Ozone Injury Responses of Ponderosa and Jeffrey Pine in the Sierra Nevada and San Bernardino Mountains in California[1]

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Abstract

*Ozone injury was monitored on foliage of ponderosa (*Pinus ponderosa *Dougl. ex Laws.) and Jeffrey (*Pinus jeffreyi *Grev. & Balf.) pines at 11 locations in the Sierra Nevada and 1 site in the San Bernardino Mountains of southern California. Ozone injury on all age cohorts of needles on about 1,600 trees was surveyed annually from 1991 to 1994. A new method for describing ozone injury to whole tree crowns, the ozone injury index (OII), was field tested and improved. The OII ranged from 0 (no injury) to 100 (the maximum possible injury). The OII multi-year average was only 5 at Lassen Volcanic Park in rural northern California and gradually increased in a southward direction west of the Sierra Nevada crest to moderate amounts (28-41) in the Sequoia National Forest and Sequoia National Park. The OII multi-year average measured at the San Bernardino Mountain site was 46. An assessment of annual changes at the 12 individual sites indicated both increases and decreases in OII from 1991 to 1994. The two most responsive indicators of the annual increments of accumulated injury, contributing 40 percent each, were chlorotic mottle and needle fascicle retention (within remaining needle whorls). Data for these components were tested with quadratic and Weibull functions against several expressions of ozone exposure (including ozone exposure indices Sum 0, Sum 60, W126, and number of hours exceeding 80 ppb during the summer exposure periods). Sum 0 was a suitable exposure index having Weibull correlation coefficients of 0.57 with percent chlorotic mottle and 0.74 with percent fascicle retention. These results provide estimates of ozone injury responses across a range of annual accumulated ozone exposures and environmental conditions during four summers.*

Introduction

In 1990-91 two companion projects were begun at analogous locations in the Sierra Nevada of California: the Sierra Cooperative Ozone Impact Assessment Study (SCOIAS) and the Forest Ozone Response Study (FOREST). Funded by a contract with the California State Air Resources Board, the principal activity of SCOIAS was to monitor ozone and meteorological variables at six Sierra Nevada sites managed by the University of California, Davis. FOREST was developed as a companion project to SCOIAS through an agreement of intent between the USDA Forest Service, Pacific Southwest Region , and the California State Air Resources Board.

The FOREST agreement led to the establishment of forest vegetation plots within 3 miles distance and 500 ft elevation of SCOIAS monitoring stations for the purpose of annual assessments of ozone injury to ponderosa and Jeffrey pine populations. The Air Resources Management Staff of the USDA Forest Service's Pacific Southwest Region provided training of field crews and actual data gathering activities in six National Forests. Other participants included Yosemite, Sequoia-Kings Canyon, and Lassen Volcanic National Parks, and the Forest Service's Pacific Southwest Research Station. The participants used accepted procedures for instrument calibration and maintenance for ozone measurements and tree injury assessment (Miller and others 1996b). The Pacific Southwest Research Station provided data management, data analysis and reporting services for FOREST (Guthrey and others 1993, 1994).

This report describes the use of the ozone injury index (OII) to monitor ozone injury to ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.) and Jeffrey pine (*Pinus jeffreyi* Grev. and Balf.) in the Sierra Nevada and San Bernardino Mountains in 1991-1994; and it provides results of tests that analyzed the relationship of annual accumulated ozone exposure expressed as Sum 0, Sum 60 and W126 to the intensity of chlorotic mottle and the retention of needle fascicles in all remaining needle whorls.

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Methods

Ozone monitoring stations established as part of SCOIAS were located at six Sierra Nevada sites including National Forests, a State Park, and private land (Van Ooy and Carroll 1995). Ozone data were also available from the National Park Service at Lassen Volcanic, Yosemite, and Sequoia-Kings Canyon National Parks and from the Forest Service at Barton Flats in the San Bernardino Mountains. At each site, three forest plots with at least 40-50 tagged ponderosa or Jeffrey pines were established within 5 km and 150 m elevation of the monitoring stations (*fig. 1*). Trees were sampled annually by pruning five branches each from about 1,700 trees distributed in 36 field plots. The ozone injury index (OII) was computed for each tree based on four weighted variables: number of annual needle whorls retained (40 percent), amount of chlorotic mottle (the ozone injury symptom) on needles of each whorl (40 percent), length of needles in each whorl retained (10 percent), and percent live crown (10 percent). The OII ranged from 0 (least severe injury) to 100 (most severe injury) (Miller and others 1996b).

