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Chapter 10

Ambient ozone patterns and effects over the Sierra Nevada: Synthesis and implications for future research

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Abstract

Spatially explicit estimates of ambient ozone (O_3) exposure to the Sierra Nevada were developed using data from an extensive survey of passive O_3 monitors. The unique data set generated from the passive monitor network elicited widespread interest. As a result, three analysts were given the data set to develop relationships and estimate spatial and temporal patterns of ambient O_3 for the Sierra Nevada. Spatial models of biweekly and seasonal O_3 distribution were constructed by each group using topographical, weather, and other information. The results of these studies suggest that most of the Sierra Nevada study area was reliably estimated, although the distribution of the measurement sites could still be improved (there was clearly an insufficient number of sites on the eastern side of the mountain range). Along with monitoring ambient O_3, evaluations of crown injury were performed at selected sites. The number of sites sampled for this study was low, and the distribution of the sample sites did not represent the distribution of the pines. In spite of these deficiencies, patterns of O_3 injury generally followed patterns of O_3 exposure risk.

1. Introduction

Since 1992, ambient ozone (O_3) concentrations and the condition of pines has been monitored at 10 locations along a north to south transect in the Sierra Nevada from Lassen Volcanic National Park in the north to Sequoia National Forest (Arbaugh et al., 1998). In 1999 these monitoring sites were used as the basis of a bioregional survey of ambient O_3 patterns and its effects (Arbaugh and Bytnerowicz, Chapter 6, this volume). 89 sites were established to monitor ambient O_3 using passive O_3 monitors (Koutrakis et al., 1993), and 25 sites were evaluated for visible injury due to O_3 injury.

The main objective of this project was to produce mapped distributions of O_3 concentrations in the western Sierra Nevada, from the Lassen National Forest to the Sequoia National Forest, using a combination of passive O_3 samplers and active O_3 monitoring stations. Part of this objective was to examine, compare and develop analytical methods useful for spatial estimation of air pollution in remote mountain areas. Previous studies (Phillips et al., 1997) have indicated that geostatistical analysis (kriging) and modern regression techniques, such as locally weighted regression, may have value for this type of data. It is not clear, however, whether one approach is better than another for this type of study.

To examine this issue, several analysts independently modeled the data, thereby providing a comparison of different analytical approaches. These analysts include a Research Statistician from the USDA Forest Service's Pacific Southwest Research Station (PSW; Preisler and Schilling, Chapter 8), a GIS Specialist from the Environmental Systems Research Institute (ESRI; Frączek et al., Chapter 9), and a Research Statistician from the Environmental Protection Agency (EPA; Lee, Chapter 7, this volume). Each analyst independently used the data set created in this project to create spatial maps of ambient O_3 over the Sierra Nevada.

Frączek et al. (Chapter 9, this volume) used ordinary cokriging applied to the O_3 dataset from passive samplers only, digital elevation data, and weather datasets. Preisler and Schilling (Chapter 8) and Lee (Chapter 7, this volume) used locally weighted non-parametric regression, with kriging as an optional residual analysis technique using both passive and active sampler O_3 datasets, digital elevation and weather data. Although Frączek et al. (Chapter 9) and Preisler and Schilling (Chapter 8) used only data for the Sierra Nevada, Lee (Chapter 7, this volume) also included data from the neighboring California Central Valley.

Another project objective was to develop mapped estimates of ponderosa and Jeffrey pine crown injury based on projected summer season ambient O_3 exposure. Using the ambient O_3 map developed in the first objective, spatial estimates of O_3 exposure risk were developed for the Sierra Nevada from the Lassen National Forest to the Sequoia National Forest. Crown injury estimates from 25 sites where then compared with the predicted O_3 concentrations for these sites to examine the ability of predicted exposure values to estimate O_3 injury for sensitive pines of the Sierra Nevada (Arbaugh and Bytnerowicz, Chapter 6, this volume).

This chapter will summarize analysis results pertaining to the adequacy of passive sampler placement and number over the Sierra Nevada, and attempt to synthesize the major themes and results of the three individual analysis efforts, along with results of the foliar injury surveys. In addition, the implications for future regional scale assessments will be discussed.

