a larger dbh.

At sites within parks there was a significant difference between Sequoia and Kings Canyon sites (Lower Kaweah and Grant Grove), the Wawona Valley site (Yosemite NP), and Camp Mather and Yosemite Valley sites (Yosemite NP) for all variables except dbh (Table 2). Survey points within sites were highly variable at Lower Kaweah, Grant Grove, and Wawona Valley sites (Figures 9 and 10). There was no consistent pattern of injury severity with whorl retention or tree diameter at all sites. There was a large difference among survey points averaged over all sites and within sites in each park. There were no obvious patterns in the significant point-to-point differences for any variable. These differences are probably due to the large within point variation that occurs due to genetics and microsite differences among trees at the survey point. Based on the pine injury observed in 1986, the five sites were characterized, relative to each other, as very slight (Yosemite Valley), slight (Camp Mather), moderate (Wawona Valley), and severe (Lower Kaweah and Grant Grove) for ozone exposure (Table 2).

Ozone Exposure and Pine Injury

There was a consistent relationship between the amount of ozone injury to pines in 1986 at the monitoring sites and the characterization of the sites based on instrument monitoring from 1987-1990 (Figure 10). With the exception of the severity of ozone injury to pines at Camp Mather, the severity of ozone injury at all other sites is in close agreement with the amount of ozone observed at those sites in 1990. The annual variation in cumulative ozone exposure at most sites is relatively minor for most years (Figure 3), although ozone monitoring at Lower Kaweah site from 1984-1990 (Figure 6B) indicates a two-fold difference in the cumulative ozone exposure can occur at the site.

The Lower Kaweah site in Sequoia NP had some of the highest ozone injury on pines (Tables 1 and 2) and the highest ambient ozone concentrations for a site with conifers (Figures 1-6). Since ozone monitoring was initiated in 1984 (Figures 5 A, B), we evaluated the ozone levels and seasonal cumulative exposure peaks that were responsible for the amount of injury observed in the 1986 cruise survey (Figure 9B). Although ozone was only monitored from June-October (1984-1986), we find that in 1985 and 1986 the highest hourly ozone averages exceeded 120 ppb, the cumulative monthly ozone exposure, highest in August in each year, reached 12,617 ppb-hr (Figure 6A). The cumulative annual ozone exposure ranged from 20,702-37,791 ppb-hr from 1984-1986 (mean equalled 27,332 ppb-hr). From 1987-1990 the monitors recorded high hourly ozone averages of 120 ppb, cumulative monthly exposures, highest in June-August, reaching 8308 ppb-hr, and cumulative annual ozone exposures ranging from 18,222-33,863 ppb-hr (Figure 6B). The seasonal rain and snow (snow converted to rain equivalent) totals indicate that the period from 1984-1986 was relatively wet (rain and snow mean of 171.2 cm compared to an 58 year mean of 171.7 cm) compared to the period 1987-1989 (rain and snow mean of 117.2 cm). These data suggest that the injury evaluations in 1986 near Lower Kaweah occurred during a relatively high ozone period coupled with relatively adequate soil moisture.

DISCUSSION

Ambient monitoring of ozone concentrations and seasonal exposure patterns in the NPS class I parks examined indicated a high degree of variability in maximum hourly averages, number of hours when hourly averages equal or exceed 60, 80, and 100 ppb, and the monthly and annual cumulative exposure equal to or greater than 60 ppb. There was also a high degree of variability in concentrations and spatial distributions of ozone at sites within parks but, in general, relative similarity in seasonal patterns of high and low ozone. The three monitors in Yosemite NP (Camp Mather, Yosemite Valley, and Wawona Valley) indicated substantial differences in ambient ozone concentrations that may be representative of many NPS units that are large and topographically diverse. Although Sequoia NP and Kings Canyon NP were characterized in this study as more polluted than Yosemite NP, there were several areas in these Parks, particularly the upper Kern Canyon and several of the large drainage basins in Kings Canyon, that were uncontaminated by ambient ozone based on the low severity of injury to the pines (Figure 7C, D). Hourly average concentrations of ozone seldom exceeded the National Ambient Air Quality Standard (NAAQS) at any site. The number of hours when ozone averages $\geq$ 120 ppb were extremely rare, representing a small fraction of the total numbers of hours of ambient monitoring. This would suggest that the current NAAQS for human health is not adequate to prevent injury to sensitive pine species.

Numerous researchers have employed different statistics to characterize ozone levels in urban and non-urban environments. Although it is well established that the exposure of plants to air containing sufficiently high levels of ozone, if environmental factors are not limiting, results in adverse effects such as visible foliar injury, reduced photosynthetic capacity, accelerated senescence and reduced retention of leaves or needles, there is no one exposure statistic that has correlated well with all of these effects. The relative lack of collocated biological monitoring and ambient monitoring makes attempts to formulate an ideal exposure statistic difficult. Lefohn and others[15] have suggested various indices which are relevant for relating air quality levels to effects on crops and vegetation. Among these are the 7-hour (0900-1559h) and 12-hour (0700-1859h) seasonal arithmetic mean used by EPA's National Crop Loss Assessment Network; SUM06, SUM08, and SUM10 which sum either the absolute concentration or the excess concentration above a certain threshold (0.06 ppm for SUM06; 0.08 ppm for SUM08, etc.) whenever the specified threshold is exceeded; and the sigmoidally weighted exposure index, W126, which considers all concentrations but gives lower weighting to concentrations below a defined threshold. In a screening procedure designed to signal the potential for existing air pollution effects in class I wilderness areas, the U.S. Forest Service[16] has chosen both a 1-hour exposure (second highest one-hour concentration for the year) and a 12-hour growing season arithmetic mean. In this study we found that cumulative exposures above a set threshold (60 or 80 ppb), calculated on a monthly or annual basis, and number of hours when the hourly averages exceeded a set threshold (60, 80, or 100 ppb) corresponded well to levels of pine injury recorded at the same sites.

Comparisons between ambient ozone monitoring and biological monitoring are most relevant when the sensitivity, symptomology, response variability of the target species is well understood. Since ozone produces a distinct foliar injury symptom (chlorotic mottle) on ponderosa and Jeffrey pines in the mountains of California, we were able to monitor the spatial and temporal trends in the distribution of this injury and make reasonable inferences, without calculating internal plant dose, on the distribution of ozone over large geographic distances. The severity of injury observed within 8 km of the five monitoring sites in 1986 is well related with the severity of ozone concentrations monitored at sites from 1986-1990 (Figure 10). Although these relationships are temporally uncoupled, the relative consistency in annual exposure of ozone at sites over time (years) suggests that such relationships may not be unreasonable.