Two of the attributes included in the computation of the OII, amount of chlorotic mottle (percent of the total needle surface) on needles in each whorl and the percent of the original complement of needle fascicles retained in each whorl, were considered the best indicators of the annual incremental increases of ozone injury to ponderosa and Jeffrey pine foliage. A schedule was established for computation of accumulated ozone exposure for each age cohort of needles

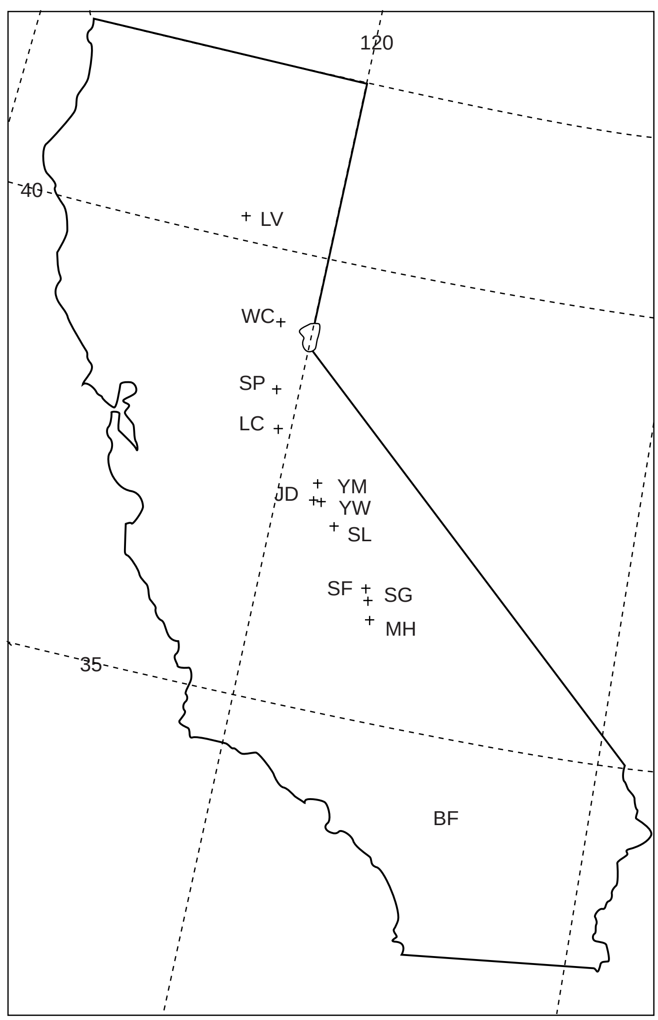

Figure 1 — Map locations of ozone monitoring sites and associated plots for monitoring ozone injury to ponderosa or Jeffrey pines.
LV = Lassen Volcanic,
WC = White Cloud,
SP = Sly Park,
LC = 5 mile Learning Center,
JD = Jerseydale,
YM = Yosemite Mather,
YW = Yosemite Wawona,
SL = Shaver Lake,
SF = Sequoia Giant Forest,
SG = Sequoia Grant Grove,
MH = Mountain Home,
BF = Barton Flats.

(*table 1*). Summer-season exposure was evaluated for each cohort, from August 1 to the injury evaluation date. August 1 was determined as the estimated date when current year needles had grown to maximum length and had measurable stomatal conductance (Temple and Miller, [this volume]). Since the SCOIAS sites were established in 1991, a full summer season of ozone data was available for only a few sites in 1991. A record of dates of injury evaluation was available for trees at each set of three plots near each monitoring station. Evaluation of all three plots ranged from 1 to 2 weeks. The beginning of the evaluation period was selected as the termination of the exposure period that had caused observed injury in that season. The exposure was initially calculated from August 1 to the first day of the foliar injury evaluation in the origin year of the needle whorl. Accumulation of ozone exposure for the cohort's second year was continued after evaluation and until October 31. Accumulation was resumed from June 1 each year until the next date of foliar symptom evaluation. This procedure was carried out for each annual needle age cohort (1991-94) until the beginning of the last period of the symptom evaluation in 1994, which had only the 1994 season of ozone exposure. The ozone exposure indices which were computed for each annual or consecutive annual time interval were Sum 0, Sum 60 (ppb), W126 (Lefohn 1992), and number of hours $\geq$ 80 ppb. The sum of the number of days in each seasonal exposure was included as a separate (dummy) variable. This variable simulates the extreme case in which daily ozone exposure is the same every day.