2. Modeling approaches

Two general approaches were used by the three analysts: geostatistical models (Webster and Oliver, 2001) and generalized additive (locally weighted regression) models (Cleveland et al., 1992; Hastie, 1992). Geostatistical methods, such as kriging, use neighboring O_3 values to describe spatial dependencies among the instances of random variables by modeling the variogram (variance of the difference between measurements at two different locations) as a function of the distance between the measurement sites. If there are spatial dependencies, the variogram normally increases with increasing distance until at a specific range a plateau is reached (Johnston et al., 2001).

Locally weighted regression models are used to estimate nonparametric functions of location, of time, and of the auxiliary variables simultaneously. Under the local regression model a smooth function of spatial location and time is included in the mean to account for any persistent features of the landscape or the environment not captured by any of the environmental or topographic variables in the model. If autocorrelations are still detected in the residuals after fitting the generalized additive model, kriging techniques may be used on the residuals to obtain better predictions at unobserved sites. The essential difference in the two approaches is that geostatistical techniques assume that data are realizations of dependent random variables with a covariance structure that is a function of spatial location. Locally weighted regression models assume that data are realizations of independent random variables. Similarities between neighboring sites are included by modeling the mean with smooth functions of spatial location and spatially explicit topographic and weather variables. The approaches differ on whether variation is dominated by local effects (such as complex topography), or whether it is better characterized by regional trends (such as regional wind patterns).

Even using the same modeling approach, the analysis approaches may differ and analyses can be quite different based on the particular covariates used and questions posed by the investigators. In these studies, models constructed by PSW and EPA were substantially different. The PSW analysis used location, Julian day, temperature, the probability of precipitation, elevation, and ambient O_3 from nearest continuous monitor to estimate maps of daily ambient O_3 concentrations. The EPA effort used a simpler model that predicted mean seasonal O_3 concentrations using location, temperature, and elevation as covariates.

The choice of data summarization also varied between studies. Passive sampler data was gathered at 2-week intervals, with all samplers being changed within the same 48-hour period. This period allowed for reliable measurements of the pollutant without danger of saturating the nitrite coating. PSW and ESRI analysts examined individual 2-week periods, which revealed within-season dynamics of spatial patterns of ambient O_3. ESRI and EPA examined the cumulative seasonal O_3 by summing 2-week-period information, and PSW analyst examined seasonal O_3 by developing seasonal probabilities of exceeding cumulative O_3 threshold values. The choice of data aggregation appeared to be linked to the investigator's choice of specific study questions.

3. Relationship between passive samplers and continuous monitors

The relationship between O_3 and nitrate (NO_3^-) formed on passive sampler filters is assumed to be linear (Preisler and Schilling, Chapter 8, this volume). Original estimates of the slope were developed by Koutrakis et al. (1993) in controlled laboratory conditions, but estimates were found not to be accurate in this study.

A plot of the linear regression lines of observed NO_3^- levels versus O_3 levels from nine collocated sites indicated that slopes and intercepts were significantly different at the various sites (Fig. 6, Preisler and Schilling, Chapter 8, this volume). The Shaver Lake active monitor appeared to be an outlier. Nitrate formation rates were more than 50% greater than at other sites for similar ambient O_3 levels. It is likely that the monitor needs to be recalibrated or that some local effect related to the monitor or sampler is causing the unusually low O_3 measurements. Consequently, observations from the Shaver Lake active monitor were not used by two of three analysts.

Additional analysis of the relationships between the estimated slopes and intercepts and explanatory variables (elevation, maximum temperature, precipitation) indicated that the intercept was increasing with maximum temperature and that intercepts at elevations higher than 1500 m were lower than average. All other relationships between the slopes and intercepts and the covariates were found to be not significant or only marginally significant. These results may indicate that passive samplers may have undocumented sensitivity to temperature, humidity or atmospheric pressure extremes. Some variability, especially to high temperature, is consistent with the chemical kinetics involved with the passive monitor approach.

In spite of these results, all three studies used a single regional estimate of α and β in the analyses. Because environmental measurements were not available at passive sampler locations and few continuous monitoring sites had meteorological instrumentation, adjusting relationships between passive and continuous monitors with environmental data was not possible. A preliminary analysis by PSW and EPA also found that using multiple estimates of α and β did not have a discernable effect on the final maps describing estimated spatial O_3 patterns.