The most serious injury observed in this study was at the Lower Kaweah and Grant Grove sites where the hourly average maxima approached 120 ppb in the summer months and cumulative monthly exposures reached 6000-9000 ppb-hr. Analyses of the ozone record at Lower Kaweah from 1984-1986 indicated that hourly ozone concentrations that seldom exceed 120 ppb, cumulative monthly exposures $\geq$ 60 ppb of 12,617 ppb-hr, and cumulative annual exposures $\geq$ 60 ppb of 37,791 ppb (Figure 6A, B) resulted in relatively high ozone injury to pines (mean of 3.1 on 0-10 index) (Table 2) within 8 km of the monitor (Figure 9). Jeffrey and ponderosa pine trees may have been physiologically active during the August months when the ambient ozone was high in 1984-1986. Although Patterson and Rundel[17] have shown that Jeffrey pine trees were physiologically depressed in the Lower Kaweah area from August-October 1988, these measurements were done during a relatively droughted period in Sequoia NP from 1986-1988 (Figure 6A). Ponderosa and Jeffrey pines at Lower Kaweah in 1986 may have been physiologically more active because of the relatively adequate precipitation, based on the 58 year mean, that occurred from 1984-1986.

Careful consideration should be given to the number and location of biomonitoring points or plots located near ambient monitors. The number of points/plots and the distance of placement from the monitor indicates that as the severity of injury increases at a site the variability of injury surrounding the monitoring site increases and more points/plots are needed to characterize the injury at the site. Additional analyses of the 1986 cruise survey data[18], particularly in the more polluted areas, would provide some insight on optimal sampling techniques. Since there is a good correlation between injury and elevation, it is reasonable to expect that the highest correlations between ozone exposure and pine response would be obtained by monitoring tree stands at elevations similar to the elevation of the ozone monitor. This would be particularly important when only a limited number of points/plots would be established. Since in this paper the 1986 survey sites were not stratified by elevations similar to the ozone monitor, we might conjecture that having 10 or more survey points around a monitor may represent the range of injury in the area. An increase in the number of survey points around the Grant Grove site (Figure 8A) would give more confidence in the injury level determined for that site.

The analysis of ozone injury data from the 1986 cruise survey points within 8 km of the five current ozone monitoring stations indicates that there appears to be a consistent relationship between the annual cumulative ozone exposure and ozone injury recorded at sites within the California Sierra Nevada (Figure 10). Based on this information the range of exposures for each injury class can be described as follows: severe, > 18,000 ppb-hr; moderate, 7,500 to 18,000 ppb-hr; and slight, < 13,300 ppb-hr. Given an observed level of ozone injury, one could hypothesize a likely range of exposures that pines may have been subjected to over the 2 to 3 year period preceding the survey. Conversely, given an annual cumulative exposure at a location, one could hypothesize what the most likely injury level for pines near that location. This observed relationship would have less predictive power in years with atypical climatology, e.g., very dry years. This correlation would likely hold true for the monthly cumulative ozone exposure ($\geq$ 60 and 80 ppb) and the number of hours when the hourly ozone average $\geq$ 60, 80, and 100 ppb. The only ozone measurement that does not seem to be consistent with overall ozone exposure or plant injury is the maximum hourly average each month.

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Table 1. Location of Parks and sites within Parks where ambient ozone monitoring has been conducted. For each monitoring site the location (park, site within park, and state), date monitoring was initiated, elevation, associated ecosystem type, cumulative annual exposure ≥ 60 ppb for 1990.

PARK	SITE	STATE	YEAR MONITORING INITIATED	ELEV. (m)	ECOSYSTEM	1990 CUMULATIVE EXPOSURE[1]
SEKI	LK	CA	1984	1890	MIXED CONIFER	25985
	GG		1990	2012	MIXED CONIFER	24506
	AM		1987	610	CHAPARRAL	33345
YOSE	WV	CA	1987	1280	MIXED CONIFER	16425
	YV		1990	1219	MIXED CONIFER	3604
	CM		1988	1432	MIXED CONIFER	2999
SAGU	HQ	AZ	1982	938	SONORAN DESERT	3482
GUMO	HQ	TX	1987	1658	CHIHUAHUAN DESERT	302
GRSA	HQ	CO	1988	2487	MIXED CONIFER	191
ROMO	LP	CO	1987	2743	MIXED CONIFER	103
GRSM	LR	TN	1990	793	MIXED HARDWOOD	11272
	CM		1988	1243	MIXED HARDWOOD	6814

[1]CUMULATIVE ANNUAL OZONE EXPOSURE ≥ 60 PPB IN 1990.

Table 2. Nested analyses of variance of ozone injury on Jeffrey and ponderosa pines in Sequoia and Kings Canyon NP and Yosemite NP. Sources of variation are parks, sites within parks, and plots within sites with trees within plots as the error term. For each variable the p-values are given. Student-Neuman-Keuls mean separation test of differences between means for the variables number of whorls, injury class (0-3), Field Pest Management (FPM), injury index (0-10), and diameter at breast height (dbh). Means followed by the same letters are not significantly different at alpha = 0.05.

Summary of Analyses of Variance

Source	df	Number Whorls	0 -3 X CM	FPM	0 - 10 Index	dbh
Park	1	.0001	.0001	.0001	.0001	.0113
Site	3	.0001	.0001	.0001	.0001	.0001
Plot	51	.0001	.0001	.0001	.0001	.0001
CV	--	21.8	130.4	31.0	112.5	83.3

SNK Mean Separation Test

Park	Site	n	Number Whorls[1]	0-3 X CM[2]	FPM[3]	0-10 Index[4]	dbh[5]
YOSE	--	540	4.5^{A}	0.19^{B}	3.4^{A}	1.2^{B}	26.2^{B}
SEKI	--	300	4.1^{B}	0.59^{A}	2.6^{B}	3.0^{A}	30.5^{A}
YOSE	WV	210	3.9^{C}	0.32^{B}	3.1^{C}	2.0^{B}	21.1^{C}
	YV	180	5.6^{A}	0.05^{D}	3.9^{A}	0.3_{D}	32.4^{A}
	CM	150	4.0^{C}	0.18^{C}	3.4^{B}	1.3^{C}	26.0^{BC}
SEKI	LK	210	4.1^{BC}	0.59^{A}	2.6^{D}	3.1^{A}	29.4^{AB}
	GG	90	4.2^{B}	0.59^{A}	2.7^{D}	2.8^{A}	32.9^{A}

[1]Mean number of whorls of needle retained at each level (Park and Site)
[2]Mean transformed percent 0-3 injury scale [0 = 0 % chlorotic mottle (CM); 1 = 1-10% CM; 2 = 11-30% CM; 3 = 31-100% CM)
[3]Field Pest Management (FPM) injury score: Negative correlation index that describes the mean number of whorls that are free of ozone injury
[4]Injury Index (0-10) of mottle severity by whorl age
[5]Diameter at breast height (dbh): diameter of tree bole (wood and bark) at 1.4 m above the ground.

