CROP LOSSES FROM AIR POLLUTANTS

A GIS REGIONAL ANALYSIS

and

STATEWIDE CROP LOSSES FROM AIR POLLUTANTS

Final Report

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Abstract

High concentrations of ambient ozone significantly reduce yields of many important crops grown in California as demonstrated by numerous controlled studies over the past 40 years. Past efforts to model crop losses used this information to estimate the magnitude of yield loss using aggregated county-wide statistics. The work reported herein expanded the methodological basis of the Crop Loss Assessment Program by using GIS technology to disaggregate the statistics used to estimate yield loss based on the geographic distribution of production areas for major commodities and interpolated $(1/d^2)$ ozone exposure indices based on 1991 and 1992 ARB ozone data. The analytical procedures used were the same in 1991 and 1992, except that in 1992, SUM06 models were used in addition to 7-hour and 12-hour seasonal mean models for estimating the yield losses for several crops. Additionally, the graphic representations of estimated yield losses were enhanced by color-coded altitudinal ramping for better topographic definition.

Ozone concentrations on a monthly basis were interpolated within state air basins using ARB air quality statistics and an imposed 2000 foot altitudinal barrier to transport. Monthly 7-hour means, a widely used exposure index for plant response functions, were used for the statewide interpolations. Ozone concentrations were highest during summer months when 7-hour means in the southern San Joaquin Valley were comparable to those observed in parts of the South Coast Air Basin.

The intensity of potential yield loss was determined using ARB air quality data and published yield response functions. Areas where potential yield losses occurred were delimited by the location and extent of irrigated farmlands within an agricultural region. Results were graphically displayed to illustrate geographic variability. Using interpolated ozone exposure indices, for example, potential yield losses for cotton grown in the San Joaquin Valley ranged from less than 10% to almost 30%.

Statewide crop-by-county estimated yield losses in 1991 and 1992 were comparable. For most crops, loss estimates varied less than 20% between years. The variability was not consistent, in that losses were higher for some crops while lower for others when the two years were compared. No discernible regional trends between years were apparent.

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Disclaimer

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Recommendations

It is important that pertinent databases are stored in a standardized format to maximize accessibility and clarity of analysis. The continued development of a GIS data management system would strengthen the ability of administrators and researchers to access, as well as, critically analyze air quality information based on their own criteria. In addition, there is a continued need for using geostatistics and multivariate methodology by which field personnel can evaluate potential yield losses at a given locale within a county, which is not represented by the county aggregate yield loss. New technology for assessing crop losses does not depend on costly experimental programs, but utilizes available information applied at a subcounty level to provide localized estimates of yield reductions and comparative analysis relative to the contribution of ozone to yield variability, in the context of other agronomically important factors.

Specific recommendations are:

1) Expand and refine the GIS based approach to estimate the regional yield loss in major crops due to ozone injury across the principal agricultural production zones in California, based upon the location of plantings and interpolated ozone exposure indices;

2) Refine methodologies to readily estimate ozone concentration contours from available air monitoring data that includes altitudinal barriers to horizontal and vertical air flow in the interpolation routine; and

3) Actively disseminate the crop loss information to public and private concerns in an understandable and meaningful context.

GLOSSARY OF TERMS AND ABBREVIATIONS

ARB	Air Resources Board
ARC/INFO	Geographic Information System Software by Environmental Systems Research Institute, Redlands, CA
CDFA	California Department of Food and Agriculture
DEM	Digital Elevation Model
ft	foot or feet
GIS	Geographic Information System
hr	Hour
km	Kilometer
MB	Megabytes
NCLAN	National Crop Loss Assessment Network
PDT	Pacific Daylight Time
ppb	Parts-per-billion
pphm	Parts-per-hundred-million
r-squared (R^2)	Sum of squares due to regression divided by total sum of squares
SAPRC	Statewide Air Pollution Research Center
TSD	Technical Support Division
UCR	University of California, Riverside
USDA	United States Department of Agriculture
VIP	Selection of best possible set of mesh points that describe topology
USGS	United States Geological Service
UTM	Universal Transverse Mercator

INTRODUCTION

ARB-sponsored work leading to estimated yield losses associated with ambient levels of ozone for important crops in California remains an important means of evaluating one aspect of the economic costs of poor air quality. Statewide projected yield losses associated with ozone, aggregated by county, are available up through 1992 (1991 and 1992 are presented in this report). Yield loss estimates for 1990 in the San Joaquin Valley showed that cotton yields were reduced by 22% on average in the San Joaquin Valley, with the greatest reduction occurring in Kern county (26%) (Mutters and Guzy, 1993). Statewide yield losses for all grapes was estimated to be 23%. Losses in table grapes were the greatest within this group (27%), because Thompson seedless are very sensitive to ozone. Among the largest bean producing counties, losses were the greatest in Fresno (26%) followed by Tulare, Stanislaus, and San Joaquin, 25%, 16% and 11%, respectively. Moderate yield reductions (6 to 15%) were estimated for alfalfa, sweet corn, lemon, onion, orange, potato, strawberry, tomato, and wheat. Losses in lettuce, nectarine, rice, and sorghum were minimal (0 to 5%). Regional variability, however, in yield losses of crops may be considerable and not apparent in the analysis of aggregated statistics.

A disaggregated approach based on Public Land Survey sections (approximately 1 square mile) units rather than county units was used in a study of cotton yield losses within the San Joaquin Valley portion of Kern county (Mutters and Guzy, 1993). In order to use the best possible ozone exposure statistics on a section basis, interpolation techniques were used to estimate ozone exposure indices. Yield loss contour maps of the region were constructed by inputting the acreage and interpolated exposure statistics into the available cotton yield loss equations. Results based on section data indicated that using the county aggregated statistics may underestimate or overestimate the actual crop loss due to ozone depending on the location in the county, ranging from an estimated loss of 12% in northwestern Kern county to 22% in the southeast area near Arvin. This difference was not apparent when using aggregated county statistics. It follows that the economic consequences of ozone induced yield reductions would be better served if calculated using the actual acreage planted of a particular crop across ozone gradients within a single county. Including areas of a county where a crop is not being grown into such predictive economic models may introduce substantial errors leading to erroneous conclusions.

Although potentially useful, even this enhanced approach suffers from the lack of data describing the agronomic factors which significantly influence yield variation and the susceptibility of a plant to ozone injury. Grower surveys requesting this type of information have proven to be only minimally successful (Mutters and Guzy, 1993). Furthermore, no attempts to date have been made to predict yield loss in economically important crops using disaggregated yield and air quality statistics for principal production zones in the state. Predictive functions applied on a grid-wise basis at the section level would provide data needed to model the geographic occurrence of yield loss under present and possible future ozone concentration scenarios.

The results of surveys of foliar injury from ozone exposure to important crops in the San Joaquin Valley have been compared with crop loss estimates reviewed above as a different measure of yield loss. Leaf injury is frequently associated with decreased plant growth and yield (e.g., Reinert et al., 1984; Kohut and Laurence, 1983; Thompson and Kats, 1970). In contrast, reduced yields in presence of high levels of ozone can occur in the absence of any visible foliar lesions (Temple et al., 1985b). Field surveys were conducted by University of California personnel to evaluate the extent and geographic distribution of ozone injury in cotton, grape, and almond in the San Joaquin Valley in 1991. Injury was evaluated at a number of sites throughout the valley where accompanying yield data was available courtesy of Dr. R. Bassett, Shafter Experiment Station, Shafter, CA. Regression analysis relating foliar injury to yield revealed no significant relationship between injury and yield. The statistical power analysis was compromised by the small sample size and the lack of data describing important environmental covariates known to influence yield (Kerby, 1990). If a standardized approach describing the relationship of foliar injury to yield is to be developed, data are needed to describe the key environmental variables from future observation plots.

Accurate ozone exposure statistics are essential for any research investigating the relationship between yield and foliar injury including areas which are not directly monitored by ARB network stations. The air flow patterns, proximity to point sources of ozone precursors and scavengers may result in excessively high or unexpectedly low levels of ozone in localized areas; some of which may be microclimates suitable for the production of specialized, yet valuable crops. Assigning exposure statistics derived from monitoring data gathered at far removed locations or with a minimal number of stations may not adequately reflect the actual ozone concentrations in the nonmonitored areas of the state. Furthermore, interpolated ozone exposure indices that consider altitudinal barriers to atmospheric transport would provide better estimates of that occurring in a given area than the simpler approach used in previous yield loss estimates.

Statement of the Problem

High levels of air pollutants, particularly ozone, are present in the state's multi-billion dollar agricultural production areas within the Sacramento Valley and San Joaquin Valley. Until the inception of the California Air Resources Board's Crop Loss Assessment Program, limited efforts had been made to synthesize and apply experimental research information on a regional basis to estimate area-wide crop losses in these important production areas. With the exception of the crop-by-county yield loss tables computed by the University of California at Riverside group, comprehensive and coordinated efforts were lacking that evaluated the yield losses associated with ozone. New analytical technologies can be successfully used to apply available information to effectively evaluate and graphically present agriculturally relevant analyses on a regional basis.

To that end, a concerted effort to develop a computer based database of agricultural and air quality related statistics in a standardized format would facilitate a number of specific analyses and graphic displays that may be required by the ARB's technical staff.

PROJECT OBJECTIVES

1) Refine methodologies to readily estimate ozone concentration contours from available air monitoring data that includes altitudinal barriers to horizontal and vertical air flow into the interpolation routine.

2) Initiate a GIS based approach to estimate regional yield loss in major crops due to ozone injury across the principal agricultural production zones in California (i.e., San Joaquin, Sacramento, Salinas, and Imperial Valleys) based upon the geographical location of the plantings and interpolated ozone exposure indices.

3) Use yield data with locationally paired agronomic information from San Joaquin Valley farms in conjunction with ARB air quality statistics to develop a multivariate regression model describing the relative contribution of ozone to yield variability on a regional scale.

4) Conduct a field survey to assess the severity and geographic distribution of ozone injury in cotton.

5) Revise and update statewide crop-by-county yield loss projections based on exposure indices calculated from interpolated ozone statistics.

6) Disseminate the information to the agricultural community and provide support to the ARB staff on agriculture related issues.

7) Implement new yield loss models and update the archival database stored at the SAPRC, UC Riverside.

LITERATURE REVIEW

The extensive body of published information pertaining to the effects of air pollution, particularly ozone, on the growth and physiology of crop plants has been continuously reviewed during the ARB-sponsored Crop Loss Assessment Program. Computer searches encompassing over 100 scientific journals were conducted at regular intervals during the previous contractual periods. Relevant literature published within the past year is reviewed and presented in two general categories: whole-plant response and physiological mechanisms associated with the response. Experimental results which expand current knowledge relevant to California agriculture are preferentially addressed. Dose-response functions describing the impact of ozone on crops important to the state's agricultural industry are incorporated into the estimated yield loss programs when applicable.

The most notable aspect of ozone related crop research published in the last two years was that it was conducted essentially outside the United States, particularly in Europe, with a few notable exceptions. Consequently, any conclusions drawn must be general in nature due to the substantially different growing environments in north and central Europe as compared to California. Papers describing domestic work dealt primarily with modeling and reinterpretation of previously published results from NCLAN (National Crop Loss Assessment Network) and ROPIS (Response of Plants to Integrated Stress).

Whole Plant Response. Retzlaff et al. (1992) reported that exposure of plum (*Prunus salicina*) to ambient and twice ambient ozone concentrations during the first two years of orchard establishment reduced leaf level photosynthesis, cross-sectional area growth of the trunk, fruit weight, and retention time of leaves. The ozone response was deemed cumulative, with multiple-year exposures having an increasingly detrimental effect on growth and yield during the crucial period of orchard establishment. The effects of ozone on the growth and productivity of mature plum trees remains undetermined. The same authors demonstrated a range of ozone sensitivities existed among four almond (*Prunus dulcis*) cultivars tested, where Nonpariel was the most sensitive and Mission the least. Sensitivity was evidenced by significant reductions in carbon assimilation, above- and belowground biomass accumulation and foliar injury at ambient and elevated concentrations of ozone. Since over 50% of the producing almond orchards in California are Nonpariel, the authors postulated that a 10% loss in Nonpariel yield could result in a $26 million reduction in production value statewide.

Ozone associated reductions in shoot dry weight and plant height in tomato (*Lycopersicon esculentum*) were accentuated at high relative humidities, 70% and 80%, respectively (Mortensen, 1992). The author hypothesized that the high stomatal conductance associated with high humidity resulted in a greater uptake of ozone. Relative humidities this high occur infrequently during the growing season in the principal tomato production zones of California. Sanders et al. (1992) found near-ambient ozone concentrations representing 7-hr means of 20 to 32 ppb stimulated common bean (*Phaseolus vulgaris*) yield. These are growing season concentrations representative of the coastal areas in the state. Similar to numerous previously completed studies, Sanders et al. found that 7-hr means of 38 and 50 ppb reduced common bean yields by 26% and 42%, respectively. Under laboratory conditions, Tonneijck (1994) discovered that high concentrations of ozone predisposed common bean to infection by *Botrytis cinera*. The author suggested, however, that episodic and chronic exposures to ozone present only a minor concern in increasing susceptibility of bean to *B. cinerea* under field conditions.

Yield reductions in spring wheat (*Triticum aestivum*), attributed to reduced kernel size and number of kernels per spike, were associated with premature senescence of the flag leaf and a reallocation of fixed carbon to belowground biomass following exposure to elevated concentrations of ozone (Fuhrer et al., 1992). Grain quality was unaffected. Results of Fangmeier et al. (1994a; 1994b) concur, in that, ozone induced yield loss was associated with a reduction in kernel number and weight, with no apparent drought X ozone interaction. Reduced yield in wheat from ozone stress was primarily a result of decreased kernel growth rate (slope of the curve when incremental growth was plotted against time); while kernel fill duration and assimilate utilization remained unchanged (Slaughter et al., 1993). In contrast, barley yields were unaffected when plants were exposed to 7-hr mean ozone concentrations of 45 ppb throughout the growing season (Pleijel et al., 1992). Comparable ozone concentrations occur in the Central Valley of California (Mutters and Guzy, 1993). Barley's insensitivity to realistic levels of ambient ozone, as compared to that of wheat, was attributed to a more efficient transport of surplus carbohydrates into the developing kernels from leaves in the lower canopy (Pleijel et al., 1992). Adaros et al. (1990) also found barley to be insensitive to ozone stress at concentrations less than 32 ppb, but incremental yield reductions were observed at increased levels of ozone.

Physiological Response. A frequently observed consequence of environmental adversity is the phenomenon of oxidative stress. By perturbing cellular metabolism, such as photosynthetic processes, many stress factors (e.g., ozone) induce the production of reactive oxygen species, which cause oxidative injury within the plant cell. Protection against oxidative stress is complex and includes both enzymatic and non-enzymatic components. Antioxidant enzymes are key to the defense against the potentially lethal effects of reactive species like superoxide radicals. Van Camp et al. (1994) demonstrated that tobacco genetically altered to produce high levels of superoxide dismutase, an enzyme which converts superoxide radicals to hydrogen peroxide and oxygen, displayed 3- to 4-fold reductions in visible ozone injury. Bender et al. (1994) discovered that levels of cellular antioxidants generally decreased with age in wheat flag leaves exposed to ozone concentrations comparable to summer levels in the lower San Joaquin Valley. Results indicate an increasing susceptibility to ozone as the growing season progresses. Sakaki et al. (1994) examined metabolic changes associated with exposure to 50 pphm ozone for 6-hr in eight crop plants. They found that membrane bound leaf lipids were reduced, apparently due to oxidative degradation. Metabolic perturbations in ozone-stressed parsley were similar to fungal and viral induced defense reactions (Eckey-Kaltenbach et al., 1994).

MATERIALS AND METHODS

Statewide 7-hr Mean Ozone Concentration. The 1990, 1991 and 1992 hourly ozone concentration data from stations in the ARB network were obtained from the Air Resources Board -- Technical Support Division (ARB-TSD). Data were assumed to be quality-assured. The 7-hr ozone concentration statistic presented in the interpolated analysis was used because it was biologically relevant, and it is used in most available crop loss equations, especially those from National Crop Loss Assessment Network (NCLAN). Additionally, unlike cumulative indices such as the SUM06, 7-hr seasonal means are comparable even if growing seasons or data sets are of unequal lengths (Lee et al., 1988).

Interpolation of Ozone Statistics. The boundaries for the air basins were constructed within the GIS based on 1:250,000 Digital Elevation Model (DEM) maps compiled and distributed by the United States Geological Survey (USGS). The DEM was obtained from the Map and Image Library, University of California, Santa Barbara, and the Teale Data Center, Sacramento, California. DEM maps are 1 degree on a side and consist of elevation values spaced every 3 degree-seconds. In relation to projected surface distances in the latitudinal range occupied by California, the elevation spacing is approximately 75 and 90 meters, along the east-west and north-south axes, respectively. Fifty-seven DEM maps are required to cover the state and constitute over 600 megabytes of data in uncompressed format. For this project, a statewide elevation map was used that had been constructed by individually projecting the DEM maps to Lambert Conformal Projection, and then resampled to a 250 meter grid resolution. The Lambert Conformal Projection had the following parameters: latitude of origin = 20.00°, first parallel = 33.00°, second standard parallel = 45.00°, longitude of origin = -120.00°, false easting = 2,000,000 meters, and false northing = 0.00 meters. The resultant grids were then merged into a single statewide coverage and used for all subsequent work.

The air basin boundaries were constructed by resampling the 250 meter grid to a resolution of 5 km using the VIP procedure (ESRI, 1992), to eliminate points in the grid not necessary for describing surface characteristics. The resultant polygon coverage was further simplified, to avoid prohibitively intense computational requirements, by the repeated application of a majority filter in ARC/INFO, to smooth the convoluted interface between the above and below 2000 ft interface. Consequently, the lower resolution air basin did not precisely follow the topology of the actual 2000 ft elevation line. These errors in placement of the air basin boundaries, however, do not compromise the intent of the statewide series of maps. The graphical display of the monthly ARB network ozone data is interpolated within reasonable geographical limits. When required for regional analysis, higher resolution coverages appropriate for modeling air flow complex in mountainous terrain, for example, can also be constructed from the DEM data.

The basin coverage was processed so that grid cells with altitudinal values were range-coded into two groups; above and below 2000 ft. The coverage was projected from Lambert to UTM zone 11, to be consistent with the coordinate system of the ARB supplied ozone data. Small high altitude islands within the air basin were eliminated from the map.

Interpolations. Interpolations were performed within air basins delimited by a 2000 ft altitudinal barrier. The 2000 ft level outlined geographic regions which approximated the administrative boundaries of legal air basins, and is generally below the inversion layer. The areas corresponding to the inversion layer base and above were excluded, because some evidence exists that ozone concentrations at the base of the inversion layer exceed that observed at ground level (Miller et al., 1972). Ozone concentrations in the area above 2000 ft and in the mountainous regions of the state were not included in the interpolations, because little information is available that describes the air flow patterns in the mountain air basins and the ozone monitoring network is relatively sparse.

The 7-hr mean ozone concentration surface for the monthly statewide representation of ozone concentration was interpolated using a 'Inverse Distant Weight' procedure in the ARC/INFO GRID module (ESRI, 1992). The data consisted of 7-hr mean concentrations derived from ozone statistics provided by the ARB. The procedure created a gridded coverage of a geographic region space divided into grid cells 1.6 km on a side (approximately 1 mile). The ozone concentration in a grid cell not containing a monitoring station was computed as the inverse distance squared weighted average of all cells containing stations within a radius of 50 km. A minimum of three known values was required to compute the average. Thus, the 50 km radius was adjusted upward when needed to meet the minimal requirements of the computation procedure. The integrity of the ozone value was preserved in the grid cells containing a monitoring station. Following the interpolation procedure, cells outside the 2000 ft delimited area were deleted using a GIS map overlay and intersect procedure using the air basin coverages. Some of the ARB network monitoring sites were located outside the air basin boundary, especially those in mountainous or remote areas; for example, Lake Gregory, Victorville, and Lake Tahoe. For points excluded from the interpolation, a circular buffer of radius 10 km was centered at the sites. The buffered zone was assigned the concentration of the site contained therein.

Yield Loss Using Interpolated 7-hr Seasonal Means. Yield losses were estimated for three major crops: cotton, grape, and tomato. These crops were chosen because of their economic importance and the considerable acreage planted in each throughout the state. Agricultural production statistics provided by the California Department of Food and Agriculture was used to identify the counties where these crops are grown. The principal production zones for the analysis were the San Joaquin Valley, Sacramento Valley, Salinas Valley, and Imperial Valley. Four digital libraries of statewide coverages (archived at the SAPRC) were used: the Digital Elevation Model, Irrigated Farmlands (Teale Data Center, Sacramento, CA and the Office of Land Conservation, Sacramento, CA), interpolated ozone concentration contours, and county lines.

Farmlands Database. The Teale Data Center was the principal source of digital statewide farmland information, with supplemental coverages of Fresno, Madera, Merced, San Joaquin, and San Luis Obispo counties obtained from the Office of Land Conservation. Digital representations of some counties (e.g., Sutter County) were not available for analysis, and are presented as missing data in the interpolated crop loss maps. The farmland database compiles digital maps captured from 1:24,000 aerial photo interpretation supplemented with field verification or high-altitude color-infrared NASA photographs, categorized according to eight mapping criteria with a minimum mapping unit size of 10 acres, and projected in UTM zones 10 and 11. Because the vast majority of important crops are grown under irrigated conditions, categories describing different classes of irrigated lands were combined using dissolve procedures in ARC/INFO to generate county coverages describing the location and size of farmlands used in the subsequent analysis. The mapping only covers potential farmland areas during the base year of 1988, and therefore the extent of planted acreage may vary slightly between years due to land management practices.

Yield Response Model Application Procedures. In order to apply interpolated ozone statistics to yield loss models, it was necessary to first select an appropriate model from the library of available models and to assign the model as an attribute describing the contour polygons in the ozone contour coverage. The most conservative model (i.e., smallest estimated yield loss) was chosen for cotton, grape, and tomato. Secondly, the polygon attribute tables were modified by creating an additional descriptive variable containing an injury index value comparatively calculated as in the crop loss assessment described above. Where calculation procedures in INFO were used to input the interpolated ozone concentrations into the yield loss equations, and a percent reduction value was assigned to each of the ozone contours. The yield reduction contour and irrigated farmland coverages were intersected within geographic limits defined by major agricultural valleys in the state. Thus, the results provided estimated yield losses within the irrigated farmlands based upon interpolated ozone statistics.

Topographic Presentation of Interpolated Yield Loss Estimates. For 1991, the topographic relief was simulated by using gray scale hillshade imposed on a gridded representation of the USGS DEM with the Z scale enhanced by a factor of 5 and a solar angle of 30 degrees originating from a northwesterly direction. For 1992, the very complex operation of color ramping was added to highlight elevation. The HSV (HUE, SATURATION, VALUE) method of the GRIDCOMPOSITE command was used to create a hillshaded display of a lattice which was shaded by elevation range. The lattice (previously obtained from a California DEM) was converted into three new lattices, each supplying one component of the HSV color model. The HUE is determined by the elevation range; the SATURATION is assigned according to broad elevation ranges and to fit particular hues; and the VALUE is determined by illumination intensity and angle of the sun.

Creation of the HUE Lattice. Each cell in the CALDEM lattice was converted into a hue value. Using the elevation values in each cell to obtain its corresponding value within a desired hue range allows the effective color ramping of the surface. Several consecutive grids in which the item value (i.e., grid elevation) was replaced with hue values corresponding to the various elevation bands, from -120 to 4400 meters. The HUE values used were designed to range between 120 ('greens' for lowlands), to 15 ('orange-brown' for mountains). Areas with negative elevations were assigned a single hue value of -1 ('tan'), whereas mountain peaks were assigned a hue value of 0 ('white'). Elevations and the corresponding hue ranges are presented in Table 1.

Table 1. Elevations and Corresponding Hue Ranges used for Color of California DEM.	
Elevation Range (meters)	Hue Range (degrees)
0 - 450	120 - 95
450 - 1050	60 - 40
1050 - 1500	40 - 30
1500 - 2200	30 - 15
2200 - 3000	210
> 3000	0

Each elevation range was "standardized" to degrees by dividing the elevation range "length" by the desired hue range. A constant saturation value of 30% with a value range for shadowing of 50 to 100% illumination originating from the northwest at a solar angle of 20 degrees was used for all maps. The intersected yield loss contours/irrigated farmlands coverage was then 'draped' over the hillshaded DEM.

Standardized elevations were added as value X so that they could be stretched over the desired hue range:

$$SEF_n = -(\text{elevation band} / \text{hue range})$$

$$HUE_{in} = (E_i / SEF_n) + X$$

Where: SEF_n = the "standardized" elevation factor for the n-th lattice;
HUE_{in} is the hue value within the i-th grid cell for the n-th lattice; and
E_i is the elevation value for the i-th cell.

As an example, hues for the range 0 - 450 m were obtained as follows:

Elevation band = (450 - 0) = 450 meters
Hue range = (120 - 95) = 25 degrees

$SEF_1 = -(450/25) = -18$ meters/degree
$HUE_{i1} = (E_i/-18) + 120$

For example, a cell with an elevation of 200 m in the DEM would be assigned the following hue value:

$$HUE = (200/-18) + 120 = 108.89$$

Hues for the range 450 - 1,050 m were obtained as follows:

Elevation band = (1050 - 450) = 600 m
Hue range = (60 - 40) = 20 degrees

SEF_2 = -(600/20) = -30 meters/degree
$HUE_{i2} = (E_i/-30) + 63.333$

Thus, a cell with an elevation of 451 m was assigned a hue value of:

$$HUE = (451/-30) + 63.333 = 48.3.$$

Statewide Crop-by-County Aggregated Yield Loss Assessments. Estimated potential yield losses due to ozone injury were estimated for 1991 and 1992 using hourly ozone data obtained from the ARB-TSD and published models describing crop response to ozone. Crop data were obtained from the Statistics Division of the California Department of Food and Agriculture. Estimated statewide yield losses for 20 crops were calculated using aggregated county-wide statistics. Data from nearby air quality monitoring stations and within the same air basin as the crop production zones, were used to calculate 7-hr and 12-hr mean exposure statistics used in the yield loss models. Exposure statistics were based on the data from the months encompassing the growing season of each crop. Ozone data from 0900 to 1600 PST, and 0800 to 2000 PST were used for the 7-hr and 12-hr means, respectively.