Table 1 — *The schedule for computation of accumulated ozone exposure and evaluation of needle injury (E) at 12 ozone-monitoring, tree plot locations in California, 1991-94.*

Origin year of accumulated	**Periods of the summer each year when ozone exposure was needle whorl before and after injury evaluation (-E)**			
	1991	***1992***	***1993***	***1994***
1991	8/1-E-10/31	6/1-E-10/31	6/1-E-10/31	6/1-E-10/31
1992		8/1-E-10/31	6/1-E-10/31	6/1-E-10/31
1993			8/1-E-10/31	6/1-E-10/31
1994				8/1-E-10/31

For each annual injury data set the amount of chlorotic mottle present was recorded as 0 (0 percent), 1 (1-6 percent), 2 (7-25 percent), 3 (26-50 percent), 4 (51-75 percent), and 5 (76-100 percent). For the regressions these ranges were represented by their midpoints (e.g., 0 = 0 percent, 1 = 3.5 percent, 2 = 16 percent, 3 = 38 percent, 4 = 63 percent, and 5 = 88 percent). Similarly, the 0 (0 percent), 1 (1-33 percent), 2 (34-66 percent), and 3 (67-100 percent) recorded values for percent of needle fascicles retained in each whorl were represented as 0 = 0 percent, 1 = 17 percent, 2 = 50 percent, and 3 = 83.5 percent.

The Weibull function was selected as the most appropriate model for relating the ozone exposure indices to foliar injury measurements (Rawlings and others 1988). The Weibull function was used successfully in the analysis of the ozone exposure of annual crop plants (U.S. Environmental Protection Agency 1986). It expresses the relationship between plant injury and ozone exposure as:

$$Y = \alpha \exp[-(x/\sigma)^c]$$

in which α = response at 0 O_3 exposure; x = accumulated O_3 exposure (in ppb-hrs); σ = accumulated ozone exposure at which α is reduced by 63 percent; and c = a dimensionless shape parameter.

Results

Ozone Monitoring from 1991-1994

Although average ozone concentrations varied at stations within a given sub-region, e.g., the central Sierra Nevada (Carroll and Dixon 1993, Van Ooy and Carroll 1995), average concentrations from north (Lassen Volcanic National Park) to south (San Bernardino Mountains) increased. Thus, we found an adequate exposure gradient to examine the relationship between ozone exposure and the injury response of pines.

OII Values Along a North to South Transect — 1992-1994

The least injury is present in the northern to central Sierra Nevada (*fig. 2a*) and the most in the south central Sierra Nevada and the San Bernardino mountains (*fig. 2b*). The observed injury amounts are generally proportional to seasonal ozone exposures reported by Van Ooy and Carroll (1995) and by Miller and others (1996a). The combined ozone and OII data sets are considered only marginally useful for providing adequate detail of the spatial distribution of injury because the locations of ozone monitors and tree plots could not be randomly selected. The change in yearly OII at any single site is considered a satisfactory indicator of exposure response because it was a repeated measurement of the same trees. Between 1991 and 1994 at the northern locations the OII rose slightly at four of six locations and was essentially unchanged at each of the two remaining locations (*fig 2a*). At the six southern locations OII declined slightly (less injury at all places where the record was complete) except at Barton Flats where it increased slightly (*fig. 2b*).

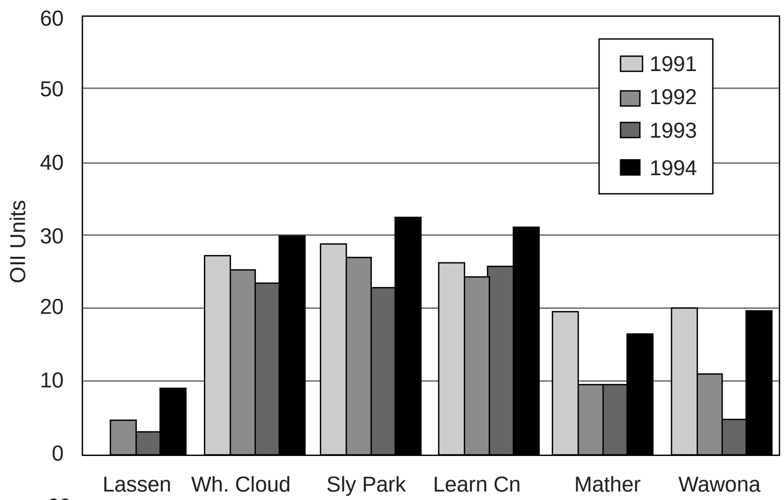

Figure 2a — Annual changes in the ozone injury index (OII) from 1991 to 1994 at six northern or central California sites: Lassen Volcanic , White Cloud, Sly Park, Learning Center, and Camp Mather and Wawona in Yosemite National Park.