4. Adequacy of sampler network

A large number of people were involved in site selection, placement, and filter exchange. It was assumed that some passive sampler locations would be incorrectly placed, vandalized, or improperly exchanged. Only 21 observations (about 2%) were impacted by operator error or vandalism by humans and bears, which was about 8% less than expected at the onset of the study.

The most frequent disturbance of passive sampler results was the presence of smoke from either controlled burns or wildland fires. Forty observations recorded the presence of smoke. Although there are no existing reports on the affects of smoke on passive sampler chemistry, it is possible that deposition of aerosols on screens might reduce diffusion rates when smoke is very dense or sustained over a long period of time. It is also possible that chemical reaction of O_3 with materials deposited on the screen may cause underestimation of O_3 concentrations by passive samplers.

Site selection and sampler number were examined as part of the three analyses conducted in the three chapters in this book (Frączek et al., Chapter 9; Preisler and Schilling, Chapter 8; Lee, Chapter 7, this volume). In general, all analysts agreed that the spatial density of O_3 sampler locations was extensive enough to cover most of the Sierra Nevada bioregion, but lacked adequate coverage in a few areas. Access difficulty, abrupt changes in topography and sparser sampler placement in the eastern Sierra Nevada contributed to some unequal spatial variation over the region. The area most affected by the lack of samplers was the southern and southeastern sections of the Sierra Nevada. This area is characterized by poor access, steep elevation gradients, and the lack of nearby continuous monitors. Few passive samplers were placed in this area because of logistical difficulties of exchanging filters due to long travel times, and the belief that ambient O_3 was negligible in the eastern Sierra Nevada due to the mountains forming a barrier to easterly transport patterns. Prediction biases were found in the analyses for the southern end of the Sierra Nevada. Prediction errors over 10 ppb were estimated by two analyses for these southern areas, which resulted in underestimates of seasonal O_3 for this area (Preisler and Schilling, Chapter 8, this volume).

Large prediction errors were also found in the northeast corner of the Sierra Nevada. The lack of passive and continuous monitors in this largely unpopulated area of the northeastern Sierra Nevada led to overestimates of the ambient O_3 in all three studies. Edge effects (spatial extrapolation at the limits of the data set) may also have contributed to the larger estimation errors in the southeast and northeast sections of the Sierra Nevada.

Analysts independently identified anomalous passive and active O_3 observations. The EPA study excluded extreme NO_3^- formation rates (< 8 or > 29 ngNO_3^-/h) from the data set, while PSW and EPA removed the Shaver

Lake continuous monitoring station relationship with passive O_3 monitors from the data set. In addition, the PSW analysis identified an anomalous passive sampler site (Woodsford in the El Dorado National Forest) as having consistently higher observed O_3 concentrations than predicted by the model. Neither site operators nor records indicate any unusual information about the Woodsford site. New observations will be needed to determine if the higher than expected values at this site will be persistent in subsequent years. Woodsford observations were not removed from the PSW analysis. The ESRI analyst did not remove any observations from the data set.

There were 85 sites measured as part of these studies, and information from 4 additional sites were contributed as part of a study conducted in Sequoia National Park. Not all studies used all of the sites, due to differences in the starting dates (lower elevation and more southern sites were started earlier, while higher elevation and more northerly sites were delayed by winter snow pack). Analysis by the ESRI study estimated the number of passive sampler sites needed to estimate mean seasonal O_3 concentrations over the Sierra Nevada with a high level of accuracy. Neither of the other studies estimated sample size requirements, but the EPA study will consider the question in future analyses.

5. Spatial patterns of ozone distribution

The addition of passive monitors to the existing continuous monitor network significantly decreased the prediction error for spatial patterns in the Sierra Nevada (Lee, Chapter 7, this volume). All studies indicated that the highest areas of cumulative ambient O_3 are found in the southwestern Sierra Nevada. In addition to this area, all studies indicated that an additional area of high O_3 occurred in the west-central Sierra Nevada, east of Sacramento and possibly in the Lake Tahoe Basin. The ESRI study generally indicated higher levels of ambient O_3 on the western side of the central Sierra Nevada, while the EPA study found that ambient O_3 concentrations declined further westward into the San Joaquin Valley. High concentrations of O_3 were found during some periods in the eastern Sierra, especially in the Mammoth Lakes area (Frączek et al., Chapter 9, this volume).

