CROP LOSS FROM AIR POLLUTANTS AND INJURY TO FOREST TREES ASSESSMENT PROGRAM

Status Report

to the

California Air Resources Board

Contract No. A833-138

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C. Ray Thompson
Principal Investigator

Gerrit Kats
Randall G. Mutters
Minn Poe

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Statewide Air Pollution Research Center
University of California
Riverside, California 92521

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ABSTRACT

The Statewide Air Pollution Research Center (SAPRC) at the University of California, Riverside (UCR) has a continuing mission to investigate the effects of air pollutants on vegetation, especially forests and agricultural crops, and to determine the losses in productivity caused by these pollutants. To further this mission, we have continued the Vegetation Loss Assessment Program to evaluate air pollutant damage to plant productivity based on modeling and field observations. This research provides information to be used by the Air Resources Board in assessing potential impacts to vegetation posed by different ozone air quality standards, and is a planning tool for guiding future research, especially in terms of forest response to ozone.

The overall project was initiated in early 1985. Phase I focused on the establishment of comprehensive computer data bases relevant to air pollutant, dose-response data for important California crop species, a critical review of key plant studies, and sponsorship of a workshop to assess current data and address informational needs. Phase II in 1986 and 1987 focused on preparation of a detailed crop loss assessment based on 1984 data and refined crop loss assessments with local agricultural input. Phase III began in 1987 and is continuing. It emphasized development of procedures and models for assessing losses to forests by focusing on key tree species, the further refinement of crop loss models, the implementation of a field verification program to assess the extent of ozone related injuries to crops at different locations in the state, and the dissemination of information on vegetation losses from air pollutants to the public, government agencies, and scientific community.

Specific tasks for 1989-90 were to:

i) Critically evaluate the current status of air pollution effects on California vegetation; ii) review the reports in the literature on tree and crop responses to air pollution and the predictive models for projecting potential vegetative loss; iii) assess the extent of injury to selected crops at different field locations; and iv) disseminate information on vegetation losses due to air pollution.

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C. Ray thompson, Gerrit Kats, Randall G. Mutters and Minn Poe

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University of California
Riverside, CA 92521

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13. ABSTRACT *(Maximum 200 Words)*

Yield loss estimates from ozone for 52 different agricultural crops on a county-wide basis for California were made for 1987 and 1988. Compared to expected yields in clean air, losses ranged between 0 and 63 percent. A field survey in 1990 indicated that leaf injury and defoliation were more pronounced in southern portions of the San Joaquin Valley, and an east-to-west gradient in losses also occurred. Some of the crop losses occurring in 1988 air quality were alfalfa, 1.3-11.1%; beans, 0-34%; cotton, 6-45%; grapes, 25-31%; onions, 4-20%; oranges, 11-63%; potatoes, 10-20%; rice, 3-7%; sugar beets, 0-9%; tomatoes, 2-22%; and wheat, 0.7-16%. The report includes an extensive bibliography of the effect of air pollution on forest vegetation; no satisfactory models exist for assessing losses to the 21 host tree species listed as "moderately or very sensitive" to air pollution. Monthly 7- and 12-hour ozone averages indicate that valuable commercial timber species in the forests in El Dorado, Placer, Riverside, San Bernardino, and San Diego counties experience the highest levels of exposures to air pollution, and the absence of monitoring sites hinders the assessment of the risk to Southern Sierra Nevada forests, which are downwind of urban and industrial conifers.

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DISCLAIMER

The statements and conclusions in this report are those of the contractor and not necessarily those of the California Air Resources Board. The mention of commercial products, their source or their use in connection with material reported herein is not to be construed as either an actual or implied endorsement of such products.

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SUMMARY

The total valuation of agricultural receipts in California were near 12 billion dollars in 1988. In addition to this agricultural abundance, the diversity of ecological niches and the associated vegetation are major assets in terms of industry, tourism, and watershed conservation. Severe air pollution is a chronic problem in the South Coast Air Basin, the Central Valley, and the Sierra Nevada Mountains. The direct impact of air pollutants on agricultural and to a lesser extent, forest vegetation has been documented and reproduced experimentally. However, few attempts have been made to synthesize the research information into a form useful to state and private concerns.

Thus the Air Resources Board (ARB) initiated a Vegetative Loss Assessment Program in January, 1985 to compile an assessment of vegetative losses due to air pollution injury on a statewide basis. The objectives for 1989 were to:

1. Form data bases relevant to the effects of O_3 on forest tree seedlings in California;
2. Survey the effects of O_3 on crops in the San Joaquin Valley;
3. Prepare reports and educational materials on the effects of air pollution on plants for use by agricultural experts;
4. Update and revise, with current information, data bases used to assess vegetation loss statewide.

The 1987 and 1988 ozone data were obtained from the Air Resources Board and 1988 and 1989 ozone data from select locations where Statewide Air Pollution Research personnel conducted field experiments. The monthly 7 and 12 hr average ozone concentrations were calculated for all monitoring sites. The ozone data was used to identify locations where a significant loss of plant productivity may occur, to cross reference with field evaluations of injury and in predictive yield loss models for various crop species. Ozone data and crop statistics were used to predict yield loss of 52 different crops on a county basis statewide. No satisfactory models for assessing losses in forest productivity due to ozone injury are available, although it was possible to draw some broad based conclusions.

A preliminary field survey of crops during late June 1990 evaluated Pima cotton, Acala cotton, almonds, grapes, alfalfa, tomatoes, onions, bell peppers, sugar beets and sweet corn for further observation. Two later field surveys were conducted to more critically assess the extent of visible ozone injury to crops in the San Joaquin Valley during August and September, 1990. Cotton, alfalfa, almonds and grapes were evaluated at several different locations with contrasting ambient concentrations of ozone. The degree of leaf injury and defoliation was most pronounced in the southern as compared to the northern portions of the valley. Foliar injury due to ozone injury was highest in counties predicted to experience the greatest loss in yield due to ambient ozone.

Photographs were taken to document the characteristic ozone injury symptoms. These photographs along with others from previous studies were used to make "Fact Sheets" containing concise descriptions of the impact of ozone injury on eight different crops. Fact sheets were made available to the ARB for distribution to interested parties. In addition, a portable display was made and delivered to the ARB which presents the effects of air pollutant on plants and on the quality of our living environment.

Forests in much of California are healthy and continue to thrive with the exceptions of those surrounding the Los Angeles basin and those east of the southern San Joaquin Valley. In these areas there is certain ozone damage to the mixed conifer forest, especially in the San Gabriel, San Bernardino and San Jacinto mountains which ring the Los Angeles basin. Lesser damage occurs in the southern Sierra Nevada slopes east of Bakersfield with injury declining as ozone exposure lessens northward. A commercial timber model currently being developed at UC Berkeley may be used in the near future to project potential economic damages associated with changes in growth caused by ozone.

A vegetation loss due to air pollutant injury workshop was held on August 28 and 29, 1989 in Riverside, California. Eight individuals attended including scientists from the University of California, USDA Forestry Service, Cooperative Extensive Service, and California Air Resources Board. Productive discussions were held concerning current research efforts and the future requirements needed to enhance the vegetative loss program.

RECOMMENDATIONS

1. Research programs are needed to evaluate the potential loss of productivity and of longevity of fruit and nut trees due to ozone injury in California. A comprehensive review of the literature has revealed that few data are available which can be used to assess the impact of air pollution on these crops which are worth 1.5 billion dollars annually. The only research in this area currently underway is an ARB funded program to study the effects of ozone on plum at the Kearney Field Station, where L. Williams has preliminary indications that ozone substantially reduced yield. This work will provide information needed to predict yearly losses in plum and prune. Extrapolation, however, of any plum model to other important tree crops such as almond, is laden with assumptions which may result in unrealistic predictions of yield losses. Field research designed to generate predictive yield models for important tree crops is economically justifiable and scientifically needed to establish the relationship between the physiological response to ozone and marketable yield.

2. To date, no models are available which can adequately predict the potential loss of forest productivity in California due to ozone injury. Three potential means of filling this information gap are to: i) consolidate existing data sets to generate a projection function; ii) gain access to models currently being developed by other agencies or research groups; or iii) establish a research program specifically targeted at generating the information needed to develop a projection model. The capacity to predict potential forest loss due to ozone injury is an essential tool for the regulatory agencies charged with the responsibility of maintaining the economic and esthetic value of California forests.

3. Based upon a critical analysis of field surveys from previous years, we suggest that a future survey be conducted on a more frequent basis throughout the growing season on small representative plots in growers' fields. Established observation plots, of selected crops, will allow for a concise assessment of injury symptom development through time on the same population of plants. The program will require the assistance of county farm advisors and cooperation of concerned growers. Reimbursement of the grower for the small loss in yield from the observation plot may be necessary. The associated cost, however, should be minimal considering a plot size of only 25 to 50 feet square. As in the past, the survey will provide mapping of injury intensity across the valley and illustrative photographs that document the progression of injury symptoms.

4. In an effort to precisely delineate between foliar ozone injury and other confounding artifacts such as leaf aging, we suggest that a charcoal filtered open-top chamber be used in conjunction with the observation plots described in Recommendation 3. One chamber per site would require only a small amount of electricity for operation and routine maintenance. In return, the additional information could be used as a local control for all field evaluations, and the plots would effectively demonstrate to growers and other agricultural professionals the severity of ozone injury to their crops.

5. In addition, the project should continue to provide: An annual update of data bases relevant to crop and forest losses from ozone; an assessment of crop losses from ozone in 1989 and an annual review workshop to provide input into the ARB vegetation loss research program.

1. INTRODUCTION

Assessment of Losses to California Crops from Air Pollution

Studies in the 1950's and 1960's utilized field surveys to estimate crop losses primarily from ozone, based on subjective estimates by experienced observers or empirical predictions based on injury in the field (Millecan, 1971, 1976; Benedict et al., 1979). Calculated losses for California varied widely from 11 to 55 million dollars depending on the year. Those assessments, however, were based on generalized assumptions that may not hold for all species or evaluate crop losses not associated with visible injury.

More recent studies have focused on estimates of economic yield losses based on experimental field studies where the pollutant levels can be controlled and/or monitored, and where plant responses were carefully measured. The CDFA's California Crop Loss Assessment (CCLA) project was developed from the original field survey approach. Initial studies involved large scale pollutant gradients with plants grown in standardized media and containers at locations where air pollutant monitoring indicated a gradient in ambient ozone concentrations (Oshima et al., 1975, 1976; McCool et al., 1986). Current CCLA activities continue to emphasize experimental research to generate data for ozone dose-response equations for California crops using closed-top field chambers (McCool et al., 1986). All of the equations generated are designed to predict only yield losses from ambient ozone data; no acreage or monetary losses are determined.

The National Crop Loss Assessment Network (NCLAN) funded by the U. S. Environmental Protection Agency focused on standardized experimental research using open-top field chambers to generate economic crop loss models. The NCLAN research was conducted at several sites, two sites in California, at Shafter and at Tracy in the San Joaquin Valley, and four in Midwestern and Eastern States. Researchers for NCLAN generated economic loss projections for 10 crops for the entire United States, with data for five crops (alfalfa, cotton, barley, lettuce, and tomato) obtained at the California sites (Heck et al., 1982, 1983, 1984a,b).

Neither the CCLA nor the NCLAN projects in California attempted to integrate other published field results into their crop loss models. Furthermore, neither study attempted to validate the crop loss models based on even a limited scale using field surveys of injury symptoms, or by examining ozone levels and area-specific yield data. Recently, researchers evaluated the overall process and assumptions involved with assessing crop losses from air pollutants (Heuss et al., 1982, Heck et al., 1984a; Lefohn and Jones, 1986). For NCLAN, various dose-response functions and economic models were tested to pick the best forms for predicting nationwide crop losses.

A number of studies have indicated that leaf injury is frequently associated with decreased plant growth and yield (Reinert, 1980). Substantial foliar injury and defoliation in dry beans and alfalfa was associated with large reductions in yield (Kohut and Laurence, 1983; Oshima et al., 1976; Olszyk et al., 1986). Thompson and Kats, (1970) found that ozone injury that was associated with a decrease in leaf chlorophyll concentration was associated with reductions in yield for grapes. Leaf injury evaluation may, therefore, give a general indication of the degree of yield loss in a number of crops such as cotton, alfalfa, beans, and grapes. For other crops such as tomatoes, onions, and wheat, leaf injury could still indicate reduced yields, although the quantitative relationship is not well established and is cultivar dependent (Oshima et al., 1975, 1977; Wukasch and Hofstra, 1977; Decoteau et al., 1986).

Field Surveys. Field surveys of injury symptoms in specific areas of the San Joaquin Valley, where ozone concentrations are known to be highest may be an effective means of identifying and assessing potential yield loss due to ozone injury. A survey focused on specific areas would allow for the examination of more crops rather than just one, such as cotton in 1988. The survey would be limited, however, to those crops growing during the mid to late summer when ozone concentrations are the highest.

Assessment of Losses to California Forests from Air Pollution

Ozone has been recognized as affecting trees in southern California since the early 1960's, and in the southern Sierra Nevada mountains since the early 1970's (Miller and Millecan, 1971; Miller et al., 1972; McBride et al., 1975; Miller, 1983). Ozone sensitive trees in both of these areas are valuable assets in terms of the major species which provide direct tangible benefits such as lumber, maintenance of watersheds for water supplies, and enhancement of recreation. The trees are also invaluable in preserving the integrity of ecosystems.

Ponderosa pine (Pinus ponderosa) and Jeffrey pine (P. jeffreyi) are two of the most ozone sensitive tree species in California (Miller and Millecan, 1971). These species have been the focus of intensive field studies in the San Bernardino and Sierra Nevada Mountains (Pronos and Vogler, 1978; Miller, 1983; Peterson et al., 1987, 1988). Those studies have documented needle injury symptoms and possible growth reductions, particularly in those areas with the highest ambient ozone concentrations.

Effects of Ozone on Seedlings of Pinus Ponderosa and Pinus Jeffrei. A small amount of research has been conducted on the effects of ozone on seedling conifers. This work is of vital concern because seedling survival is crucial for the replacement of mature forests lost by logging or natural death. Miller and McBride (1975) found variable estimates of mortality of mature ponderosa pines in the San Bernardino Mountains to be 8-10% over a four year period. Miller (1973) observed an 8% loss during a three year study while, Cobb and Stark (1970) estimated 24% mortality of mature trees to occur over the same period of time. Taylor (1973) reported that ozone levels of 8 pphm or higher for 12.6 hrs/day caused moderate to severe damage to ponderosa pine. Miller and Stolte (1984) fumigated seedling ponderosa, digger (Pinus sabinana) and Jeffrey pines with 10 and 20 pphm ozone which caused visible injury to ponderosa and Jeffrey but less to digger pine. Root dry weights were reduced significantly by the higher level of ozone in all species. Aitken et al. (1984) fumigated ponderosa pine seedlings with successive levels of ozone and found the threshold for visible injury to be between 25 and 30 pphm after treatment for 21 days, 10 hrs/day. Hogsett and Tingey (1989) reported that ponderosa pine seedlings were reduced in diameter by 7 and 11% after fumigation with 6.7 and 7.1 pphm ozone respectively during the previous season. Stem dry weight was reduced 8 and 11% and root weight was reduced 5 and 26%. Second year needles had 10 and 26% less biomass than controls and visible needle mottle.

The assessment of ozone injury to forests has not been emphasized to date. Efforts are needed to consolidate currently available data to begin to assess the loss of forest productivity due to ozone. A definitive assessment cannot be made until the results are available from the large number of current forestry studies. However, groundwork and a preliminary assessment may be made for forests based on available ambient ozone data and current information focusing on the effects of ozone on Jeffrey pine (Pinus jeffreyi) and ponderosa pine (P. ponderosa), two of the most sensitive forest species in California.

A mechanism for the immediate feedback of currently available information would strengthen the research planning process on a state level and may allow for more rigorous research goals and objectives to be established. This data base is necessary to indicate the patterns of pollutant exposures on an hourly, monthly, seasonal, and yearly basis that occur at those sites where susceptible tree species grow in order to assist in planning appropriate ozone exposures for controlled experiments. Most of the data is expected to be for seedling trees, which would at least give an indication of the effects of ozone on productivity of new forests.

Trees which are valuable as lumber growing in more remote areas are evaluated both by maturity and size of resource plus accessibility, i.e., roads and terrain and distance to lumber mills. In the Sierra Nevada where commercial logging is an established industry the above-noted factors would be major considerations. Evaluation of forest losses around the Los Angeles Basin are determined more by esthetics than by economics. Thus, attempts to assign economic or dollar values to growing or mature trees, in or near parks, recreation areas and population centers are difficult. The value of trees in such areas for shade, landscaping enhancement and other esthetic considerations far outweigh the monetary return which could be realized by harvesting.

Educational Materials

An ongoing objective of this project is to present information on the effects of ozone on crop and trees. Past workshops, seminars, and reports have targeted the scientific community. No publication, however, was available which readily present the results from this study to growers, county extension personnel, and the general public. Many such general information requests have been received and the only publications available regarding this project have been sections of the interim reports. Short descriptions of the crop loss results or "fact sheets" are needed for distribution to interested individuals in all areas of the state.