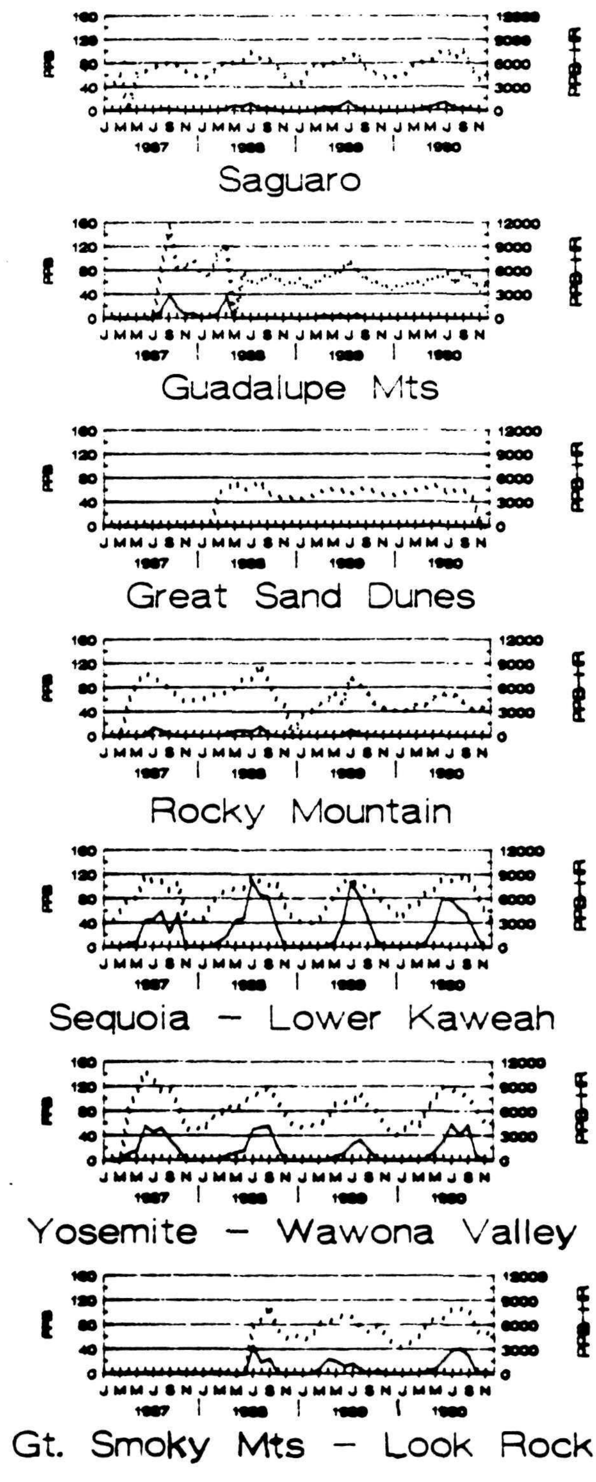


Figure 1. Maximum hourly ozone averages (dash - ppb) and cumulative ozone exposure ≥ 60 ppb each month (line - ppb-hr) from 1987-1990 in eight class I NPS units in the United States from 1987-1990. Ozone exposures are estimated for each month when data capture of hourly averages < 100%.

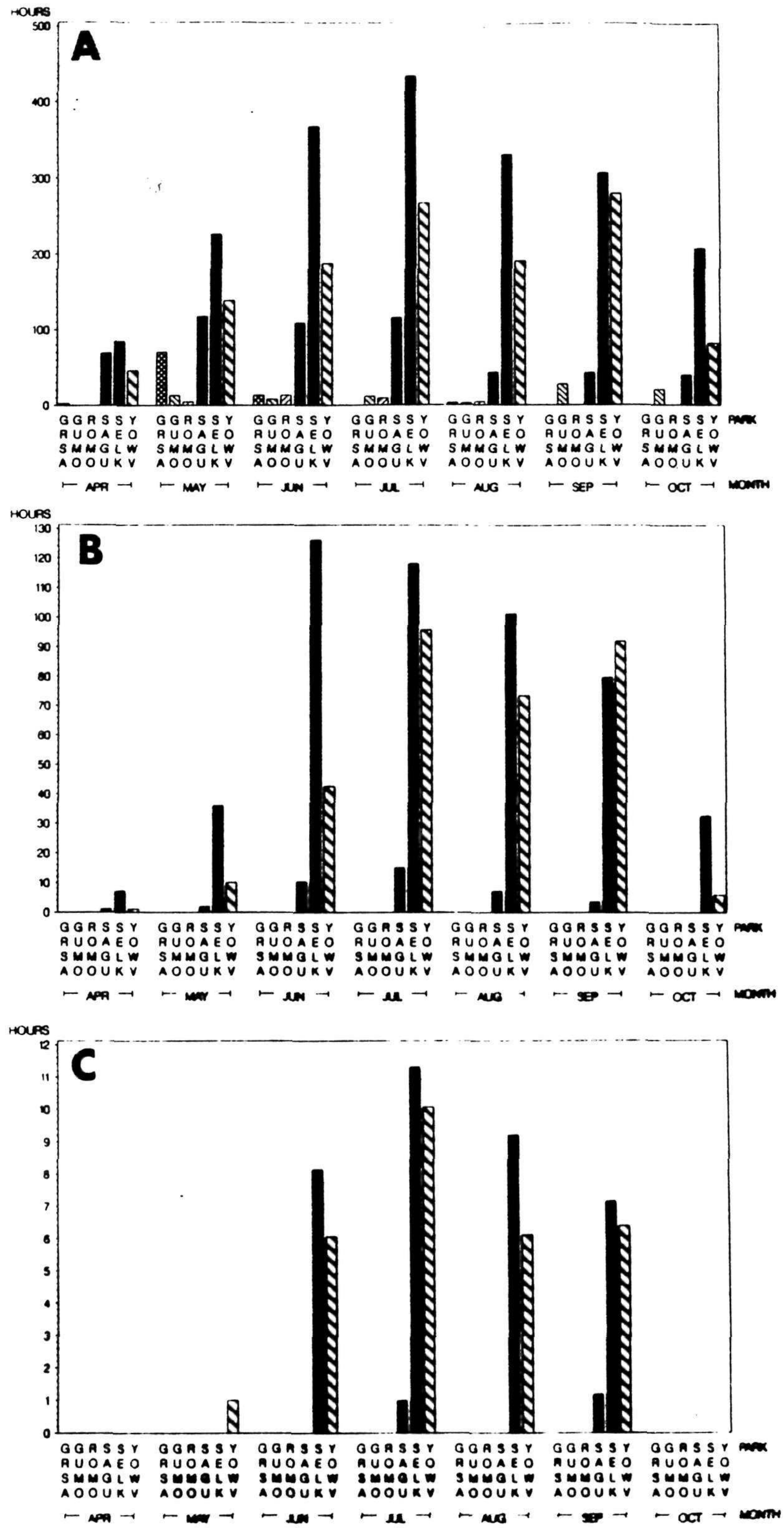


Figure 2. Total number of hours when the hourly ozone averages were ≥ 60 ppb (a), 80 ppb (b), and 100 ppb (c) in 1990 for Great Sand Dunes NM (GRSA), Guadalupe Mountains NP (GUMO), Rocky Mountain NP (ROMO), Saguaro NM (SAGU), Sequoia NP - Lower Kaweah site (SELK), and Yosemite NP - Wawona Valley site (YOWV).