6. Intra-seasonal patterns of ambient ozone

Ambient O_3 varied greatly during the sampling season. Both the PSW and ESRI analyses indicated that periods of high O_3 were observed in June, July, and September. August had lower regional O_3 levels, perhaps due to convective air masses and associated periods of rain and down canyon winds. Spatial patterns of O_3 through time also varied. During some sampling periods, a north to south gradient of O_3 increase was prevalent, but not an east to west gradient. At other times, an east to west gradient was large, while a north to south gradient was less. It is likely that changes in prevailing daily wind patterns and temperatures along the western and eastern sides of the Sierra Nevada are responsible for the diversity of these patterns. Periods with higher valley temperatures and stronger air flow appeared to coincide with high O_3 levels along the entire western side of the Sierra Nevada (and a high area along the eastern side), while cooler temperatures may have resulted in stronger north to south O_3 gradients.

7. Relationship of temperature and precipitation with ambient ozone

The PSW study conducted a detailed analysis of auxiliary variables, including probability of precipitation and maximum daily temperature (Preisler and Schilling, Chapter 8, this volume). Increasing probability of rain was slightly negatively associated with ambient O_3, while temperature was strongly positively associated with ambient O_3. Frączek et al. (Chapter 9, this volume) also found that low O_3 concentrations co-occurred with frequent rain events. This supports other studies (Wolff and Lioy, 1978; Chock et al., 1982; Van Ooy and Carroll, 1995) that found the most important variable for modeling O_3 concentrations was ambient air temperature.

8. Relationship of elevation with ambient ozone

Previous studies have observed that ambient O_3 continuously increases with elevation (Brace and Peterson, 1998) or increases to a maximum then becomes level or decreases with further increases in elevation (Miller et al., 1996; Alonso et al., 2002). When the estimated effects of temperature were removed, the PSW study showed a significant increasing trend in ambient O_3 concentrations with increasing elevation. The EPA study observed that seasonal mean ambient O_3 increased up to an elevation of 1500 m, then leveled off at higher elevations. Apparently, ambient O_3 tends to increase with elevation, when all other environmental factors are constant. However, increasing elevation is also associated with decreasing temperatures. Both factors together may lead to the observation of a leveling of ambient O_3. In addition, after initial increases of O_3 concentrations at lower elevations downwind of the photochemical smog source areas, O_3 concentrations may decline due to dilution of the pollutant, uptake by vegetation, and reactions with various landscape features.

9. Relationship of ozone injury with ambient ozone patterns

Twenty-five sites near selected passive O_3 samplers, were surveyed using the Forest Pest Management (FPM) method. The FPM method is less costly to perform than the Ozone Injury Index (OII) evaluation used for Project FOREST, and the results of both survey types can be related to each other with a high degree of accuracy at the plot level (Arbaugh et al., 1998). All tree observations were made between August 15 and September 15 when injury development was the most apparent (Table 1).

Several previous studies (Miller et al., 1996; Salardino, 1996; Arbaugh et al., 1998) found linear relationships between ambient O_3 and foliar injury in the Sierra Nevada. Maps of estimated probabilities for cumulative O_3 levels for a period of 140 days starting May 25 indicate that the central and southwestern Sierra Nevada were likely to have been exposed to SUM0 values greater than 201.6 ppm (seasonal average of 60 ppb) (SUM0 is the cumulative sum of all hourly O_3 concentrations over an exposure period) (Fig. 1). A southeastern area of the Sierra Nevada also is estimated to have high exposure (SUM0 $>$ 201.6 ppm) with 95% probabilities. This may be due to valley wind patterns transporting air pollution over the southern end of the Sierra Nevada,