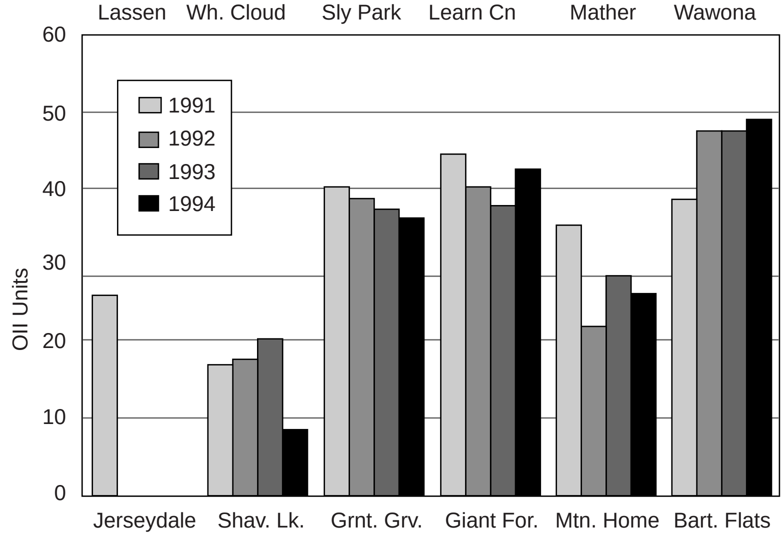

Figure 2b — Annual changes in the ozone injury index (OII) from 1991 to 1994 at five south-central Sierra Nevada sites and one southern California site: Jerseydale, Shaver Lake, Grant Grove and Giant Forest in Sequoia-Kings Canyon National Park, Mountain Home State Park, and Barton Flats in the San Bernardino National Forest. Data are incomplete for Jerseydale from 1992 to 1994 because of unusual amounts of bark beetle-caused mortality.

Correlation of Percent Chlorotic Mottle with Several Ozone Exposure Indices and Cumulative Days of Exposure

The year by year change of percent chlorotic mottle is illustrated as a function of accumulating ozone exposure received by current-year, 1-year-old, 2-year-old, and 3-year-old needles. The data were tested with a number of fitted curves, including quadratic and a Weibull function. The latter was selected for this application because it is a monotonically decreasing (or increasing) fit that more likely applies to the expected biological response in this case. The r^2 for both quadratic and Weibull fits were computed. The corrected regression coefficients for percent chlorotic mottle and each of the exposure indices were:

Index	*Quadratic*	*Weibull*
Sum 0	.583	.574
Sum 60	.592	——
W126	.596	——
Hrs ≥ 80	.553	——
Expos. Days	.433	.424

The r^2 for Sum 0 was not the highest value for quadratic fits but it was the only form of accumulated ozone exposure that converged to the required parameters needed for the Weibull fit. These results point to Sum 0 as an acceptable exposure index to apply in this situation. Therefore, the Weibull equation for percent chlorotic mottle (PCM) and Sum 0 was:

PCM = 100-100*EXP(-(Sum 0/1579000) 2.170)

During the 1991 to 1993 seasons the Sum 0 accumulated exposure ranged between 0 and 600,000 ppb-hrs (*fig. 3*). It was not feasible to observe a needle whorl for longer than three seasons (e.g., 1991 needles could not be used in 1994) because many needle fascicles would have abscised and those few remaining would have less chlorotic mottle. These results indicate that Sum 60, W126, and hrs ≥ 80 are not feasible to use because these data did not converge to the required parameters needed for the Weibull curve fit. Accumulated number of exposure days had the lowest coefficient.