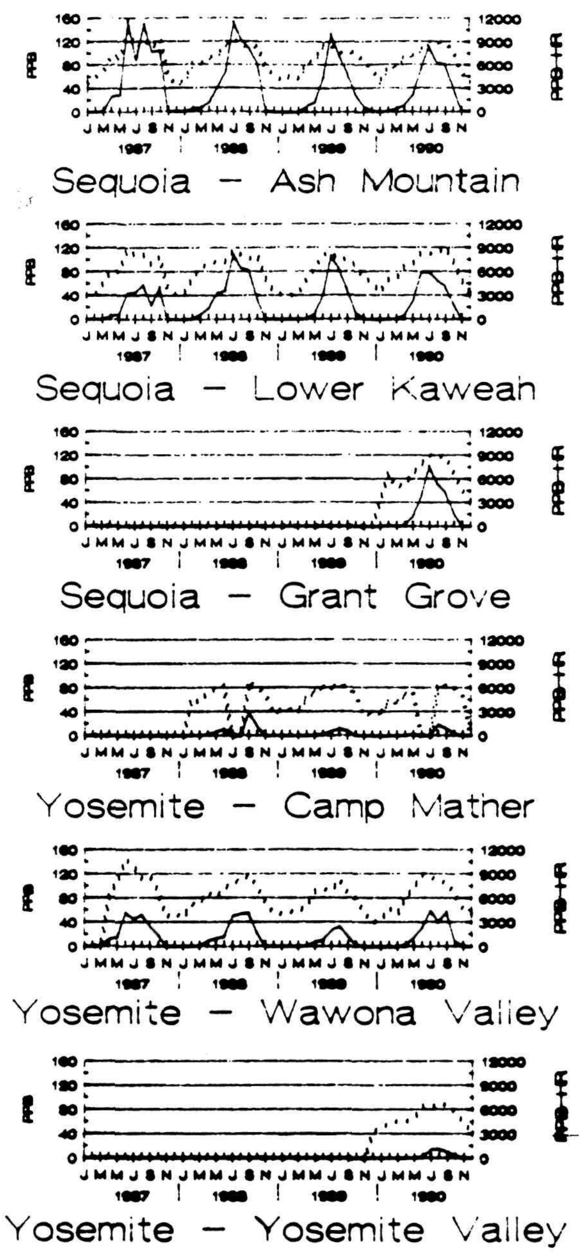


Figure 3. Maximum hourly ozone averages (dash - ppb) and cumulative ozone exposure ≥ 60 ppb each month (line - ppb-hr) from 1987-1990 in Sequoia NP (Ash Mountain and Lower Kaweah), Kings Canyon NP (Grant Grove), and Yosemite NP (Camp Mather, Wawona Valley, and Yosemite Valley) from 1987-1990. Ozone exposures are estimated for each month when data capture of hourly averages < 100%.

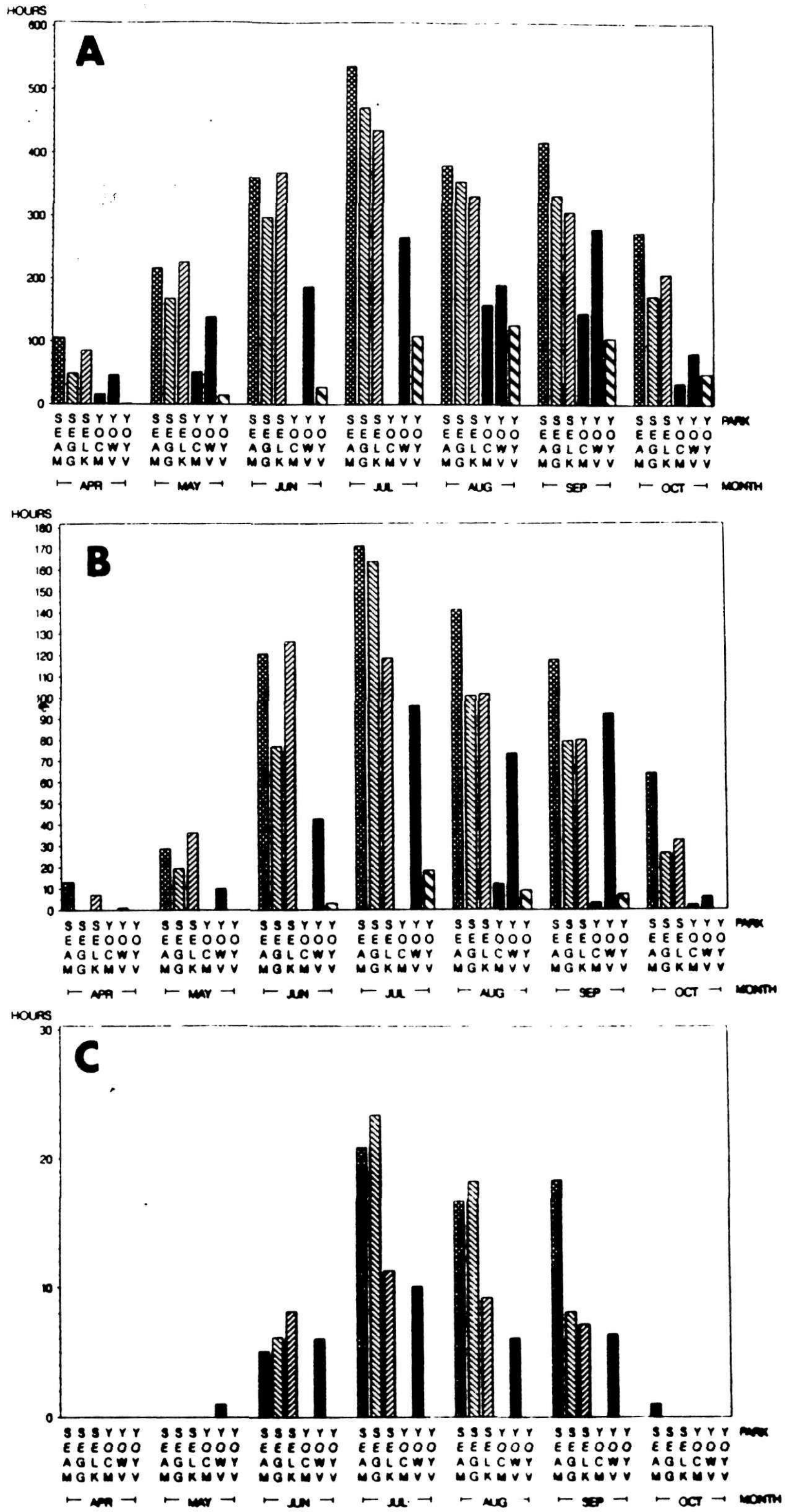
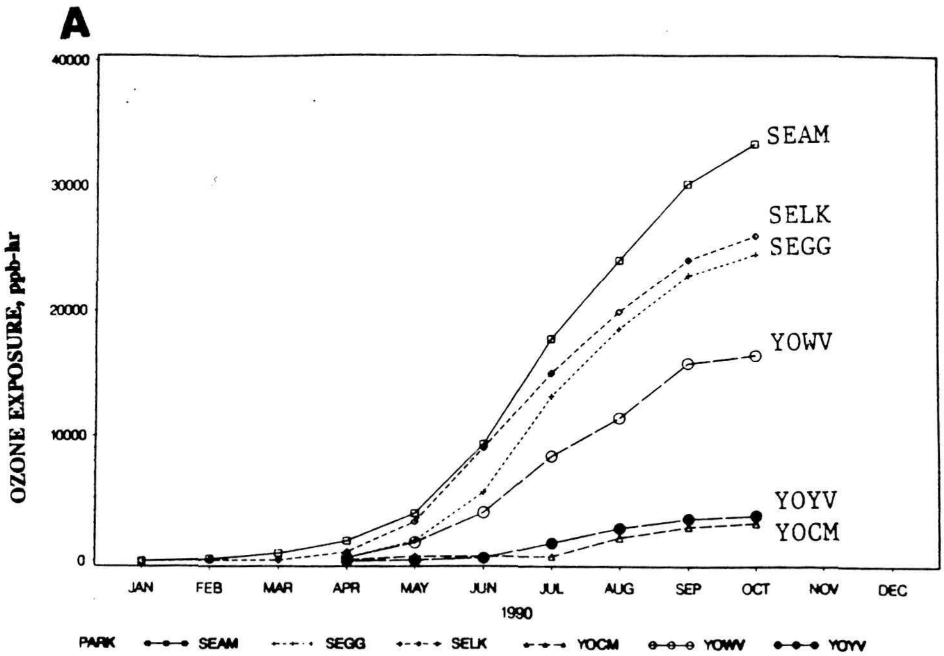