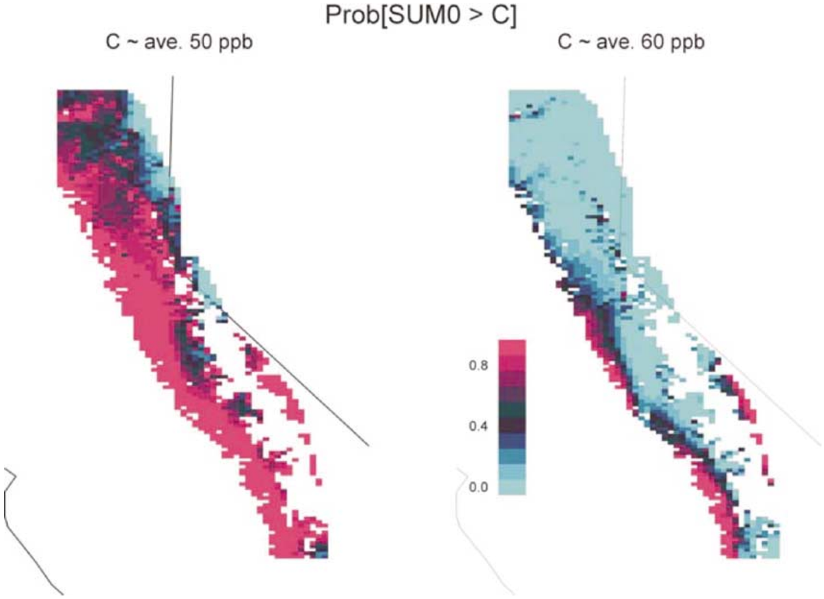

Figure 1. Estimated probabilities of SUM0 values exceeding two critical levels: average seasonal ppb-hr $>$ 50 and $>$ 60. SUM0 was calculated for a period of 140 days starting May 25, 1999.

Table 1. Site locations and average tree characteristics for 25 Forest Pest Management (FPM) evaluated sites along the western side of the Sierra Nevada. FPM scores were calculated from three branches averaged to plot. Any visible injury caused the whorl to be counted as an injured whorl. Crown position 2 is intermediate, 3 is codominant, and 4 indicates open-growing trees

Forest	Site	North to South Order	Crown Position (Median)	Whorl Retention (Median)	DBH (Average, cm)	Live Crown Ratio (Average)	Height (Aveage, ft.)	FPM Score (Average)
Lassen NF	Hat Creek	1	3.0	4.17	13.72	58.83	58.6	3.38
Lassen Volcanic NP	*Manzanita Lake*[a]	2	3.0	4.00	14.78	63.67	59.0	2.86
Lassen NF	Mineral	3	3.0	4.00	10.82	52.83	49.6	2.78
Plumas NF	Bucks Lake	4	2.0	4.33	11.91	70.57	54.3	3.82
Plumas NF	Little Grass Valley Reservoir	5	3.0	3.50	12.18	71.17	60.3	3.43
Tahoe NF	Downieville	6	3.0	3.33	13.38	48.33	103.7	3.13
Tahoe NF	*White Cloud*[a]	7	3.0	3.33	14.48	60.50	73.9	2.61
Tahoe NF	Foresthill Seed Orchard	8	3.0	3.00	18.48	70.83	77.0	2.30
Tahoe/Eldorado NF	Blodgett[a]	9	3.5	3.00	13.74	69.00	101.0	3.34
Eldorado NF	Sly Park	10	3.0	2.83	19.08	53.33	103.0	2.46
Eldorado NF	Bear/Lumberyard	11	3.0	4.33	22.91	69.50	81.0	3.11
Stanislaus NF	Avery	12	3.0	3.00	17.53	52.67	105.5	2.67
Stanislaus NF	*Five Mile*[a]	13	4.0	3.33	11.27	58.62	81.5	2.58
Stanislaus NF	Reed Creek	14	4.0	3.83	14.52	46.67	95.2	2.87
Yosemite NP	Mather	15	3.0	3.33	13.04	52.83	78.8	2.78
Yosemite NP	*Turtleback Dome*[a]	16	2.0	4.00	20.17	63.67	75.4	2.82
Yosemite NP	Wawona	17	3.0	3.67	21.73	63.00	110.6	2.66
Sierra NF	Poison Meadow	18	3.0	4.67	23.28	57.83	82.4	2.18
Sierra NF	*Shaver*[a]	19	3.0	4.67	19.11	55.17	101.0	3.01
Sierra NF	Teakettle	20	3.0	4.33	20.20	58.00	78.0	3.16
Sequoia NP	Stony Creek	21	2.5	2.83	18.69	58.00	77.5	2.81
Sequoia NP	*Lower Kaweah*[a]	22	3.0	2.67	11.83	48.17	91.2	2.89
Sequoia NF	Mountain Home	23	3.0	3.33	13.83	62.50	70.8	0.62
Sequoia NF	Parker Pass	24	3.0	4.83	17.48	68.83	74.0	2.48
Sequoia NF	Liebel/Piutes	25	3.0	5.33	20.90	65.00	91.3	3.70