Background Ozone Concentrations. Background concentrations (no yield loss) were used as a standard against which current losses were compared. The estimated yield losses were calculated using 2.72 and 2.50 pphm ozone in the 7-hr and 12-hr means, respectively. The 12-hr base concentration was used by NCLAN researchers (e.g., Heck et al., 1984a; 1984b), and it represents relatively clean air. The 7-hr base concentration was calculated with the following equation: 7-hr = (12-hr - 0.004143) x 0.919 (Thompson et al., 1976). The 0.22 pphm difference between the two background concentrations was shown to have less effect on yield loss than other factors, such as the geographic resolution used in the analysis (Heck et al., 1984a). It is noteworthy that both background concentrations represent ozone levels found in pristine environments, and are probably not attainable in any crop production zone in California. The reported yield losses were, therefore, overestimated. They were retained to provide consistency with past crop loss estimates for comparative purposes.

Seven-hour average concentrations of ozone in the San Joaquin Valley may typically range from 4.5 to 5.5 pphm. A 10-hr base ozone concentration of 2.59 pphm was used for potato (Pell et al., 1988). The value was calculated by linear interpolation between 2.5 and 2.72.

Yield Loss Equations. SUM06 models were added to the Crop Loss computer programs (Table 2). Ten models were chosen from among 54 SUM06 models provided (Appendix, Table A) courtesy of Dr. H. Lee, ManTech, Corvallis, Oregon. SUM06 models are Weibull functions with the following form:

$$Y = A \exp(-X / B)^{C}$$

where:
- Y = yield;
- A = maximum yield at zero ozone;
- X = seasonal ozone concentration;
- B = ozone concentration where A is reduced by 63 %;
- C = dimensionless shape parameter.

Table 2. Exposure-response Curves using 24-hr SUM06 Values (pphm-hr) for Selected NCLAN Cases.

Crop	Cultivar	A	B	C	R^2	10%*	30%*
Corn	Pioneer	7317	92.6	2.82	0.93	42	64
Corn	Pag	8155	94.4	4.32	0.80	56	74
Cotton	Acala	9808	71.2	2.00	0.96	23	43
Cotton	Acala	7859	78.0	1.31	0.85	14	36
Dry Bean	Cal Lt Red	2488	27.4	3.89	0.72	15	21
Dry Bean	Cal Lt Red	2489	44.2	2.69	0.71	19	30
Lettuce	Empire	7197	54.9	5.51	0.74	37	46
Potato	Norchip	5901	93.8	1.00	0.63	10	34
Wheat	Abe	5150	53.9	3.08	0.90	26	38
Wheat	Arthur	4456	60.9	2.18	0.92	22	38

* SUM06 corresponding to the prescribed % loss (after Lee et al., 1988)

SUM06 is the sum of hourly ozone values at and above 6 pphm summed over the total number of hours and days for each month. Missing hourly data adjustments for SUM06 were performed as follows:

SUM06 = (Full # of hr x SUM06)/(observed # of hr).

Where "full # of hours" means the total possible hours for the month and "observed # of hr" means the number of hours with reported ozone values. "Observed" is not the same as the number of hours at or above 6 pphm. The "SUM06" on the right of the equal sign is the accumulated sum from the ozone data file; the "SUM06" on the left of the equal sign is the SUM06 adjusted for missing data.

The number of hours at or above 6 pphm each month was adjusted in the same manner as SUM06 and was printed out in the exposure statistics by month for each site (Appendix, Table B and C).

Missing data adjustments (above) were made if the following criteria were met:

1. If more than three hourly ozone readings were missing between 9:00 a.m. and 8:00 p.m. inclusive (0900-2000 PDT) or if more than nine hourly ozone readings were missing over the whole 24-hr period, then the whole period was considered missing;

2. If the month did not have at least 21 days of available data, the whole month was considered missing;

3. If the month had 21 or more days of available data, but fewer than its total number of days, it was adjusted to a full month:

SUM06 = (Full # days x SUM06)/(Observed # days).

An explanation of the terms and % yield loss calculations is presented in Table 3. Crops where no losses were observed under experimental conditions at ozone concentrations expected to occur during the appropriate growing season are listed in Table 4. A maximum of four models per commodity were used for estimating 1991 yield losses. In contrast, up to eight models were used in 1992. Table 8 presents predicted yield losses in 1992 from a maximum of four models per crop. Thus, 1991 and 1992 values could more readily be compared. Results from all models employed in 1992 are presented in Table F of the Appendix.

Table 3. Description of the Terms and Procedures used to Estimate Statewide Yield Loss due to Ozone on a County-basis.

Yield Loss Equation (Linear Example)
Yield = a + (b x ozone exposure) Where: Yield = value observed at a given level of ozone exposure; and Ozone Exposure = 7-hr, 10-hr, or 12-hr mean ozone concentration (pphm).
Yield Loss Index Equation (I)
$I = (a + bX)/(a + bX^1) = 1$ Where: I = loss index as a fraction of 1.00, if I = 1 then no loss from ozone; X = ozone exposure; and X^1 = background ozone index (e.g., 2.72 and 2.50 for 7-hr and 12-hr mean concentrations, respectively.
Percent Yield Loss Equation
Percent Loss = (1.00 - I) x 100
Potential Yield Loss Equation
Potential Loss = (Actual Yield/ I) Where: Actual Yield = Aggregated county production statistics from the CDFA.
Statewide Potential Yield Loss Equation
Statewide Potential Yield = (Actual Yield)/(Potential Yield) Where: Actual Yield = Sum of all reported yields from all counties for a single crop.
Statewide Percent Yield Loss Equation
Statewide Percent Loss = (1.00 - Statewide Potential Yield) x 100

Table 4. Crops where No Yield Reductions were Observed in Response to Ozone Exposure under Controlled Experimental Conditions.	
Crop	Reference
Barley	Temple et al. (1985a)
Broccoli	Temple et al. (1990)
Celery	Takemoto et al. (1987)
Green pepper	Takemoto et al. (1987)
Strawberry	McCool et al. (1986)
Sugar beet	McCool et al. (1986); Brewer (1978)

$Base_7$ = 7-hr mean for background ozone = 2.72 pphm.
$Base_{12}$ = 12-hr mean for background ozone = 2.50 pphm.

Alfalfa Hay

1. $I = [32.67 - (1.3902 \times 12\text{-hr})]/[32.67 - (1.3902 \times Base_{12})]$

   -- Olszyk et al. (1986).

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

   -- McCool et al. (1986).

   Where: 10 pphm = [max observed hourly ozone - 10];
   the sum of hourly values > 1 pphm over the entire season.

3. $I = [118.96 - (4.088 \times 12\text{-hr})]/[118.96 - (4.088 \times Base_{12})]$

   -- Brewer (1982).

4. $I = [3{,}160 - \text{base year} - (109.63 \times 12\text{-hr})]/[3{,}160 - \text{base year} - (109.63 \times Base_{12})]$

Equation adapted from Temple et al. (1988) which considered ozone, water stress, and year. The loss estimates assumed that all alfalfa was grown under well-watered conditions, thereby omitting the water stress term.

Alfalfa Seed

Alfalfa hay predictive equations were used.

Beans - Dry

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

   -- McCool et al. (1986).

2. $I = [2{,}878 \times e\text{-}(7\text{-hr}/12.0)^{1.171}]/2{,}878 \times e\text{-}(Base_7/12.0)^{1.171}]$

   -- Heck et al. (1984a).

Equations 3 through 5 are for four different cultivars of dry bean, exposed to three concentrations of ozone at UCR in 1987 (personal communication; P. Temple, UCR).

3. $I = [163.6 - (9.787 \times 12\text{-hr})]/[163.6 - (9.787 \times Base_{12})]$

   -- Ozone response equation for bean cultivar 'Sal Small White'.

4. $I = [165.8 - (13.57 \times 12\text{-hr})]/[165.8 - (13.57 \times Base_{12})]$

   -- Ozone response equation for bean cultivar 'Sutter Pink'.

5. $I = [167.6 - (13.98 \times 12\text{-hr})]/[167.6 - (13.98 \times Base_{12})]$

   -- Ozone response equation for bean cultivar 'Yolano Pink'.

Cantaloupes

1. $I = [35.8 - (2.808 \times 7\text{-hr}]/[35.8 - (2.808 \times Base_7)]$

This equation was calculated from data in Snyder et al. (1988) for muskmelon, and are not specifically for cantaloupes, honeydew melons, or watermelons. The equation, however, was used for the above three crops as it is the only one available. Ozone concentrations were calculated for 0900-1600 CST from figures in the paper, and yield from data in the text. In 1986, ozone concentration (pphm) and yield (kg/chamber) were 1.35 and 31.3 for charcoal-filtered air, and 3.65 and 24.9 for nonfiltered air, respectively. In 1987, ozone concentration and yield were 3.2 and 28.9 for charcoal-filtered air, and 4.4 and 22.6 for nonfiltered air, respectively. A linear regression equation was calculated from these data to describe the relationship between ozone concentration (x) and yield (y).

Corn - Field

1. $I = [11{,}618.5 \times e\text{-}(7\text{-hr}/16.0)^{3.709}]/[11{,}618.5 \times e\text{-}(Base_7/16.0)^{3.709}]$

   -- Kress and Miller (1985).

Corn - Silage

1. $I = [11{,}618.5 \times e\text{-}(7\text{-hr}/16.0)^{3.709}]/[11{,}618.5 \times e\text{-}(\text{Base}_7/16.0)^{3.709}]$

– Kress and Miller (1985).

The entire plant is harvested for silage, unlike field corn, where only the grain is the marketable product. This equation was developed from field corn research, therefore, it would not reflect the changes in leaf mass associated with ozone exposure.

Corn-Sweet

1. $I = [315.02 - (12\text{-hr} \times 8.2988)]/[315.02 - (\text{Base}_{12} \times 8.2988)]$

– Thompson et al. (1976).

Cotton

1. $I = [367 \times e\text{-}(7\text{-hr}/11.1)^{2.71}]/[367 \times e\text{-}(\text{Base}_7/11.1)^{2.71}]$

– Heagle et al. (1986).

2. $I = [0.8462 + (.049 \times 7\text{-hr})]/[0.8462 + (.049 \times \text{Base}_7)]$

– Brewer et al. (1982).

3. $I = [2{,}059 - (82 \times 7\text{-hr})]/[2{,}059 - (82 \times \text{Base}_7)]$

– Temple et al. (1985b).

4. $I = [1{,}988 - (1545.32 \times (7\text{-hr})^2)]/[1{,}988 - (1545.32 \times (\text{Base}_7)^2)]$

– Temple et al. (1985b).

5. $I = [32.3 - (2.025 \times 12\text{-hr})]/[32.3 - (2.025 \times \text{Base}_{12})]$

– Ozone response equation for cotton variety 'C1' from Temple (1990b).

6. $I = [38.6 - (2.663 \times 12\text{-hr})]/[38.6 - (2.663 \times \text{Base}_{12})]$

– Ozone response equation for cotton variety 'GC 510' from Temple (1990b).

7. $I = [32.6 + (3.535 \times 12\text{-hr}) - (0.6721 \times (12\text{-hr})^2)]/[(32.6 + (3.535 \times \text{Base}_{12}) - (0.6721 \times (\text{Base}_{12})^2)]$

– Ozone response equation for cotton variety 'SS2086' from Temple (1990b).

Grain Sorghum

1. $I = [8{,}149 \times e\text{-}(7\text{-hr} / 31.7)^{2.952}]/[8{,}149 \times e\text{-}(Base_7/31.7)^{2.952}$

-- Kress and Miller (1985).

Grapes

1. $I = [9{,}315 - (647 \times 12\text{-hr})]/[9{,}315 - (647 \times Base_{12})]$

-- Thompson and Kats (1970).

2. $I = [1.121 - (0.0663 \times 12\text{-hr})]/[1.121 - (0.0663 \times Base_{12})]$

-- Brewer (1983).

Lemons

1. $I = (-[0.5004 + (0.6224 \times 12\text{-hr})]/[0.5004 + (0.6224 \times Base_{12})] + 1] \times -0.5) + 1$

After 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.

Lettuce

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

-- McCool et al. (1986).

2. $I = [3{,}187 \times e\text{-}(7\text{-hr}/12.2)^{8.837}]/[3{,}187 \times e\text{-}(Base_7/12.2)^{8.837}]$

-- Temple et al. (1986).

Onions

1. $I = [11.1 - (0.881 \times 12\text{-hr})]/[11.1 - (0.881 \times Base_{12})]$

-- McCool et al. (1986).

2. $I = [5{,}034 - (109.41 \times 12\text{-hr})]/[5{,}034 - (109.41 \times Base_{12})]$

-- Temple et al. (1990).

Oranges

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

   -- Olszyk (1989).

2. $I = (-[53.7 - (12\text{-hr} \times 2.611)]/[53.7 - (Base_{12} \times 2.611)] + 1] \times -0.05) + 1$

   -- Kats et al. (1985) and Olszyk et al. (1990). The ozone data were for the two-years preceding the harvest.

Potato

1. $I = [11{,}736 - (390 \times 10\text{ hr})]/[11{,}736 - (390 \times Base_{10})]$

   -- Ozone concentration from 1000-2000 EDT for tuber weight; Pell et al. (1988).

2. $I = [5{,}848 - (347.6 \times 10\text{ hr})]/[5{,}848 - (347.6 \times Base_{10})]$

   -- Pell et al. (1988).

Rice

1. $I = [1.0851 \times e\text{-}(7\text{-hr} \times 0.0275)]/[1.0851 \times e\text{-}(Base_7 \times 0.0275)]$

   -- Kats et al. (1985).

2. $I = [1.0687 - (0.024 \times 7\text{-hr})]/[1.0687 - (0.024 \times Base_7)]$

   -- Linear regression fitted to the data from Kats et al. (1985).

3. $I = [e\text{-}(7\text{-hr}/20.16)^{2.474}]/[e\text{-}(Base_7/20.16)^{2.474}]$

   -- Weibull function fitted to the data from Kats et al. (1985).

Tomato - Fresh Market

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

   -- McCool et al. (1986).

Tomato - Processing

1. $I = [100 - (2.28 \times 10^{-2} \times 10 \text{ pphm})] \times 0.01$

   -- McCool et al. (1986).

2. $I = [32.9 \times e\text{-}(7\text{-hr}/14.2)^{3.807}]/[32.9 \times e\text{-}(Base_7/14.2)^{3.807}]$

   -- Heck et al. (1984b).

3. $I = [9{,}055 - (323.67 \times 12\text{-hr})]/[9{,}055 - (323.67 \times Base_{12})]$

   -- Ozone response equation for tomato variety 'FM785' from Temple (1990a).

4. $I = [6{,}315 - (210.7 \times 12\text{-hr})]/[6{,}315 - (210.7 \times Base_{12})]$

   -- Ozone response equation for variety 'UC204C' from Temple (1990a).

5. $I = [8{,}590 - (412.8 \times 12\text{-hr})]/[8{,}590 - (412.8 \times Base_{12})]$

   -- Ozone response equation for tomato variety 'E6203' from Temple (1990a).

Wheat

1. $I = [5{,}295 \times e\text{-}(7\text{-hr}/14.5)^{3.326}]/[5{,}295 \times e\text{-}(Base_7/14.5)^{3.326}]$

   -- Kress and Miller (1985).

2. $I = [7{,}857 \times e\text{-}(7\text{-hr}/5.3)^{1.000}]/[7{,}857 \times e\text{-}(Base_7/5.3)^{1.000}]$

   -- Heck et al. (1984b).

Calculation of Ozone Exposure Crop Loss Percentages. Where possible, crops restricted to particular regions within counties were matched with ozone statistics from stations in those same regions. For example, crops grown in the Coachella Valley of Riverside county were matched to nearby stations, and not to stations located in the Riverside metropolitan area. Additionally, the closest monitoring stations were not always located in the same county where the crops were grown. For example, vegetable production in Santa Barbara county is primarily in the area of Santa Maria. Monitoring stations closest to that city were located in southern San Luis Obispo county. One ozone value for an entire county was used in most cases, which may represent the average concentration over several sites where the crop was grown.

Multivariate Analysis of Variables Influencing Cotton Yield. Original agronomic data collected from 30 field sites in the San Joaquin Valley in 1990 was provided by Dr. T. Kerby, former UC Cotton Specialist, Shafter Experiment Station, Shafter, California. The site specific measured variables (Table 5) from 21 of Kerby's 30 sites were paired with 1990 interpolated 7-hr mean ozone indices (May, June, July and August) and used as predictive variables in a regression analysis of yield variability across location. Only agronomic data from the 21 sites falling within the ozone interpolation boundaries were used.

Table 5. Agronomic Variables* and Ozone Exposure Index Concentrations used in the Regression Analysis of Cotton Yield Variability in the San Joaquin Valley of California for the 1990 Growing Season.

Variable	Variable	Ozone Index
Planting Date	Soil K	May Ozone
Seeding Rate	Soil Zn	June Ozone
Plant Density	Soil pH	July Ozone
Row Spacing	Soil Saturation %	August Ozone
Harvest Date	Soil EC	
Plant Height	Petiole P	
No. of Nodes	Petiole K	
Soil N	Petiole Zn	
Soil P		

* From T. Kerby, 1990.

The monthly ozone values were highly correlated ($R^2 > 0.96$, data not shown). Therefore, for the 1990 season, any one month would have sufficed for the analysis. Yield was plotted against each of the independent variables to check for possible curvilinear effects or spurious data points. Only yield versus density was identified as such and therefore a density-squared term was also entered into the analysis.

Both stepwise and backward regression analyses were conducted. No noteworthy differences between the two approaches were detected, therefore, only the results from the stepwise analysis were included herein. The initial stepwise regression was run with P to enter set at 0.15, to identify variables of possible significance, including the four monthly ozone concentrations. The remaining variables were used incrementally in a stepwise fashion in decreasing order of probable significance.

Ozone Injury to Cotton in the San Joaquin Valley. A field survey to identify the extent and severity of ozone injury to cotton in the Central Valley was conducted during August and September, 1992. Eleven locations were surveyed from southern Kern to Madera county, on both the east and western sides of the Valley (Table 6 and Appendix, Table D).

Cotton observation plots were established in variety trials conducted by Dr. R. Bassett, USDA Agronomist, Shafter Experiment Station, Shafter California. A photographic record of the development of injury symptoms throughout the season was maintained. Characteristic foliar ozone injury symptoms in cotton are interveinal chlorotic mottling and leaf bronzing.

Plant stands in each observation plot were thinned to a plant density of four plants per meter to ensure that canopy closure did not contribute to early leaf senescence, a symptom associated with ozone injury in cotton. Plot row length was two meters. Five representative plants were chosen for evaluation within each row.

Injury evaluations were based on a 0-10 scale where 0 corresponded to 0% of the leaves affected (essentially all leaves green and healthy). Ten corresponded to 100% of the leaves injured and/or abscised. A rating of 2, therefore, indicated that 20% of the leaves exhibited ozone injury symptoms. A rating of 5 indicated 50% of the leaves were affected, and so forth. The fraction of senescent and dropped leaves (bare nodes) per plant was determined by a cumulative count and rounded off to the nearest 10% increment. All sites were visited within a three-day period.

Table 6. Location of the Observation Plots for Evaluating Ozone Injury to Cotton in the San Joaquin Valley in 1992.	
Location No.	Closest Town
1	Arvin
2	Wasco
3	Buttonwillow
4	Tulare
5	Corcoran
6	Lemoore
7	Five Points
8	Madera
9	Firebaugh
10	Chowchilla

The leaf injury ratings for cotton described above were expressed as follows to produce a single value for injury. Injury ratings ranged from 0 and 1, where plants with an injury rating of 1 had injury on all leaves.

Injury Rating = (D + I)/(D + I + G)

Where: D = number of empty nodes where leaves dropped off;
I = number of leaves showing injury symptoms; and
G = number of green unaffected leaves.

Thus, a rating of 1 indicated that all leaves were affected by ozone as indicated by foliar lesions or premature abscission; a rating of 0 indicated no visible signs of injury. Values were determined on the main stem.

The evaluation variables were subjected to a principal component analysis to ascertain the relative importance of each to the final injury rating (Goldstein and Dillion, 1983). A weighted injury (WI) was calculated based upon the relative contribution of each component (D, I, or G) to the overall observed injury level to the plants. The occurrence of foliar injury symptoms were correlated with yield across locations.

RESULTS AND DISCUSSION

Yield Loss Estimates. Statewide estimated yield losses in 21 crops were estimated by comparing actual yields to those that may have occurred in 1991 and 1992 (Tables 7 and 8). Background levels were either 2.50 or 2.72 pphm, for 12-hr and 7-hr means, respectively. These background concentrations are based upon the results of the NCLAN program. Whether the 12-hr or 7-hr mean was used for comparison depends upon the crop specific projection model as discussed in Materials and Methods. Yield in tons represents the actual harvested yield. Potential yield was calculated by adjusting the actual yield by percent loss. Losses for each commodity by county are presented in expanded form in Tables E and F in the Appendix. Monthly ozone exposure indices for all reporting monitoring stations in 1991 and 1992 are listed in Tables B and C in the Appendix.

In 1991, estimated statewide weighted average yield losses for alfalfa ranged from 0.5% to 13% for models 2 and 1, respectively (Table 7). Estimated losses were higher than predicted during the two previous years with 7.1% and 7.9% losses in 1989 and 1990, respectively. The apparently small impact of ozone on statewide yields of alfalfa were not unexpected, because it is periodically harvested during the growing season. Therefore, the foliage is exposed to ambient ozone for relatively short periods of time during vegetative stages of development. The highest losses were estimated to occur in production areas with high ambient ozone, such as Los Angeles (25%), Kern (20%), and San Bernardino (22%) counties using model 1 (Table E, Appendix). Alfalfa grown for seed, however, is not harvested for hay and the leaves would experience a greater ozone exposure, as evidenced by the slightly greater predicted loss. The losses were estimated using models developed for alfalfa hay where the foliage was periodically harvested and therefore may be an underestimate.

Yield loss in dry bean ranged from 1.5% to 20% in 1991. Among the major bean producing counties, losses were greatest in Kern (32%), Merced (15%), and Fresno (26%) counties using model 4 (Appendix Table E). Orange county experienced the greatest losses (49%), where a relatively few number of acres were planted in bean, and therefore constituted a small fraction of the total statewide production. Cantaloupe yield was estimated to be reduced by 32% statewide; and the highest losses were expected to occur in Fresno county (38%). Notably, the predictive model used for cantaloupe was derived from data describing the response of muskmelon to ozone, and should be viewed as only an indicator of potential loss. Sweet corn yields were reduced by an estimated 6 % in 1991.

Average yield loss in cotton was 19% statewide in 1991 (Table 7), with a range from 15% to 28% for models 8 and 4, respectively. Yields in the Imperial Valley (8% loss) were the least affected by ozone. In contrast, yields were estimated to be reduced by as much as 20% in Kern and 17% in Merced counties, using model 3 for comparison. These are predicted losses based on aggregated county-wide statistics and the losses are not necessarily distributed uniformly across the individual counties.

Overall, grape yields were reduced by 23% statewide. In counties with substantial acreage, potential losses in Riverside county (33%) were the highest, whereas the grape yields in Napa and Monterey counties were essentially unaffected (Appendix Table E). The same predictive equations were used for all types of grapes. The variability in average yield losses among the different types of grape reflected different ambient ozone concentrations in a particular growing region. Yields in lemon were reduced by 8%. In contrast, orange yields may have been reduced by 27% statewide. The large difference was attributable to the results of model 2, which predicted a 56% yield reduction in orange at ambient ozone concentrations in some regions (Table E). The model has subsequently been omitted from the yield loss computer program, because the results were not consistent with field observations or comparisons of actual yields between two production areas with contrasting air qualities.

Rice yields were relatively unaffected (3.5% on average), a function of the relatively good air quality in the northern portion of the Sacramento Valley and intrinsic tolerance to ozone stress. Indications of the relative tolerance of a particular crop to ozone stress is evidenced by a consistency in actual yields across production zones with different degrees of air pollution during the growing season. Relatively minor losses were observed in silage, sorghum, fresh and processing tomatoes, and wheat with average losses of 2%, 0.6%, 0.5%, 3% and 5.3 %, respectively.

Estimated yield losses in 1992 (Table 8) were generally comparable for most crops as compared to estimated losses in 1991 (Table 7). Highest estimated yield losses occurred in cantaloupe, cotton, grape-all, grape-raisin, and grape-table with 32%, 17%, 23%, 27%, and 24%, respectively. Losses were the greatest in the counties of the San Joaquin Valley and in those regions in and around the South Coast Air Basin (SoCAB). Yield losses between 10% and 20% were predicted for bean, grape-wine, orange, and potato. Reductions of less than 10% were expected to have occurred in alfalfa hay and seed, corn-sweet, lemon, lettuce, rice, silage, sorghum-grain, sugar beet, tomato-fresh, tomato-processing, and wheat.