Figure 4. Total number of hours when hourly ozone averages were ≥ 60 ppb (a), 80 ppb (b), and 100 ppb (c) in 1990 at Ash Mountain (SEAM) and Lower Kaweah (SELK) in Sequoia NP, Grant Grove (SEGG) in Kings Canyon NP, and Camp Mather (YOCM), Wawona Valley (YOWV), and Yosemite Valley (YOYV) in Yosemite NP.



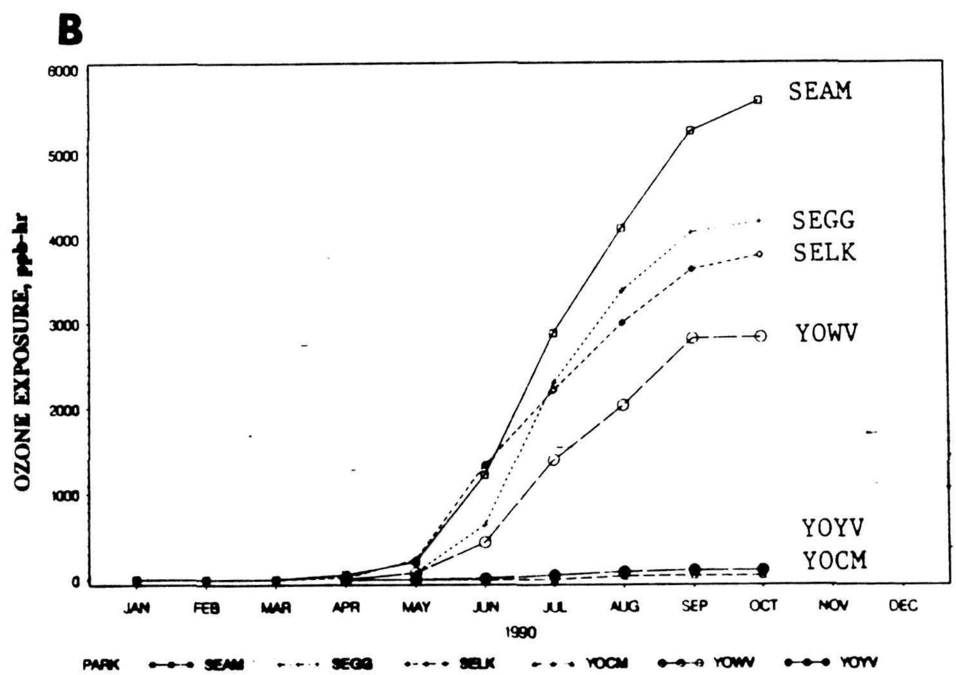
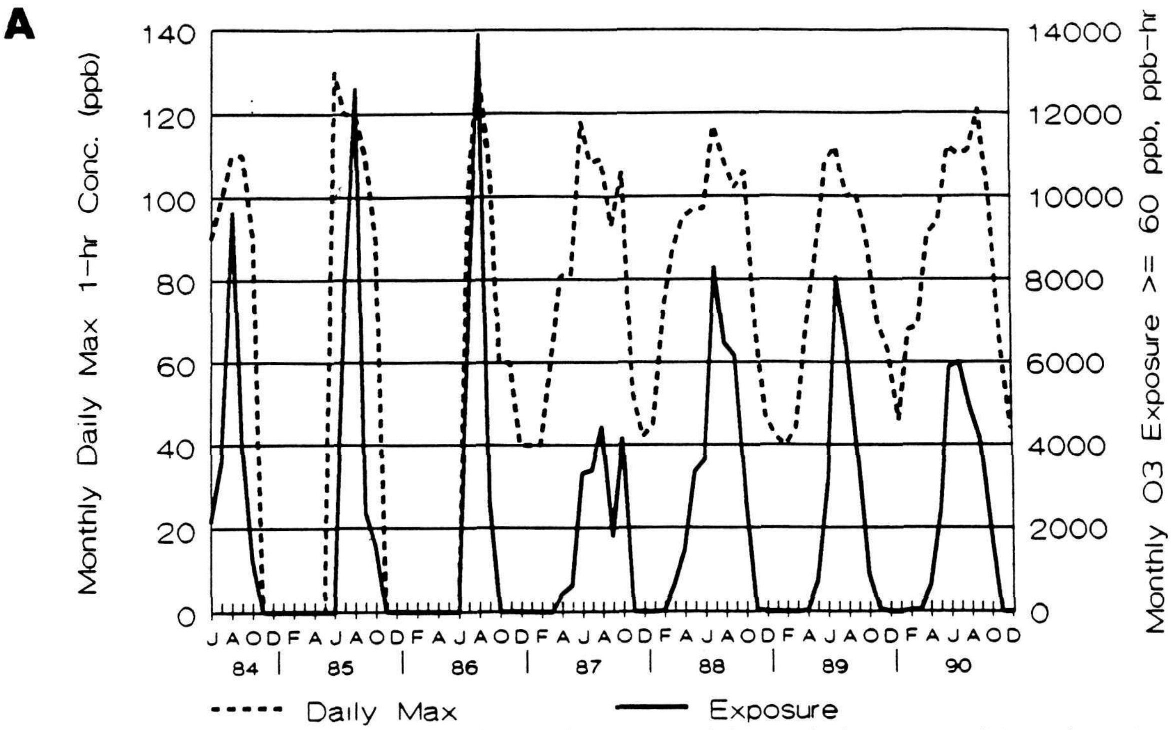


Figure 5. Cumulative ozone exposures ≥ 60 ppb (A) and 80 ppb (B) in 1990 for Ash Mountain (SEAM), Lower Kaweah (SELK), Grant Grove (SEGG), Camp Mather (YOCM), Wawona Valley (YOWV), and Yosemite Valley (YOYV). Ozone exposures are estimated for each month in 1990 when data capture of hourly averages < 100%.