A portable display presenting information on the injury of vegetation from air pollution is an effective means for increasing public awareness. The display would include photographs, text, handouts, and other materials to inform the viewer on the effects of air pollution as well as indicate individuals to contact for more information.

Statement of the Problem

No coordinated effort to evaluate vegetation losses (crops and forest) from air pollutants, especially O_3, in California existed prior to the inception of the ARB Crop Loss Assessment Program. The ARB program has made considerable progress in the assessment of current knowledge and its application to predictive models. However, further efforts are needed to conduct a survey of and to estimate actual yield losses for a variety of crops in the San Joaquin Valley, to develop models that predict ozone effects on forests, to prepare written information accessible to concerned parties statewide, and to further update air quality and crops response data bases.

Objectives for 1989-1990

The objectives were to:

(1) Update all data bases so that the best possible information is available for the assessments.
(2) Revise and update the statewide loss assessments for 1987.
(3) Survey the effects of ozone on crops in the San Joaquin Valley.
(4) Prepare educational information on the air pollution effects on vegetation for use by agricultural experts in the field.
(5) Form relevant data bases and to conduct a preliminary analysis of the effects of O_3 on forest tree seedlings in California.
(6) Prepare reports and educational materials for presentation and distribution of results from this crop loss assessment project.

II. METHODS-CROP LOSS

Survey of Air Pollution Injury to Crops

Three surveys of air pollution injury to crops in the San Joaquin Valley were made between June and September, 1990. An initial survey was conducted in June to determine the stages of development of the various crops of interest. Cotton, almond, grape, alfalfa, tomato, onion, bell peppers, sugar beet, bean and sweet corn were observed. Cotton, Pima and Acala varieties, almond, alfalfa and grape were chosen for the survey. The foliage of these crops was exposed to the chronic levels of ozone that occur during August and September and which cause visible injury symptoms. It was determined that tomato, onion, sugar beet and bean would be harvested in early to mid-July and therefore escaped elevated chronic exposures to ozone.

Established cotton research plots (Dr. T. Kirby, UC Cotton Research Station, Shafter, CA) that were in close proximity to plantings of the other crops of interest were used as a general guideline in site selection. Sites were chosen in geographical areas in the San Joaquin Valley where ozone concentrations were expected to be high (e.g., SE of Bakersfield and SE of Fresno) and comparatively low as in the west side of the valley (e.g. West Side Field Station near Five Points). Evaluations were made in 27 locales at 86 different crop sites (Fig. 1).

Crop Selection. The ozone sensitive crops that were surveyed and their characteristic injury symptoms are listed in Table 1. Leaf injury and abscission in alfalfa, cotton and grape has been shown to be correlated with yield reductions (Thompson and Kats, 1970; Oshima et al., 1976; Kohut and Laurence, 1983; Olszyk et al., 1986). No yield data was available for almond, but reduced vegetative growth was associated with foliar ozone injury (McCool and Musselman, 1990).

Cultivars of Pima cotton ('S-6'), Acala cotton ('SJ-2'), grapes (Thompson seedless), and almonds (Nonpareil) were chosen for the survey based upon susceptibility to ozone injury and frequency of plantings. The cultivar(s) of alfalfa was not known.

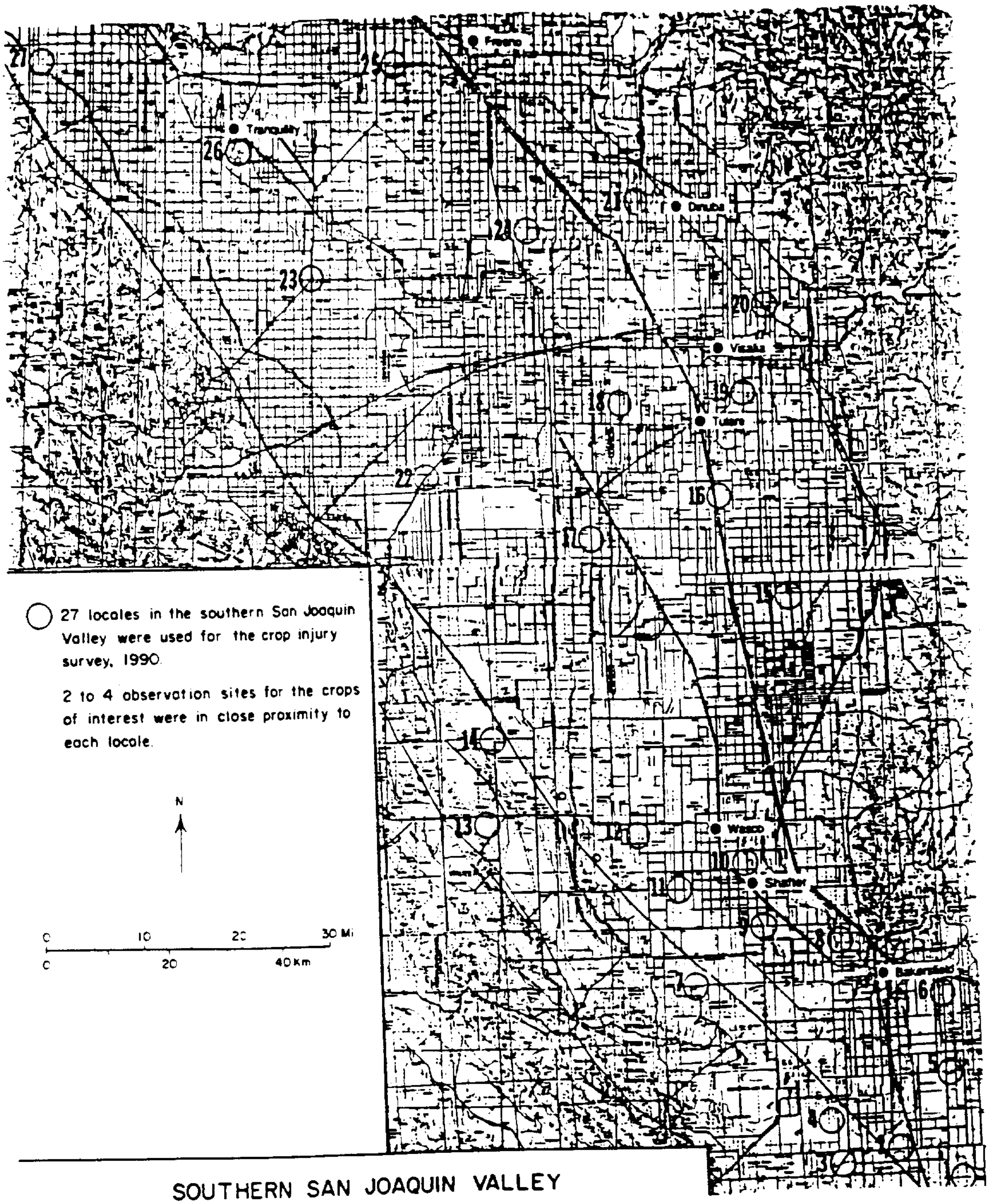

Figure 1. Locales used in the survey of air pollution injury to crops in the the San Joaquin Valley, 1990.

Table 1. Crops evaluated in the field survey and their characteristic foliar ozone injury symptoms

Crop	Injury Symptoms
Alfalfa	White flecking on upper leaf surface and leaf sensecence.
Almond	Leaf chlorosis, senescence and "shot hole" symptom.
Cotton	Interveinal chlorotic mottling.
Grape	Slight leaf stippling and accelerated senescence.

Injury Evaluation. Two surveys were conducted in August and September, 1990. Injury evaluations were based on 0-10 scale where 0 corresponded to 0 percent of the leaves affected (essentially all leaves green and healthy) and 10 corresponded to 100 percent of the leaves injured and/or abscissed. A rating of two, therefore, indicated that 20 percent of the leaves exhibited ozone injury symptoms. A rating of five indicated that 50 percent of the leaves were affected, and so forth. All sites were visited within the 3 day period of each survey. The fraction of senescent and dropped leaves (bare nodes) per plant was determined by a cumulative count and rounded off to the nearest 10 percent increment. The range of injury present in the observation plots is presented in Table B of the appendix.

In cotton, four representative plants were chosen, each from a different row, starting 5 m from the road. Each plant was rated by estimating the fraction leaf injury on the main and all side branches.

Four complete grape canes were selected from four different rows, starting three rows from the road. A count was made of leaves dropped and leaves with senescent symptoms. Injury ratings per plant were expressed as a fraction of the number of leaves missing or injured over the total number of leaves on the cane. Since no unique ozone symptoms occur on Thompson seedless grapes at ambient ozone concentrations, senescence was the only criterion used.

Almond groves were selected that had trees with young growth of branches a least 30 cm long. Four trees per grove were selected in different rows beginning three rows from the road. The fraction of senescent and dropped leaves was determined by a cumulative count on three branches on each of the four trees.

Four alfalfa plants were chosen that were 5 m apart starting 5 m from the road. The fraction of senescent and dropped leaves was determined by a cumulative count on three stems per plant. Only mature plants will exhibit overt ozone injury symptoms. Since alfalfa is harvested every three to four weeks, one or more smog episodes would have to occur during the period between harvests for visible symptoms to be apparent.

Injury Illustration. Photographs of visible symptoms characteristic of ozone injury were taken of plants growing in "high" and "low" ozone locales. Comparable procedures with similar leaf arrangements and lighting were used for all photographs.

Statistical Analyses of Injury Evaluations. Injury ratings were analyzed using a one-way analysis of variance and the mean values were statistically separated using a protected LSD.

Presentation of the Effects of Ozone on Crop Plants

Photographs from the 1989 field survey, numerical data from the 1988 crop yield loss assessment, and photographs of demonstration plants were used to prepare a packet of information or "fact sheets" that describe the effects of ozone on crops. The sheets focused on several vegetable crops, and a few fruit crops. The text was prepared so that growers could easily comprehend the significance of air pollutant effects on crops. The information was mailed in the fall of 1990 to the ARB.

The portable display included photographs and text which would inform the viewer regarding the effects of air pollution. The display fits an area slightly smaller than a standard 1.2 m x 2.4 m (4 x 8 foot) poster board, similar to that used at scientific meetings. Graphics were provided by Media resources, University of California, Riverside.

Revise and Update Assessments

Assessments were made of potential crop losses from O_3 to California crops during 1987 and 1988. Computer tapes containing hourly O_3 data for all sites in the State were obtained from the Aerometrics Division of the ARB. Crop data for 1987 and 1988 were obtained from the CDFA, and entered manually into a computer data base. Each county air monitoring site and crop growing season data was evaluated and revised as necessary based on changes from 1986. Crop losses for 1987 were calculated based on all available O_3 concentration-crop yield loss equations as described below. The numerical data bases for O_3 data and crop data were updated. No new crop loss equations were available. Literature data covering plant biochemical, physiological, growth, and yield responses to O_3 also was updated. The time period of from 0900 to 1600 PST was used for seven-hour loss equations, and 0800 to 2000 PST for 12-hour loss equations.

Background Ozone Concentrations. The predicted yield losses were calculated using 2.72 and 2.50 pphm ozone for the 7 and 12 h base ozone concentrations respectively. The 7 h base concentrations was calculated using the following equation: 7 h = (12 h - 0.004143) x 0.919, where n = 1002 and r = -0.9586 (as for 1984, 1985 and 1986). It was recognized that a base ozone concentration of 2.72 pphm differs from the 2.50 pphm used in National Crop Loss Assessment Network (NCLAN) assessments (Heck et al., 1984a,b). Additional computer analysis, however, revealed that the 0.22 pphm difference in base concentrations had less impact on the predicted yield loss than other factors, such as greater geographical resolution used in the analysis. A growing season average 12 h base concentration of 2.50 pphm ozone was previously used by the NCLAN researchers (Heck et al. 1982, 1983 and 1984a,b), and it represents relatively clean air production zones in California.

For potato, a 10 h base ozone concentration of 2.59 pphm was used. The value was calculated by extrapolating between 2.50 and 2.72 pphm using the equation: 2.50 + [0.40 x (2.72 - 2.50)].

Ozone Concentration-Yield Loss Equations. No new equations were used for the 1987 and 1988 versus the 1986 assessment. All of the equations used are indicated by a "+" in the following summary. Single equations suggested for the in-depth revised assessment and future economic analysis are indicated by a "*". Wherever possible, equations have the same number as in the previous assessments. Up to eight equations are listed for each species. An explanation of terms and percent yield loss calculations are presented in Table 2.

Alfalfa Hay

Equation #1

$$I = [32.67 - (1.3902 \times 12\ hr)]/[32.67 - (1.3902 \times Base12)]$$

The equation was based on Olszyk et al. (1986a).

Equation #2

$$I = [100 - (9.258 \times 10^{-3} \times 10\ pphm)] \times 0.01$$

The equation was based on McCool et al. (1986).

Equation #3

+ $I = [118.96 - (4.088 \times 12\ hr)]/[118.96 - (4.088 \times Base12)]$

The equation was based on Brewer (1982).

Equation #4

*,+ $I = [3160 - Base\ yr. - (109.63 \times 12\ hr)]/[3160 - Base\ yr. - (109.63 \times Base12)]$

This equation is based on Temple et al. (1987), and is adapted from an original equation which considered ozone, water stress, and year of the study. All of California was considered to be under well-watered (non-water stress) conditions for this analysis so the water stress term was omitted. For year, Base yr. = 21 for 1984, and 0 for 1985. This equation and not #3 is now used for the assessment as the data have been accepted

Table 2. Calculation of crop loss percentages due to ozone exposures

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- Sample O_3 Exposure Crop Yield Equation (Linear)

  (1) Yield = a + (b x Ozone exposure)

  where the ozone exposure is a 12-hour (12-hr) or 7-hour (7-hr) growing season average, or hours x pphm for pphm >10 (10 pphm). The 10 pphm equations give percent yield reduction directly.

- Sample County Yield Loss Index Equation

  (2) $I = \frac{a + bx}{a + bx'}$

  where I = loss index as a fraction of 1.00 = no loss; x = ambient air ozone dose or trial ozone standard; and x′ = a 'base' or background dose, e.g., 2.5 pphm seasonal average for 12 hour equations or 2.72 pphm seasonal average for 7 hour equations, or 2.59 for 10 hour equations.

- Sample County Percent Yield Loss Equation

  (3) Percent Loss = (1.00 - I) x 100

- Sample County Potential Yield Equation

  (4) $\text{Potential Yield} = \frac{\text{Actual Yield}}{I}$

- Sample Statewide Potential Yield Equation

  (5) $\text{Statewide Potential Yield Index} = \frac{\Sigma \text{ Actual Yields}}{\Sigma \text{ Potential Yields}}$

  where actual yields are for all counties in the State where the crop is grown.

- Sample Statewide Percent Yield Loss Equation

  (6) Statewide Percent Loss = (1.00 - Statewide Potential Yield Index) x 100

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for publication and should appear shortly. This equation also is preferable as it is based on NCLAN research with multiple ozone concentrations, and not just a few concentrations as for equation #3.

Alfalfa Seed

* Equation #4 for alfalfa hay was used

Barley

Equation #1

* I = 0. Seven-hour equation was based on Temple et al. (1985b).

Beans-Dry

Equation #1

$$I = [100 - (0.024 \times 10 \text{ pphm}) \times 0.01$$

The equation was based on McCool et al. (1986).

Equation #2

$$I = [2878 \times e^{-(7hr/12.0)^{1.171}}]/[2878 \times e^{-(Base7/12.0)^{1.171}}]$$

The equation was based on Heck et al. (1984b), and Kohut et al. (1983).

* Equations #3-#6 were for four different cultivars of dry beans which were exposed to three concentrations of ozone at Riverside in the summer of 1987 (P. Temple, UC Riverside, personal communication). The losses for the four cultivars were averaged to determine the statewide yield loss for dry beans in 1986. The ozone data for all four cultivars was collected in Pacific Daylight Time (PDT), therefore a separate analysis had to be conducted using PDT hourly ozone data for the sites where beans were grown.

Equation #3

$$I = [25.2 + (20.147 \times 12\ hr) - (1.8011 \times 12\ hr^2)] / [25.2 + (20.147 \times Base12) - (1.8011 \times Base12^2)$$

The equation was for the cultivar 'Linden Red Kidney'.

Equation # 4

$$I = [163.6 - (9.787 \times 12\ hr)] / [163.6 - (9.787 \times Base12)]$$

The equation was for the cultivar 'Sal Small White'.

Equation #5

$$I = [165.8 - (13.57 \times 12\ hr)]/[165.8 - (13.57 \times Base12)]$$

The equation was for the cultivar 'Sutter Pink'.

Equation #6

$$I = [167.6 - (13.98 \times 12\ hr)]/[167.6 - 13.98 \times Base12)]$$

The equation was for the cultivar 'Yolano Pink'.