[a] Collocated active monitor.

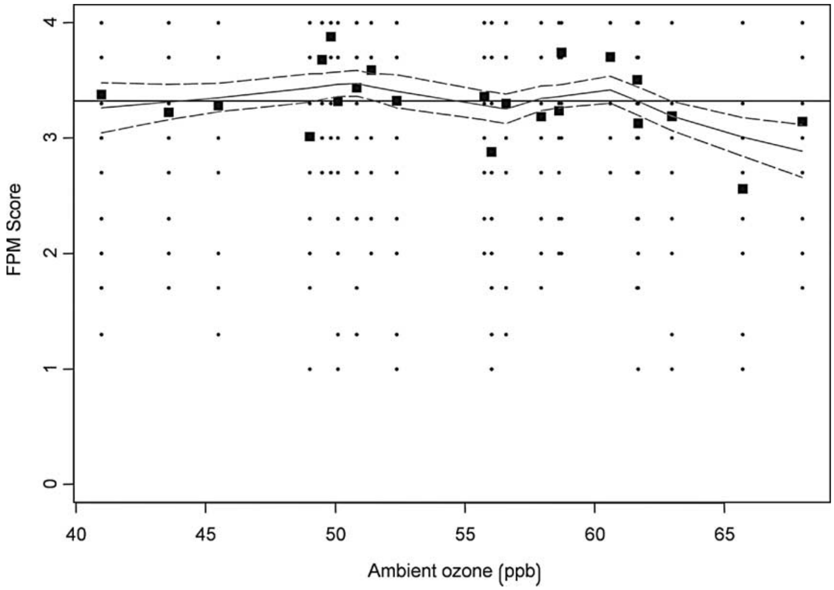

Figure 2. Forest Pest Management (FPM) ozone injury scores (squares) compared with average seasonal ambient ozone (ppb) estimated from passive samplers. All injury sites were within 2 miles of passive ozone samplers. Points are the individual 2-week passive ozone values, the thin solid line is the average ambient ozone estimate, and the dashed lines are the ±2 standard errors, and the thick solid line is the mean regional FPM score.

or northerly winds transporting air pollution from the Los Angeles Basin to the southeastern edge of the mountain range, or both.

High exposure risk areas did not always result in moderate or high injury to pines (Fig. 2). A clear relationship between exposure and injury only appeared when average seasonal ambient O_3 exceeded 60 ppb. Site specific factors, such as aspect, soil water balance, and phenotypic response by local populations, also affect expression of visible injury (Arbaugh et al., 1998; Grulke, 1999). In addition, differences in the experience or judgment of the evaluating crews can also affect the severity of injury reported. It also should be noted that both the OII and FPM take into account cumulative effects of O_3 on pine branches over several years of the exposure. These indices are more suitable for comparison of the O_3 effects between pine stands at a landscape level than for establishment of a relationship between a single year exposure (or a single photochemical smog season, i.e., spring through early fall) and injury of branches. The chapters by Goldstein et al. (Chapter 4), Grulke (Chapter 3), and Panek et al. (Chapter 14, this volume) discuss these and other problems such as effects of water availability on injury development, capacity of trees to take up pollutants at night and winter, biochemical defense mechanisms of plants to photochemical pollutants, and other considerations.

A limitation of the FPM surveys became apparent during the analysis. The FPM surveys were located only on the western side of the Sierra Nevada, and thus only partially match the area of the passive O_3 survey. Although it is generally assumed that interior and eastern side sites have little or no O_3 injury, the lack of data reduces our ability to quantify the spatial relationship between ambient O_3 and foliar injury. This problem is a legacy of the FOREST system that was also designed for the western side of the Sierra Nevada.