Table 7. Statewide Predicted Yield Losses Associated with Ozone, 1991 (Appendix, Table E).

Crop	Yield (tons)	—— Predictive Model —— 1	2	3	4	Mean
Alfalfa	8,192,579	12.9	0.5	10.2	10.3	8.5
Alfalfa – seed	20,741	15.2	0.6	12.0	12.1	10.0
Beans – dry	193,589	1.5	19.6	0	18.3	9.9
Cantaloupe	551,203	31.5	—	—	—	31.5
Corn – sweet	73,408	5.7	—	—	—	5.7
Cotton	659,903	18.1	15.1	16.0	27.5	19.2
Grape – all	3,983,290	25.5	20.8	—	—	23.2
Grape – raisin	2,265,061	29.8	24.6	—	—	27.2
Grape – table	624,657	29.8	24.5	—	—	27.2
Grape – wine	2,137,025	20.9	17.0	—	—	19.0
Lemon	552,675	8.2	—	—	—	8.2
Lettuce	3,307,765	0	1.2	0	0	0.3
Onion	997,156	18.5	4.1	—	—	11.3
Orange	1,048,001	16.8	8.3	—	—	12.6
Rice	1,472,608	4.5	4.3	1.8	—	3.5
Silage	7,605,046	1.8	—	—	—	1.8
Sorghum – grain	10,582	0.6	—	—	—	0.6
Tomato – fresh	625,080	0.5	—	—	—	0.5
Tomato – process	10,011,403	0.9	2.2	0	8.8	3.0
Wheat	1,223,362	0.4	10.2	—	—	5.3

Table 8. Statewide Predicted Yield Losses Associated with Ozone, 1992 (Appendix, Table F).						
	Yield	—— Predictive Model ——				
Crop	(tons)	1	2	3	4	Mean
Alfalfa	7,373,770	13	0.2	10.2	10.3	8.5
Alfalfa – seed	15,884	14.9	0.6	11.7	11.8	9.8
Beans – dry	161,470	0.4	18	0	16.7	8.8
Cantaloupe	561,383	32.2	—	—	—	32.3
Corn – sweet	134,171	5.8	—	—	—	5.8
Cotton	752,896	16.4	14.3	15	23.8	17.4
Grape – all	5,788,934	25.8	21.2	—	—	23.4
Grape – raisin	2,842,431	29.1	24	—	—	26.6
Grape – table	7,244,165	26.7	22	—	—	24.4
Grape – wine	2,037,589	22.2	18.2	—	—	20.2
Lemon	722,126	9.2	—	—	—	9.2
Lettuce	3,014,892	0	0.8	—	—	0.4
Onion	884,530	14.4	3.3	—	—	8.9
Orange	2,553,885	18.5	9.2	—	—	13.9
Rice	1,700,814	6.4	5.7	2.7	—	4.9
Silage	5,733,269	2.1	14.3	6.1	—	7.5
Sorghum – grain	14,801	0.5	—	—	—	0.5
Tomato – fresh	567,792	0.6	—	—	—	0.6
Tomato – process	8,526,907	1.1	2.7	0	9.8	3.4
Wheat	1,485,192	0.3	9.8	—	—	5.1

Statewide Interpolations, 1991. The twelve maps, one for each month in 1991, which show statewide 7-hr mean ozone concentrations at the ARB network sites, and points in between where interpolation was possible, demonstrate the extreme seasonal variability in air quality within and between the major air basins of California in 1991 (Figures 1 through 12). During January (Figure 1) the mean ozone concentrations of all interpolatable regions were between 0 and 4 pphm, except for four locations at elevations presumably near the inversion layer base. Sites in the Los Padres National Forest (near Santa Barbara), and Alpine-Victoria (in the hills east of the San Diego metropolitan area) were also higher when compared to the adjacent areas. The limits of the interpolation are apparent on the eastern edge of the Imperial and Coachella Valleys (Figure 1).

Ozone concentrations increased around most metropolitan areas during February of 1991 (Figure 2). Interestingly, the air quality began deteriorating in the Fresno, southern San Joaquin Valley and San Diego areas before the area surrounding San Bernardino and Riverside metropolitan areas, which characteristically experience some of the highest ozone levels in the state.

In March, higher ozone concentrations were observed in the majority of the San Joaquin and SoCAB (Figure 3). The area around Alpine, west of San Diego, continued to report some of the highest ozone concentrations in the state during March and April (1991 Figure 4). The transport of air pollution from the valley floor to the mountains surrounding the SoCAB was apparent during April when the Lake Gregory station in the San Bernardino mountains reported mean ozone values of 6 to 8 pphm. A similar statewide distribution of air quality trends was observed in May, except the influence of the Bakersfield metropolitan area became apparent on regional air quality in the southern San Joaquin Valley (Figure 5). Otherwise, the ozone levels across the state in March and April were comparable.

The months of April through October saw much of the monitored area affected by 7-hr means in excess of 4 pphm. The only exceptions were some coastal areas in Los Angeles, Santa Barbara, western Fresno and Merced counties, and the central coastal region and the northern Sacramento Valley.

A substantial increase in ozone concentration during June as compared to previous months (Figure 6) coincided with the occurrence of higher temperatures and the development of an inversion layer over the valleys in the southern portion of the state. Mean ozone concentrations jumped from around 4 pphm to greater than 8 pphm in the eastern SoCAB. On the eastern side of the San Joaquin Valley from south-of-Bakersfield to north-of-Fresno, the 7-hr means were at levels known to significantly reduce the yield in some crops under experimental conditions (NCLAN). Ozone levels in the Alpine area remained high, while in the coastal areas from Point Conception north to Point Reyes, ozone concentrations were relatively constant during the first six-months of the year.

Air quality in the communities adjacent to and in the mountains surrounding the SoCAB was at its worst during July 1991, with the 7-hr mean ozone concentration exceeding 8 pphm over a large area of the basin (Figure 7). Moreover, ozone concentrations in Bakersfield and Fresno were comparable to those observed in parts of the SoCAB. In agricultural areas south of these metropolitan areas, ozone levels were greater than 8 pphm in July, when a large portion of the major crops are in, or approaching, the reproductive stage of development. The area of intense ozone exposures shrank in August (Figure 8) relative to July. Only the areas that experience consistently poor air quality during the summer months, such as Glendora, Riverside, Lake Gregory, and Bakersfield, reported concentrations greater than 8 pphm in August. Statewide, air quality in September (Figure 9) was comparable to that observed in August, except ozone levels were greater around Bakersfield and Fresno.

The decrease in daytime temperatures and the breakup of the inversion layer over the major air basins in California resulted in an improvement in air quality at all reporting stations in October (Figure 10). Mean ozone concentrations across the state during October, November (Figure 11) and December (Figure 12) were comparable to those reported in March, February, and January, respectively, of the same year.

A number of observations comparing sites at elevations in excess of 2000 ft, near the base of the inversion layer, with nearby sites at lower elevations in the air basins, demonstrated vertical differences in ozone concentrations, with the higher altitude sites exposed to significantly greater ozone doses. Distinct differences in ozone exposure were seen between sites near the inversion base vs. nearby lower altitude sites (e.g., Lake Gregory vs. San Bernardino Fourth Street, Alpine-Victoria vs. El Cajon, and Los Padres National Forest vs. Santa Barbara). The importance of assessing the effects of elevated ozone concentrations on natural resources at and above the inversion layer base remains unresolved.

Figure 1. Statewide 7-hr Mean Ozone Concentration for January 1991.

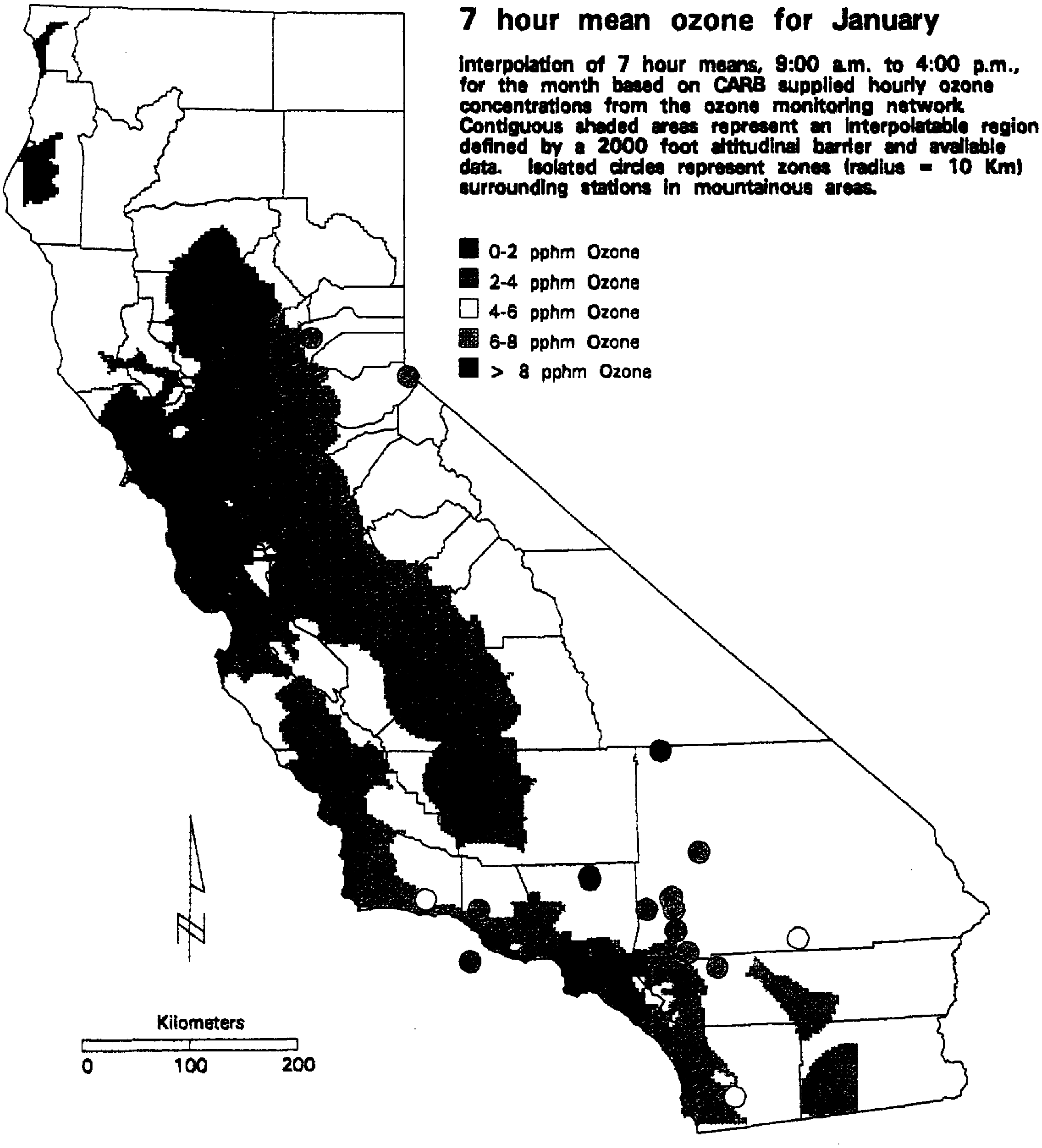


Figure 2. Statewide 7-hr Mean Ozone Concentration for February 1991.

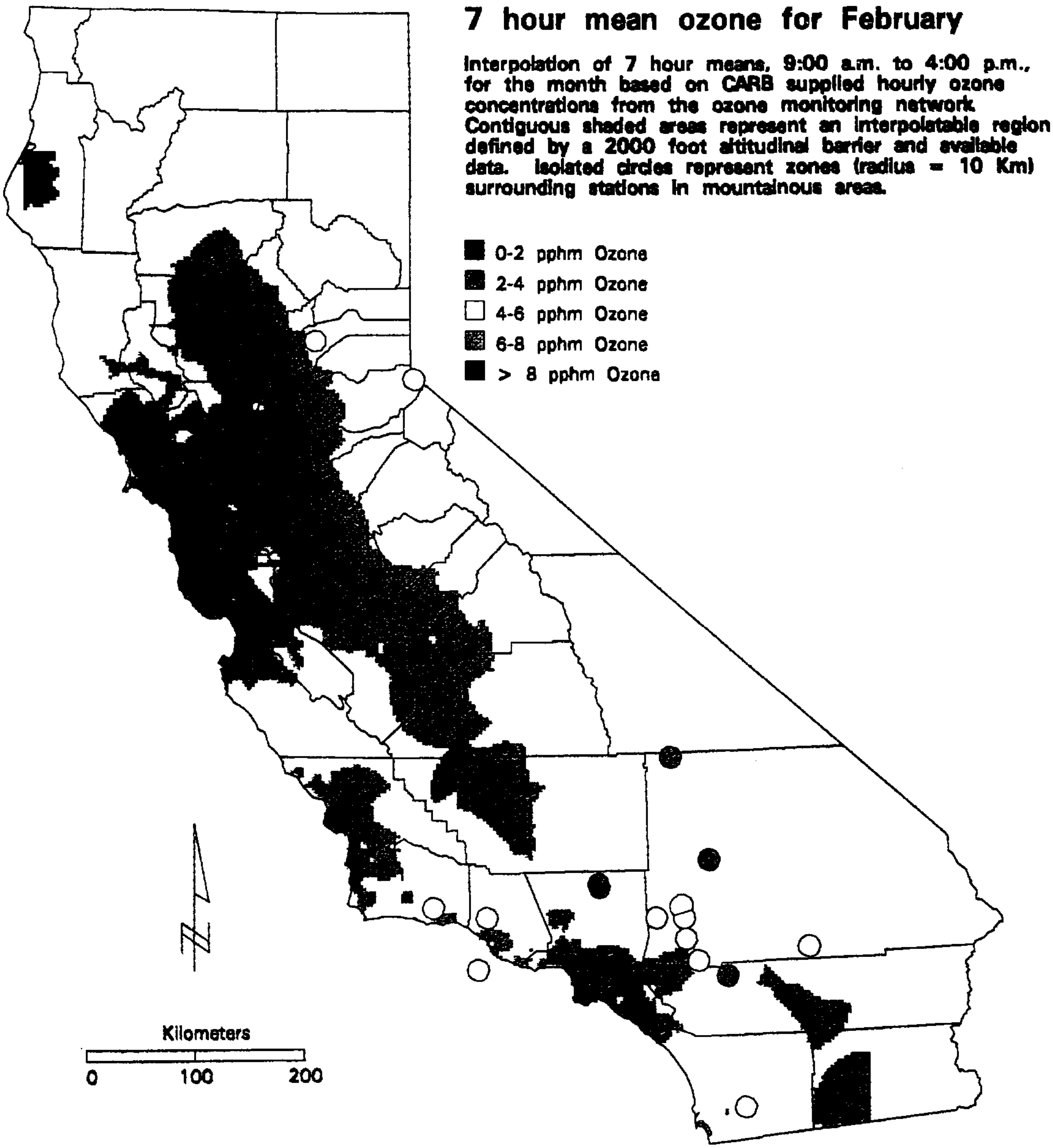


Figure 3. Statewide 7-hr Mean Ozone Concentration for March 1991.

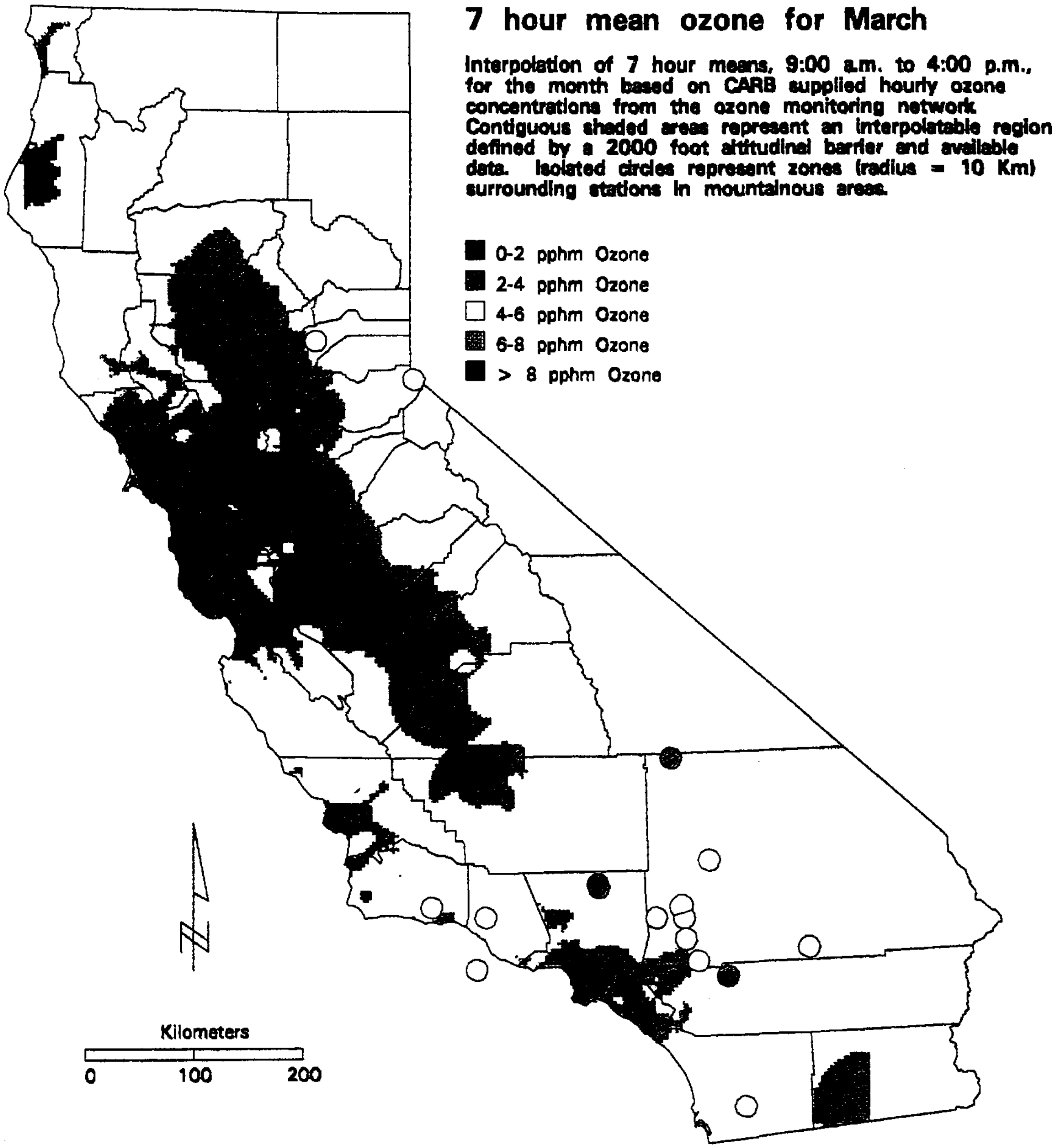


Figure 4. Statewide 7-hr Mean Ozone Concentration for April 1991.

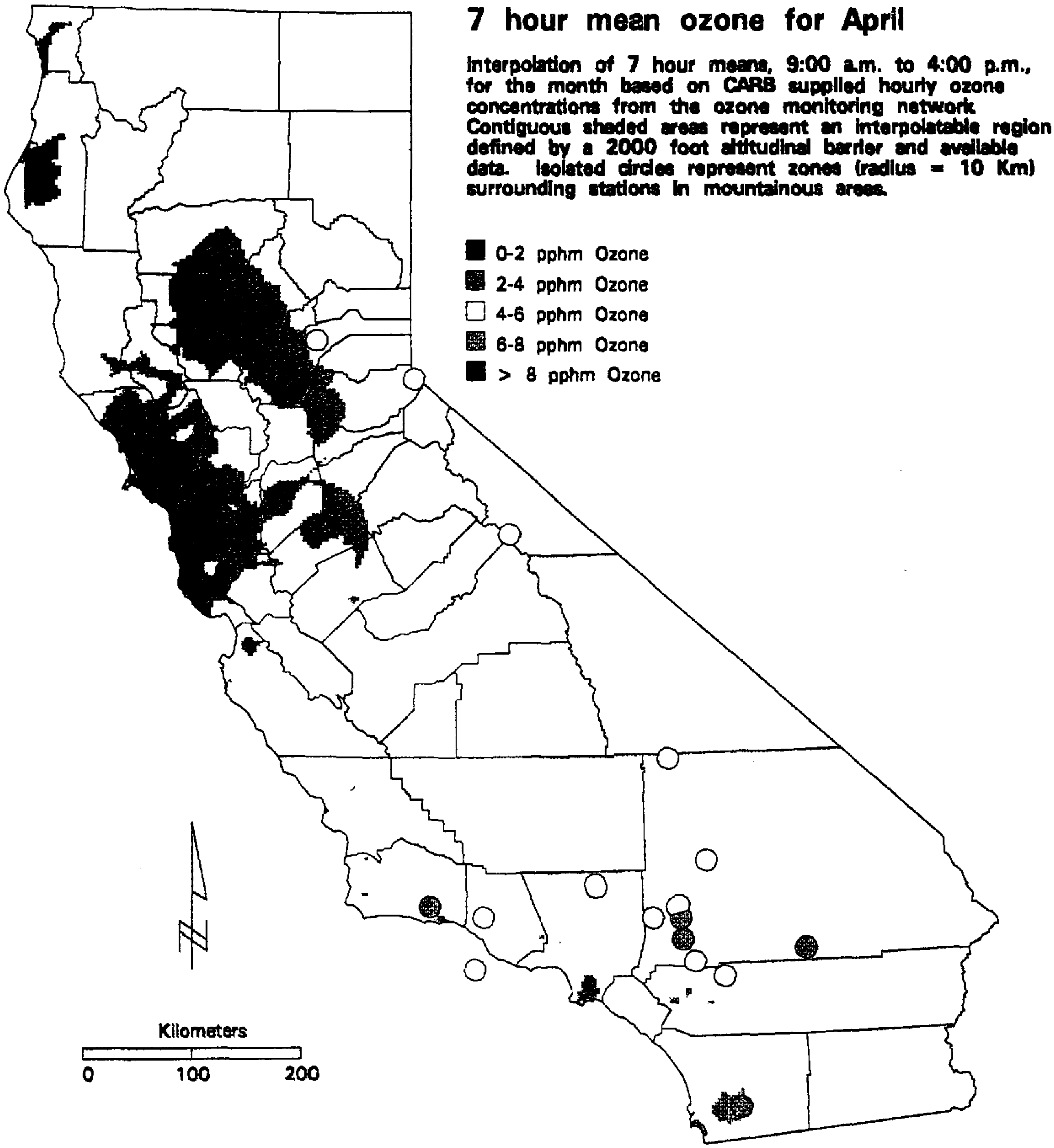


Figure 5. Statewide 7-hr Mean Ozone Concentration for May 1991.

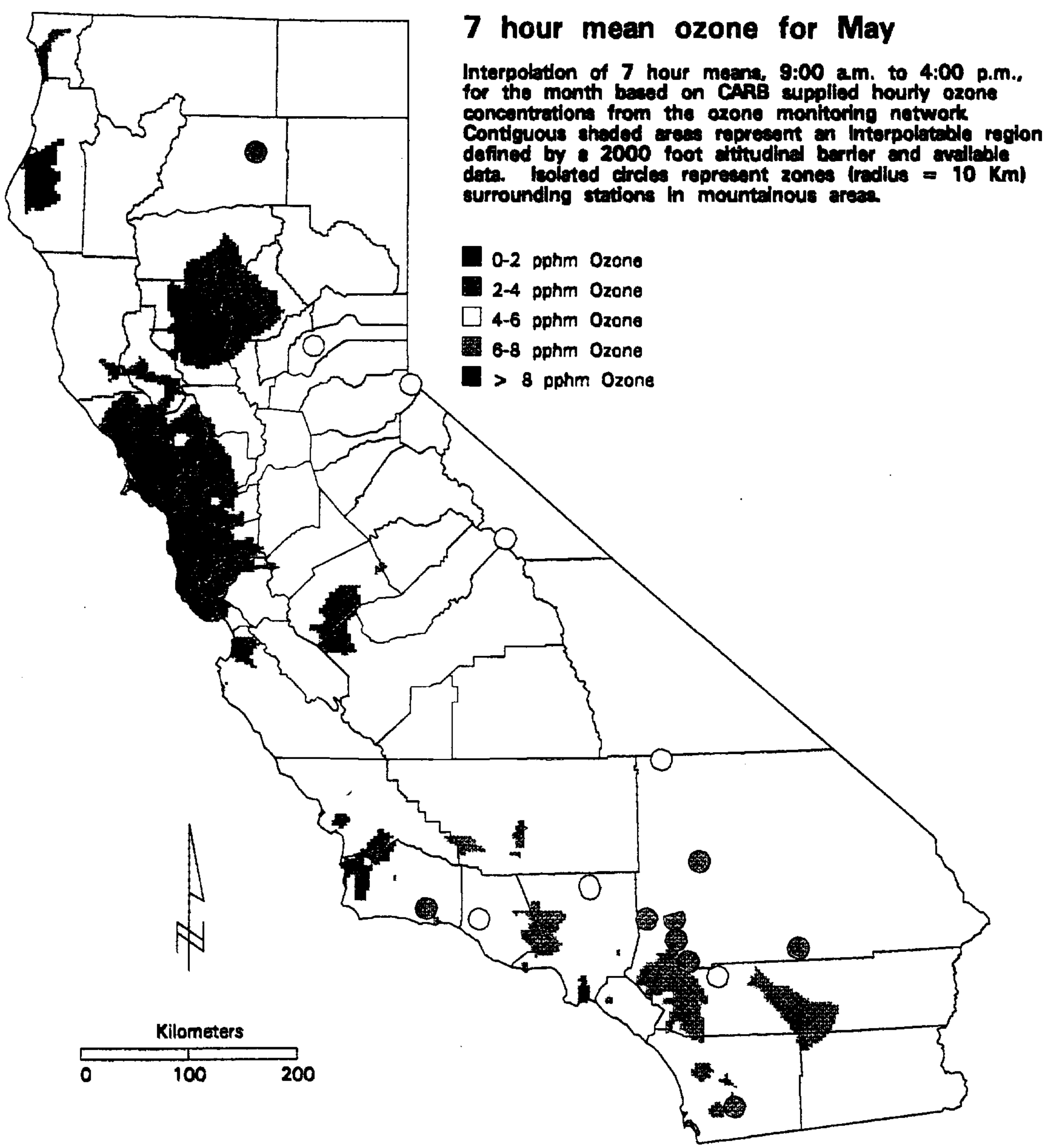


Figure 6. Statewide 7-hr Mean Ozone Concentration for June 1991.