Broccoli

* Equations #1-#4 were for four different cultivars of broccoli which were exposed to three concentrations of ozone at Riverside in the winter of 1987-88. (P. Temple, UC Riverside, personal communication). The only cultivar which had any change with ozone exposures was for equation one, the other three cultivars gave no changes. However, even equation #1 the change was an increase in yield and not a yield loss where broccoli is grown. Thus, the statewide yield loss for broccoli in 1986 was assumed to be zero. The ozone data for all four cultivars was collected in Pacific Daylight Time (PDT), therefore a separate analysis had to be conducted using PDT hourly ozone data for the sites where broccoli is grown.

Equation #1

$$I = [2199 + (187.58 \times 12\ hr)]/[2199 + (187.58 \times Base\ 12)]$$

The equation was for the cultivar 'Green Belt'.

Equations #2-#4

$$I = 0$$

The equation was the same for the cultivars 'Green Duke', 'Commander', and 'Emperor'.

Celery

Equation #1

$$* \ I = 0.$$

The 12-hour equation is based on Takemoto et al. (1987).

Corn-Field

Equation #1

$$* \ I = [11618.5 \times e^{-(7hr/16.0)^{3.709}}]/[11618.5 \times e^{-(Base7/16.0)^{3.709}}]$$

The equation was based on Kress and Miller (1985b).

Corn-Silage

Equation #1

$$* \ I = [11618.5 \times e^{-(7hr/16.0)^{3.709}}]/[11618.5 \times e^{-(Base7/16.0)^{3.709}}]$$

The equation was the field corn equation of Kress and Miller (1985b).

Corn-Sweet

Equation #1

*,+ $I = [315.02 - (12\ hr \times 8.2988)]/[315.02 - (Base12 \times 8.2988)]$

The equation was based on Thompson et al. (1976).

Cotton

Equation #1

$$I = [367 \times e^{-(7\ hr/11.1)^{2.71}}]/[367 \times e^{-(Base7/11.1)^{2.71}}]$$

The equation was based on Heagle et al. (1986).

Equation #2

$$I = [0.8462 + (0.049 \times 7\ hr)]/[0.8462 + (0.049 \times Base7)]$$

The equation was based on Brewer et al. (1985).

Equation #3

* $I = [2059 - (82 \times 7\ hr)]/[2059 - (82 \times Base7)]$

The equation was based on Temple et al. (1985c).

Equation #4

$$I = [1988 - (1545.32 \times 7\ hr^2)]/[1988 - (1545.32 \times Base7^2)]$$

The equation was for a cool, moist year as described by Temple et al. (1985c).

Equations #5-#8 were for four different cultivars of cotton which were exposed to three concentrations of ozone at Riverside in the summer of 1987 (P. Temple, UC Riverside, personal communication). The data were not used for the crop loss assessment for cotton because equation #3 was based on data collected in the San Joaquin Valley using many more ozone concentrations. The ozone data for all four cultivars was collected in Pacific Daylight Time (PDT), therefore a separate analysis had to be conducted using PDT hourly ozone data for the sites where cotton is grown.

Equation #5

$$I = [32.3 - (2.025 \times 12\ hr)]/[32.3 - (2.025 \times Base12)]$$

The equation was for the cultivar 'C1'.

Equation #6

$$I = [38.6 - (2.663 \times 12\ hr)]/[38.6 - (2.663 \times Base12)]$$

The equation was for the cultivar 'GC 510'.

Equation #7

$$I = [25.4 + (8.833 \times 12\ hr) - (1.0528 \times 12\ hr^2)]/ (25.4 + (8.833 \times Base12) - (1.0528 \times Base12^2)]$$

The equation was for the cultivar 'SJ2'.

Equation #8

$$I = [32.6 + (3.535 \times 12\ hr) - (0.6721 \times 12\ hr^2)]/ (32.6 + (3.535 \times Base12) - (0.6721 \times Base12^2)]$$

The equation was for the cultivar 'SS2086'.

Grain Sorghum

Equation #1

$$* \quad I = [8149 \times e^{-(7\ hr/31.7)^{2.952}}]/[8149 \times e^{-(Base7/31.7)^{2.952}}]$$

The equation was based on Kress and Miller (1985a).

Grapes

Equation #1

$$+\ I = [9315 - (12\ hr \times 647)]/[9315 - (Base12 \times 647)]$$

The equation was based on Thompson and Kats (1970).

Equation #2

$$*,+\ I = [1.121 - (0.0663 \times 12\ hr)]/[1.121 - (0.0663 \times Base12)]$$

The equation was based on Brewer (1983) and Brewer (unpublished data).

Green Pepper

Equation #1

$$*,+\ I = 0$$

The equation was based on Takemoto et al. (1987). It is not used for the assessment as green peppers are not a separate crop in the CAR model.

Lemons

Equation #1

$$*,+\ I = [[-[0.5004 + (0.6224/12\ hr)]/[0.5004 + (0.6224/Base\ 12)] + 1] \times -.5] + 1$$

The equation was based on Thompson and Taylor (1969) assuming that lemon trees cycled between "on" and "off" years comparable to oranges. Ozone was assumed to have no effect on lemons during "off" years. The ozone data were for two years before the harvest year, i.e. 1984.

Lettuce

Equation #1

$$I = 0$$

The 12-hour equation was based on Olszyk et al. (1986b).

Equation #2

$$I = [100 - (5.19 \times 10^{-2} \times 10\ \text{pphm})] \times 0.01$$

The equation was based on McCool et al. (1986).

Equation #3

$$* \quad I = [3187 \times e^{-(7\ \text{hr}/12.2)^{8.837}}]/[3187 \times e^{-(\text{Base7}/12.2)^{8.837}}]$$

The equation was based on Temple et al. (1986).

Equation #4

$$I = 0.$$

The 12-hour equation was calculated by P. M. McCool, UC Riverside (personal communication).

Equations #5-#8

Equations #5-#8 were for four different cultivars of lettuce which were exposed to three concentrations of ozone at Riverside in the winter of 1987-88 (P. Temple, personal communication). There was no loss for any of the four cultivars. The data were not used for the crop loss assessment for lettuce because equation #3 was based on data collected in the San Joaquin Valley using many more ozone concentrations. The ozone data for all four cultivars was collected in Pacific Daylight Time (PDT), therefore a separate analysis had to be conducted using PDT hourly ozone data for the sites where lettuce is grown.

$$I = 0.$$

The equation was the same for cultivars Dark Green, Prizehead, Parris Island Cos, and Royal Green.

Melons (Cantaloupes, Honeydew, Watermelon)

* I = [35.8 - (2.808 x 7 hr]/[35.8 - (2.808 x Base7)]

The equation was calculated from data shown in Snyder et al. (1988). Data were for muskmelon and not specifically for cantaloupes, honeydew melons, or watermelons. The equation, however, was used for those species as it is the only one available. Ozone concentrations were calculated for 0900-1600 CST from figures in the paper and yield data came from the text. Ozone concentrations and yields during the study, respectively in 1986, were 1.35 pphm and 31.3 kg/chamber for charcoal-filtered air; and 3.65 pphm and 24.9 kg for nonfiltered air. Ozone concentrations and yields, respectively in 1987, were 3.2 pphm and 28.9 kg for charcoal-filtered air; and 4.4 pphm and 22.6 kg for nonfiltered air. A linear regression equation was calculated from these for ozone concentration (x) and yield (y) data points.

Onions

Equation #1

I = [11.1 - (0.881 x 12 hr)]/[11.1 - (0.881 x Base12)]

The equation was based on McCool et al. (1986), and McCool (personal communication).

* Equations #2-#5 were for four different cultivars of onions which were exposed to three concentrations of ozone at Riverside in the winter of 1987-88. (P. Temple, personal communication). The only cultivar which had any change with ozone exposures was for equation #2, the other three cultivars gave no changes. Thus, the statewide yield loss for onions in 1986 was assumed to be the average of the losses for the four cultivars. The ozone data for all four cultivars was collected in Pacific Daylight

Time (PDT), therefore a separate analysis had to be conducted using PDT hourly ozone data for the sites where onions are grown.

Equation #2

$$I = [5034 - (109.41 \times 12 \text{ hr})]/[5034 - (109.41 \times \text{Base } 12)]$$

The equation was for the cultivar 'Rio Bravo'.

Equations #3-#5

$$I = 0$$

There equation was the same for the cultivars 'Nu Mex', 'Colossal', and 'Rio Hondo'.

Oranges

Equation #1

$$I = [53.7 - (12 \text{ hr} \times 2.611)]/[53.7 - (\text{Base12} \times 2.611)]$$

The equation was based on Olszyk (1989).

Equation #2

$$I = [178.0 - (12 \text{ hr} \times 19.1280)]/[178.0 - (\text{Base12} \times 19.1280)]$$

The equation after Thompson and Taylor (1969).

Equation #3

$$* + I = [[-[53.7 - (12 \text{ hr} \times 2.611)]/[53.7 - (\text{Base12} \times 2.611)] + 1] \times -.5] + 1$$

The equation was based on Kats et al. (1985b) and Olszyk (1989). The ozone data were for two years before the harvest year, i.e. 1984.

Potatoes

Equation #1 (Appendices D-1 through D-4)

$$+ \quad I = 0$$

The data from Foster et al. (1983) is not applicable on a statewide basis as described in Thompson and Olszyk (1986).

Equation #2 (Appendix D-5).

$$* \; I = [11736 - (390 \times 10\ hr)] \; / \; [11736 - (390 \times Base\ 10)]$$

The equation from Pell et al. (1988) relates ozone concentration to total weight of harvested tubers. The cultivar was "Norchip." The equation was based upon plants growing in charcoal-filtered (CF) air, nonfiltered (NF) air, NF plus 33% of ambient ozone, NF air plus 66% of ambient ozone, and NF plus 99% of ambient ozone; which resulted in growing season average ozone concentrations of 2.4, 4.8, 6.7, 8.5, and 10.0 pphm. Unfortunately, the ozone data were based on 1000-2000 EDT daylight hours. Therefore, a small separate run will be made to determine 10-hour averages for counties where potatoes are grown in California and the losses will be calculated by hand using a background ozone concentration of between 2.59 pphm for 12 hours and 2.72 pphm for seven hours.

Equation #2 (Appendix D-5).

$$I = [5848 - (347.6 \times 10\ hr)] \; / \; [5848 - (347.6 \times Base\ 10)]$$

The equation, also from Pell et al. (1988) is for Grade One tubers, the highest grade for commercial production.

Rice

Equation #1

$$+ \quad I = [1.0851 \times e^{-(7\ hr \times 0.0275)}]/[1.0851 \times e^{-(Base7 \times 0.0275)}]$$

The seven-hour equation was recalculated using the treatment mean data of Kats et al. (1985a). This exponential equation had a slightly higher correlation coefficient than the linear equation. The exponential equation was used for the preliminary assessment.

Equation #2

$$+ \quad I = [1.0687 - (0.024 \times 7\ \text{hour})]/[1.0687 - (0.024 \times \text{Base7})]$$

The equation was recalculated on a linear basis using the revised seven-hour values as described for equation 1.

Equation #3

$$*,+ \quad I = [e^{-(7\ \text{hr}/20.16)^{2.474}}]/[e^{-(\text{Base7}/20.16)^{2.474}}]$$

This equation was calculated by Dr. David Glyer of the Department of Agricultural and Resource Economics from raw data described in general in the paper by Kats et al. (1985a). The Weibull function equation was calculated for use in the NCLAN national assessment and will be used in the revised assessments so that the results are comparable to NCLAN's. The equation is based on individual pot data for all three cultivars. A value of 2.5 pphm was assumed for the two out of seven hours when ozone was not added during weekdays, and both weekend days.

Spinach

Equation #1

$$I = [100 - (4.006 \times 10^{-2} \times 10\ \text{pphm})] \times 0.01$$

The equation was based on McCool et al. (1986).

Equation #2

$$* \quad I = [1.199 - (7\ \text{hr} \times 0.0625)]/[1.199 - (\text{Base7} \times 0.0625)]$$

The equation was based on Heagle et al. (1979).

Strawberries

Equation #1

$$* \; I = 0$$

The 10 pphm equation was based on McCool et al. (1986).

Sugar Beets

Equation #1

$$I = 0$$

The 10 pphm equation was based on McCool et al. (1986).

Equation #2

$$* \; I = 0$$

The 12-hour equation was based on Brewer (1978).

Equation #3

$$I = [64.7 - (2.58 \times 12 \text{ hr})]/[64.7 - (2.58 \times \text{Base12})]$$

The equation (#3) was for red table beets based on McCool et al. (1986). It is included only for comparison purposes and not to represent the effects of ozone on sugar beets. However, the equation could represent table beets in the specialized localities where they are grown.

Tomatoes-Fresh Market

Equation #1

$$* \; I = [100 - (2.32 \times 10^{-2} \times 10 \text{ pphm})] \times 0.01$$

The equation was based on McCool et al. (1986).

Tomatoes-Processing

Equation #1

$$I = [100 - (2.28 \times 10^{-2} \times 10 \text{ pphm})] \times 0.0^{\cdot}$$

The equation was based on McCool et al. (1986).

Equation #2

$$* \; I = [32.9 \times e^{-(7hr/14.2)^{3.807}}]/[32.9 \times e^{-(Base7/14.2)^{3.807}}]$$

The equation was based on Heck et al. (1984b) and Temple et al. (1985a).

Equations #4-#7 were for four different cultivars of tomatoes which were exposed to three concentrations of ozone at Riverside in the summer of 1987 (P. Temple, UC Riverside, personal communication). The data were not used for the crop loss assessment for tomatoes because equation #2 was based on data collected in the San Joaquin Valley using many more ozone concentrations. The ozone data for all four cultivars was collected in Pacific Daylight Time (PDT), therefore a separate analysis had to be conducted using PDT hourly ozone data for the sites where tomatoes are grown.

Equation #3

$$+ \; I = [731 - (43.844 \times 12hr)]/BaseT$$

The equation was based on a personal communication from R. Brewer. The base represents the yield at 4.31 pphm ozone. Any ozone concentration below this would have a negative (actually zero) loss. The common base is 542.

Equation #4

$$I = [9055 - (323.67 \times 12\ hr)]/[9055 - (323.67 \times Base12)]$$

The equation was for the cultivar 'FM783'.

Equation #5

$$I = [6119 + (1269.1 \times 12\ hr) - (135.6707 \times 12\ hr^2)]/ (6119 + (1269.1 \times Base12) - (135.6707 \times Base\ 12^2)$$

The equation was for the cultivar 'Hybrid 31'.

Equation #6

$$I = [6315 - (210.7 \times 12\ hr)]/[6315 - (210.7 \times Base12)]$$

The equation was for the cultivar 'UC204C'.

Equation #7

$$I = [8590 - (412.8 \times 12\ hr)]/[8590 - (412.8 \times Base12)]$$

The equation was for the cultivar 'E6203'.

Turnip

Equation #1

$$I = [155.5 - (10.26 \times 12\ hr)]/[155.5-(10.26 \times Base12)]$$

This equation was recalculated by P. M. McCool based on the original data described in McCool et al. (1986). It is not used for the assessment as turnips are not a separate crop in the CAR model.

Wheat

Equation #1

$$I = 0$$

The 12-hour equation is based on Olszyk et al. (1986b).

Equation #2

$$* \ I = [5295 \times e^{-(7\ hr/14.5)^{3.326}}]/[5295 \times e^{-(Base7/14.5)^{3.326}}]$$

The equation was based on Kress et al. (1985).

Equation #3

$$I = [7857 \times e^{-(7\ hr/5.3)^{1.000}}]/[7857 \times e^{-(Base7/5.3)^{1.000}}]$$

The equation was based on Heck et al. (1984b).

Calculation of Ozone Exposure-Crop Loss Percentages. The same formulas described in the 1980 assessment also were used in the current assessments (Thompson and Olszyk, 1986). A number of assumptions were made for each crop in order to use the dose-response equations for statewide crop loss assessments. These assumptions were based on information in the crop and air quality data bases, along with discussions with research scientists, county farm advisors, and recommendations from the 1985, 1986, 1987, 1988, and 1989 workshops. The equations give data for the county yield loss indexes (I). The indexes are then converted to % loss by equation (3) of Table 2. The equations include ozone concentrations in three forms: 12-hour (0800-2000) growing season averages (12 hr), 7-hour (0900-1700) growing season averages (7 hr), and hours x pphm > 10 pphm for the growing season (10 pphm). The loss index for potatoes was calculated by hand using a 10-hour (0900-1900 PST) equation. One ozone value for an entire county was used, which may represent the average concentration over several sites where the crop was grown. Concentrations of ozone used to estimate crop loss in the west sides of Fresno and Kings counties were lower as compared to the concentrations used in the east side of the same counties. Ozone concentrations were based on air monitoring data for Five Points (westside) and the Fresno area (eastside) as discussed in the 1989 vegetation loss report.