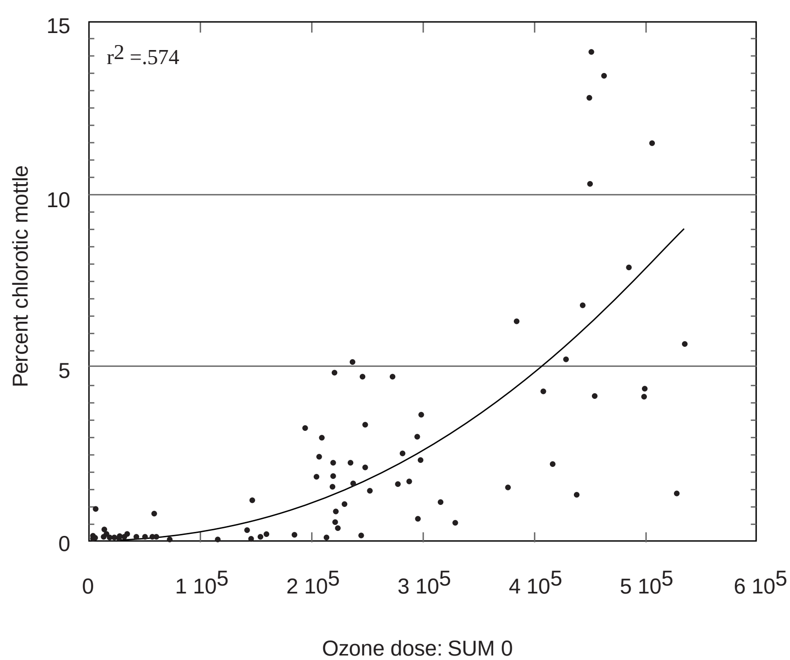

Figure 3 — Weibull curve fit of percent chlorotic mottle accumulated by 1991 to 1993 whorls in relation to Sum 0 ozone.

Correlation of Percent Fascicle Retention with Several Ozone Exposure Indices and Cumulative Days of Exposure

As chlorotic mottle develops on needle fascicles, the natural abscission of needle fascicles within each annual whorl increases thereby leaving whorls with fewer needle fascicles until eventually all needle fascicles abscise and the entire whorl is gone. The corrected r^2 values show Sum 0 to be the Weibull fits:

Index	*Quadratic*	*Weibull*
Sum 0	.759	.742
Sum 60	.675	.613
W126	.653	.609
Hrs ≥ 80	.443	.411
Expos. Days	.692	.669

Because the expected biological response corresponds to the monotonically decreasing form of the Weibull function, it was selected for relating percent fascicle retention (PFR) to the selected exposure indices, e.g., in the case of Sum 0:

PFR = 83.5*EXP(-(Sum 0/732600) 3.057)

For the Weibull fit of Sum 0 data versus percent fascicle retention (*fig. 4*) the maximum amount for Sum 0 exposure is 800,000 ppb-hr as compared to 600,000 ppb-hr for percent chlorotic mottle because it was feasible to use a longer time span (1991-94) for percent fascicle retention than for percent chlorotic mottle (1991-93).

Three Dimensional Display of the Sum 0 Exposure Index, and the Frequency of Sampled Trees in Original Classes of Chlorotic Mottle

Because the Weibull function correlations of Sum 0 versus percent chlorotic mottle involve transformed data, such as the midpoint value of each class, 1 = 1-6 percent (3.5 percent) and 2 = 7-25 percent (16 percent) etc., we examined the distribution of the untransformed data. We related the frequency of trees to the original chlorotic mottle classes as a function of Sum 0 exposure index (*fig. 5*). The threshold above which category 1 (1 to 6 percent) chlorotic mottle appears is about 150,000 ppb. The equivalent threshold values for category 2 (7 to 25 percent) chlorotic mottle could be more useful as a category to monitor because needle fascicle abscission begins at this level.

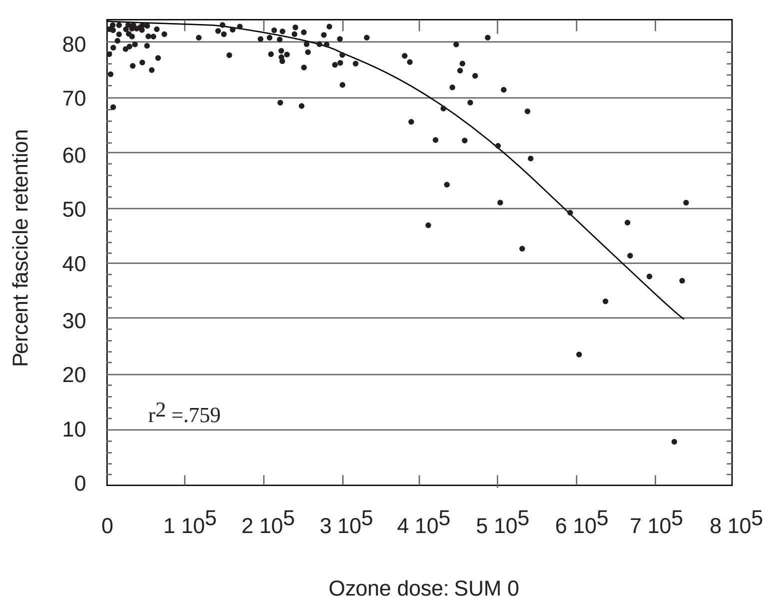

Figure 4 — Weibull curve fit of percent needle fascicle retention accumulated by 1991 to 1994 whorls in relation to Sum 0 ozone.