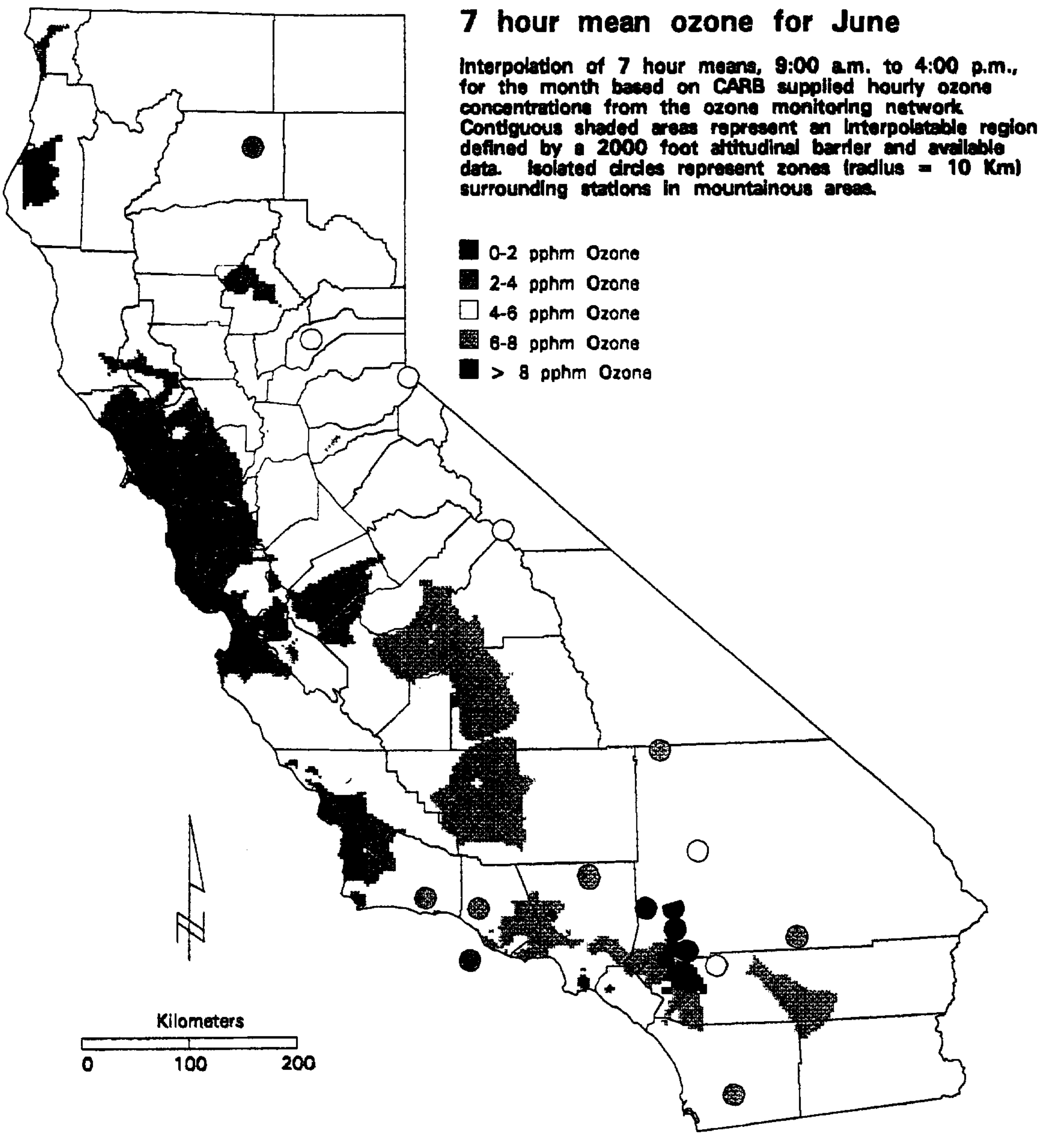


Figure 7. Statewide 7-hr Mean Ozone Concentration for July 1991.

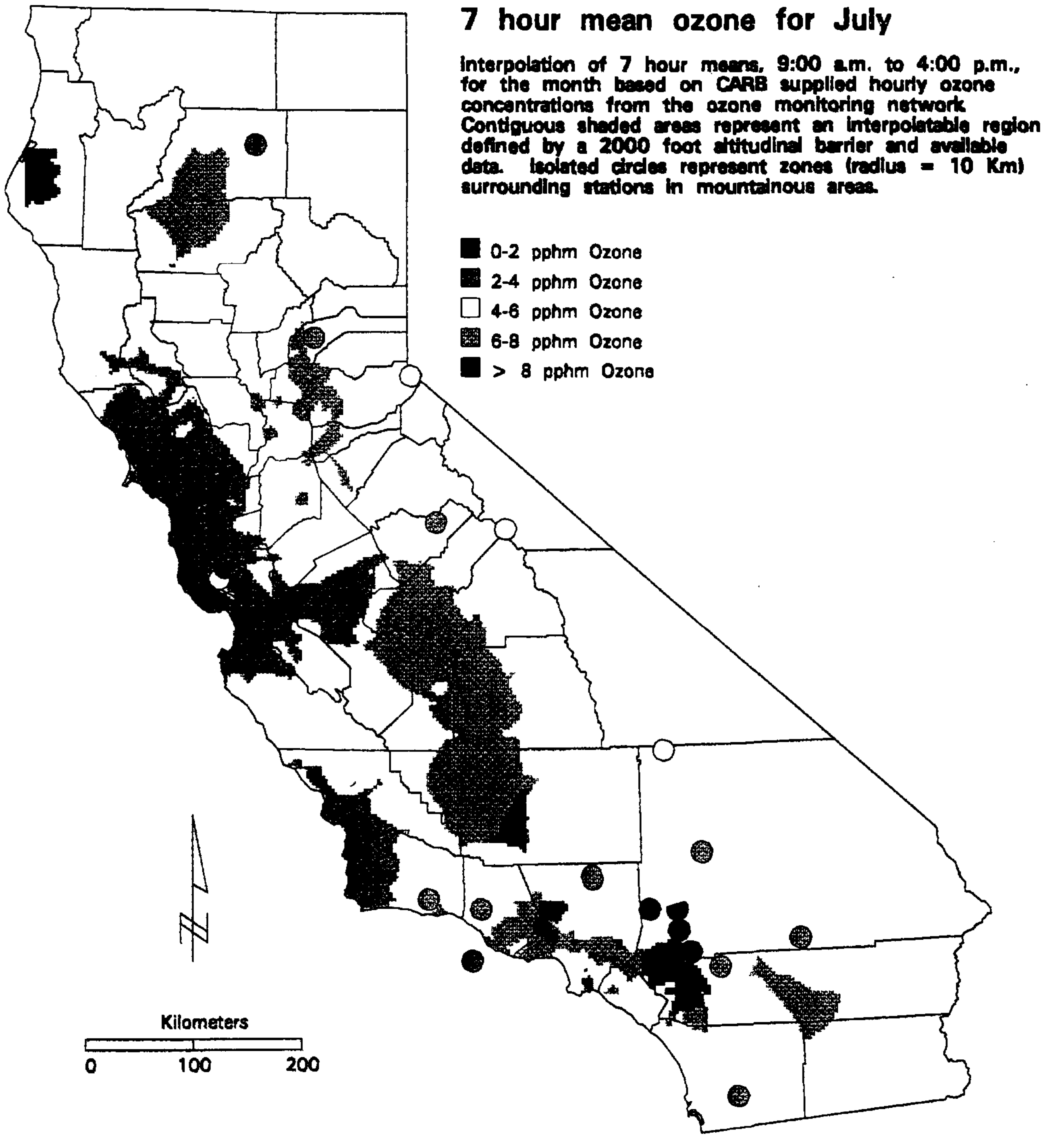


Figure 8. Statewide 7-hr Mean Ozone Concentration for August 1991.

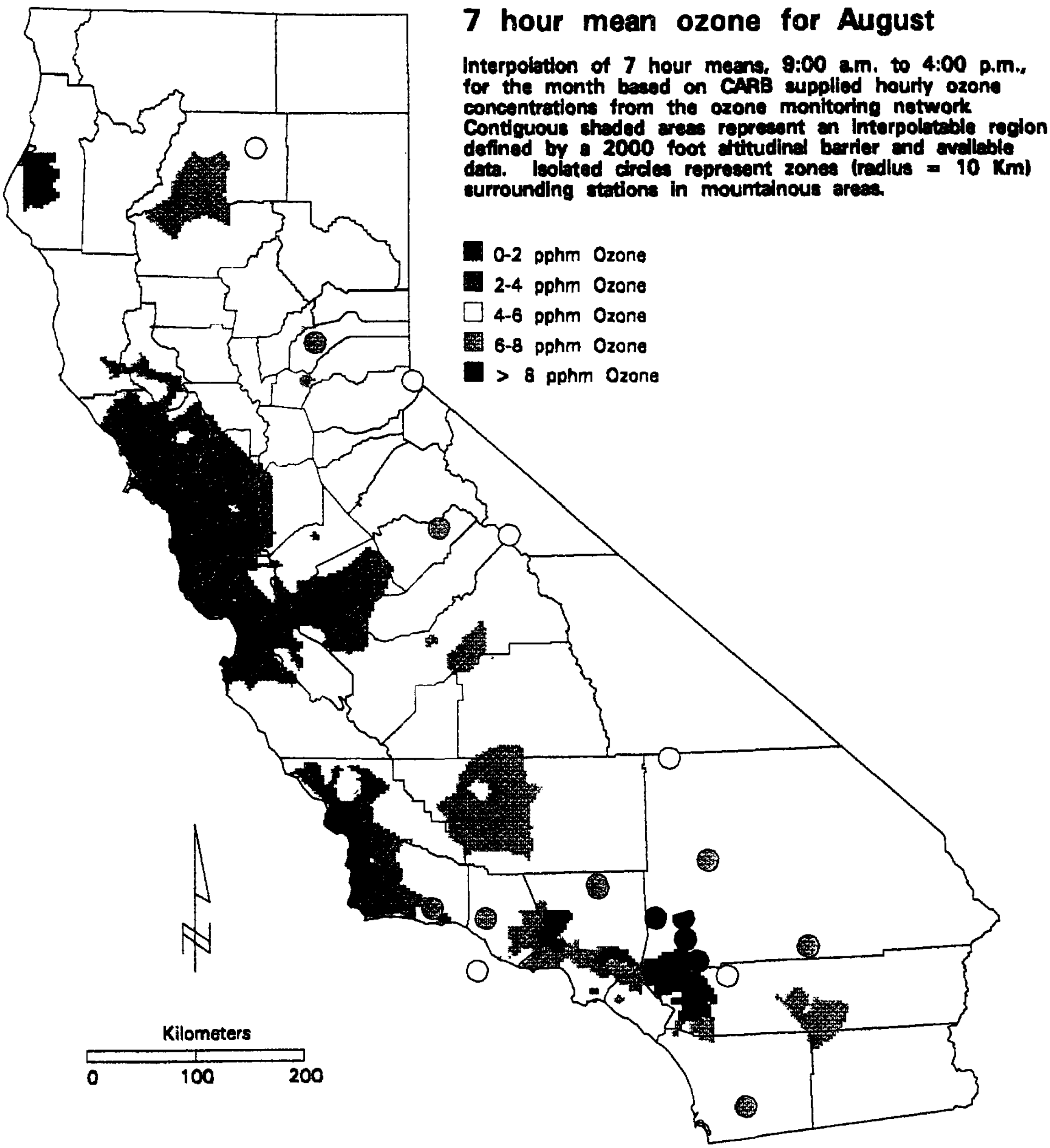


Figure 9. Statewide 7-hr Mean Ozone Concentration for September 1991.

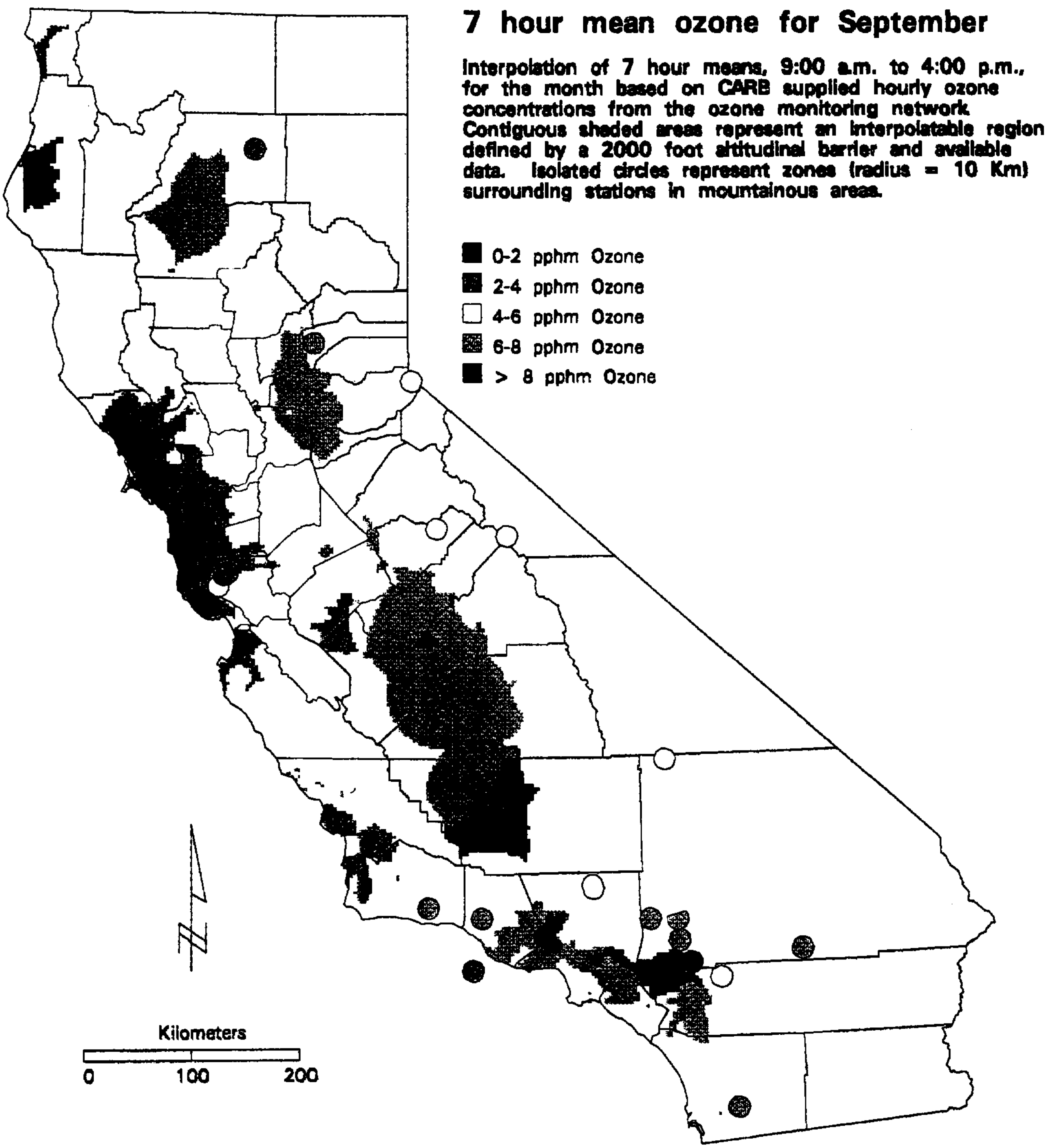


Figure 10. Statewide 7-hr Mean Ozone Concentration for October 1991.

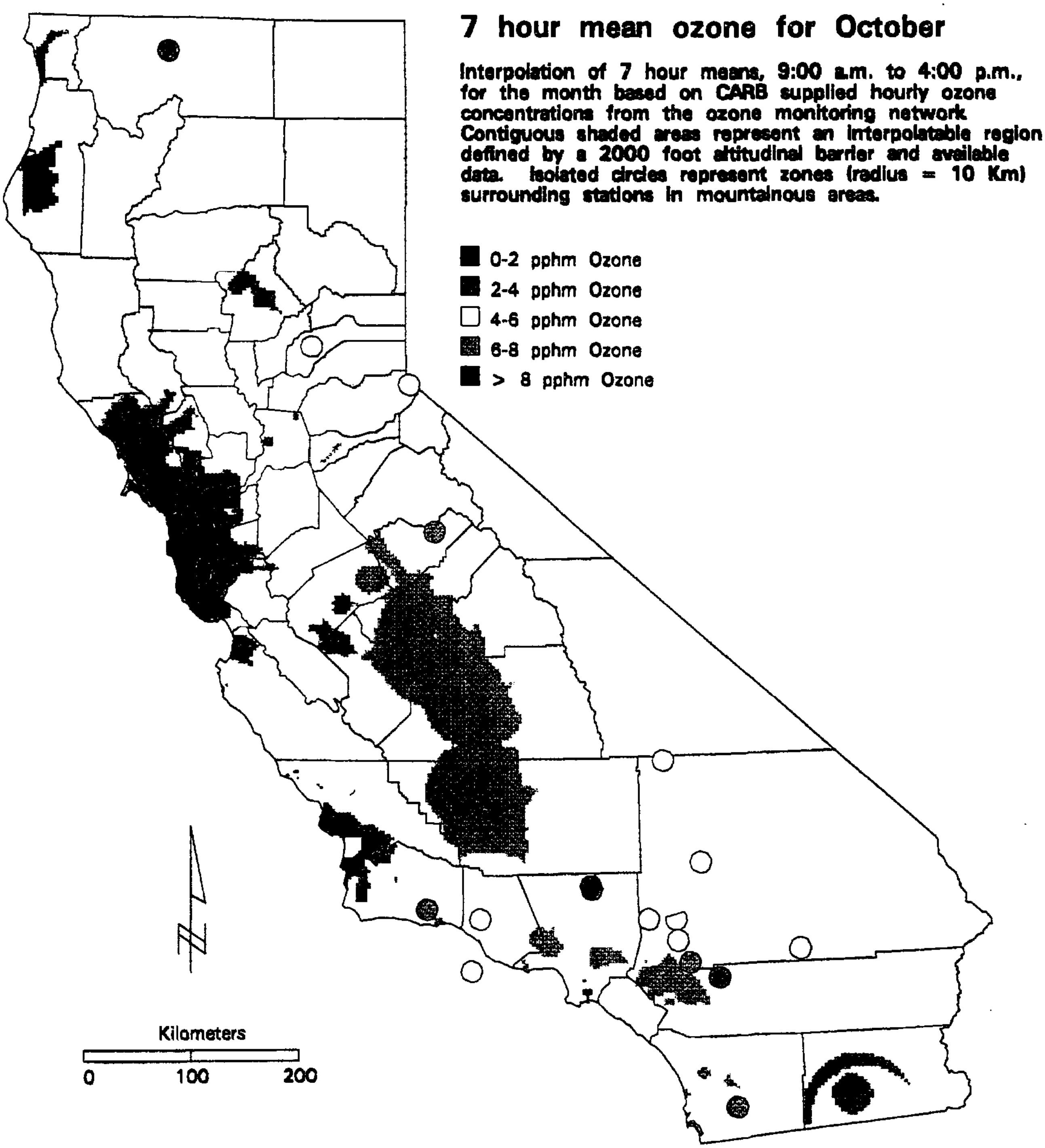


Figure 11. Statewide 7-hr Mean Ozone Concentration for November 1991.

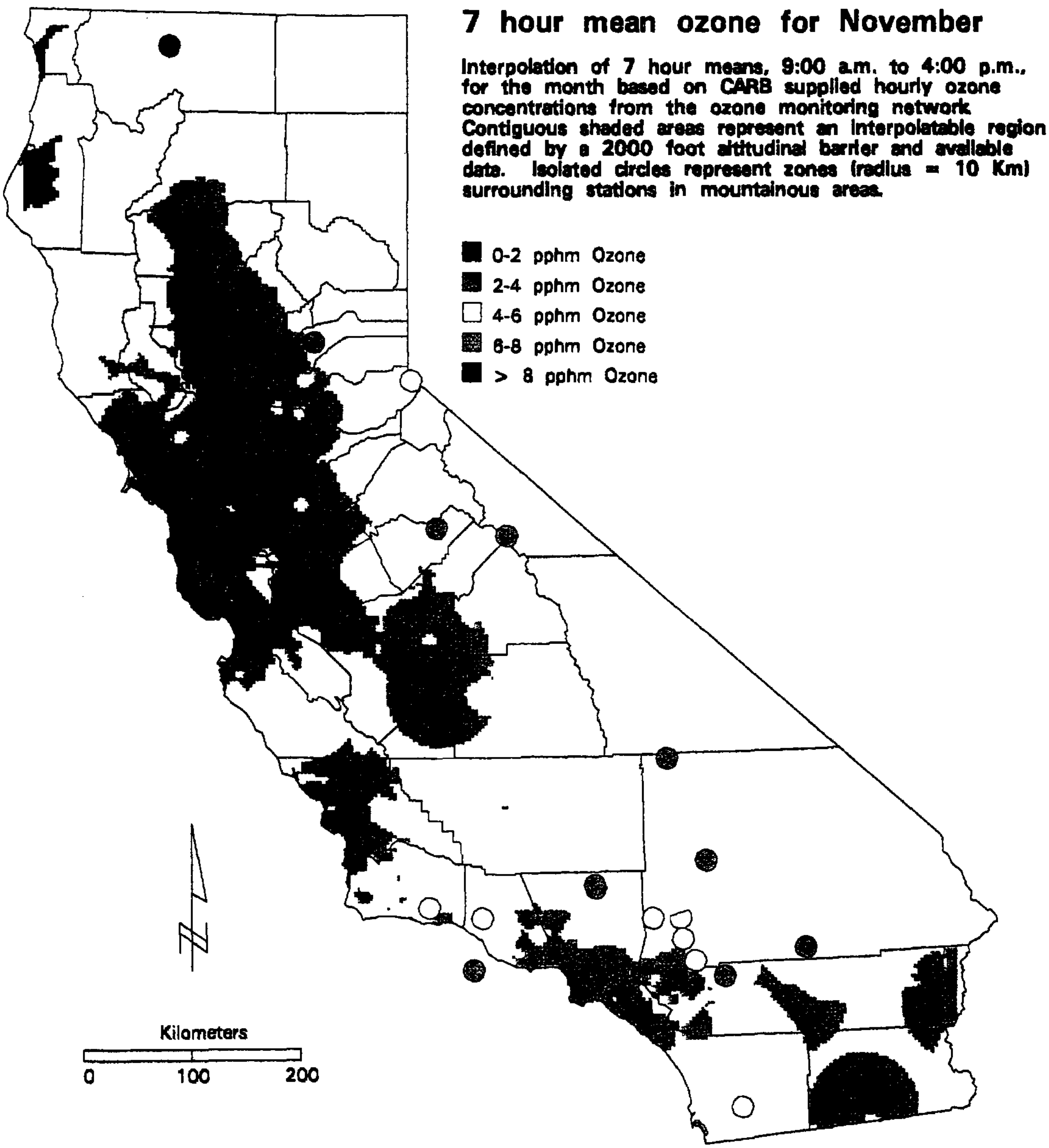
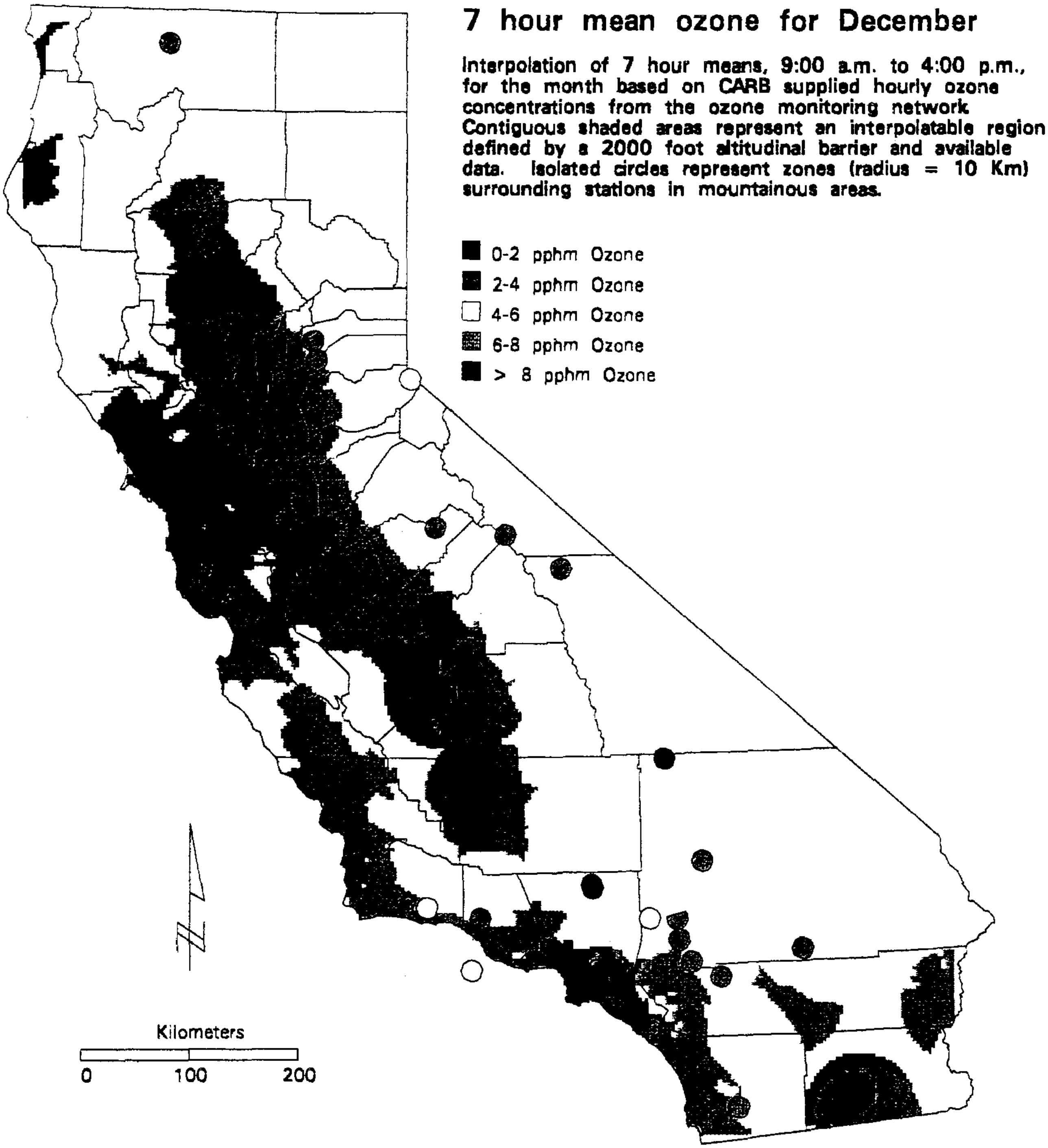


Figure 12. Statewide 7-hr Mean Ozone Concentration for December 1991.