A



RAIN (cm)	116.8	105.4	193.0	70.4	76.7	81.0	Mean (58 years) = 119.4 cm
SNOW (cm)	271.8	151.5	558.8	279.4	368.3	586.7	Mean (58 years) = 523.2 cm

B

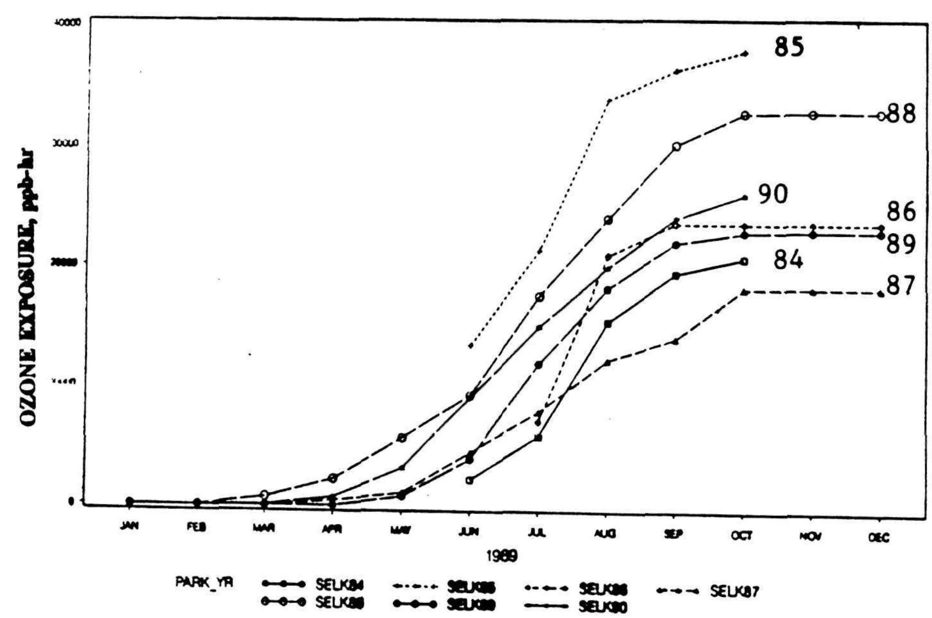


Figure 6. (a) Maximum hourly average ozone concentrations (dash=ppb) and cumulative exposure ≥ 60 ppb (line=ppb-hr) each month at Lower Kaweah in Sequoia NP from 1984-1990. (b) Cumulative annual ozone exposure ≥ 60 ppb at Lower Kaweah from 1984-1990. Ozone exposures are estimated for each month when data capture of hourly averages < 100%. Ozone monitoring in 1984-1986 was conducted from June-October.