III. RESULTS AND DISCUSSION-CROP LOSS

A. Survey of Air Pollution Injury to Crops in the San Joaquin Valley

The alfalfa grown only in the extreme southern end of the San Joaquin Valley showed visible signs of ozone injury (Table 3). Although the foliar injury observed at locale 5B was greater than that at all other locales, the injury was minimal. Adequate field evaluation of alfalfa was limited because it was harvested every three to four weeks. Overt injury occurred if the plants experienced one or more smog episodes during the period between harvests. Different cultural practices in combination with contrasting environments resulted in shifts in harvest schedules which prohibited the comparison between the same two fields at different times of the growing season. The leaf injury gradients (Fig. 2) indicated that foliar injury of alfalfa was more pronounced south of Bakersfield, but the intensity of the injury may be underestimated due to the complications associated with the survey.

Ozone associated foliar lesions in almond were the most severe around Arvin in the southern Central Valley and diminished northward (Table 4). Greater than 60 percent of the total leaf surface was affected in representative trees in this area. Orchards in Kern County showed the largest degree of leaf injury (Fig. 3). Almond trees from Kings and Tulare counties northward exhibited only minor ozone injury symptoms. Small interveinal chlorotic spots were associated with ozone injury on almond leaves (Fig. 4). Careful observation was needed to differentiate between ozone and mite injury, particularly during the latter part of the growing season when mites were the most active. The leaf injury gradients demonstrated the degree to which air pollutants concentrate in the southern end of the valley. Ozone injury of almond was associated with reduced vegetative growth (McCool and Musselman, 1990), yet it remains undetermined whether yield is also adversely affected.

For both Acala and Pima cotton significant differences in the levels of ozone injury existed between the northern and southern portions of the valley (Tables 5 and 6). Ozone leaf injury symptoms in both cotton types (Figs. 5 and 6) showed a distribution similar to that of almonds (Fig. 3). Substantial leaf injury was observed in southern Kings and Tulare counties and throughout Kern county. Figures 7 and 8 illustrate ozone

Table 3. Mean ozone leaf injury ratings for alfalfa and analysis of variance in the San Joaquin Valley, 1990. 0 = no visible injury, 10 = complete chlorosis and/or abscission

Locale		Mean	SD
5B	On Wheeler Ridge Rd. near corner of Bear Mt. Blvd.	1.3	1.0
20	N of Bakersfield on Calloway Rd.	0.5	0.6
11	NW of Bakersfield on 7th STD R. near Zachary Rd.	0.5	0.6
18	W of Shafter on Lerdo Hwy near Scofield Ave.	0.3	0.5
12	N of Hwy 46 on Scofield Ave.	0.3	0.5
16	Near Tipton on Ave. 152	0.3	0.5
5	W of Tulare on Rd. 28	0.0	0.0
8	N of Visalia on Hwy 63 near Ave. 352	0.0	0.0
24C	N of Riverdale on Elkhorn near Elm Ave.	0.0	0.0
9	Near Kerman on Whites Bride near Howard Ave.	0.0	0.0
26C	Near Mondota on Bass Rd.	0.0	0.0
28	Near Three Rocks on Hwy 33 and Kamm Ave.	0.0	0.0

Source	DF	SS	MS	F
Treatment	11	6.000	0.545	2.805
Error	36	7.000	0.194	
Total	47	13.000		

LSD = 0.6

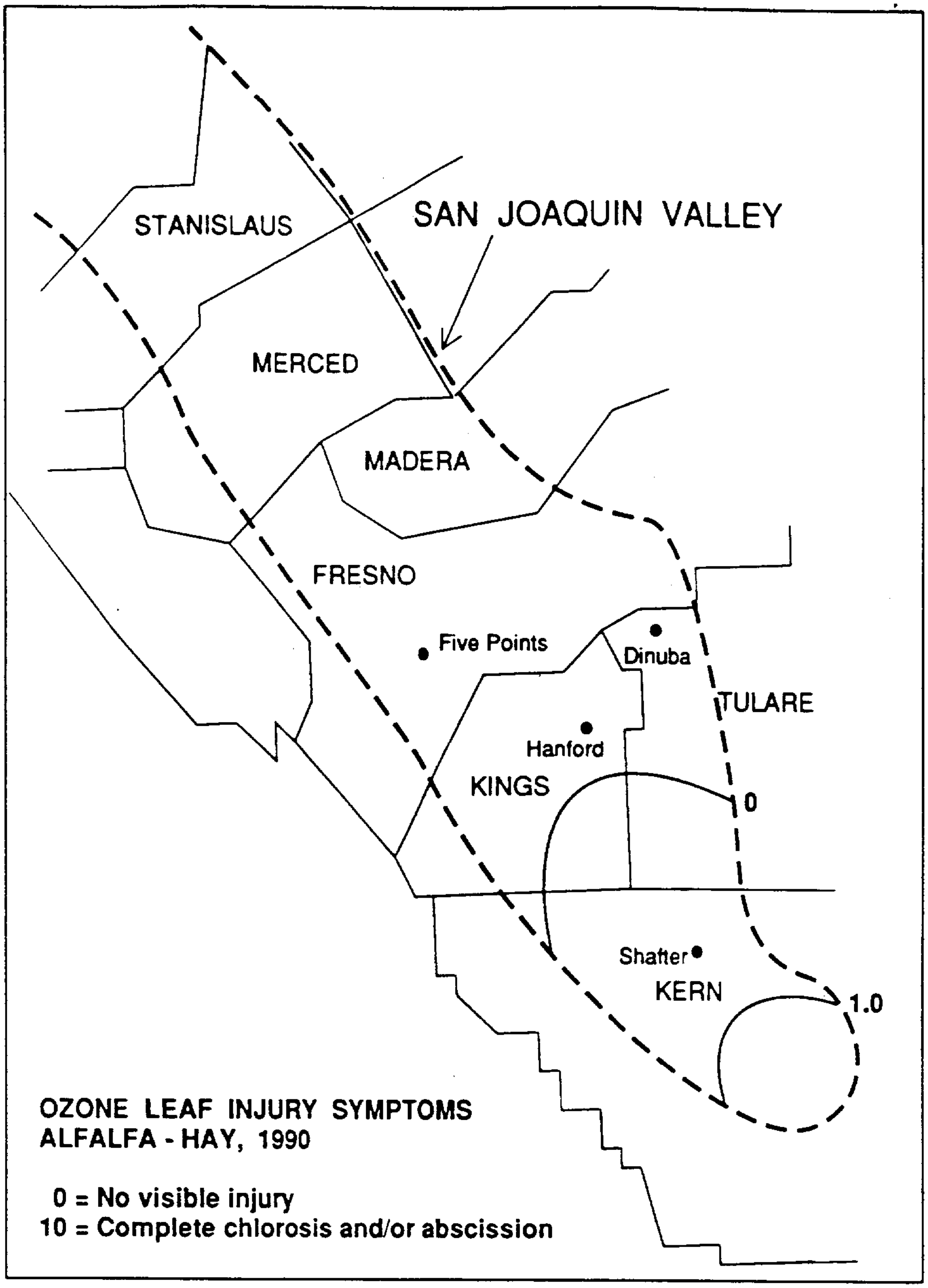

Figure 2. Distribution of ozone leaf injury symptoms in alfalfa in the San Joaquin Valley, 1990.

Table 4. Mean ozone leaf injury ratings for almonds and analysis of variance in the San Joaquin Valley, 1990. 0 = no visible injury, 10 = complete chlorosis and/or abscission

Locale		Mean	SD
8A	S of Arvin on Wheeler Ridge Rd. near Sebastian Rd.	6.5	1.3
7	S of Hwy 58 on Wheeler Ridge R. near Hermosa Rd.	4.3	1.0
11	SE of Buttonwillow on Stockdale Hwy near Morris Rd.	3.8	1.0
8	N of Bakersfield on Calloway Rd.	3.5	1.3
10B	N of Bakersfield on Reina Rd.	3.3	0.5
25A	N of Shafter on Shafter Ave.	3.0	1.4
19	On Lerdo Hwy W of Hwy 99	2.8	0.5
6	W of Shafter on Lerdo Hwy on Scaroni Ave.	2.8	1.3
25C	W of Wasco on Jackson Ave. and Rowlee Rd.	2.3	1.7
24A	E of Tulare on Rd. 140 near Ave. 256	2.0	0.8
20	N of Visalia on J 15 near Ave. 352	1.5	0.6
1	Near Five Points at West Side Field Station	1.5	1.3
12	E of Selma on Fowler Ave. near Conejo Ave.	1.3	1.0
10A	N of Riverdale on Elkhorn near Hwy 41	1.3	1.3
23	W of Fresno on Whites Bridge Rd. near Hayes Ave.	0.5	0.6
26A	Near Kerman on Whites Bridge Rd. near Floyd Ave.	0.5	0.6
26C	W of Kerman on Whites Bridge Rd. and Shasta Ave.	0.5	0.6
24B	Near Mondota on Bass Rd.	0.3	0.5

Source	DF	SS	MS	F
Treatment	17	177.125	10.419	10.092
Error	54	55.760	1.032	
Total	71	232.875		

LSD = 1.4

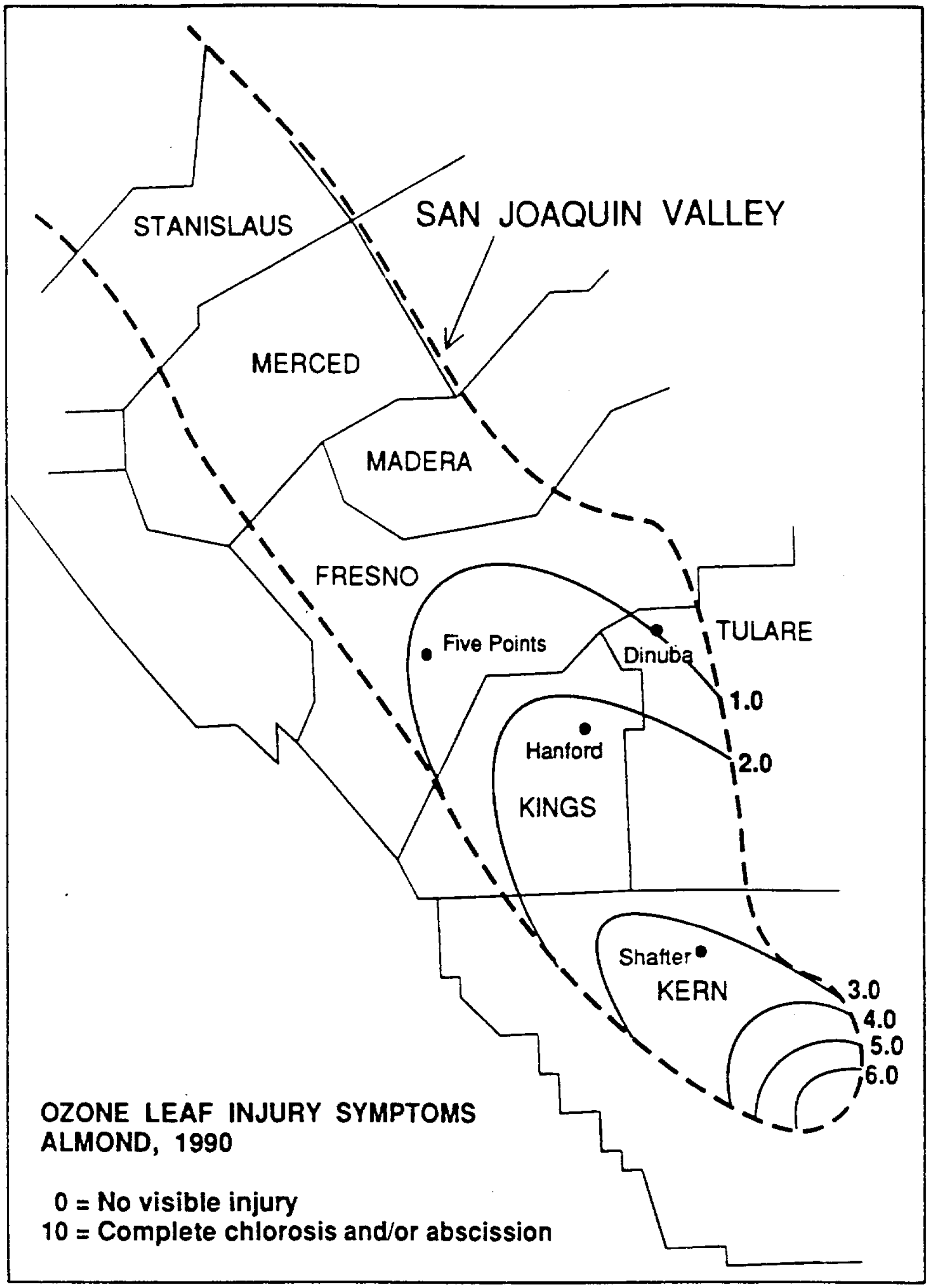

Figure 3. Distribution of ozone leaf injury symptoms in almond in the San Joaquin Valley, 1990.

Figure 4. Ozone injury symptoms on almond leaves.

Table 5. Mean ozone leaf injury ratings for Acala cotton and analysis of variance in the San Joaquin Valley, 1990. 0 = no visible injury, 10 = complete chlorosis and/or abscission

Locale		Mean	SD
1	S of Arvin on Sebastian Rd.	6.5	0.6
2	On Copus Rd. E of Hwy 99	6.3	1.7
4	Off Old River Rd., S of Copus Rd.	5.8	1.0
3	On Old River Rd., near Herring Rd.	5.3	0.5
5	W of Arvin on Wheeler Ridge Rd., near Sunset Blvd.	5.0	0.8
8	N of Bakersfield on Calloway Rd.	4.8	0.5
12	NW of Bakersfield on Snow Rd., near Enos Ln.	4.5	0.6
9	Near Shafter at Cotton Research Station	4.0	0.0
25	W of Shafter on Lerdo and Scofield	4.0	0.8
17	W of Wasco on Gun Club Rd., near Jackson	3.8	0.5
15	SW of Lost Hills near Brown Material Rd. & Hwy 33	3.5	0.6
10	N of Lost Hills near Twisselman Rd. & I-5	3.3	1.0
11	Near Tipton on J 26	3.0	0.8
24	Near Corcoran on Quail Ave.	2.8	1.0
22	NE of Kettleman City near Hwy 41 & Omaha Ave.	2.5	0.6
13	Near Five Points at West Side Field Station	2.0	0.8
14	W of Selma on Elkhorn Ave. & Fowler Ave.	1.5	0.6
23	W of Fresno on Whites Bridge Rd., Near Fowler Rd.	1.5	0.6
26C	W San Joaquin on San Mateo Ave.	1.3	0.5
26	Near Mendota on Bass Rd.	1.0	0.8
27	W of Firebaugh near I-5 on Russell Ave.	1.0	0.8

Source	DF	SS	MS	F
Treatment	20	238.952	11.948	19.808
Error	63	38.000	0.603	
Total	83	276.952		

LSD = 1.1

Table 6. Mean ozone leaf injury ratings for Pima cotton and analysis of variance in the San Joaquin Valley, 1990. 0 = no visible injury, 10 = complete chlorosis and/or abscission

Locale		Mean	SD
1	S of Arvin on Sebastian Rd.	7.3	1.0
8A	Off Old River Rd., S of Copus Rd.	7.3	1.0
3	2 miles N of Copus Rd. W of Old River Rd.	6.5	0.6
4	SE of Buttonwillow on Adohr	5.5	1.3
9	N of Bakersfield on Reina Rd.	5.0	0.8
7	NW of Bakersfield on Snow Rd., near Enos Ln.	4.8	0.5
10	Near Shafter at Cotton Research Station	4.8	0.5
15	W of Wasco on Gun Club Rd., near Jackson Ave.	4.8	0.5
20	SW of Lost Hills near Brown Material Rd. & Hwy 33	4.3	0.5
16	N of Lost Hills near Twisselman Rd. & I-5	3.5	0.6
12	E of Pizley near Rd. 176 and Ave. 88	3.3	0.5
23	Near Tipton at Intersection of Rd. 120 and Ave. 152	3.3	0.5
17	Near Corcoran on Quail Ave.	3.0	0.8
18	W of Tulare on Ave. 248 and Rd. 28	2.8	0.5
22	N of Ivanhoe, near Ave. 360 and Rd. 28	2.5	0.6
14	Near Huron on Palmer Ave.	1.8	1.0
13	Near Five Points at West Side Field Station	1.8	0.5
26A	W of Kerman on James Rd, N of Whites Bridge rd.	1.8	1.0
26B	Near Tranquility on Adams Ave. and Contra Costa Ave.	1.8	0.5
26C	Near Mendota on Bass Rd. and Kings Mendota Canal	1.5	0.6
27	Near I-5 on Russell Ave.	1.3	0.5
28	Near Three Rocks on Hwy 33 and Clarkson	1.3	0.5

Source	DF	SS	MS	F
Treatment	21	306.830	14.611	29.901
Error	66	32.250	0.489	
Total	87	339.080		