10. Conclusions and future directions

Development of statistical models describing patterns of ambient O_3 over space and time are now practical due to the development of low-cost passive sampler systems. The modeling efforts reported similar estimated R^2's (58% to 71% from regression studies) and root mean square errors (6.7 ppb to 8.2 ppb). Further improvements in the accuracy of predictions may be possible because residual analysis indicates unexplained spatial patterns remain in the data.

In theory the best analytical choice for analysis depends on whether variation is local, which favors using geostatistical approaches, or whether regional trends dominate the variation between sample locations, which indicates that localized regression may be more appropriate. Air pollution formation consists of multiple local processes, but regional atmospheric processes dominate transport in the San Joaquin Valley. These processes result in few local differences in O_3 concentration at the edge of the Sierra Nevada.

As an air mass enters the Sierras, however, the complex terrain may create local differences in spatial O_3 patterns and concentrations (Carrol et al., Chapter 2, this volume). Little information exists about the effect of the complex topography and surface friction characteristics on large-scale pollution transport. The lack of spatial autocorrelation after using locally weighted regression modeling (Lee, Chapter 7; Preisler and Schilling, Chapter 8, this volume) may indicate that large-scale trends continue to dominate the variability in the Sierra Nevada. This conclusion is supported by the slightly lower variations resulting from the PSW and EPA analyses relative to the ESRI approach. In practice, however, the final spatial patterns developed from the analyses had few differences, especially if only significant spatial patterns are considered. This lack of difference may indicate that the choice of analysis approach may not be as important as the careful application of the approach chosen.

The design of the foliar survey segment of this study was less adequate. The distribution of the sample sites used in this study was not based on the spatial distribution of sensitive trees in the Sierra Nevada, but centered around an existing network of sites located along the western side. Thus, interior and eastside sites were not sampled, making it difficult to quantify the ability of the O_3 exposure risk maps to estimate spatial patterns of O_3 injury to sensitive pines.

The foliar survey information did have great value for developing future foliar survey work. Both Forest Health Management (Campbell et al., 2000) and the Forest Service Air Quality Management (Air Resource Management, 1998; Plymale et al., Chapter 12, this volume) are developing long-term foliar monitoring networks for the Sierra Nevada. In the future, information from these networks will be used to develop models of spatial risk estimation to pine and understory plant injury based on patterns of O_3 exposure.

The results of these studies also indicate that large-scale wind patterns, temperature, and elevation are important auxiliary variables. Measurement of wind and temperature should be conducted as part of the sampling effort in future assessments and use of passive monitors. Measurement of temperature is presently economically feasible; however, measurement of large-scale wind patterns is much more difficult. In this study, upslope delivery from the San Joaquin Valley, trans-Sierra delivery, and eastside wind patterns are likely large determinants of resulting air pollution patterns; however, characterizing them involves a separate spatial or transport modeling effort. If a careful characterization of regional wind patterns is included in the analysis, it is likely that much of the importance of latitude and longitude in the existing spatial models can be reduced, allowing development of more functional rather than location-based models.

Two-week long averages of O_3 concentrations are useful for evaluating potential risks associated with the pollutant effects at the landscape level. However, for better understanding of transport of the polluted air masses and more accurate evaluation of O_3 phytotoxic effects, information on real-time concentrations of the pollutant are needed. In that regard, some new approaches that utilize passive sampler O_3 data with collocated O_3 active monitors allow for estimates of short-term (hourly) O_3 concentrations (Krupa et al., 2001; Tuovinen, 2002). Newly available portable O_3 monitors (that are battery operated and do not require constant temperature) will allow for denser networks of real-time instruments in the future. Based on improved information of real-time O_3 concentrations and other data (environmental parameters, phenology, water status of plants, gas exchange curves, defense potential of key forest species, etc.), models predicting potential phytotoxic effects of the pollutant to forests could be developed. These models would be more accurate in predicting responses of plants than the pollutant exposure-based models.

References

Air Resource Management, 1998. A Regional Strategy for Air Resource Management. USDA FS Pacific Southwest Region Ecosystems Conservation Report, Sacramento, CA, 20 p.