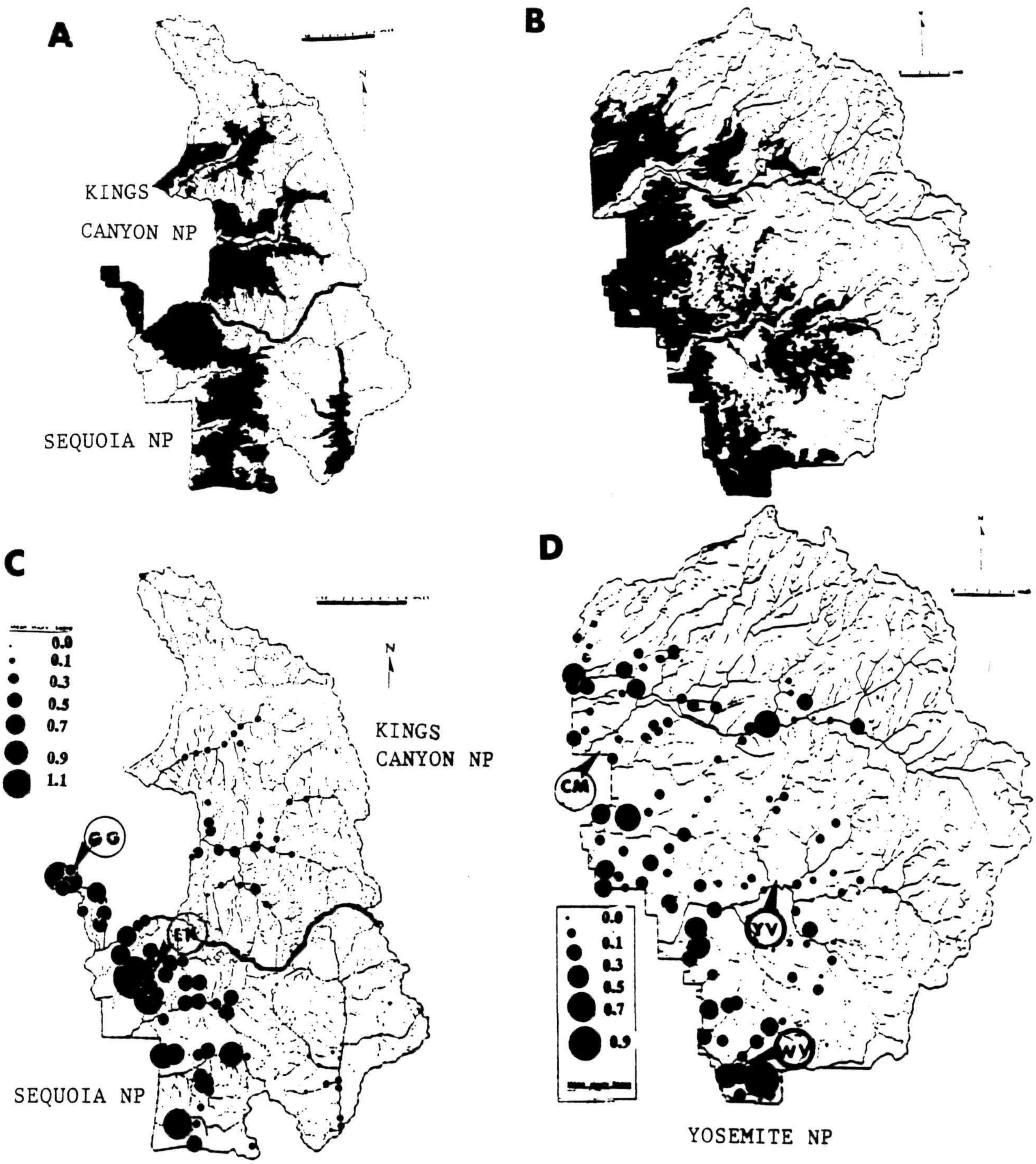


Figure 7. (a) Distribution of ponderosa and Jeffrey pines in Sequoia and Kings Canyon NPs and (b) Yosemite NP that were surveyed for ozone foliar injury in 1986. (c) Distribution and mean severity of injury (0-3 injury classes) at 98 survey sites in Sequoia and Kings Canyon NPs and (d) 110 survey sites in Yosemite NP. (c) Existing ozone monitoring sites (1990) are Lower Kaweah (LK) in Sequoia NP and Grant Grove (GG) in Kings Canyon NP. (d) In Yosemite NP ozone monitoring in 1990 was conducted at Camp Mather (CM), Yosemite Valley (YV), and Wawona Valley (WV).

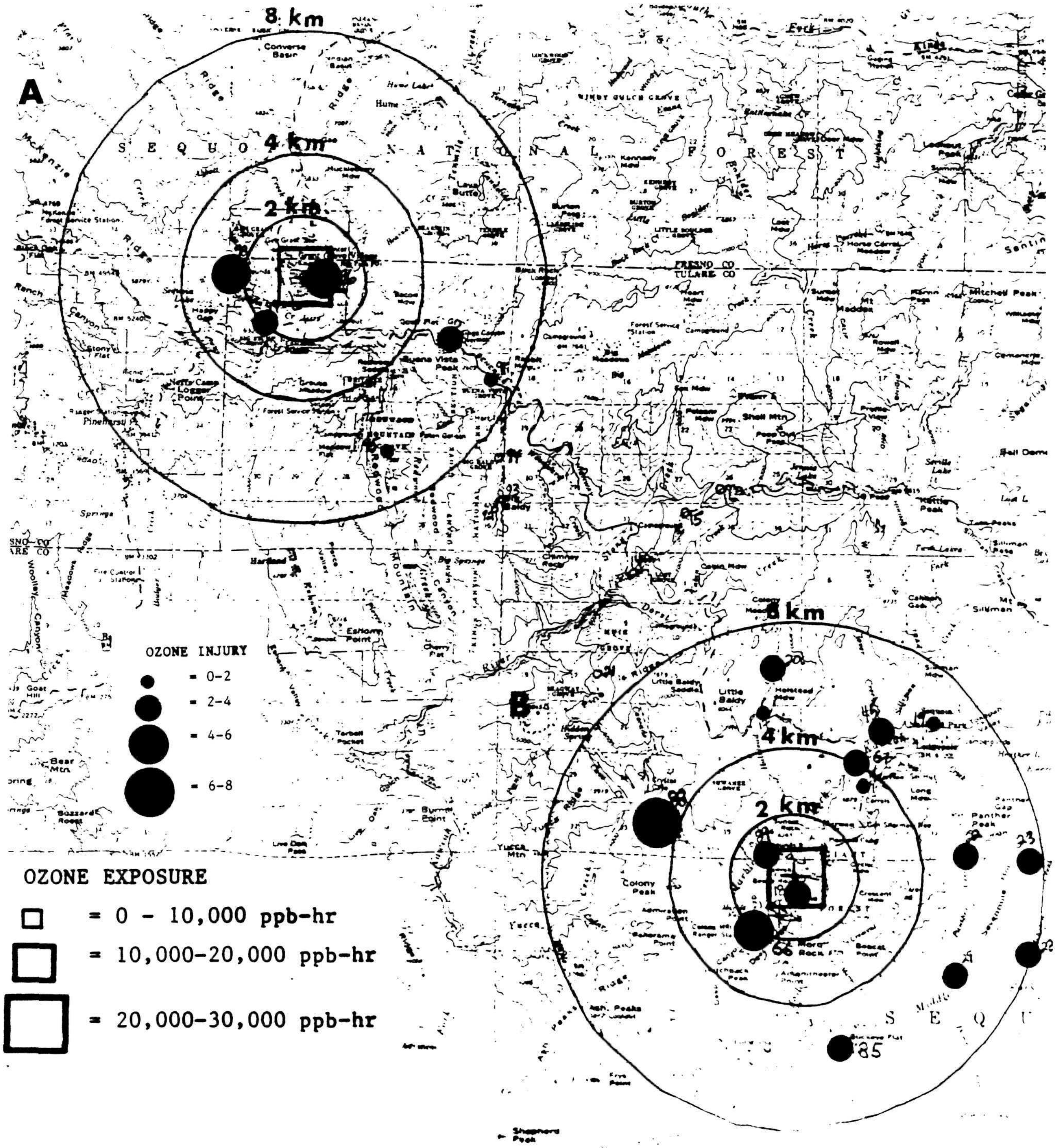


Figure 8. (a) Distribution of 1986 ozone injury survey points (●) within 8 km of the current ozone monitoring sites (□) operating at Grant Grove in Kings Canyon NP and (b) at the Lower Kaweah in Sequoia NP. Monitoring sites (□) are separated by a minimum of 25 kilometers. Radii indicate distance of ozone injury survey points from the monitor. Closed circles indicate the relative severity of the ozone injury in 1986 (mean 0 - 10 injury index score). Squares indicate the relative differences in the annual cumulative ozone exposure ≥ 60 ppb in 1990 at each site (ppb-hr).