LSD = 1.0

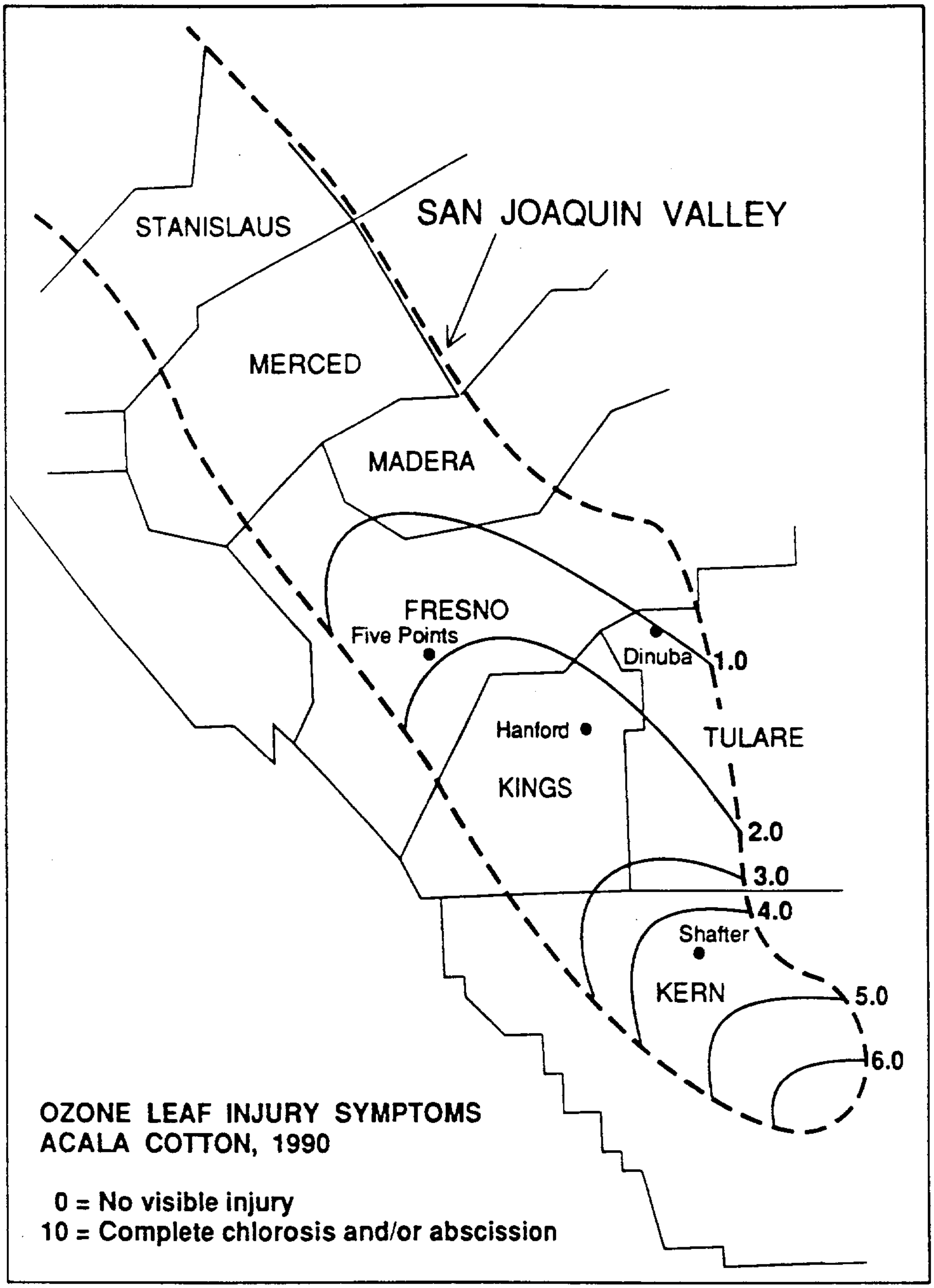

Figure 5. Distribution of ozone leaf injury symptoms in Acala cotton in the San Joaquin Valley, 1990.

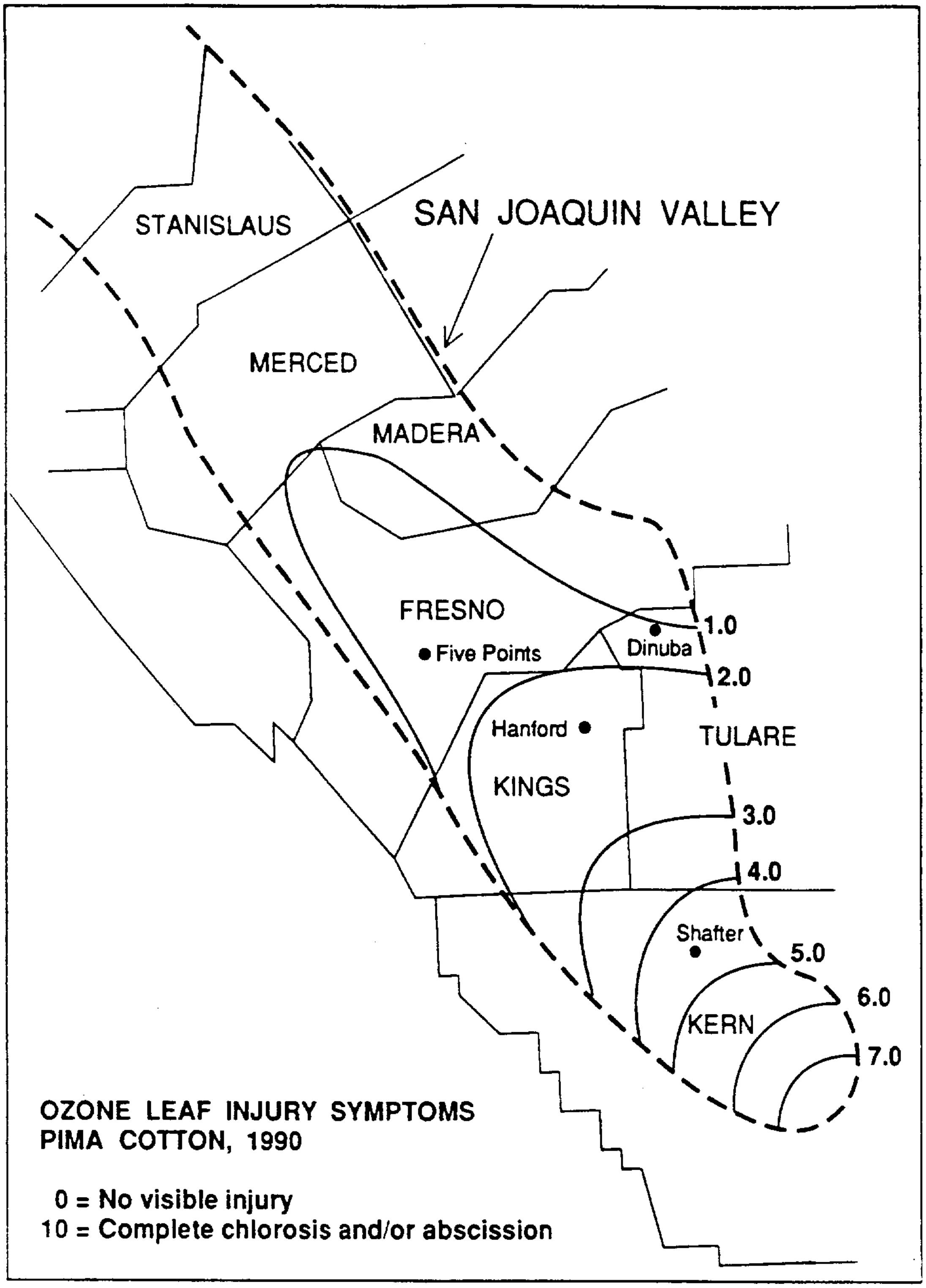

Figure 6. Distribution of ozone leaf injury symptoms in Pima cotton in the San Joaquin Valley, 1990.

Figure 7. Ozone injury of Acala cotton leaves.

Figure 8. Ozone injury of Pima cotton leaves.

leaf injury symptoms in Acala and Pima cotton, respectively. Ozone injury of Acala cotton leaves caused an accelerated senescence (Fig. 7). The mottled appearance and interveinal darkening were characteristic symptoms. A mosaic of chlorotic lesions was typical of ozone injury to Pima cotton leaves (Fig. 8).

Pima cotton was more sensitive to ambient ozone concentrations than was Acala cotton as demonstrated by the higher injury ratings for Pima in southern Kern county (Figs. 5 and 6). Temple et al. (1985c) reported that ozone reduced yield in cotton. The extent to which the survey results relate to actual yields can only be inferred based upon model projected yield losses. No attempt was made to measure yield in the actual observation plots. This is, however, a logical next step if visible injury ratings are to be developed into a viable diagnostic tool for field personnel.

Grape leaves (Thompson seedless, var.) exhibited the highest incidence of ozone injury south of Arvin as compared to that observed in the rest of the valley (Table 7). Leaf injury gradients indicated that ozone stress was less on the west side of the valley in both Fresno and King counties (Fig. 9). Ozone caused chlorotic and necrotic areas in the leaf margins (Fig. 10). Stressed leaves sometimes abscissed prematurely leaving empty nodes along the vines. Grape vineyards in the Mendota area were infested with leaf hopper during the second survey. It was difficult to identify ozone injury under these circumstances due to the insect damage. Additionally, the raisin grape growers dried the harvested fruit on paper between the rows in September and October. Therefore, access to previously surveyed fields was not guaranteed and mechanical damage of the foliage that occurred during harvest further complicated the precise assessment of foliar health.

The survey was extremely time consuming due to the distances between locales and the need to locate plantings that are at comparable stages of development. Established observation plots in grower's fields across the valley would enhance our ability to evaluate and compare the extent of crop injury occurring at different locations when crops are at the same stage of development. A standardized approach is needed to establish the relationship between foliar injury and yield loss under field conditions. Site locations and the injury ratings of representative plants are presented in Table B of the Appendix.

Table 7. Mean ozone leaf injury ratings for grape (Thompson seedless, var.) and analysis of variance in the San Joaquin Valley, 1990. 0 = no visible injury, 10 = complete chlorosis and/or abscission

Locale		Mean	SD
1	S of Arvin on Wheeler Ridge Rd. near Sebastian Rd.	4.8	1.0
6	W of Arvin on Wheeler Ridge Rd. near Bear Mt. Blvd.	4.0	0.8
5	S of Hwy 58 on Hwy 184 and Muller Rd.	3.3	1.0
10A	N of Shafter on Shafter Ave.	3.3	0.5
25A	W of Wasco on Hwy 46 near Wildwood Ave.	3.3	0.5
15	E of Pixley near Ave. 88 and Rd. 208	2.8	0.5
19	W of Tulare on Ave. 248 and Road 60	2.3	1.0
25B	E of Tulare on Cartmill Rd. near Rd. 140	2.3	0.5
12	N of Visalia on Hwy 63 near Ave. 352	1.3	0.5
23	E of Dinuba on Mtn View Ave. near Rd. 72	1.5	0.6
18	E of Hwy 99, Mt View Ave. and Rd. 42	1.5	1.3
20	Near Five Points and West Side Field Station	1.5	0.6
26C	W of Fresno on Whites Bridge Rd. near Hayes Ave.	1.3	0.5
26A	Near Kerman on Whites Bridge Rd. near Howard Ave.	1.0	0.8
21A	W of Kerman on James Rd. N of Whites Bridge Rd	1.0	0.0
26D	N of Mendota on Bass Rd	1.0	0.8
21	E of Hwy 33 on San Mateo Ave.	0.8	1.0

Source	DF	SS	MS	F
Treatment	16	89.382	5.586	9.997
Error	51	28.500	0.559	
Total	67	117.882		

LSD = 1.1

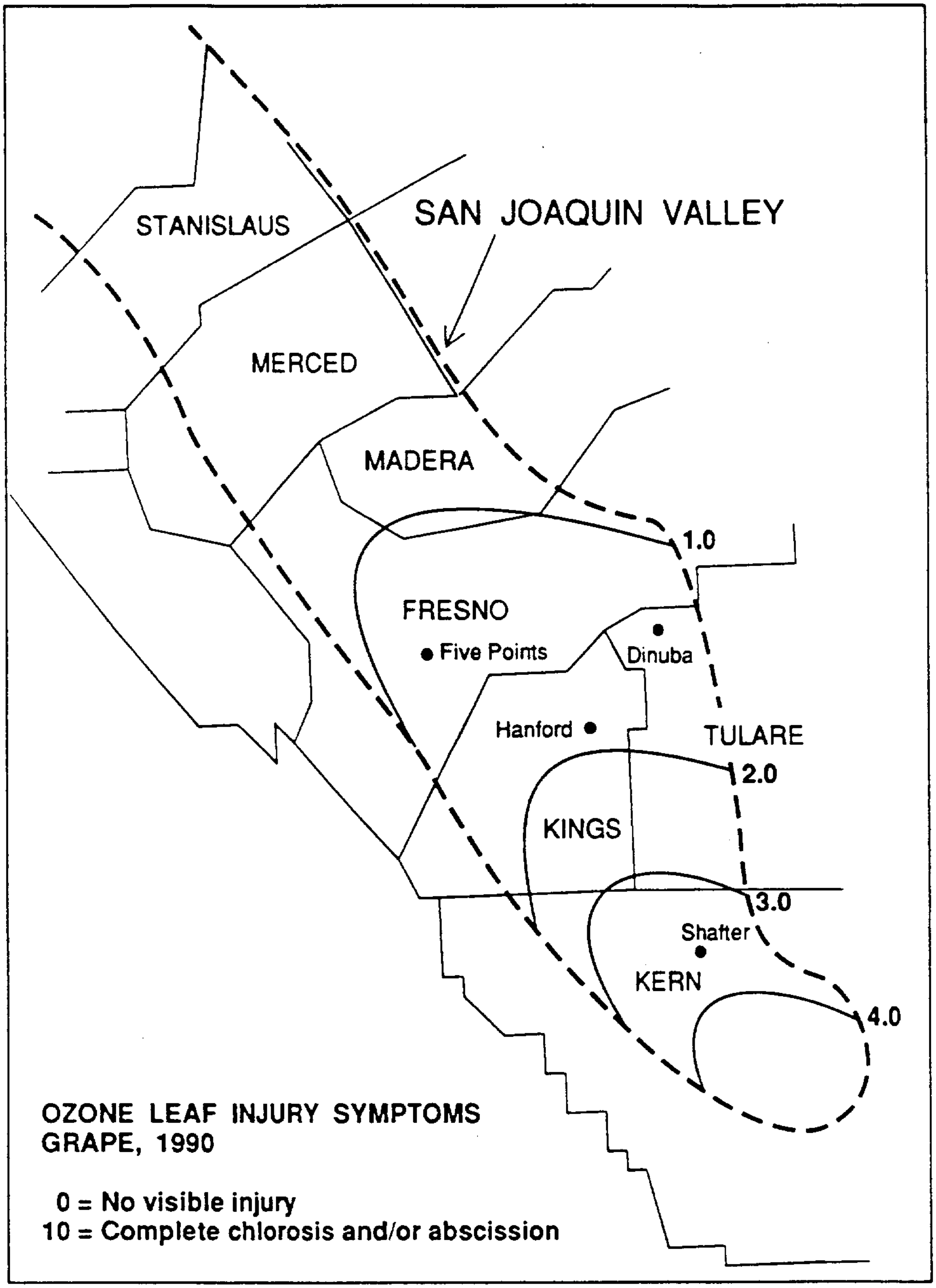

Figure 9. Distribution of ozone leaf injury symptoms in grape (Thompson seedless, var.) in the San Joaquin Valley, 1990.

Figure 10. Ozone injury symptoms on grape leaves.

B. Predicted Losses of Crop Yields Across California in 1987 and 1988

Ozone was estimated to reduce yields statewide by more than 15% for dry bean, cantaloupe, cotton, grape and orange in 1987 (Table 8). A similar trend was observed for these crops in 1988 with the exception of orange, where yields were reduced by 11.3% as compared to 20.5% in 1987. The 12 hr ozone averages from April to October 1986 were used to calculate the 1988 yield loss in orange (Table C, Appendix). Yield in orange was highly correlated to the ozone concentrations that occurred 2 yr prior to harvest, during floral bud formation (D. M. Olszyk, EPA Corvallis Oregon, personal communication). The losses for dry bean, cotton, and grape were comparable to those found in preceding years. The losses for cantaloupe should be considered tentative because the only available model was based upon yield losses associated with ozone under the humid conditions of southern Indiana (Snyder et al., 1988). The dry summer conditions in California may alter the diurnal response of stomata in a manner which changes the degree of ozone injury associated with specific ozone concentrations. Moreover, the losses of yield and foliar lesions in cantaloupe in Indiana may also be attributed to micronutrient toxicity as well as exposure to ozone (D. Mengel, Purdue University, personal communication).

Projected yield losses for alfalfa, cotton, and grape are higher in the southern counties of the San Joaquin Valley (Figs. 11, 12, 13). Field observations predicted a similar distribution of foliar injury for these crops (Figs. 2, 5, 9). Yield losses were higher on the east sides of Fresno and Kings Counties than on the west. An east-west ozone gradient may also exist in Merced County. Projected losses in excess of 25% across the entire county for cotton and grape may overestimate the degree of ozone injury.