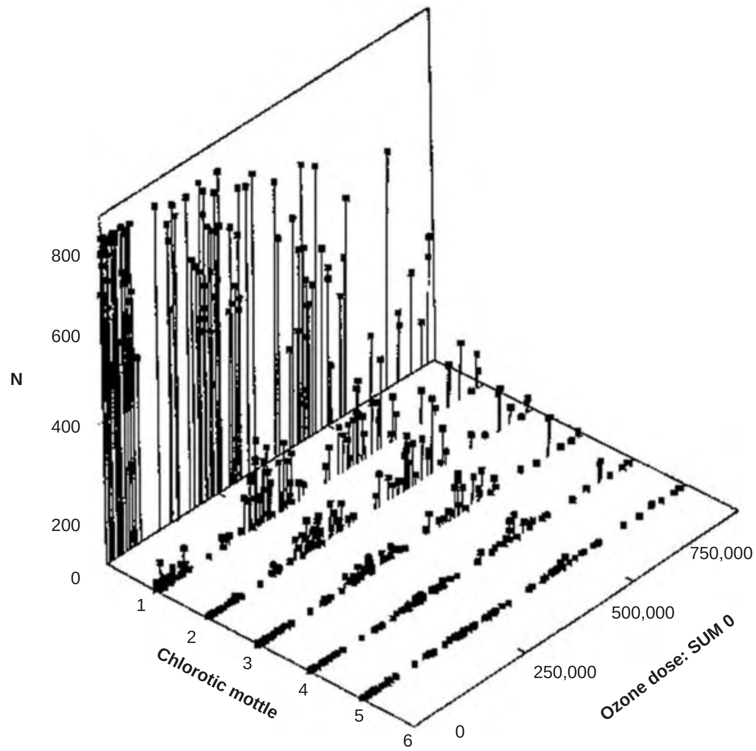

Figure 5 — Distribution of 1991 to 1994 annual whorls from all trees into original categories for chlorotic mottle as a function of Sum 0 ozone exposure index during the same period.

Discussion

The time resolution for examining pine needle response to ozone can vary from daily examination of physiological variables (Grulke and Lee, [In press]; Temple and Miller, [this volume]) to annual visual ratings of injury. For the purpose of evaluating annual increments of injury increase and comparing yearly changes, the visual rating method used in this study, the OII (Miller and others 1996b), appears to provide a reliable estimate. It could be improved by the inclusion of an estimate of the seasonal pattern of stomatal conductance and an estimate of ozone flux to pine foliage, but this improvement generally requires concurrent field measurements of stomatal conductance. Attempts to apply models of ozone flux that are parameterized primarily by atmospheric conditions (temperature and relative humidity) have realized very limited success as predictors (Fredericksen and others 1996) when compared to flux estimates based on actual conductance measurements.

Because of the relative simplicity of the OII, we recommend it as a suitable protocol for monitoring yearly injury. In our study we have used a large number of trees (1,700) to evaluate the visual change of individual age cohorts of needles on each tree exposed to ozone in their initial year and in successive years. Certainly the climate and soil-water availability conditions from 1991 to 1994 were variable and caused important yearly differences in ozone uptake and incremental changes of needle injury amounts. However, annual differences were detected by the chlorotic mottle element of the OII (Temple and Miller, [this volume]), and to a lesser degree by the OII itself. In further support of the visual estimation procedure of the OII, it was possible to include enough trees to represent the range of genetic resistance or susceptibility of ponderosa and Jeffrey pines as well as trees in different crown position classes (e.g. dominant, codominant, etc). Large sample numbers are usually difficult to achieve with physiologically-based response variables (Grulke and Lee [In press]). By using the OII or its most sensitive components, we can examine further the different versions of a possible air quality standard that may be appropriate for the task of protecting ozone-sensitive tree species.

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