Statewide Interpolations, 1992. Statewide monthly ozone concentrations in 1992 followed a seasonal trend similar to that observed in 1991 (Figures 13-24). Ozone concentrations were lowest during December and January, and highest during July and August. Overall ozone levels during 1992 appeared to be lower than in 1991 with the exception of May and August in which concentrations were higher (Figures 17 and 20).

Yield Loss Estimates Using Interpolated Ozone Statistics, 1991. The geographic distribution of estimated yield losses, graphically presented below, were delimited by the extent of irrigated farmland. The individual crops were not grown across the entire geographic extent illustrated. Information on the exact location and acreage of the major commodities was not readily attainable. Although such a database would be of vast usefulness. Those crops discussed were assuredly grown under irrigated conditions. Consequently, some knowledge of where specific crops were actually grown is needed to properly interpret the figures below.

Estimated yield reductions due to ozone exposure in tomato, a relatively tolerant crop, ranged from less than 1% in the Delta area of the Sacramento Valley to greater than 3% in isolated areas of Sacramento and Yolo counties (Figure 25), with seasonal mean ozone concentrations of 5 and 6 pphm, respectively . A Thompson seedless grape response function predicted that grape yield reductions ranged from less than 3% in Napa county to greater than 18% in Sacramento county (Figure 26). The influence of the on-shore air flow into Yolo and western Sacramento counties was evidenced by the relatively small estimated yield loss (6-12%). The "puddling" of the air mass in northern portion of the valley was apparent because of the higher potential losses at that end of the Valley.

Estimated yield loss for tomato in the San Joaquin Valley followed a north-south gradient with losses less than 2% in San Joaquin, Stanislaus, and Merced counties and greater than 8% in southern Kern county (Figure 27) where ozone concentration ranged from 4.8 pphm in San Joaquin to 7.8 pphm in Kern county. Thompson seedless grape yields were reduced by an estimated range of less than 10% in the northern Valley to greater than 30% south of Bakersfield (Figure 28). The effects of the Fresno urban area on air quality was evidenced by estimated losses of 25-30% in eastern Fresno county. Yield reductions in cotton followed a trend similar to grape (Figure 29). The largest yield reductions occurred south of Bakersfield and the smallest in San Joaquin and Stanislaus counties.

Tomato yields were essentially unaffected by ozone in the Salinas Valley, with losses ranging from 1 to 2% (Figure 30). Grape, a more sensitive crop, experienced considerably larger reductions, as high as 13% in the southern Valley (Figure 31).

Yields of tomato in Riverside and Imperial counties (Coachella and Imperial Valleys) were small (less than 5%; Figure 32). Grape yield, in contrast, may have been reduced by as much as 35% in western Riverside county (7-hr mean = 9.5 pphm) and substantially less in the agricultural areas surrounding the Salton Sea (7-hr mean = 5.1 pphm; Figure 33). Cotton yield in the Imperial Valley was only minimally impacted by ozone in 1991 (Figure 34).

Figure 13. Statewide 7-hr Mean Ozone Concentration for January 1992.

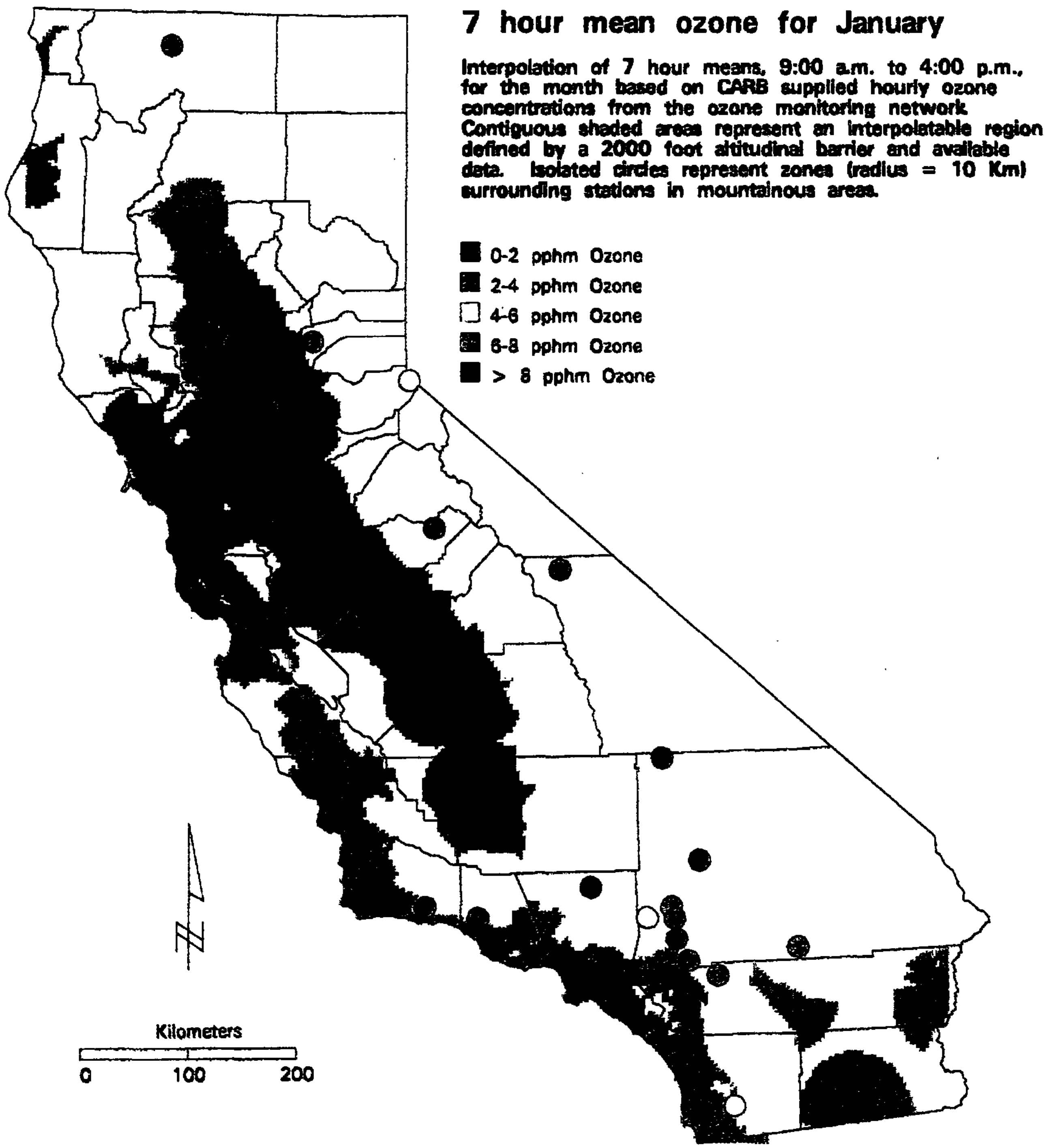


Figure 14. Statewide 7-hr Mean Ozone Concentration for February 1992.

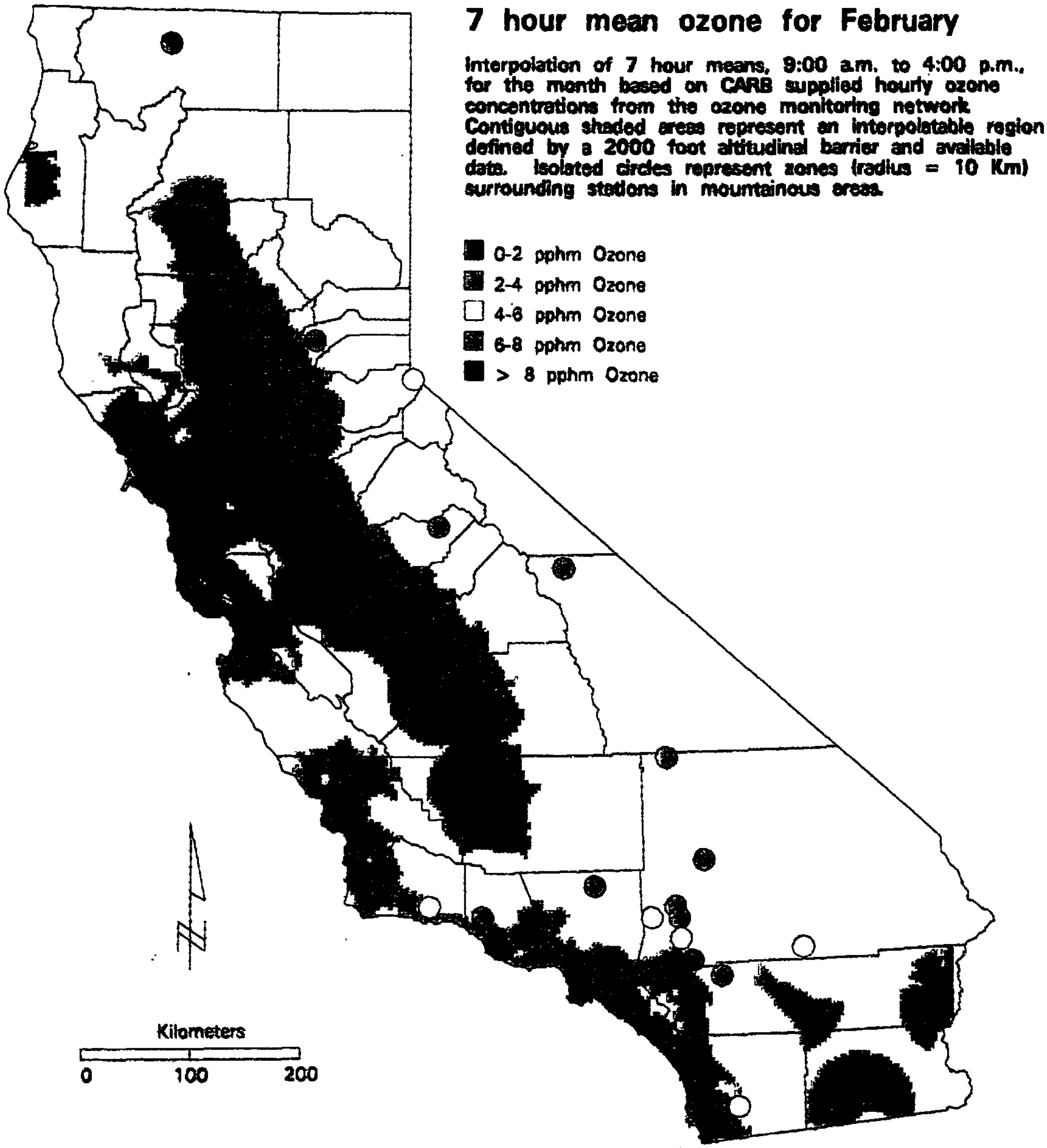


Figure 15. Statewide 7-hr Mean Ozone Concentration for March 1992.

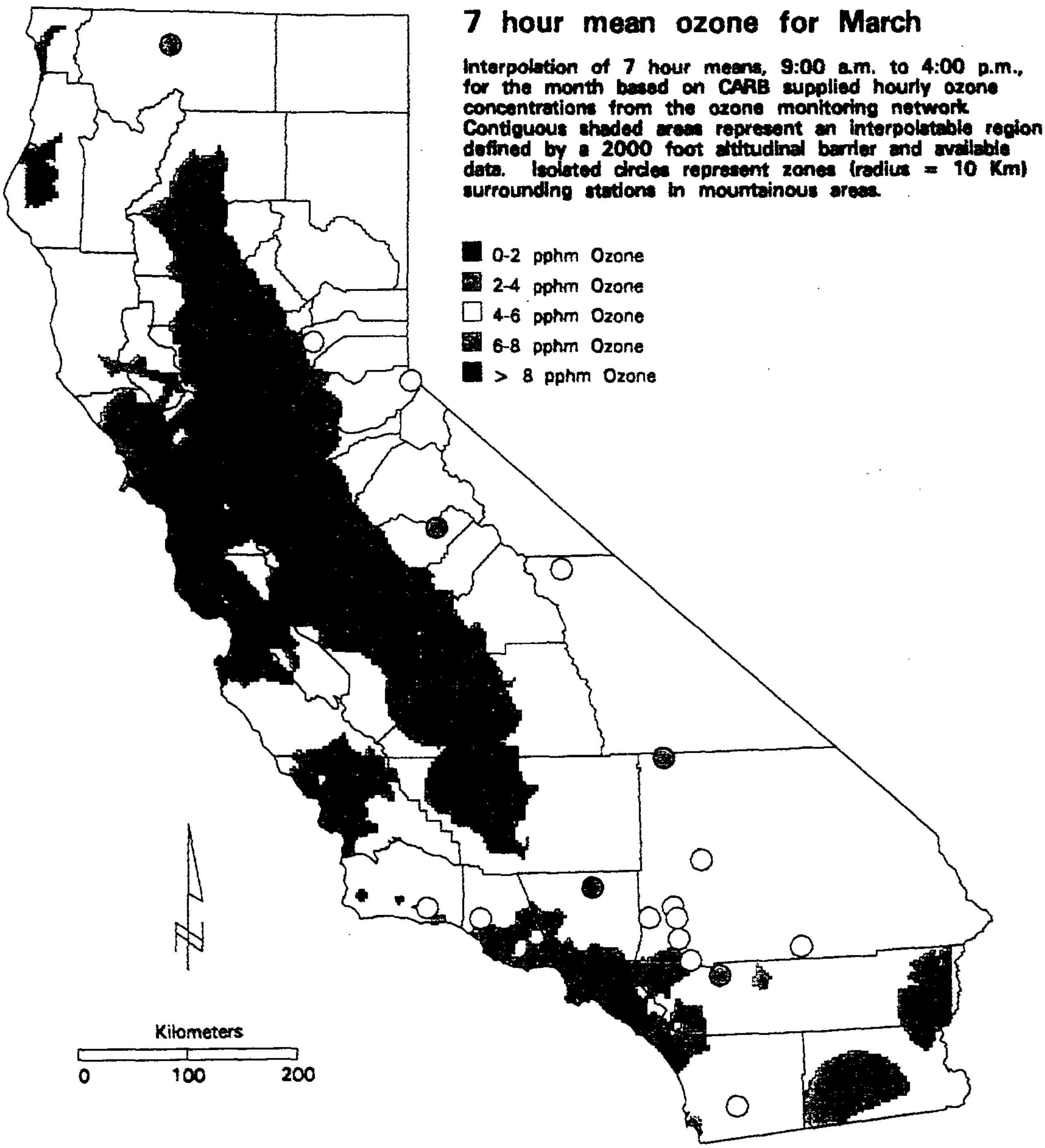


Figure 16. Statewide 7-hr Mean Ozone Concentration for April 1992.

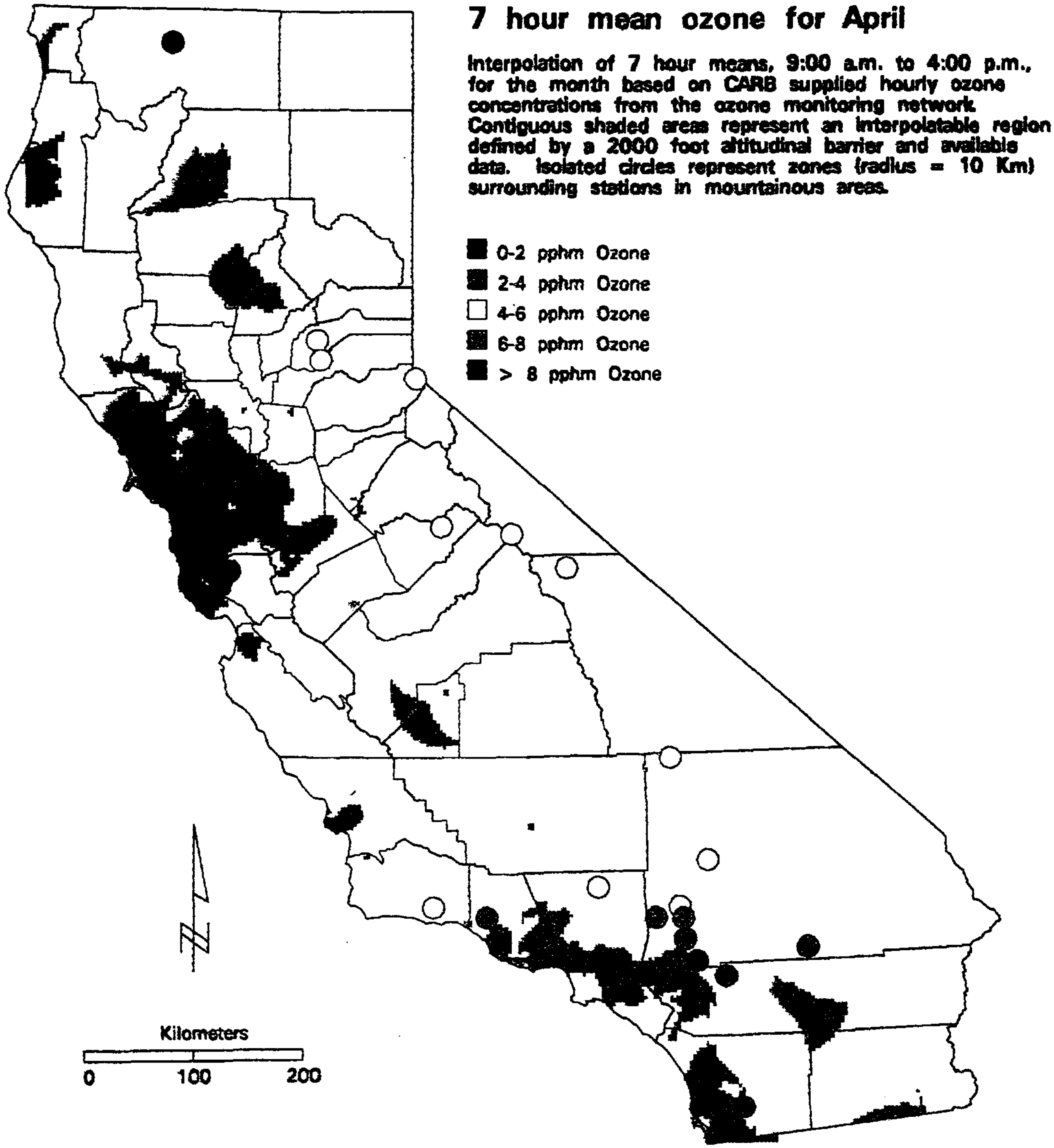


Figure 17. Statewide 7-hr Mean Ozone Concentration for May 1992.

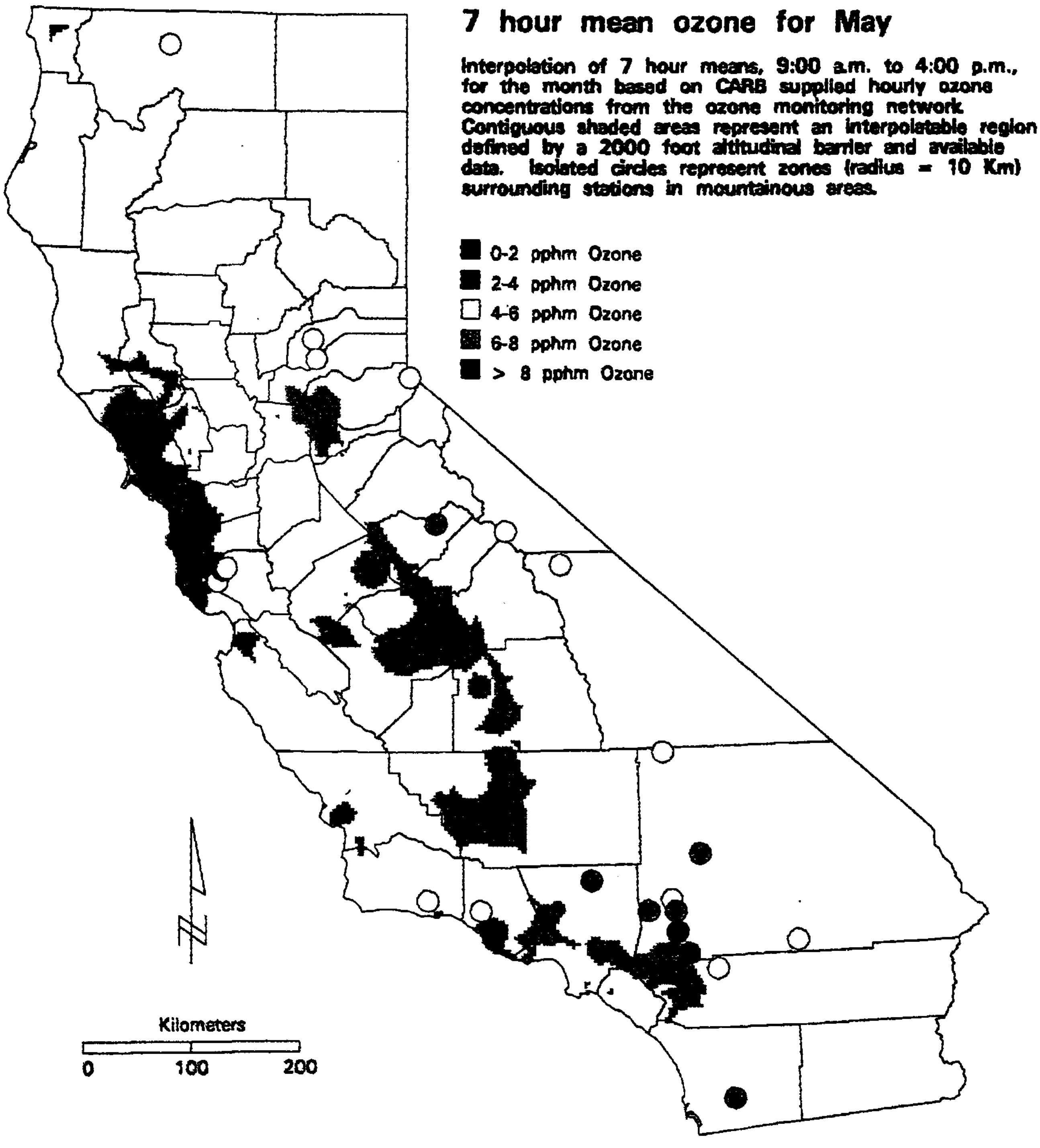


Figure 18. Statewide 7-hr Mean Ozone Concentration for June 1992.