Moderate yield reductions (6-15%) were calculated for alfalfa-hay, alfalfa-seed, lemon, onion, potato and wheat in 1989 on a statewide basis. Losses to onion and wheat were predicted to be only slight (1-5%) in 1988, while the losses in the other four crops were comparable in 1988 and 1987. Yield reductions for alfalfa-hay calculated on a county basis in the San Joaquin Valley (Fig. 11) were substantially greater than the statewide estimates (Table 8). Regional variability in yield losses of other crops may also be considerable. A critical analysis of yields and

Table 8. Estimated crop yield losses from ambient ozone across California in 1987 and 1988

County	Equation #	1987 Mean	1987 Range	Equation #	1988 Mean	1988 Range
		% Loss			% Loss	
Alfalfa-Hay	Ave (1 to 4)	7.5	1.4-11.0	Ave (1 to 4)	7.5	1.3-11.1
Alfalfa-Seed[a]	Ave (1 to 4)	8.9	1.9-13.1	Ave (1 to 4)	9.0	1.7-13.3
Barley-All	1	0	0	1	0	0
Beans-Dry[b]	Ave (1 to 4)	12.1	0-23.5	Ave (1 to 6)	19.3	0-34.1
Broccoli	1	0	0	Ave (1 to 4)	0	0
Cantaloupes[c]	1	32.0	*	1	31.8	*
Celery	1	0	*	1	0	*
Corn-Field	1	2.1	*	1	1.4	*
Corn-Silage	1	3.8	*	1	2.6	*
Corn-Sweet	1	4.7	*	3	4.8	*
Cotton	Ave (1 to 4)	21.4	15.8-31.7	Ave (1 to 8)	24.9	6.2-44.9
Grapes-All	Ave (1 to 2)	28.5	26.1-31.3	Ave (1 to 2)	28.0	25.2-30.7
Lemons[d]	1	8.4	*	1	8.6	*
Lettuce	Ave (1 to 3)	0.4	0-1.8	Ave (1 to 4)	0.4	0-1.4
Onions	Ave (1 to 2)	11.0	4.0-17.9	Ave (1 to 2)	12.0	4.3-19.7
Oranges[d]	Ave (1 to 3)	20.5	7.2-40.0	Ave (1 to 3)	32.3	11.3-63.0
Potatoes	Ave (1 to 2)	14.7	9.9-19.4	Ave (1 to 2)	15.2	10.3-20.1
Rice	Ave (1 to 3)	5.7	3.2-7.2	Ave (1 to 3)	5.6	2.7-6.5
Sorghum-Grain	1	1.1	*	1	0.9	*
Sugar Beets	Ave (1 to 3)	3.2	0-9.7	Ave (1 to 3)	2.9	0-8.6
Tomatoes-Fresh	1	1.8	*	1	1.6[e]	*
Tomatoes-Processing	Ave (1 to 3)	20.2	16.3-22.9	Ave (1 to 7)	10.4	1.7-21.8
Wheat	Ave (1 to 3)	9.4	0-17.9	2	5.4	0.7-15.6

[a]Uses Temple et al. (1987) equation for alfalfa hay.
[b]Averaged across results for four bean cultivars.
[c]Equation based on muskmelon data from Snyder et al. (1988).
[d]Assumes half of orchards are having an "on" year; half an "off" year in terms of productivity.
[e]Assumed no values greater than 10 pphm and, therefore, no losses on west sides of Fresno and Kings Counties.
* = One model available for predicting yield loss.

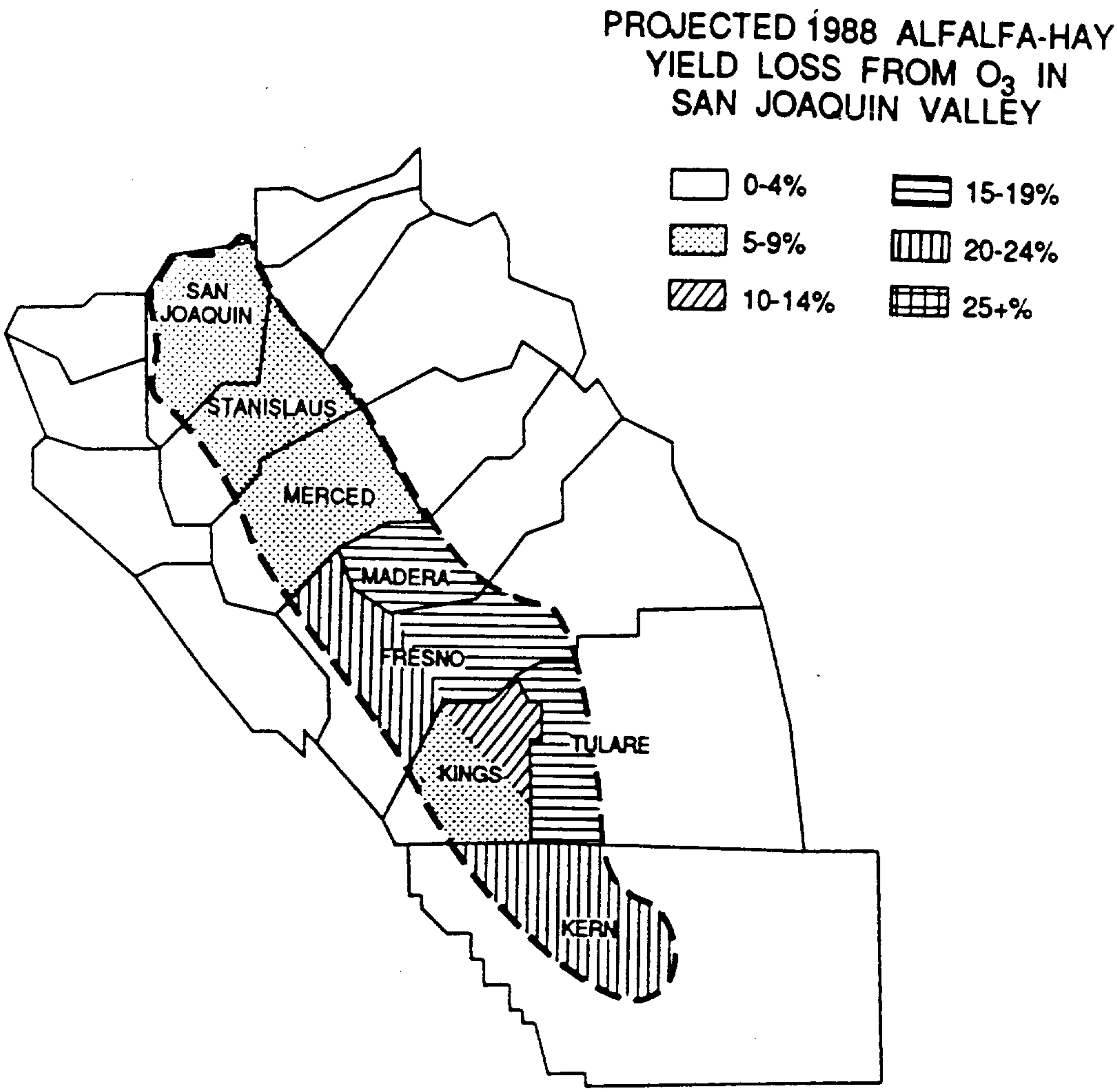

Figure 11. Projected yield loss in alfalfa from ozone injury in the San Joaquin Valley by county in 1988.

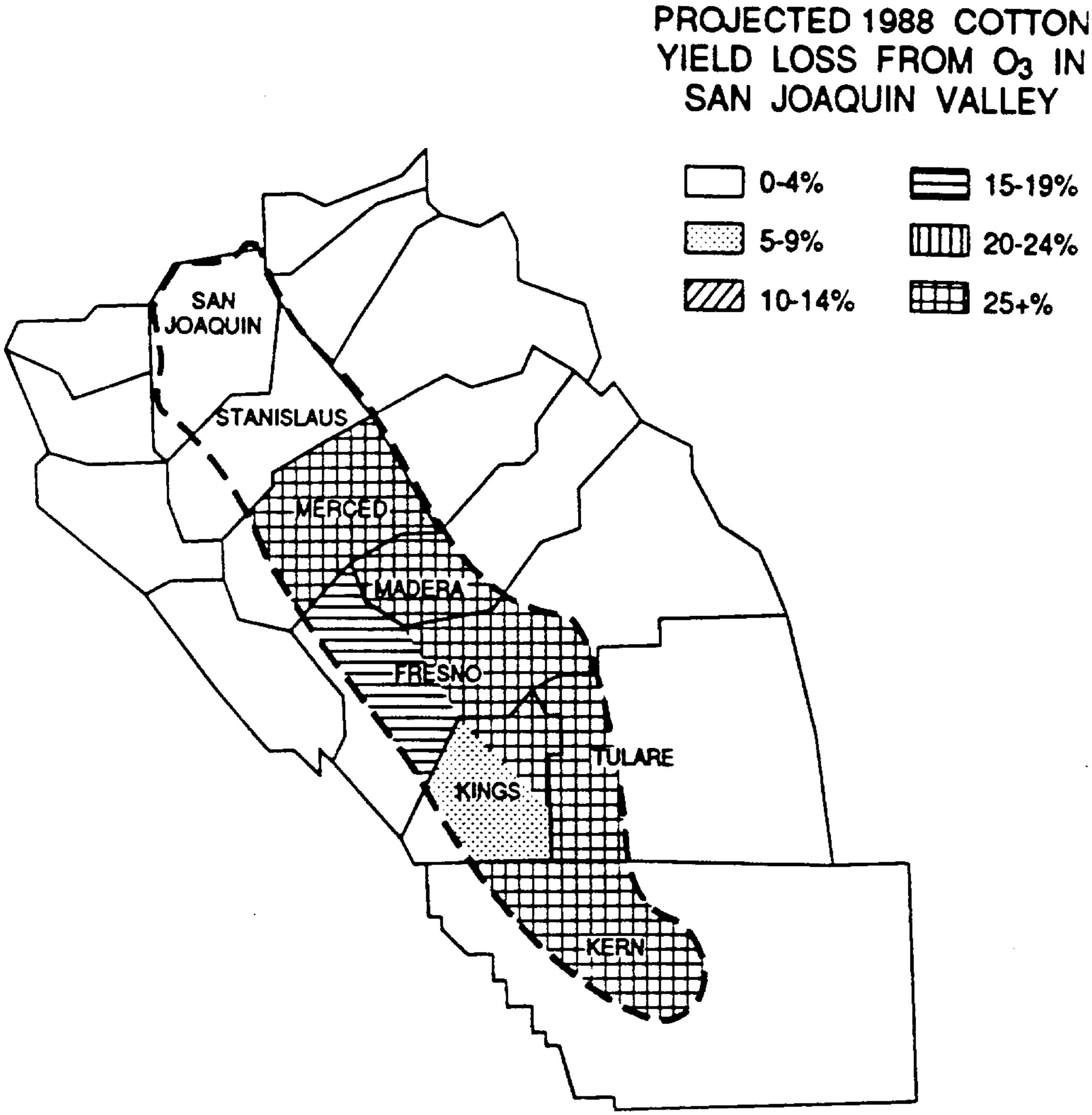

Figure 12. Projected yield loss in cotton from ozone injury in the San Joaquin Valley by county in 1988.

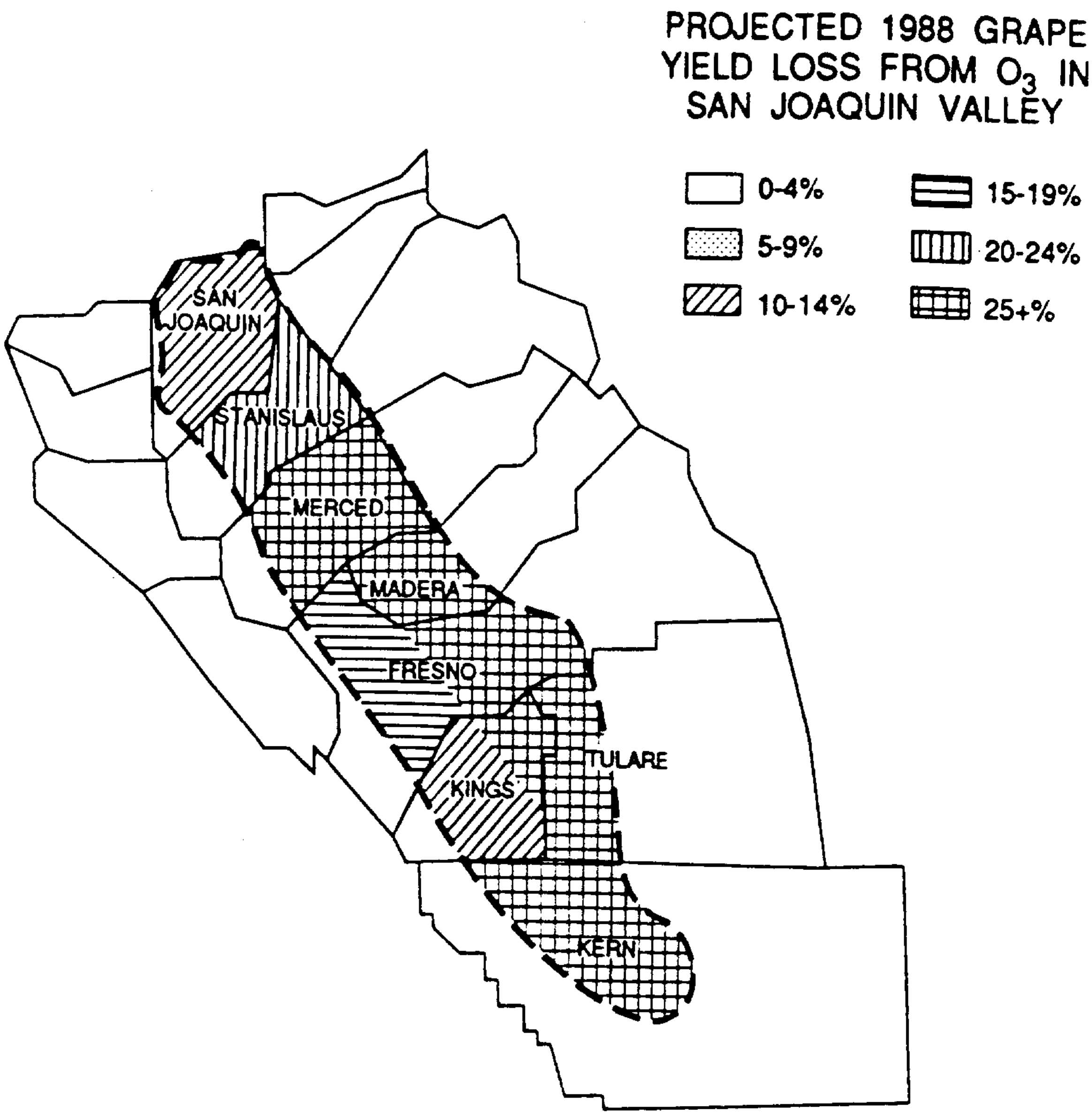

Figure 13. Projected yield loss in grape (all types) from ozone injury in the San Joaquin Valley by county in 1988.

ozone concentrations in the area where a crop was predominantly grown may prove to be a more useful criteria for assessing losses. It would certainly provide more relevant information to growers and concerned professionals in those areas. This data is available from the Tables D and E in the Appendix.

Slight losses (1-5%) were calculated for corn, rice, sorghum, and tomato in 1987 and 1988. Losses to sugar beet were higher in 1987 (3.2%) than in 1988 (0%). These estimated losses were about the same as those in preceding years, except for sweet corn which was higher in 1986.

There were no losses for four crops in 1987 and 1988: barley, broccoli, celery and lettuce. Potato showed no loss in 1988. These are cool season crops grown when ambient ozone concentrations were low. Although, when sugar beets were grown during summer they were very resistant to ozone injury. Ozone exposure reduced leaf quality in lettuce without affecting total biomass. Crop quality was not considered in the current crop loss assessment.

No data were available for 24 other crops, primarily fruit and nut trees. Foliar injury by ozone has been observed in some tree crops, such as almond, although no data on yield reduction are available. Ozone reduced photosynthesis in plum and preliminary results indicated a substantial reduction in yield (W. Retzlaff, Kearney Field Station, personal communication).

Table 12 presents mean values of estimated yield losses from more than one predictive function for some crops. A wide range of predicted values occurred for beans, cotton, onion and orange. The variability reflected the dynamic nature of crop response to ambient ozone under the different environmental conditions present during the studies when the different models were developed.

C. Data Base Update

The air quality, crop productivity and yield loss modeling databases were updated. Crop productivity data are available for 1958 through 1988. Hard copies of reprints of all references reviewed in this report and listed in Table A of the Appendix are available to the ARB staff.

D. <u>Meetings Attended and Presentations</u>

Dr. D. M. Olszyk presented a summary of our findings concerning the effects of air pollution on crops in the San Joaquin Valley before the Committee on Natural Resources and Wildlife of the California Senate, Modesto, CA., August 14, 1989.