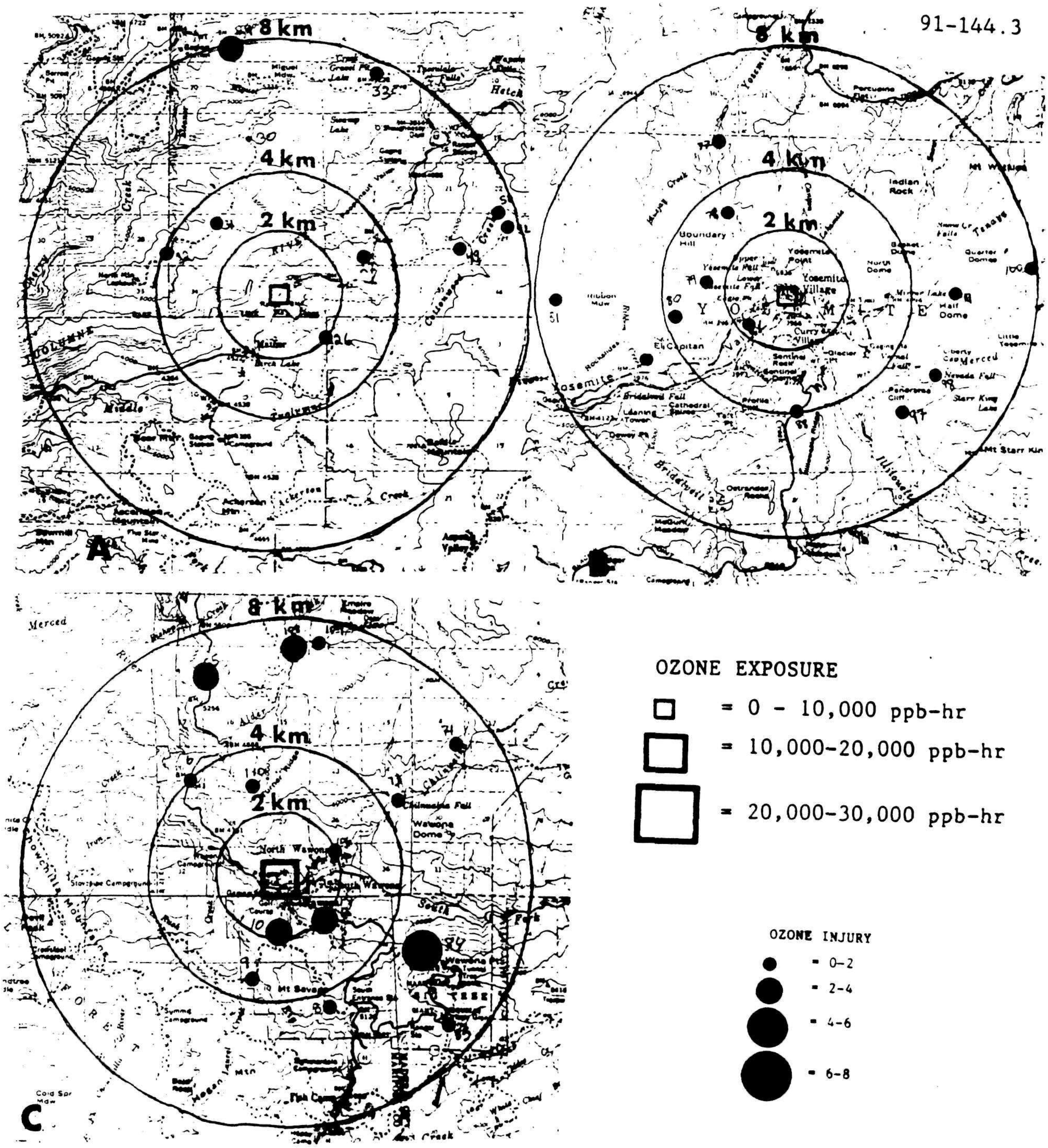


Figure 9. (a) Distribution of 1986 ozone injury survey points (●) within 8 km of the current ozone monitoring sites (□) operating at (a) Camp Mather, (b) Yosemite Valley, and (c) Wawona Valley in Yosemite NP. Monitoring sites (□) are separated by a minimum 24 kilometers. Radii indicate distance of ozone injury survey points from the monitor. Closed circles indicate the relative severity of the ozone injury in 1986 (mean 0 - 10 injury index score). Squares indicate the relative differences in the annual cumulative ozone exposure $\geq$ 60 ppb in 1990 (ppb-hr).

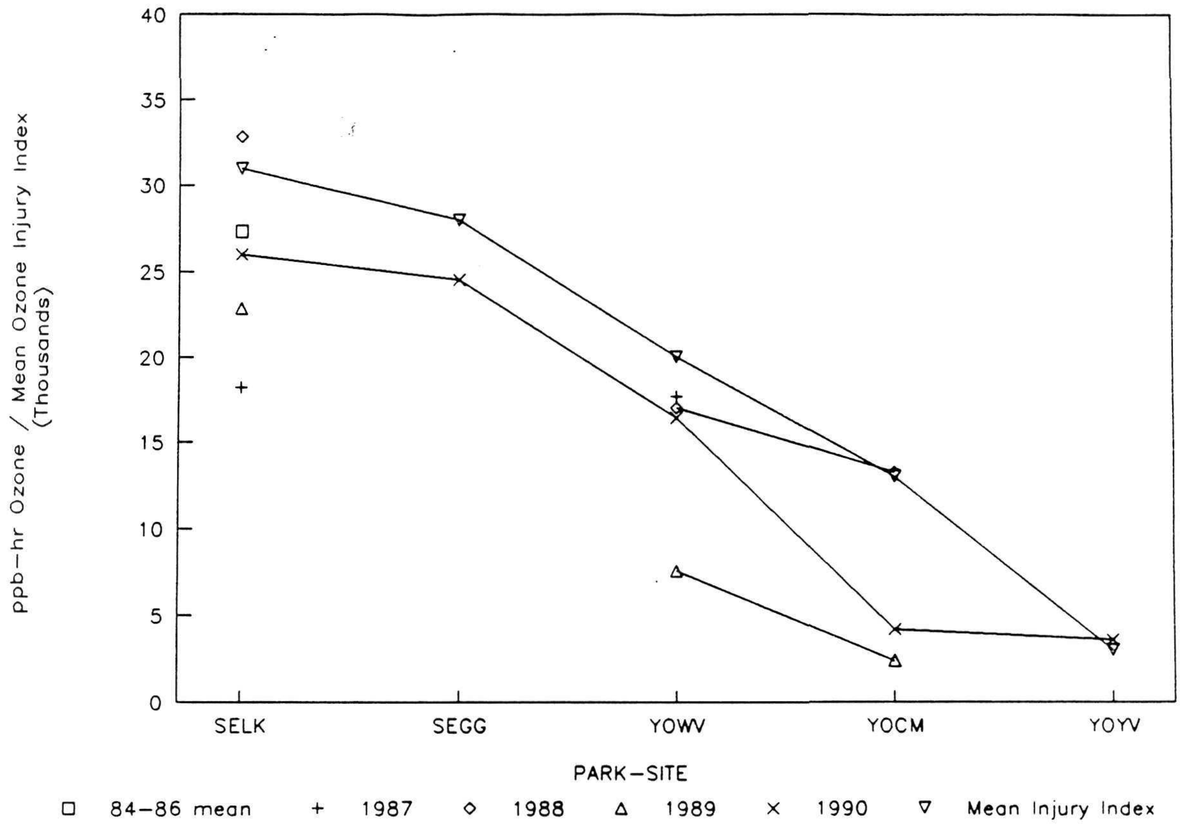


Figure 10. Relationship between the mean severity of ozone injury (0-10 injury index X 10000) on ponderosa and Jeffrey pines at survey sites in 1986 within 8 km of five current ozone monitoring sites and the annual ozone exposure ($\geq$ 60 ppb) recorded at each site from 1987-1990 (ppb-hr). The mean annual ozone exposure for Lower Kaweah site for the years 1984-1986 is also compared to the injury observed at that site in 1986. Sites are in Sequoia NP (SELK-Lower Kaweah), Kings Canyon NP (SEGG-Grant Grove), and Yosemite NP (YOWV-Wawona Valley; YOCM-Camp Mather; YOYV-Yosemite Valley).