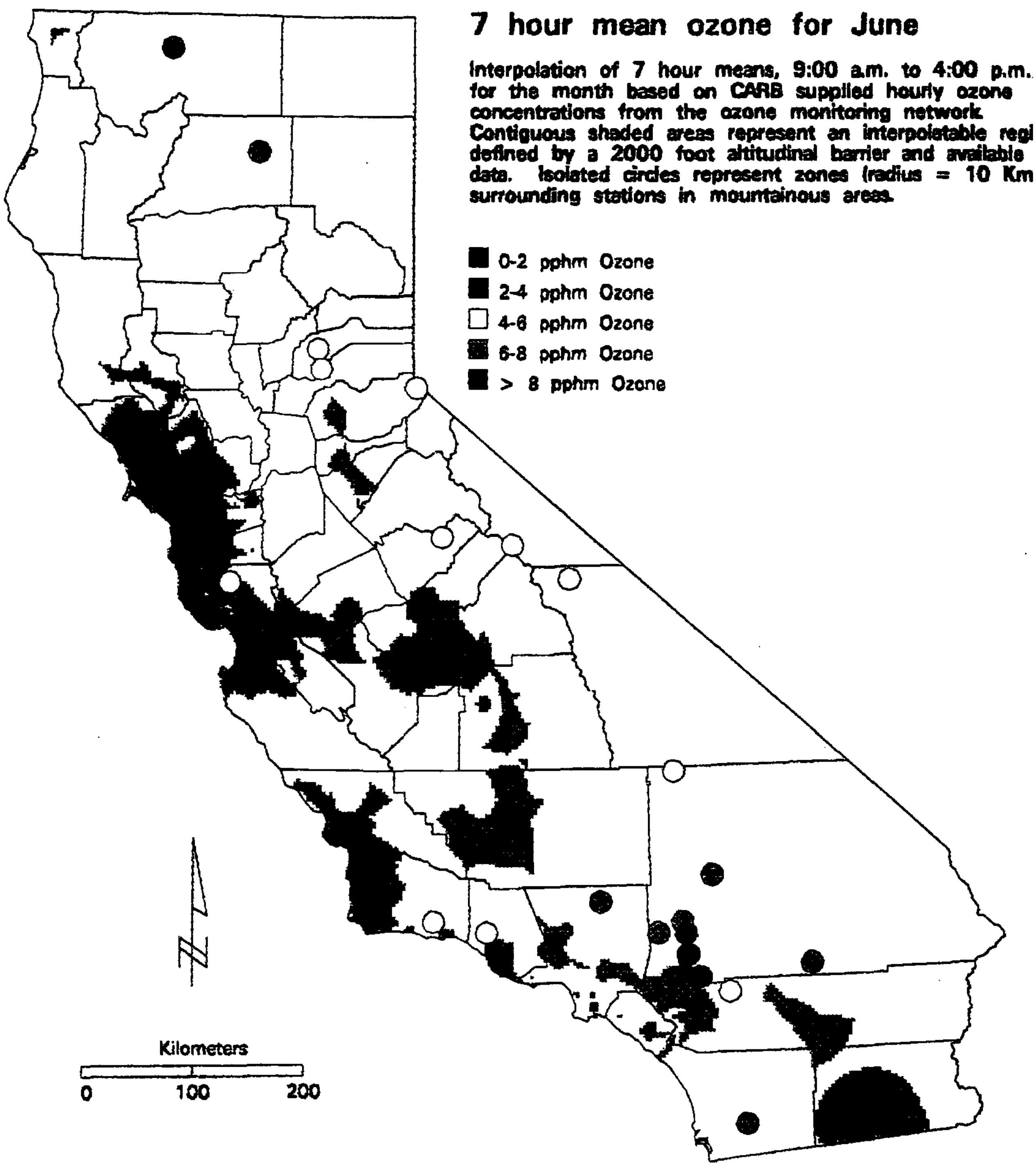


Figure 19. Statewide 7-hr Mean Ozone Concentration for July 1992.

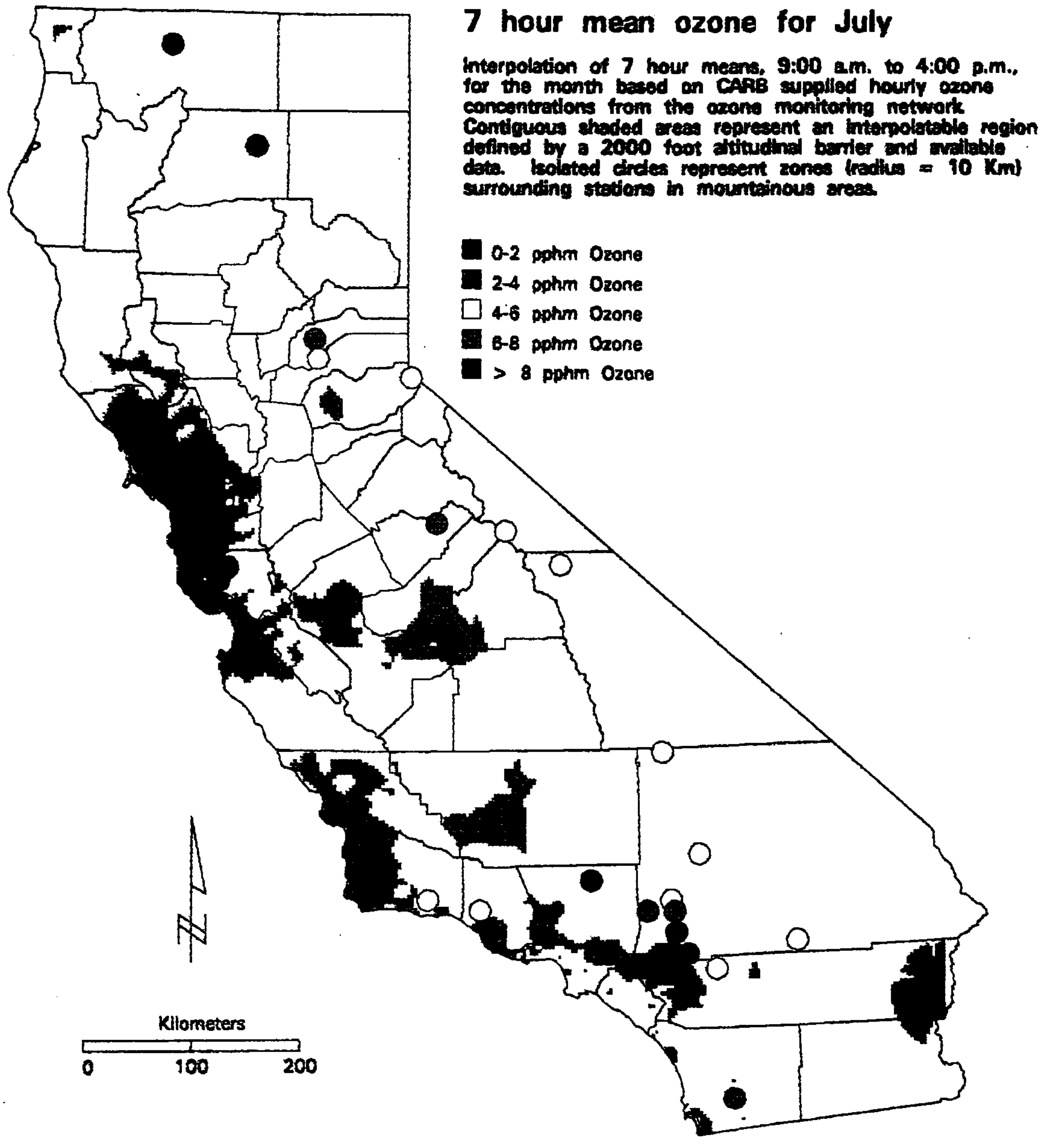


Figure 20. Statewide 7-hr Mean Ozone Concentration for August 1992.

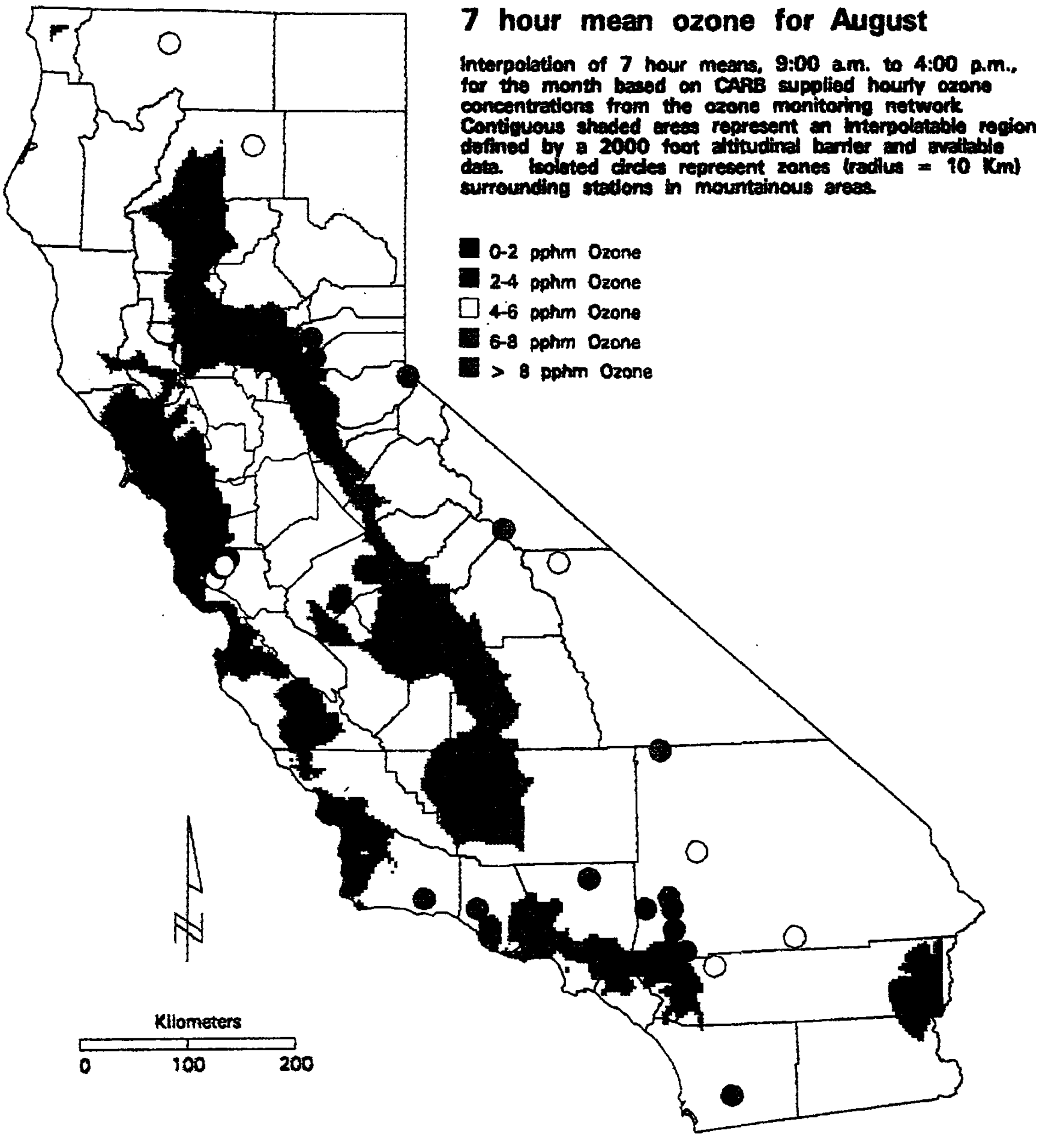


Figure 21. Statewide 7-hr Mean Ozone Concentration for September 1992.

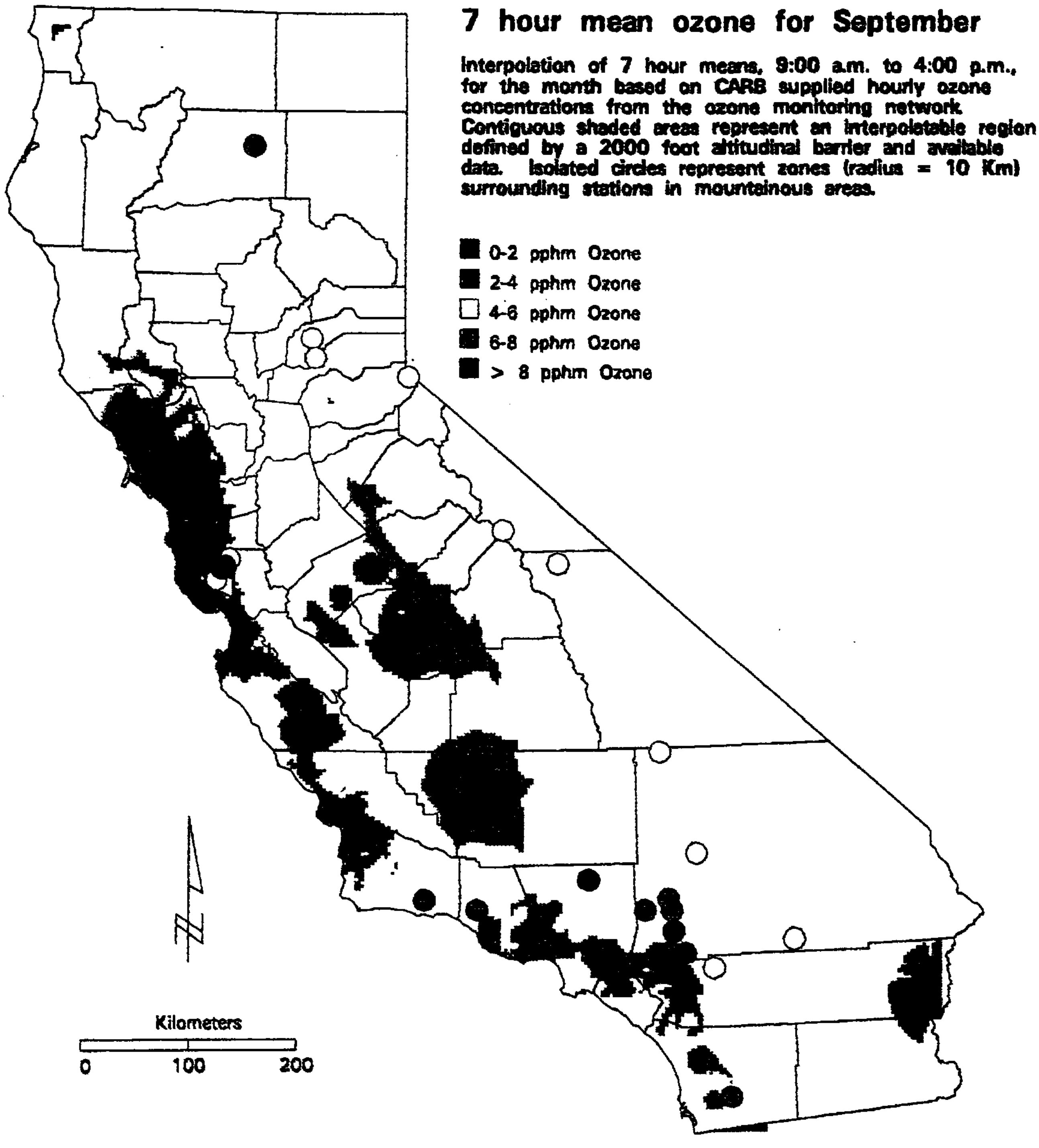


Figure 22. Statewide 7-hr Mean Ozone Concentration for October 1992.

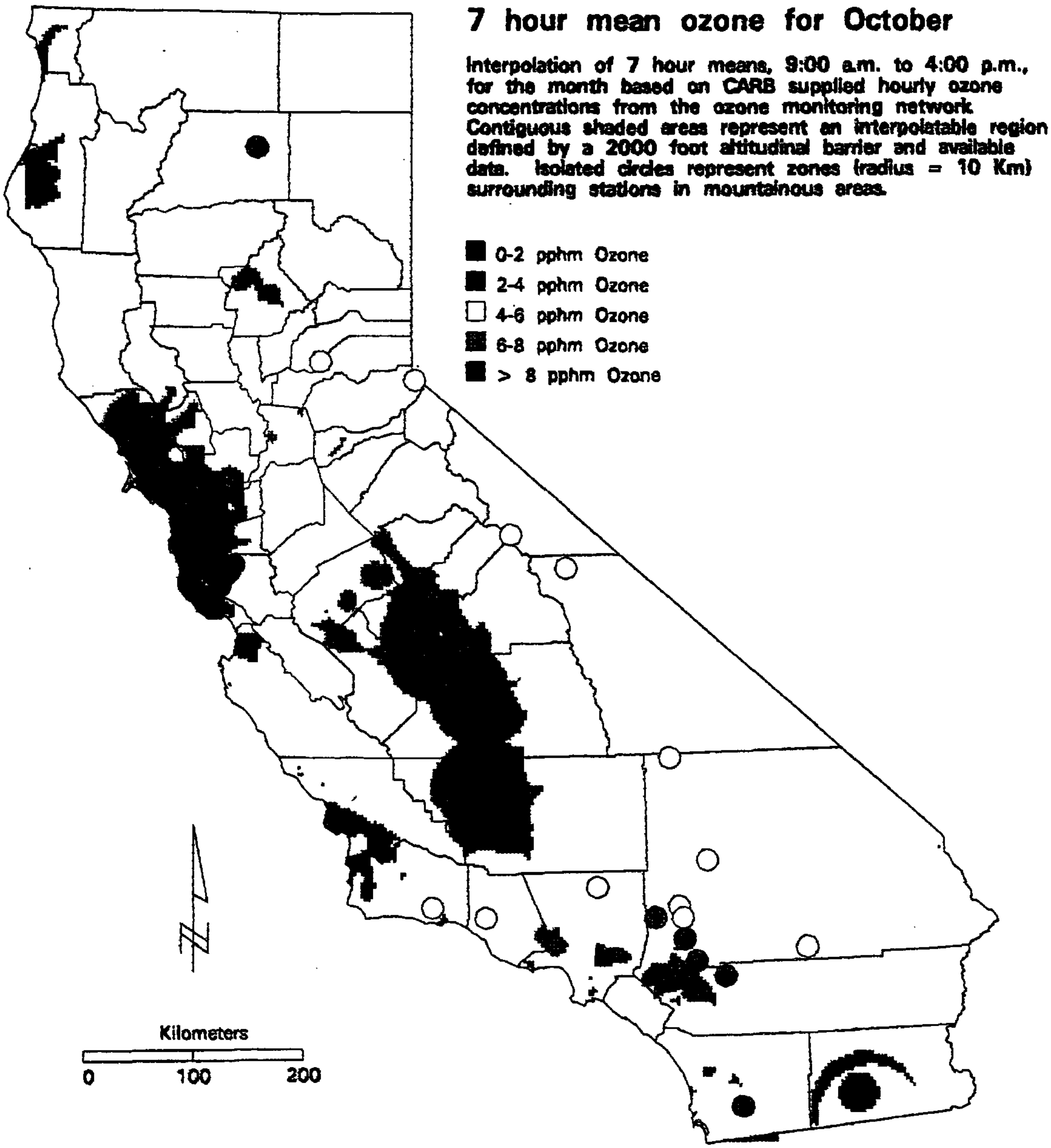


Figure 23. Statewide 7-hr Mean Ozone Concentration for November 1992.

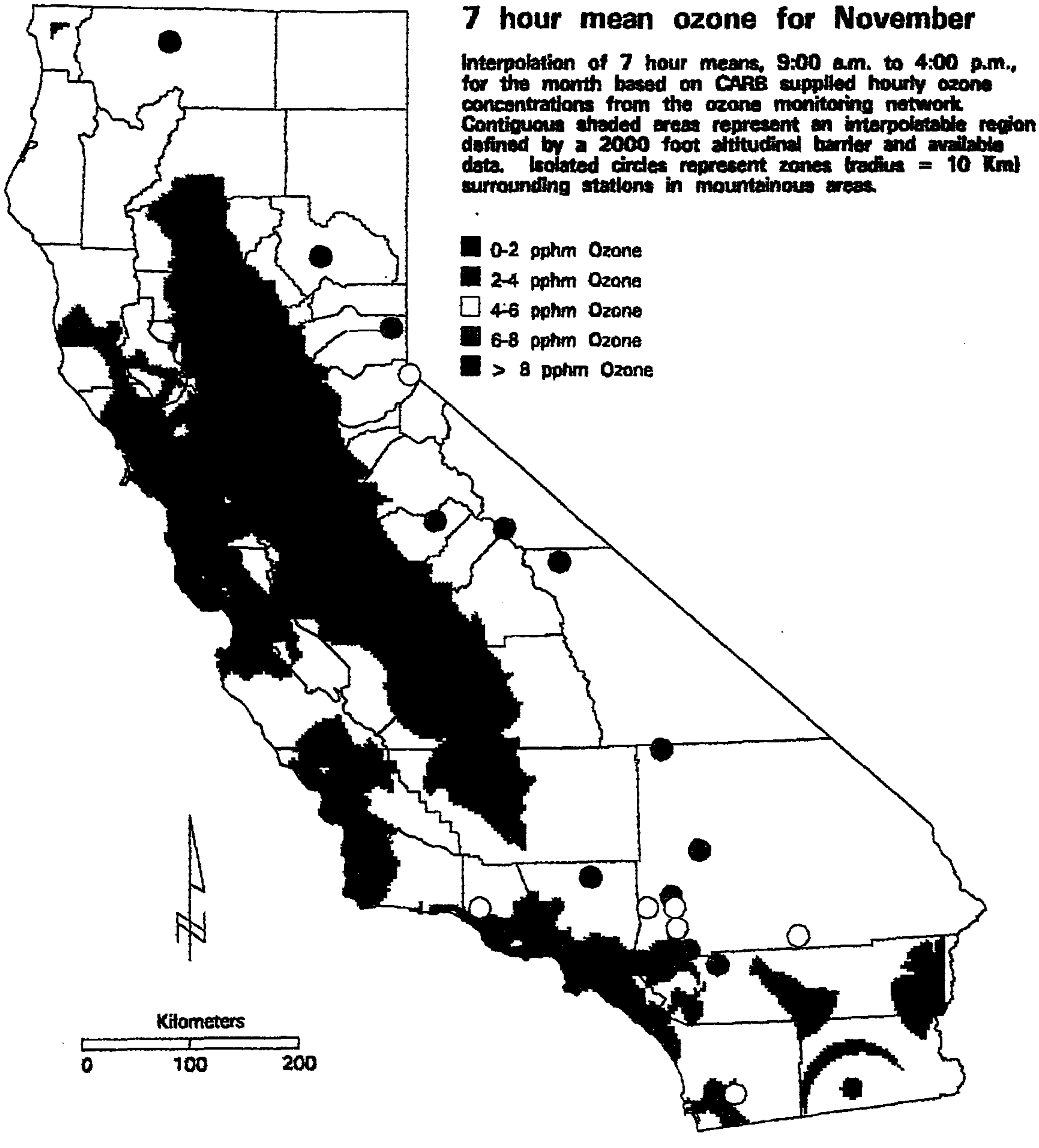


Figure 24. Statewide 7-hr Mean Ozone Concentration for December 1992.

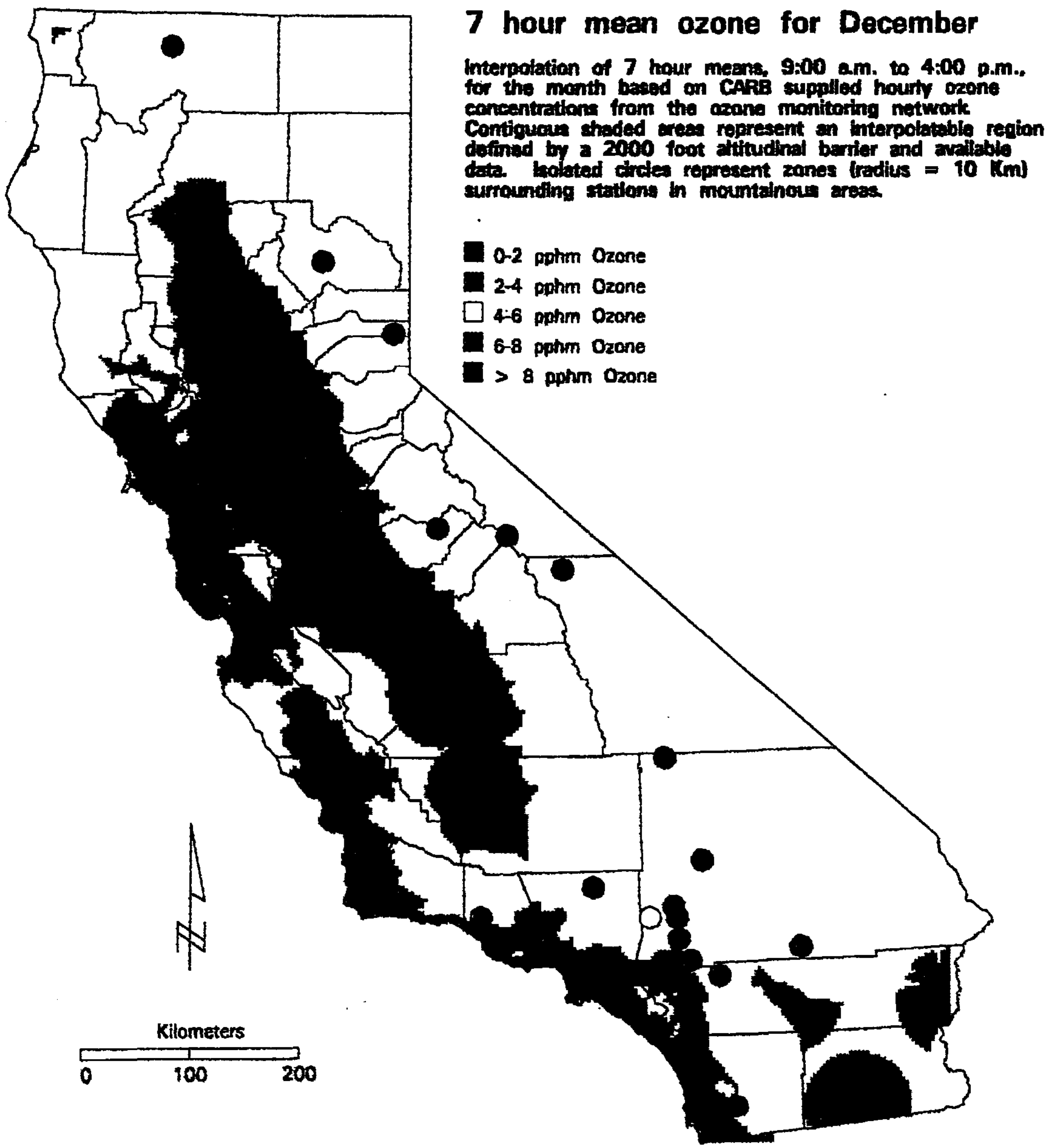


Figure 25.