This meeting was called by Senator McCorquodale August 21-22, 1989. Dr. David Olszyk conducted the Annual Crop Loss Workshop, Riverside, CA, (Table F, appendix).

September 25, 1989 Dr. C. Ray Thompson presented a summary "Effect of Air Pollution on Citrus - A Kern County Perspective" at the Annual Citrus Meeting at the Farm and Home Advisors Conference Offices Bakersfield, CA.

March 5, 1990 Dr. C. Ray Thompson accompanied Dr. J. B. Mudd to the offices of the California Air Resources Board and conferred with Dr. John Holmes and Staff concerning continued cooperation of the Statewide Air Pollution Research Center with the California Air Resources Board.

April 11, 1990 Dr. C. Ray Thompson made a presentation "Air Pollution Effects on Valley Crops" at the Spring Meeting of the San Joaquin Valley Entomology Association at the Fresno County Farm Advisors Office, Fresno, CA.

April 24-29, 1990 Dr. C. Ray Thompson and Dr. R. Mutters attended the 22nd Annual Air Pollution Workshop, Toronto, Canada where they conferred with scientists from the U.S., Canada and several European countries concerning air pollution effects on vegetation and possible control measures. Dr. R. Mutters presented an invited paper entitled "Relationship between Measurements of Physiological Processes and Integrated Whole Plant Response to Environmental Stress."

September 11-13, 1990 Dr. C. Ray Thompson and Dr. R. Mutters attended the California Conference on Air Pollution, UC Riverside hosted by the Statewide Air Pollution Research Center.

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V. METHODS-FOREST LOSS

A. Review of the Literature on the Effects of Ozone on Forest Trees in California

A literature search was made to obtain all relevant references to ozone effects on ponderosa pine (*Pinus ponderosa*) and Jeffrey pine (*P. jeffreyi*), two species thought to be among the most susceptible to ozone injury (Miller et al., 1963, 1969, 1971, 1982). Ozone injury of these two species has been observed in both the Sierra Nevada Mountains and the mountains surrounding the Los Angeles Basin (Pronos and Vogler, 1978; Peterson et al., 1987; Peterson and Arbaugh, 1988; Miller, 1983). The literature review focused on quantitative reports that associated effects with specific ozone concentrations, with a particular emphasis on the results from studies conducted as part of the federal Western Conifer Cooperative program and research programs funded by Southern California Edison and the Electric Power Research Institute.

A computer file of Table A was made available to the ARB containing the references obtained in the literature search. The references were checked and evaluated for general usefulness for forest loss assessments. A description and summary of the key studies for forest assessment was provided to ARB staff and is included in the Results and Discussion section of this report.

B. Concentrations of Ozone Near Forested Areas

ARB Aerometric Data Division data was used to calculate the 7 and 12 h average ozone concentration on a monthly basis at monitoring sites in or near forested areas for 1987 and 1988. Ozone concentrations were used to evaluate whether or not ozone exposure levels can be adequately characterized for forests. Ozone concentrations directly measured in or near forests were also compared to those predicted to occur in mountain regions by computer generated ozone isopleths across the entire state.

Ozone data from 132 state operated monitoring sites and 4 research locations was used to calculate the 7 h averages for June, 1988. The geographical coordinates of all monitoring sites were digitized and entered into a computer based automated cartography system (Surface II, DEC VAX 8820, UC Riverside). Ozone isopleths were constructed from estimated surface values evaluating a two-dimensional polynomial regression fitted to ozone monitoring site coordinates and the mean ozone concentrations from those sites. The coincidence of ozone in the forested areas of California are represented by isopleths of low resolution and are intended, therefore, to provide only an estimation of concentration gradients and distribution of ozone.

VI. RESULTS AND DISCUSSION

A. Review of the Literature on the Effects of Ozone on Forest Trees in California

California, because of its varied topography and climate, supports a wide variety of trees from alpine through temperate to sub-tropical species. Over 100 native species plus several introduced from other areas thrive in locations where soil, water and temperatures are suitable (Wieslander and Jensen, 1946). These are affected by air pollutants from a number of sources, but primarily by photochemical oxidants, mainly ozone, a reaction product of fossil fuel combustion. Table 9 lists 13 species which have been shown to be the most sensitive to ozone.

Following earlier field evaluations of the sensitivity of western conifers to ozone, Miller et al. (1983) fumigated eleven species of conifer seedlings and two hybrids with 0.36 ppm ozone for 12 hr/day for 37 days under natural forest conditions. The *Pinus jeffreyi* x *P. coulteri* hybrid and *P. monticola* were the most sensitive. The order of decreasing sensitivity of others was *P. ponderosa*, *P. jeffreyi*, *Abies concolor*, *P. coulteri*, *A. magnifica*, *P. radiata* x *P. attenauta*, *P. attenauta*, *Calocedrus decurrens*, *Psuedotsuga macrocarpa*, *Pinus lambertiana* and *P. ponderosa* var. scopulorum.

Forest succession as affected by air pollutants was investigated by McBride et al. (1985) in the mixed conifer forest of southern California. Observation of permanent plots dominated by ponderosa pine or white fir (*Abies concolor*) for a ten-year period suggests the eventual dominance of incense cedar (*Calocedrus decurrens*) because of its greater tolerance to ozone.

The areas most severely affected by ozone are the mountain slopes which ring the Los Angeles Basin: the San Gabriel, San Bernardino and San Jacinto National Forest plus the Sierra Nevada range east of the Sacramento-San Joaquin Valleys. Minor injury is seen east of both the San Francisco Bay area and the North Central air basins. In these areas the predominant species at risk are ponderosa and Jeffrey pine.

Table 9. Ozone sensitive tree species

Common Name	Genus and Species
Very sensitive	
Ponderosa pine	Pinus ponderosa
Jeffrey pine	Pinus jeffreyi
Western White Pine	Pinus monticola
Big Cone Douglas Fir	Psuedotsuga macrocarpa
Monterey pine	Pinus radiata
Coulter pine	Pinus coulteri
Sycamore	Platanus racemosa
Cherry	Prunus spp.
Ash	Fraxinus spp.
Aspen	Populus tremuloides
Oregon ash	Fraxinum oregana
Black cottonwood	Populus tricocarpa
Oregon white oak	Quercus garryana
Moderately Sensitive	
Knobcone pine	Pinus attenauta
Lodgepole pine	Pinus contorta
Sugar pine	Pinus labertiana
Torrey pine	Pinus torreyana
White fir	Abies concolor
Western juniper	Juniper occidentalis
Giant sequoia	Sequoia gigantea
Coast redwood	Sequoia sempervinens

Taylor (1973a) found peak levels of 0.20 ppm of ozone along an 18 mile stretch of the crest of the San Bernardino Mountains and levels exceeded .08 ppm for 6.5-12.5 hrs daily from June through September 1972. McCutchan and Schroeder (1973) described five classes of weather patterns common between June and September in this area; two of which result in high oxidant levels on the inland mountain slopes. These oxidant levels presently have declined to about 2/3 of the previous highs because of emission controls in the Basin. Steady improvements in growth of both ponderosa and Jeffrey pines at 15 plots near Lake Arrowhead during the period of 1974-1988 mirror the improving atmosphere (Miller and McBride, 1989; Miller et. al., 1989). Amounts of precipitation were more important in affecting tree growth than ambient ozone concentrations. Miller et al. (1986) observed the spatial variability in ozone concentrations in the San Bernardino Mountains and surrounding area for a five year period during midsummer months at eleven monitoring stations. The stations extended 40 km, east to west and from 1478 m to 2328 m in elevation. Data comparisons were available from established urban stations at 360 and 402 m. At Sky Forest (1709 m) average maximum ozone was 0.19-0.20 ppm while in San Bernardino at 360 m levels were 0.16-0.17 ppm. Barton Flats which is 31 km east and at 1891 m and Redlands at 402 m were about equal at 0.15-0.16 ppm, but the higher elevations had persistent overnight levels of 0.04-0.07 ppm while the Valleys approached zero. Concentrations were reduced at locations more remote from the basin but several factors, temperatures, wind and terrain influence the movement of the polluted air mass as it moves eastward and upward.

Miller et al. (1972) surveyed oxidant occurrence, temperatures and wind vectors in the Central Valley, Sierra Nevada foothills and as far east as Mineral King Valley. In addition, vertical profiles of total oxidant and temperature were determined from aircraft. Evidence was recorded of transport of photochemical oxidant from the Central Valley to Mineral King and oxidant formation from incoming pollutants was observed in Mineral King Valley.

Asher (1956) observed a chlorotic mottling of pine needles but could find no ready explanation for this effect and called it "X disease." Later Miller and co-workers recognized the effects of ozone on ponderosa pine (Miller et al., 1963; Miller, 1965; Miller and Parmeter, 1965, 1967). Needle mottle, and premature loss of needles were seen both in the mountains and on young plants exposed experimentally to ozone. Further work showed that ozone caused reduced photosynthesis and chlorotic decline of this species. The combined effects of bark beetles plus ozone resulted in death of trees (Stark et al., 1968; Cobb et al., 1968; Miller et al., 1968, Parmeter and Miller, 1968).

Miller and Van Doren (1982) studied needle retention of ponderosa and Jeffrey pine as an indication of ozone exposure. Saplings were observed in five sites in the San Bernardino National Forest which had progressively less ozone exposure during summer. Direct correlation of ozone dosage and needle drop was observed indicating that this index may serve to indicate exposure levels in the field to ozone. Luck (1987) observed that high levels of ozone were associated with fewer mature cones on ponderosa and Jeffrey pines. The extent of overt ozone injury to pines in the southern Sierra Nevada was evaluated in a three-year study by Vogler and Pronos (1980). Overall injury was slight, but individual trees showed slight to moderate injury in 1974 which became intensified by 1977 at elevations between 1646 and 2286 m.

Peterson and Arbaugh (1988) investigated the growth patterns of Ponderosa pines at 56 locations (1400 trees) extending from Sequoia National Park northward to Lake Tahoe. Comparisons were made between trees showing needle mottle in the southern area versus northern sites which showed no injury. There was no evidence of growth reductions on an area-wide bases, but some locations in the southern Sierra had some recent growth reductions. A similar study by Peterson et al. (1989) in the same area showed that a high degree of variation in overt symptoms occurred. Patterns were evident when individual trees were measured which showed a high degree of correlation between ozone exposure and injury. Crown condition, as opposed to growth increments, may be a better index of long-term stand health because trees with sparse crowns allow competing species to become more dominant due to greater incident solar radiation in the understory. Peterson and Arbaugh (1988) found that although ozone levels were high enough in the southern Sierra Nevada to cause foliar markings, no effects on radial growth were seen. Winter precipitation was directly correlated with growth. Miller et al. (1987) found that many other factors, such as soil moisture, root development and shading were more important to the survival of giant sequoia (<u>Sequoiadendron giganteum</u>) than atmospheric ozone.

Peterson et al. (1987) found that mean annual radial increment of trees in Sequoia and Kings Canyon National Parks with symptoms of ozone injury was 11 percent less than trees at sites without ozone injury. Larger diameter trees (>40 cm) and older trees (>100 yr) had greater decreases in growth than smaller and younger trees. Differences in radial growth patterns of injured and uninjured trees were prominent after 1965. Winter precipitation accounted for a large proportion of the variance in growth of all trees, although ozone-stressed trees were more sensitive to interannual variation in precipitation and temperature during recent years.

A limited amount of biochemical and physiological work has been done to show the effects of ozone on trees. Peroxidase and superoxide activities in Norway spruce were reported to be lower in trees grown in carbon-filtered air as compared to ambient air, but ascorbic acid was higher (Castillo et al., 1987 and 1988). These results indicate that measuring a number of biochemical changes may be desirable for providing a reliable index of exposure of plants to ozone. Evans and Miller (1972a) conducted histological and biochemical studies of ozone injury to needles of ponderosa pine and found cellular proteins and nucleic acid formation to be disrupted. Cell wall destruction occurred after five to seven days fumigation with 0.45 parts-per-million (ppm) ozone for 12 hrs/day. Visual damage occurred after two or three weeks. Further histological work (Miller and Evans, 1972b) with ponderosa, Jeffrey, Coulter and sugar pines showed similar symptoms, but ponderosa and Jeffrey pines were most affected (Evans and Miller, 1973 and 1975).

Bingham and Coyne (1989) measured photosynthetic rates and stomatal conductance of pine needles exposed to ozone and water stress. Water stressed needles were less affected by ozone presumably due to drought induced stomatal closure. Coyne and Bingham (1980, 1981, 1982) found as oxidant stress increased the needles fixed and retained less CO_2, while ozone levels did not significantly effect the optimal temperature for photosynthesis. Photosynthesis, dark respiration, growth and foliar injury of four one-year-old pine seedlings were observed for four months in the San Gabriel Mountains above the Los Angeles basin by Bytnerowicz et al. (1989). No significant changes in growth, photosynthesis or dark respiration were observed for Coulter or ponderosa pines when plants grown in ambient ozone concentrations (0.067-0.108 ppm) were compared to those grown in charcoal-filtered air. Because these effects occur gradually, positive determination is difficult in short-term studies.

Bytnerowicz et al. (1989) in a one-year mineral nutritional study found that ponderosa pine needles contained less nitrogen when exposed to ambient air as compared to carbon-filtered air in an area of high ambient ozone (San Gabriel Mountains, elevation 800 m). Reduced nitrogen in mineral nutrient solution caused significant reductions in N, P, Ca, K and chlorophyll in pine needles but reduced magnesium had no effect. Root susceptibility of pines to disease was studied by James et al. (1975, 1980, 1982) by inoculating soil in which test plants were grown with Fomes annosus, a soil fungi. Colonization of roots of ponderosa pines was much greater in those stressed by ozone.

Combined effects of photochemical oxidants, ozone plus PAN (peroxyacylnitrates), on juvenile needles of ponderosa pine by Davis (1977) showed that some antagonism in effect occurred. Ozone alone at a given level caused more injury than the combined pollutants. No chemical reaction of the pollutants prior to entering the needles was observed. The response appeared to by physiological within the plant cell.

Miller and co-workers (1983) fumigated ponderosa pine, Jeffrey pine and giant sequoia with increasing levels of ozone plus SO_2. The pines were most sensitive to low levels (20 pphm) of equal amounts of the two pollutants but sequoia was most sensitive to twice these levels. Miller and Stolte (1984) measured ozone and SO_2 levels in the forested areas of the southern San Joaquin Valley east of Bakersfield and concluded that the levels of SO_2 were so minimal that air pollutant injury could be ascribed fully to ozone.

Temple (1988) and Westman and Temple (1989) studied the effects of ozone and acidic mists on two-year-old Jeffrey pine and giant sequoia seedlings during May and June of 1985 and 1986. Ozone at 0.10 and 0.20 ppm caused needle mottle on Jeffrey pine and reduced stem, leaf and root growth during 1986. Acidic mists of pH 3.4 and 2.7 stimulated pine growth but pH 2.0 inhibited. Ozone at 0.20 ppm plus acidic mist of pH 2.0 reduced growth of giant sequoia. Leaf analysis showed acidic mists accumulated as nitrate and sulfate and mobilized iron and manganese. The decrease in chlorophyll b content due to the acidic mist treatment was greater in giant sequoia leaves as compared to pine leaves.

In summary, forests in much of California are healthy and continue to thrive with the exceptions of those surrounding the Los Angeles basin and those east of the Southern San Joaquin Valley (Barnard et al., 1989). In these areas there is certain ozone damage to the mixed conifer forests especially in the San Gabriel, San Bernardino and San Jacinto mountains which ring the Los Angeles basin. Lesser damage occurs in the southern Sierra Nevada slopes east of Bakersfield with injury declining as ozone exposure lessens northward.

Chronic ozone injury to ponderosa pine (Pinus ponderosa) and related species, Jeffrey pine (Pinus jeffreyi) was identified in the San Bernardino and adjacent mountains in the early 1950's (Bytnerowicz et al., 1989). Needle mottle, premature abscission of needles, sparse crown condition and the added stress of bark beetles resulted in the death of many mature trees. These have been logged in many areas and a succession of more resistant trees such as incense cedar (Calocedrus decurrens) has occurred. Plots of ponderosa pine in the San Bernardino Mountains ranging over a gradient of decreasing ozone exposure were observed for three intervals from 1974 to 1988 for changes in crown condition and increases in stem cross section. During this time ozone concentrations declined from the mid 1960's to the mid 1970's and have remained about the same until 1988. Crown condition improved from 1974-1988 in 9 of 11 plots. Increases in stem cross section were not related to oxidant dosage in plot-to-plot comparisons but many other factors influence this index. Oxidant dosage was correlated weakly with stem cross section in individual plots. Establishment of new seedlings was highest during a moist period of 1978-83 and lowest during the dry period with high ozone levels of 1974-79.