Alonso, R., Bytnerowicz, A., Arbaugh, M.J., 2002. Vertical distribution of ozone and nitrogenous pollutants in an air quality class I area, the San Gorgonio Wilderness, Southern California. The Scientific World 2, 10–26.

Arbaugh, M.J., Miller, P.R., Carroll, J., Takemoto, B., Procter, T., 1998. Relationship of ambient ozone with injury to pines in the Sierra Nevada and San Bernardino Mountains of California, USA. Environ. Pollut. 101, 291–301.

Brace, S., Peterson, D.L., 1998. Spatial Patterns of tropospheric ozone in the Mount Rainier region of the Cascade Mountains, USA. Atmos. Envrion. 32, 3629–3637.

Campbell, S., Smith, G., Temple, P., Pronos, J., Rochefort, R., Anderson, C., 2000. Monitoring for ozone injury in West Coast (Oregon, Washington, California) Forests in 1998, USDA Forest Service General Technical Report, PNW-GTR-495.

Chock, D.P., Kumar, S., Herrmann, R.W., 1982. An analysis of trends in oxidant air quality in the south coast air basin of California. Atmos. Environ. 16, 2615–2624.

Cleveland, W.S., Grosse, E., Shyu, W.M., 1992. Local regression models. In: Chambers, J.M., Hastie, T.J. (Eds.), Statistical Models in S. Wadsworth & Brooks/Cole, Pacific Grove, CA, pp. 309–376.

Grulke, N., 1999. Physiological responses of ponderosa pine to gradients of environmental stressors. In: Miller, P., McBride, J. (Eds.), Oxidant Air Pollution Impacts in the Montane Forests of Southern California: The San Bernardino Mountain Case Study. In: Ecological Studies, Vol. 134. Springer-Verlag, New York.

Hastie, T.J., 1992. Generalized additive models. In: Chambers, J.M., Hastie, T.J. (Eds.), Statistical Models in S. Wadsworth & Brooks/Cole, Pacific Grove, CA, pp. 249–307.

Johnston, K., Ver Hoef, J., Krivoruchko, K., Lucas, N., 2001. Using ArcGIS Geostatistical Analyst. Environmental Systems Research Institute, Inc., Redlands, CA, USA.

Koutrakis, P., Wolfson, J.M., Bunyarovich, A., Froelich, S.E., Koichiro, H., Mulik, J.D., 1993. Measurement of ambient ozone using a nitrite-coated filter. Anal. Chem. 65, 209–214.

Krupa, S., Nosal, M., Peterson, D.L., 2001. Use of passive ambient ozone (O_3) samplers in vegetation effects assessment. Environ. Pollut. 112, 303–309.

Miller, P.R., Guthrey, R., Schilling, S., Carroll, J., 1996. Ozone injury responses of ponderosa and Jeffrey pine in the Sierra Nevada and San Bernardino Mountains in California. In: Bytnerowicz, A., Arbaugh, M.J., Schilling, S. (Eds.), Proceedings of the International Symposium on Air Pollution and Climate Change Effects on Forest Ecosystems, February 5–9, 1996, Riverside, CA. USDA For. Serv. Gen. Tech. Rep. PSW-GTR-166.

Phillips, D.L., Lee, E.H., Herstrom, A.A., 1997. Use of auxiliary data for spatial interpolation of ozone exposure in southeastern forests. Environmetrics 8, 43–61.

Salardino, D., 1996. Exposure/response of Ponderosa and Jeffrey pines to ozone in the Sierra Nevada Mountains. Master of Science Thesis, University of California, Davis, CA.

Tuovinen, J.-P., 2002. Assessing vegetation exposure to ozone: is it possible to estimate AOT40 by passive sampling? Environ. Pollut. 119, 203–214.

Van Ooy, D.J., Carroll, J.J., 1995. The spatial variation of ozone climatology on the western slope of the Sierra Nevada. Atmos. Environ. 29, 1319–1330.

Webster, R., Oliver, M., 2001. Geostatistics for Environmental Scientists. John Wiley & Sons, New York.

Wolff, G.T., Lioy, P.J., 1978. An empirical model for forecasting maximum daily ozone levels in the northeastern US. J. Air Pollut. Control Assoc. 28, 1034–1038.