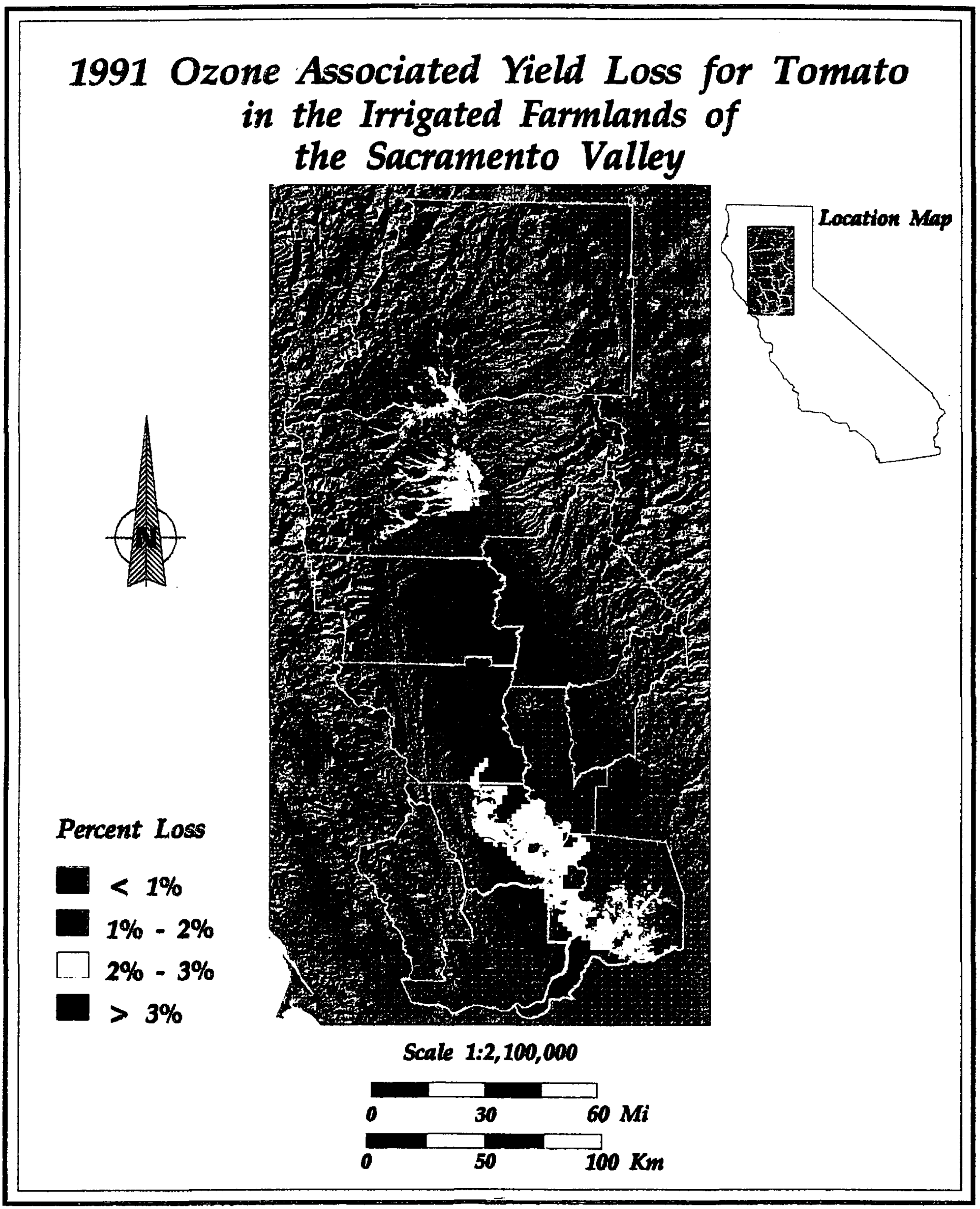

1991 Ozone Associated Yield Loss for Tomato
in the Irrigated Farmlands of
the Sacramento Valley
Location Map
Percent Loss
< 1%
1% - 2%
2% - 3%
> 3%
Scale 1:2,100,000
0
30
60 Mi
0
50
100 Km

Figure 26.

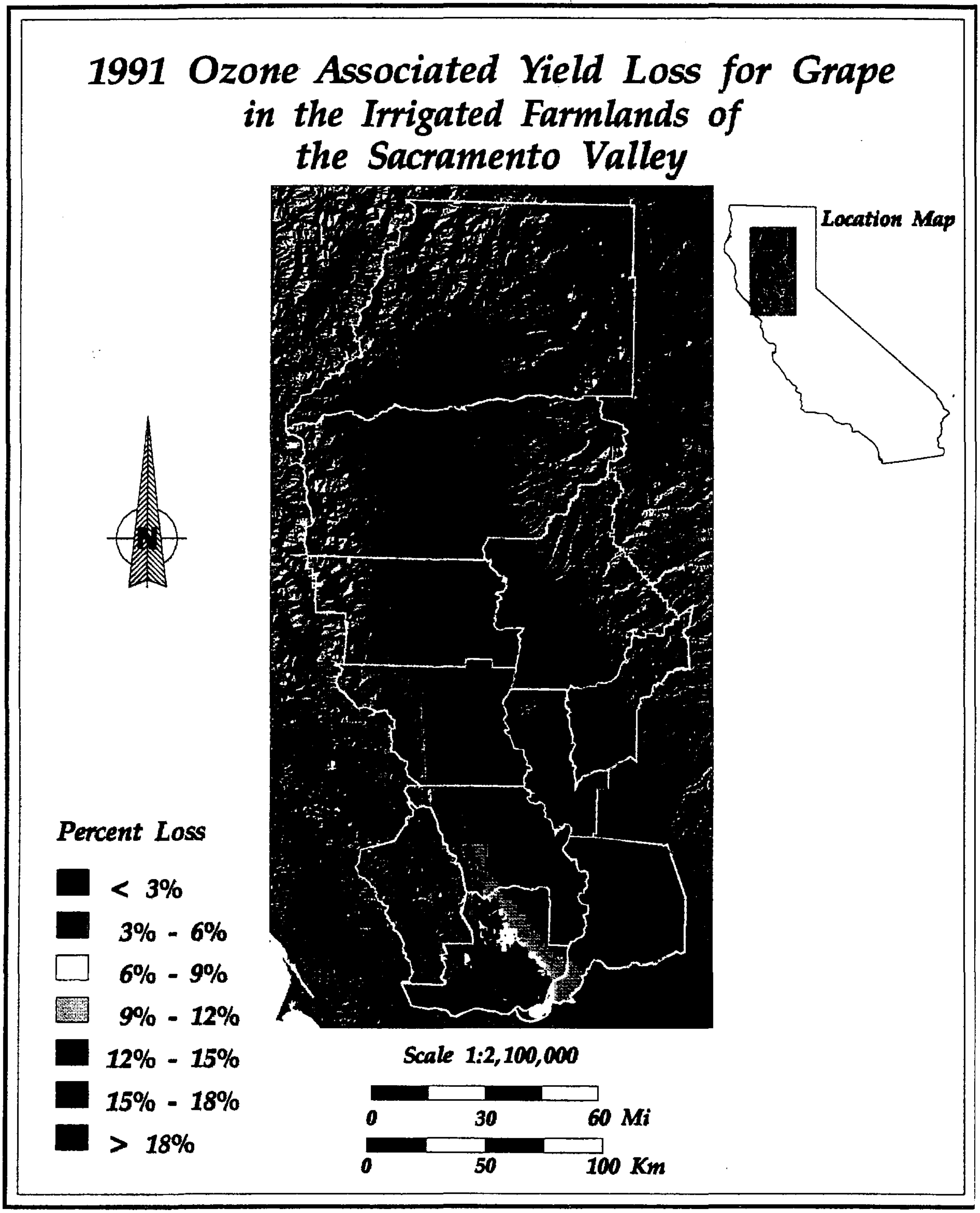
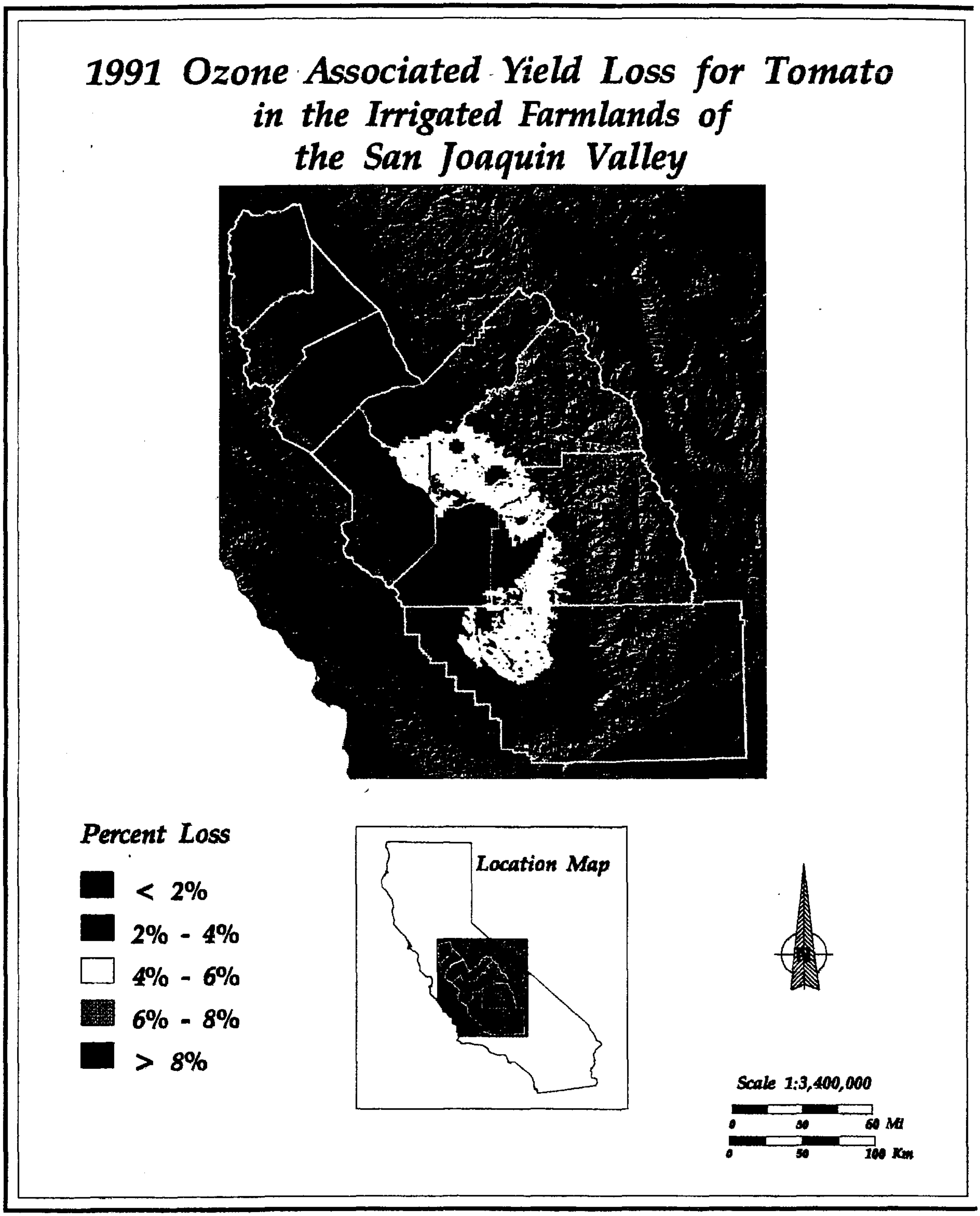
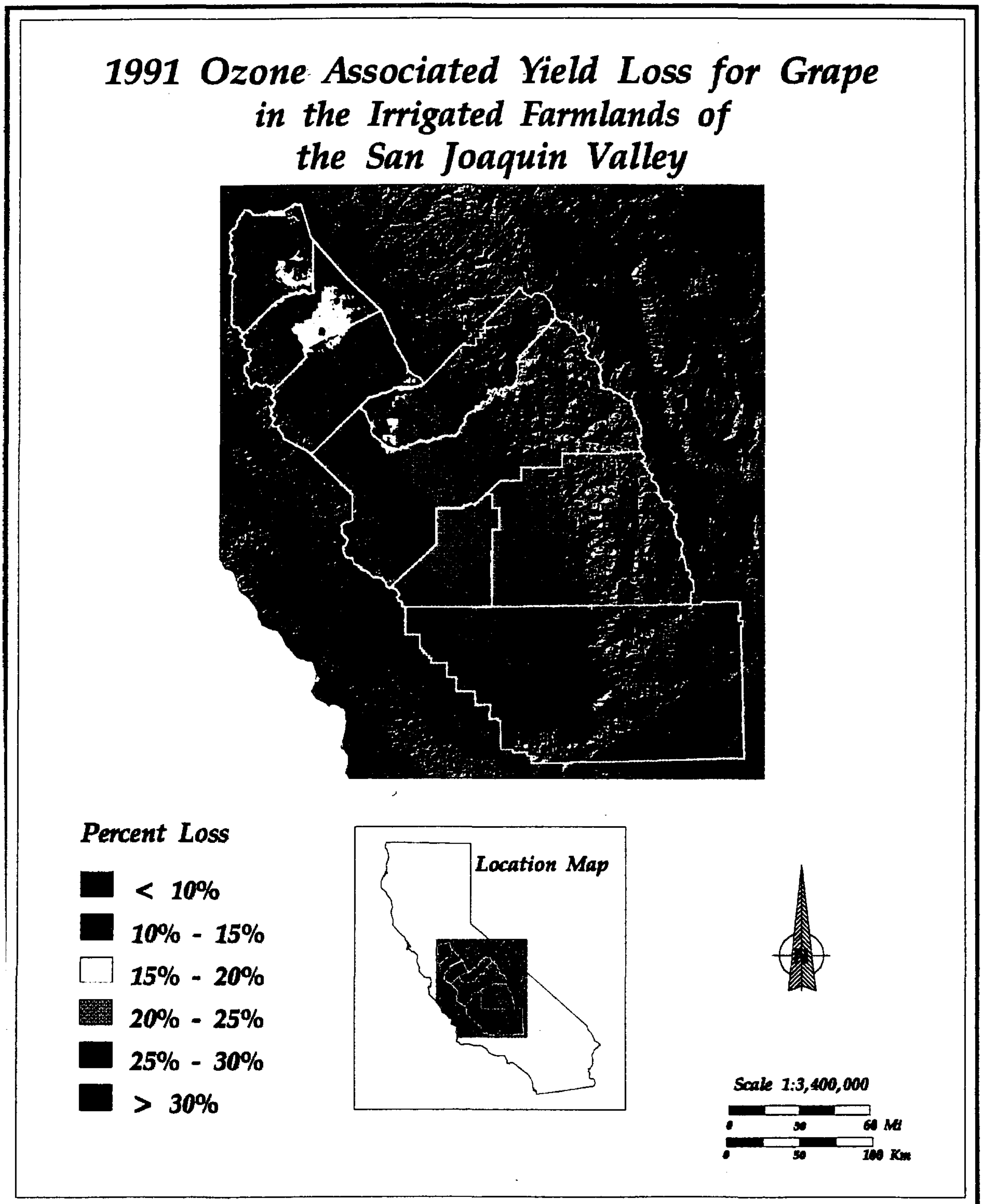

1991 Ozone Associated Yield Loss for Grape
in the Irrigated Farmlands of
the Sacramento Valley
Location Map
Percent Loss
< 3%
3% - 6%
6% - 9%
9% - 12%
12% - 15%
15% - 18%
> 18%
Scale 1:2,100,000
0
30
60 Mi
0
50
100 Km

Figure 27.



1991 Ozone Associated Yield Loss for Tomato in the Irrigated Farmlands of the San Joaquin Valley
Percent Loss
< 2%
2% - 4%
4% - 6%
6% - 8%
> 8%
Location Map
Scale 1:3,400,000
60 Mi
100 Km

Figure 28.


1991 Ozone Associated Yield Loss for Grape
in the Irrigated Farmlands of
the San Joaquin Valley
Percent Loss
< 10%
10% - 15%
15% - 20%
20% - 25%
25% - 30%
> 30%
Location Map
Scale 1:3,400,000
0
30
60 Mi
0
50
100 Km

Yield Loss Estimates Using Interpolated Ozone Statistics, 1992. Sutter county is not included because a digital database of irrigated farmland was not available. The range and geographic distribution of potential yield reductions in tomato in the Sacramento Valley were comparable in 1992 and 1991 (Figures 35 and 25). Yield loss for rice ranged from 4% in Sacramento to 8% in Tehama county (Figure 36). Seasonal mean ozone concentrations ranged from 4.9 pphm in West Sacramento to 5.9 pphm in Tehama county.

Yield reductions in tomato were projected to be less in 1992 than in 1991 in the San Joaquin Valley (Figures 37 and 27). Seasonal mean ozone levels were somewhat lower in the southern and eastern portions of the Valley. Short-term episodes and daily peak concentrations of ozone are indistinguishable when using seasonal averages. Numerous researchers demonstrated that acute, short-term exposures to ozone may significantly reduce yields in many crops (e.g., Heck et. al., 1982). Thus expected yield losses calculated using seasonal means may not represent actual crop response. Cotton losses in the Bakersfield area (Figure 38) may have been as high as 30%; projected lows of 5% occurred in Stanislaus county. Ozone means in these counties ranged from 4.5 pphm to 7.8 pphm in Stanislaus and Kern counties, respectively.

Tomato productivity in the Salinas Valley (Figure 39) and Coachella Valley (Figure 40) were unaffected by air pollution in 1992. Cotton yields were reduced by no more than 15% in the Imperial Valley (Figure 41).

Field Survey of Ozone Injury Symptoms in Cotton. The incidence of ozone injury to Acala cotton leaves (Table 9) was greatest at locations in the southern end (e.g., Location 1, Arvin) of the San Joaquin Valley and decreased northward (Location 8, Madera). An injury index derived by dividing the sum of dropped and injured leaves (D + I) by the total number of leaves along the main stem (D + I + G), revealed that the green leaves (G) constituted a smaller portion of the total leaves at the southern sites, as compared to that observed at the northern locations. Values approaching 1.00 represent no green and healthy leaves present, and values approaching 0 reflect a minimal amount of ozone injury. For example, the injury index for cotton in the Arvin area had a value of 0.72, whereas the index was only 0.37 at the relatively cleaner Madera location.

Principal component analysis demonstrated that the weighted contribution to the degree of injury among the three leaf conditions monitored was greatest for the green leaves (Table 9). The weighted contribution of each of the three leaf conditions, D, I, and G (dropped, injured and green, respectively), demonstrated that the number of green leaves was individually the best indicator of injury. Ozone injury calculated by a linear weighted function (WI, Table 9) produced a range of values from 9.29 in the Arvin area to 3.10 near Madera (Location 8). The greater number of green leaves resulted in more negative injury value. The greater WI value, the greater the occurrence of ozone injury symptoms. All three measured injury components (D, I, G) were significantly different between locations ($p < 0.01$). However, neither ozone or WI were reliable predictors of yield across location (Table 9). Although 7-hr mean ozone concentrations paralleled injury symptoms geographically, yield did not. Regressions of WI and 7-hr mean ozone individually on yield produced nonsignificant R^2 values of 0.05 and 0.02, respectively.

Figure 29.

1991 Ozone Associated Yield Loss for Cotton in the Irrigated Farmlands of the San Joaquin Valley

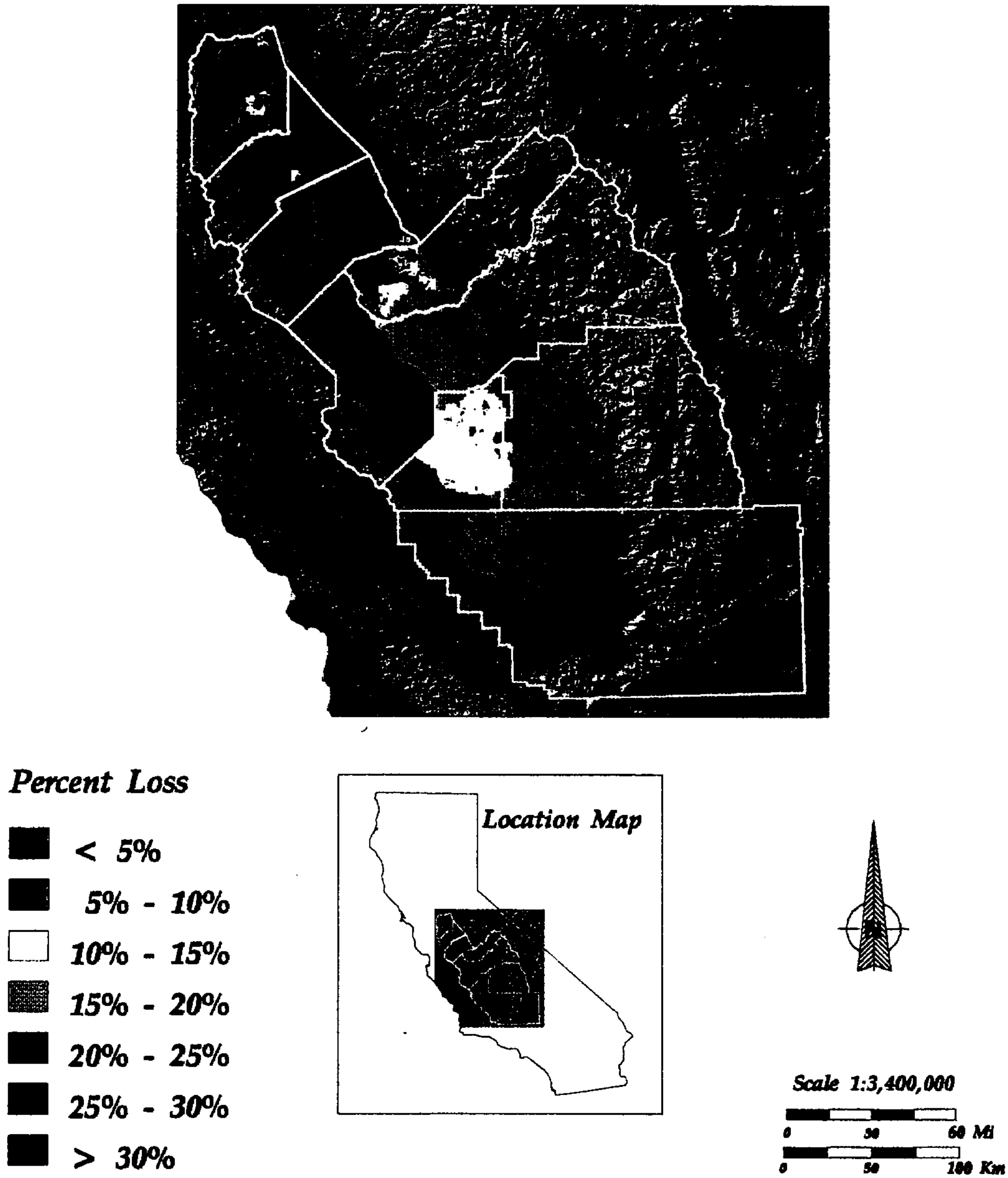
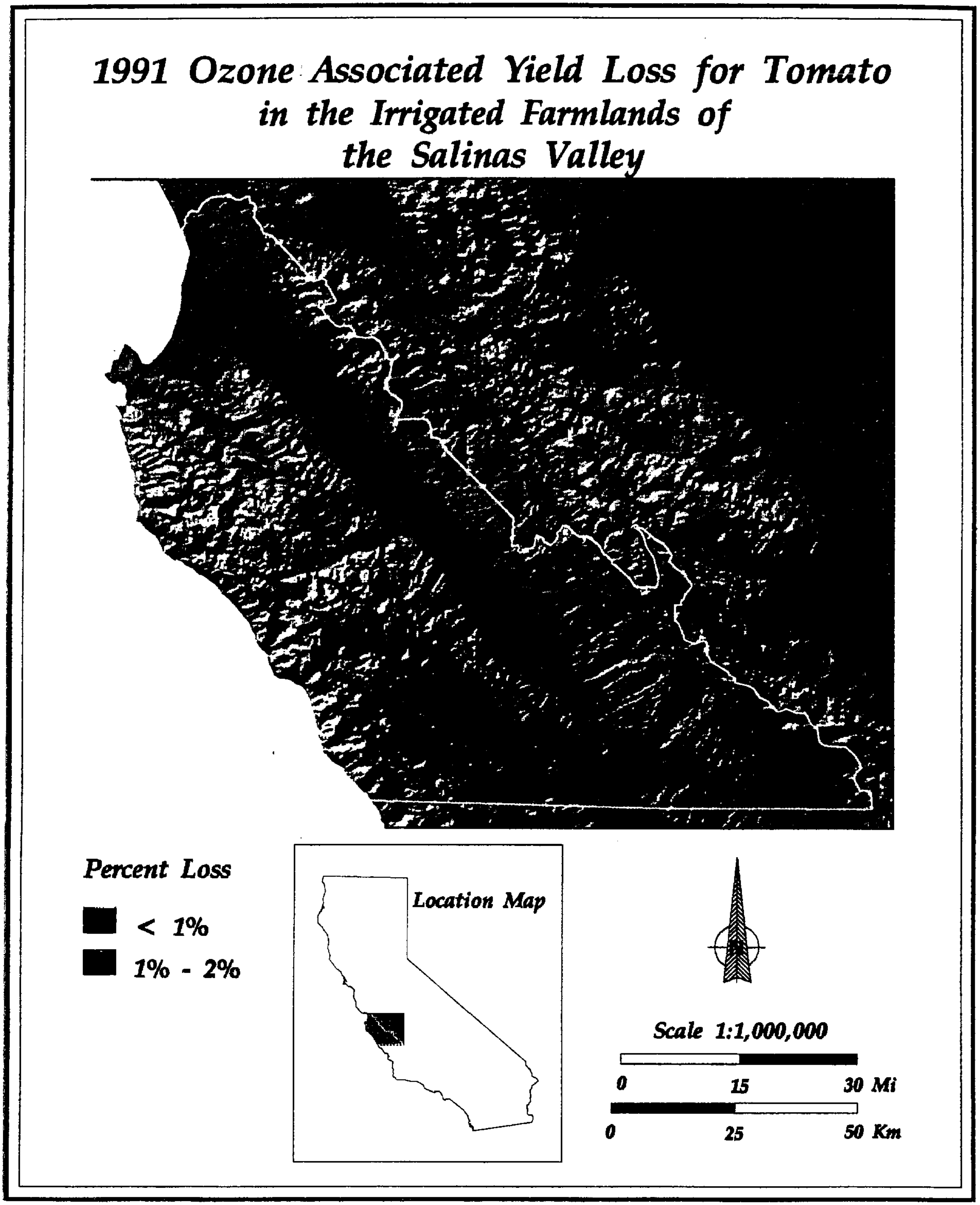


Figure 30.