Ozone injury to forests east of Bakersfield in the San Joaquin Valley is seen as needle mottle and crown dieback, but definite evidence of reduced growth due to the pollutant was not observed. Proceeding northward to Sequoia and Kings Canyon the gradient of ozone declined with a concurrent reduction in injury symptoms.

B. Concentrations of Ozone Near Forested Areas

The monthly 7 and 12 h ozone averages near forested area were comparable in 1987 and 1988 (Tables 10 and 11). Peak concentrations primarily occurred during the period of May to September. The potential exists, in San Bernardino, San Diego and Placer counties, for trees to be injured during both the spring flush and late season growth stages. Stomatal conductance in ponderosa pine was reduced in the presence of drought (Bingham and Coyne, 1980) and a decrease in ozone injury has been demonstrated to be associated with stomatal closure in cotton (Temple et al., 1987). The ambient ozone present in May and June may be more injurious than the generally higher levels observed in August and September because water would not be a limiting factor and stomatal conductance would be high.

Seasonal ozone averages (Table 12) indicate that forests in El Dorado, Placer, Riverside, San Bernardino and San Diego counties experience the highest levels of exposures to air pollution. Miller et al. (1972) demonstrated that ozone or its chemical precursors can be transported over long distances. The relatively high concentrations of ozone observed in Placer and El Dorado counties represent the eastward transport of air pollutants from the Sacramento area and potentially from the Bay area as well. The absence of monitoring sites in the southern Sierra Nevada is indicative of the current limitations in assessing the loss of tree productivity in that portion of the state. Ozone monitoring sites are needed in the counties of the southern Sierra Nevada adjacent to the San Joaquin Valley. The continued urban and industrial growth in the San Joaquin Valley will result in an increase in photochemical air pollution reaching the forest of the Sierra Nevada. At present there is an inadequate data base available to monitor ozone levels in that area and evaluate the vigor of these important forest ecosystems.

Table 10. 7 and 12 hour ozone averages (pphm) at air monitoring stations near forested areas in 1987

1987	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
S Lk Tahoe-Bijou	.03	.04	.04	.05	.05	.05	.05	.06	.06	.05	.03	.04
El Dorado Co.	.03	.03	.04	.05	.05	.05	.06	.06	.06	.04	.03	.03
S Lk Tahoe-Tahoe Bl	.04	.04	.04	.05	.05	.05	.05	.06	.06	.05	.03	.03
El Dorado Co.	.03	.03	.04	.05	.05	.05	.05	.06	.05	.04	.03	.03
Ukia					.03	.04	.02	.04	.03	.04		
Mendocino co.					.03	.04	.02	.03	.03	.04		
Mammoth Lakes	.05	.05	.04	.04	.04	.05	.05	.06	.06	.04	.04	.04
Mono Co.	.04	.04	.04	.04	.04	.05	.05	.06	.06	.04	.03	.03
Rocklin	.02	.02	.04	.05	.05	.05	.05	.05	.04	.04	.02	.02
Placer Co.	.02	.02	.03	.04	.05	.05	.05	.05	.04	.03	.01	.02
Auburn	.03	.03	.04	.05	.06	.07	.06	.08	.07	.05	.03	.03
Placer Co.	.03	.03	.04	.05	.06	.07	.06	.08	.07	.05	.03	.03
Quincy	.03	.03	.04	.05	.05	.05						
Placer Co.	.02	.02	.04	.05	.04	.05						
Lake Gregory	.03	.04	.04	.07	.08	.11	.10	.09	.09	.05	.04	.03
San Bernardino Co.	.03	.03	.04	.07	.07	.11	.11	.10	.09	.05	.04	.03
Redding					.05	.06	.06	.07	.06	.05		
Shasta Co.					.04	.06	.05	.07	.05	.03		
Anderson				.04		.06	.05	.06	.05	.05		
Shasta Co.				.04		.05	.05	.06	.05	.04		
Yreka				.05	.04	.05	.05	.05	.05	.03	.03	.02
Siskiyou Co.				.04	.04	.05	.04	.05	.04	.03	.02	.02
Alpine-Victoria	.04	.04	.05	.07	.08	.08	.08	.08	.08	.08	.05	.04
San Diego Co.	.04	.04	.05	.07	.07	.07	.07	.07	.07	.06	.05	.04

First line gives 7 h ozone averages for 0900-1600 PST.
Second line gives 12 h ozone averages for 0800-2000 PST.

Table 11. 7 and 12 hour ozone averages (pphm) at air monitoring stations near forested areas in 1988

1988	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
S Lk Tahoe-Bijou	.04	.04	.05	.05	.06	.05	.05	.06	.06	.06	.04	.04
El Dorado Co.	.04	.04	.04	.05	.06	.05	.05	.06	.05	.05	.04	.03
S Lk Tahoe-Tahoe Bl	.04	.04	.04	.05	.05	.04	.05	.06	.05	.05	.03	.03
El Dorado Co.	.03	.04	.04	.04	.05	.04	.05	.05	.05	.04	.03	.03
Ukia				.04		.03	.04					
Mendocino co.				.04		.03	.03					
Mammoth Lakes	.04	.04	.04	.05	.06	.05	.05	.06	.06	.04	.04	.03
Mono Co.	.03	.04	.04	.05	.06	.05	.06	.06	.06	.04	.04	.03
Rocklin	.02	.03	.04	.04	.05	.05	.06	.06	.06	.05	.02	.02
Placer Co.	.01	.03	.04	.04	.04	.05	.06	.05	.06	.05	.02	.02
Auburn	.01	.04	.05	.05	.06	.06	.08	.07	.07	.06	.03	.03
Placer Co.	.01	.04	.05	.05	.06	.06	.08	.07	.07	.06	.03	.03
Colfax				.04	.04	.06	.08	.07	.07	.06	.03	.03
Placer Co.				.04	.04	.06	.08	.07	.07	.05	.02	.02
Lake Gregory	.03	.04	.05	.07	.08	.11	.12	.11	.08	.06	.04	.03
San Bernardino Co.	.03	.04	.05	.07	.09	.11	.12	.12	.08	.06	.03	.03
Redding				.04	.04	.04	.06	.06	.05	.04		
Shasta Co.				.04	.04	.04	.05	.05	.05	.03		
Yreka	.02	.03	.04	.04	.04	.04	.04	.05	.05	.03		.02
Siskiyou Co.	.01	.02	.03	.04	.04	.04	.04	.05	.04	.03		.02
Alpine-Victoria	.04	.05	.06	.07	.08	.08	.09	.09	.09	.08	.05	.04
San Diego Co.	.04	.05	.06	.06	.07	.07	.08	.08	.07	.06	.04	.04

First line gives 7 h ozone averages for 0900-1600 PST.
Second line gives 12 h ozone averages for 0800-2000 PST.

Table 12. 7 h ozone averages (pphm) from April to October 1987 and 1988 at air monitoring stations near or in forested areas. ND = no data available

County	Site No.	1987	1988
		(pphm)	
El Dorado	680	5.5	6.3
El Dorado	684	5.3	7.0
Mendocino	763	3.3	3.7
Mono	785	4.9	5.9
Placer	810	4.7	5.9
Placer	813	6.3	6.4
Placer	817	ND	6.0
*Riverside		7.0	ND
San Bernardino	181	9.0	9.7
Shasta	558	5.0	4.7
Shasta	564	5.2	ND
Siskiyou	861	4.6	4.1
San Diego	128	7.9	8.3

*USDA Forestry Service research site.

C. <u>Coincident Distribution of Approximate Concentrations of Ozone with Stands of Ponderosa and Jeffrey Pines</u>

Indigenous stands of ponderosa and Jeffrey pines in California south of approximately 38°N latitude (Yosemite National Park) were exposed to potentially injurious levels of ozone during June, 1988 (Figs. 14 and 15). Stands north of this latitude and in the coastal mountain ranges were subjected to relatively low concentrations of ozone during the same period. The distribution pattern and concentrations of ozone were comparable to that observed during April through September of the same year (data not shown). Trees on the western slope of the Sierra Nevada in Tulare and Kern counties were subjected to ozone levels similar to that experienced by trees in the mountains surrounding the South Coast Air Basin (SCAB). A direct correlation, however, between tree vigor and air

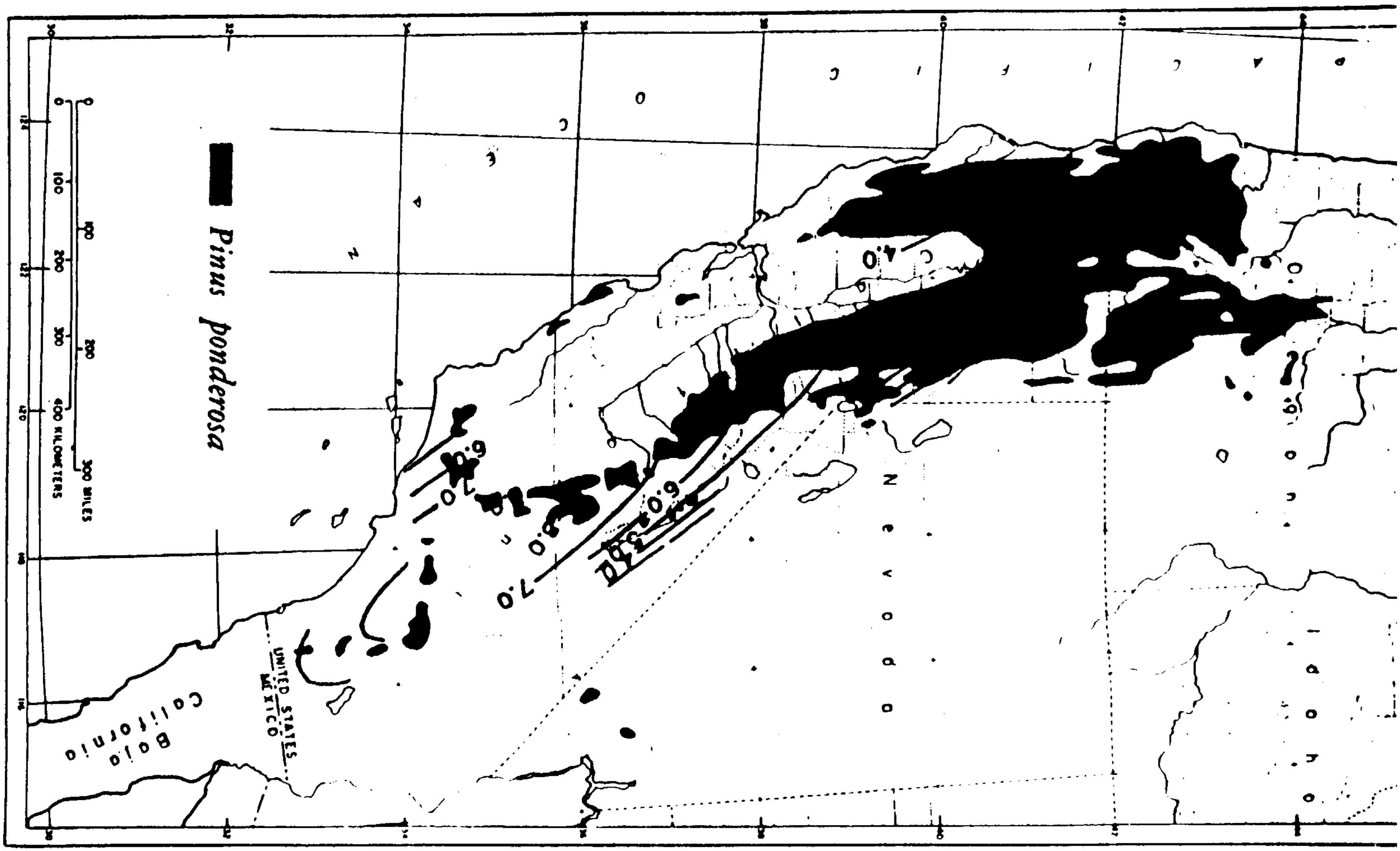

Figure 14. Approximate distribution of ponderosa pine in California with overlay of ozone concentration gradients for June 1988.

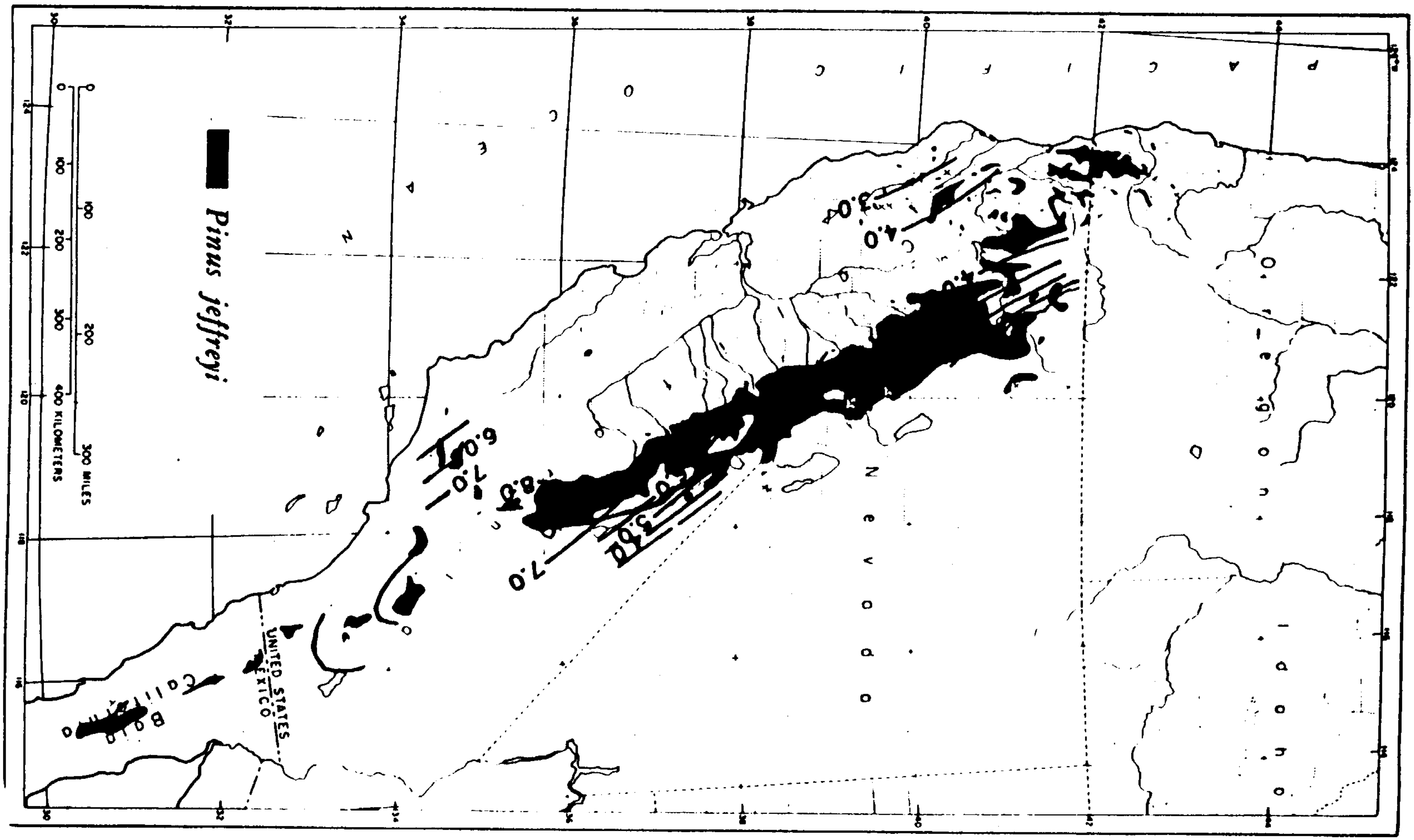

Figure 15. Approximate distribution of Jeffrey pine in California with overlay of ozone concentration gradients for June, 1988.

quality in the two geographical areas is tenuous. Forests in the Los Angeles area have been exposed to chronic high concentrations of ozone for the past 20 to 30 years (Miller et al., 1963). In contrast, the observed concentrations of ozone in Tulare and Kern counties were a more recent development. The long-term consequences of ozone injury on forest productivity in the Sierra Nevada is not well understood. The air quality will decline in the "pristine" areas of the Sierra Nevada as the urbanization of the San Joaquin Valley continues. Peterson and Arbaugh (1986) for example reported ozone related foliar lesions on ponderosa pine near Giant Sequoia National Park. It is doubtful whether trees in the Sierra Nevada will exhibit a decline in productivity similar to that observed for the forests in the SCAB due to the difference in climatic conditions and their interactions with ozone and other air pollutants. Controls on motor vehicles and industrial emissions continue to reduce pollutant levels. The extremely high concentrations of ozone that were observed in the SCAB in the mid 1970's are unlikely to occur in the Sierra Nevada Mountains. Moreover, the number of vehicles in the Central Valley is considerably less than that concentrated near the forests surrounding the SCAB.

The San Gabriel and Tehachapi Mountains did not appear to impede the distribution of ozone between the SCAB and the southern San Joaquin Valley. In contrast, the ozone concentration rapidly decreased from the summit of the Sierra Nevada eastward.

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