1991 Ozone Associated Yield Loss for Tomato in the Irrigated Farmlands of the Salinas Valley
Percent Loss
< 1%
1% - 2%
Location Map
Scale 1:1,000,000
0
15
30 Mi
0
25
50 Km

Figure 31.

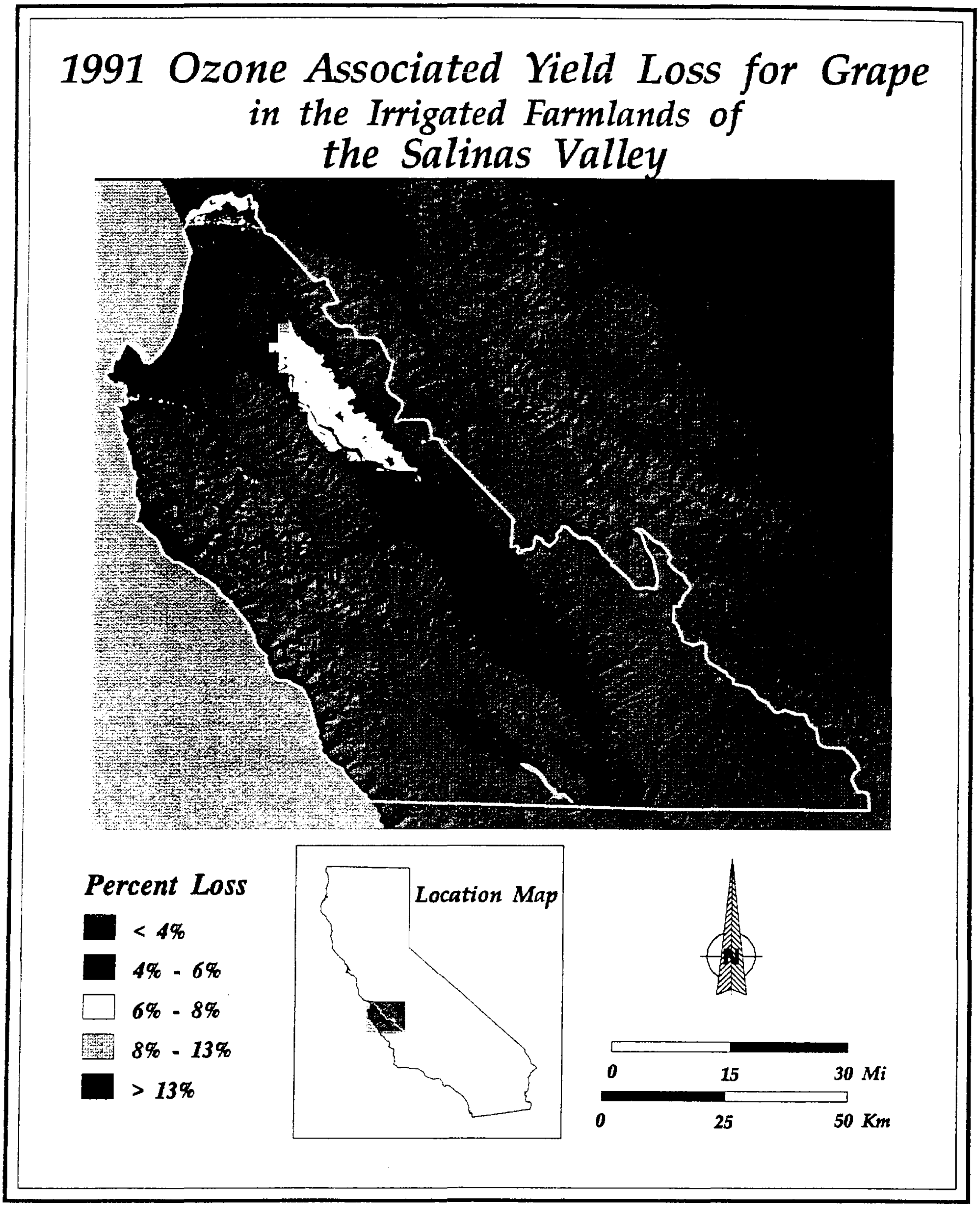

1991 Ozone Associated Yield Loss for Grape
in the Irrigated Farmlands of
the Salinas Valley
Percent Loss
< 4%
4% - 6%
6% - 8%
8% - 13%
> 13%
Location Map
N
0
15
30 Mi
0
25
50 Km

Figure 32.

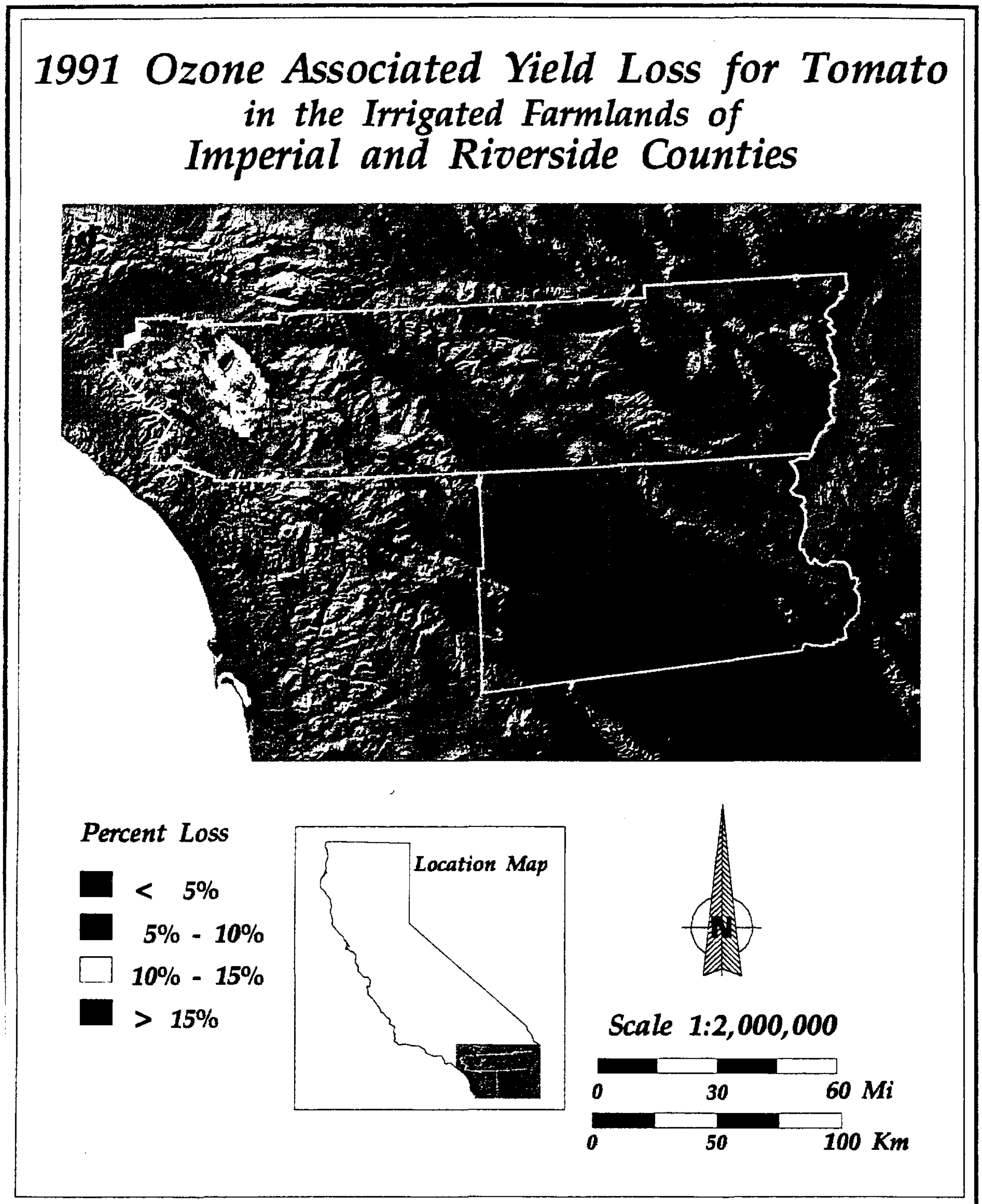
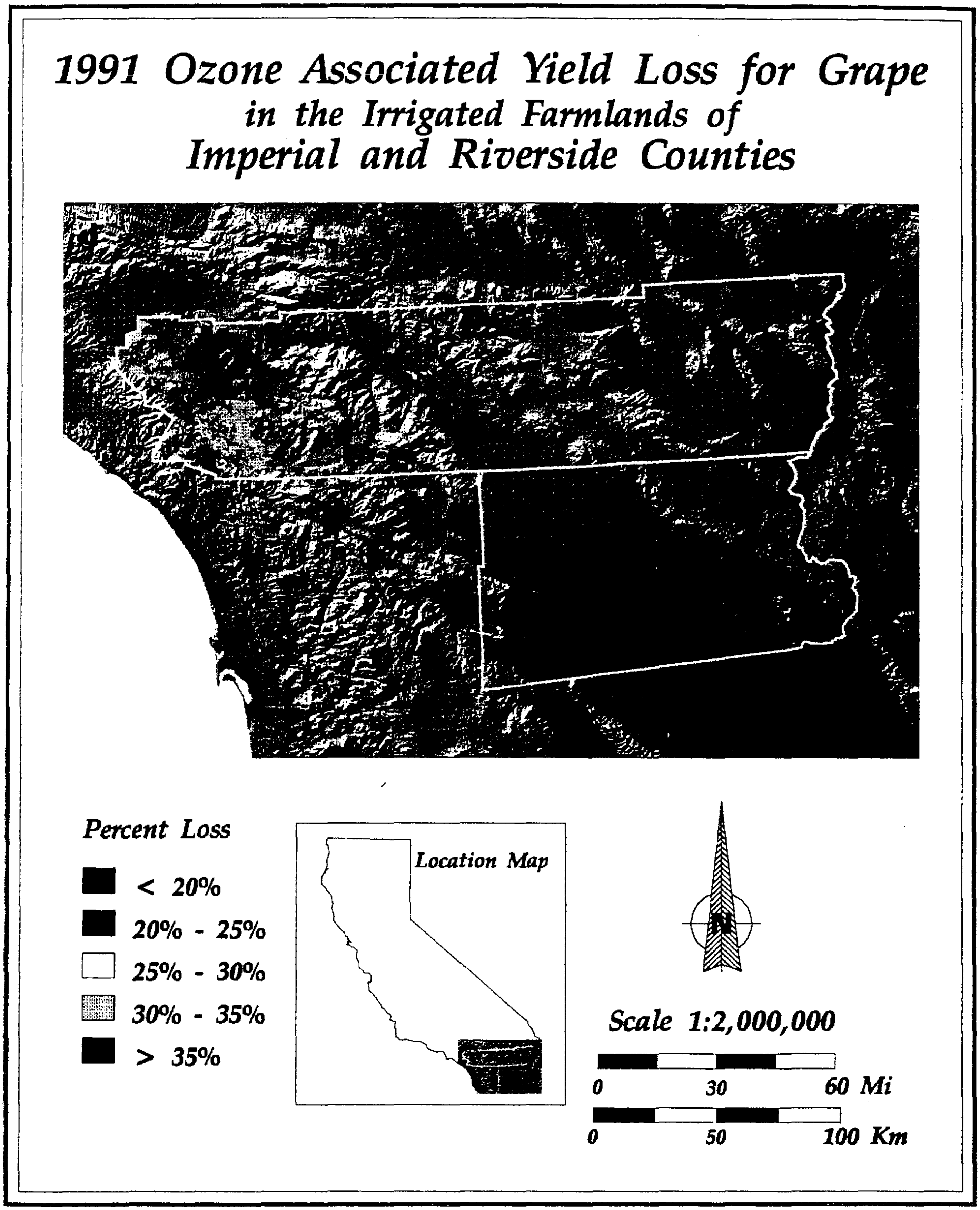

1991 Ozone Associated Yield Loss for Tomato
in the Irrigated Farmlands of
Imperial and Riverside Counties
Percent Loss
< 5%
5% - 10%
10% - 15%
> 15%
Location Map
N
Scale 1:2,000,000
0
30
60 Mi
0
50
100 Km

Figure 33.



1991 Ozone Associated Yield Loss for Grape
in the Irrigated Farmlands of
Imperial and Riverside Counties
Percent Loss
< 20%
20% - 25%
25% - 30%
30% - 35%
> 35%
Location Map
N
Scale 1:2,000,000
0
30
60 Mi
0
50
100 Km

Figure 34.

1991 Ozone Associated Yield Loss for Cotton in the Irrigated Farmlands of Imperial and Riverside Counties

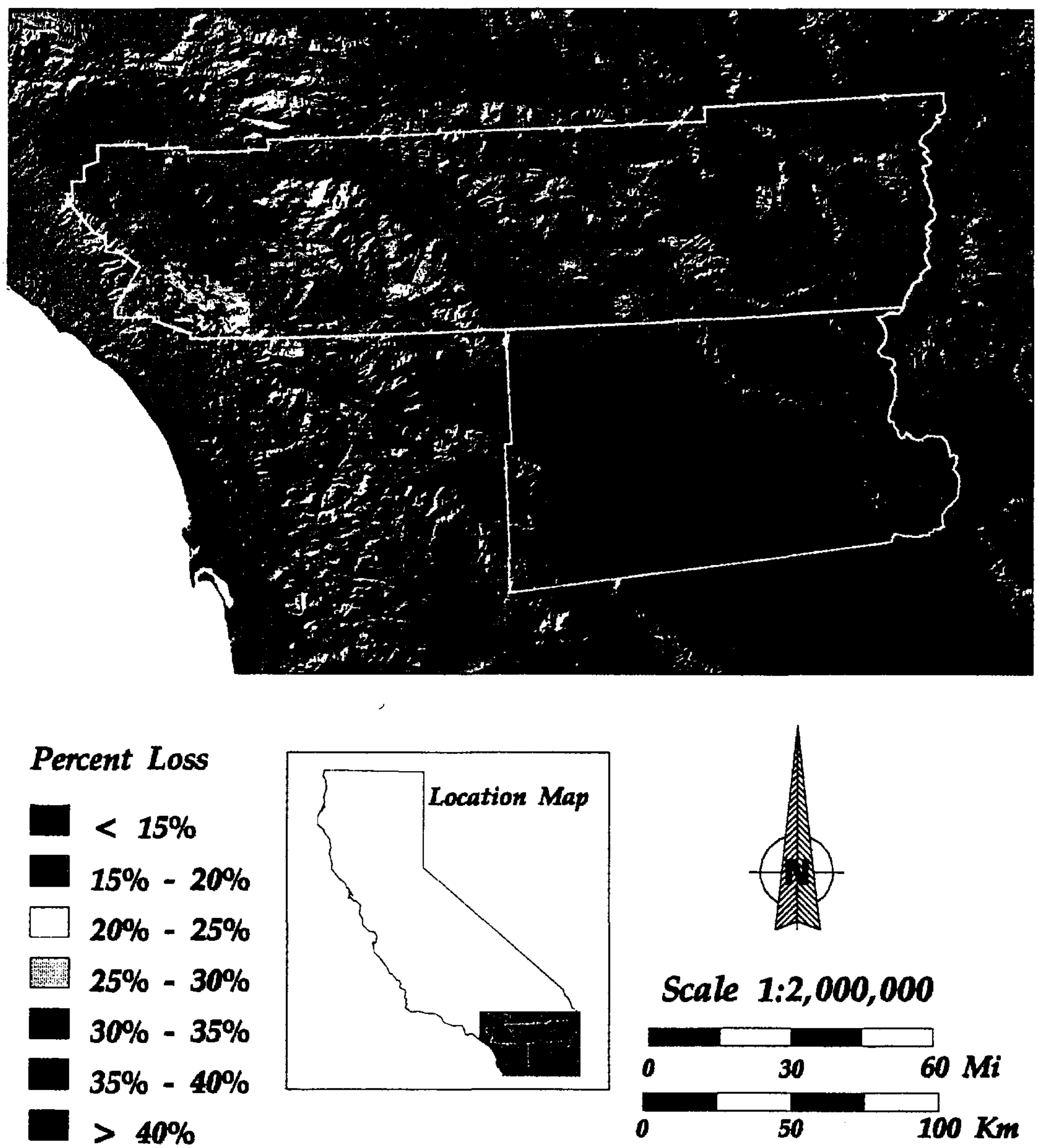


Figure 35.

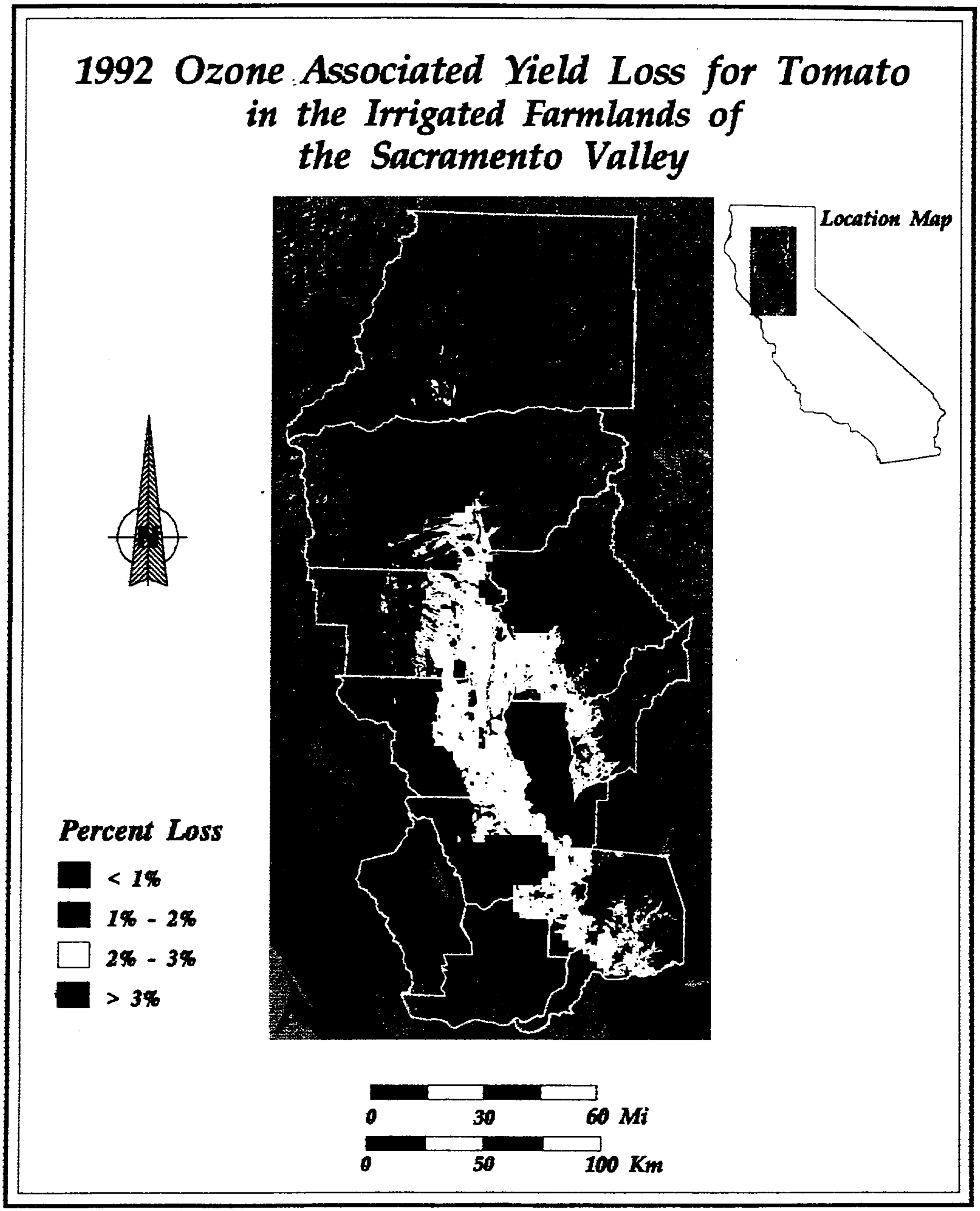

1992 Ozone Associated Yield Loss for Tomato in the Irrigated Farmlands of the Sacramento Valley
Location Map
Percent Loss
< 1%
1% - 2%
2% - 3%
> 3%
0
30
60 Mi
0
50
100 Km

Figure 36.

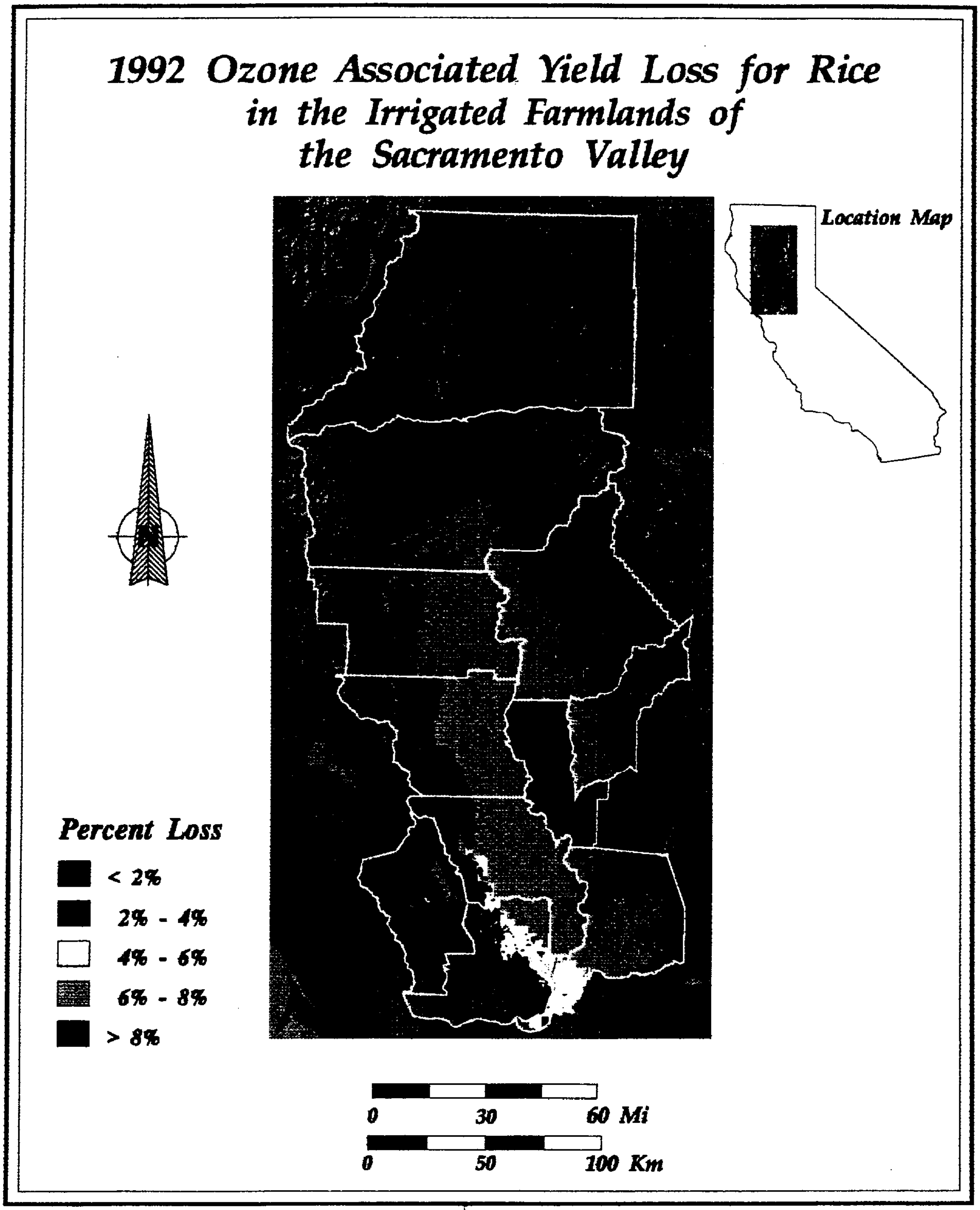

1992 Ozone Associated Yield Loss for Rice
in the Irrigated Farmlands of
the Sacramento Valley
Location Map
Percent Loss
< 2%
2% - 4%
4% - 6%
6% - 8%
> 8%
0
30
60 Mi
0
50
100 Km

Figure 37.

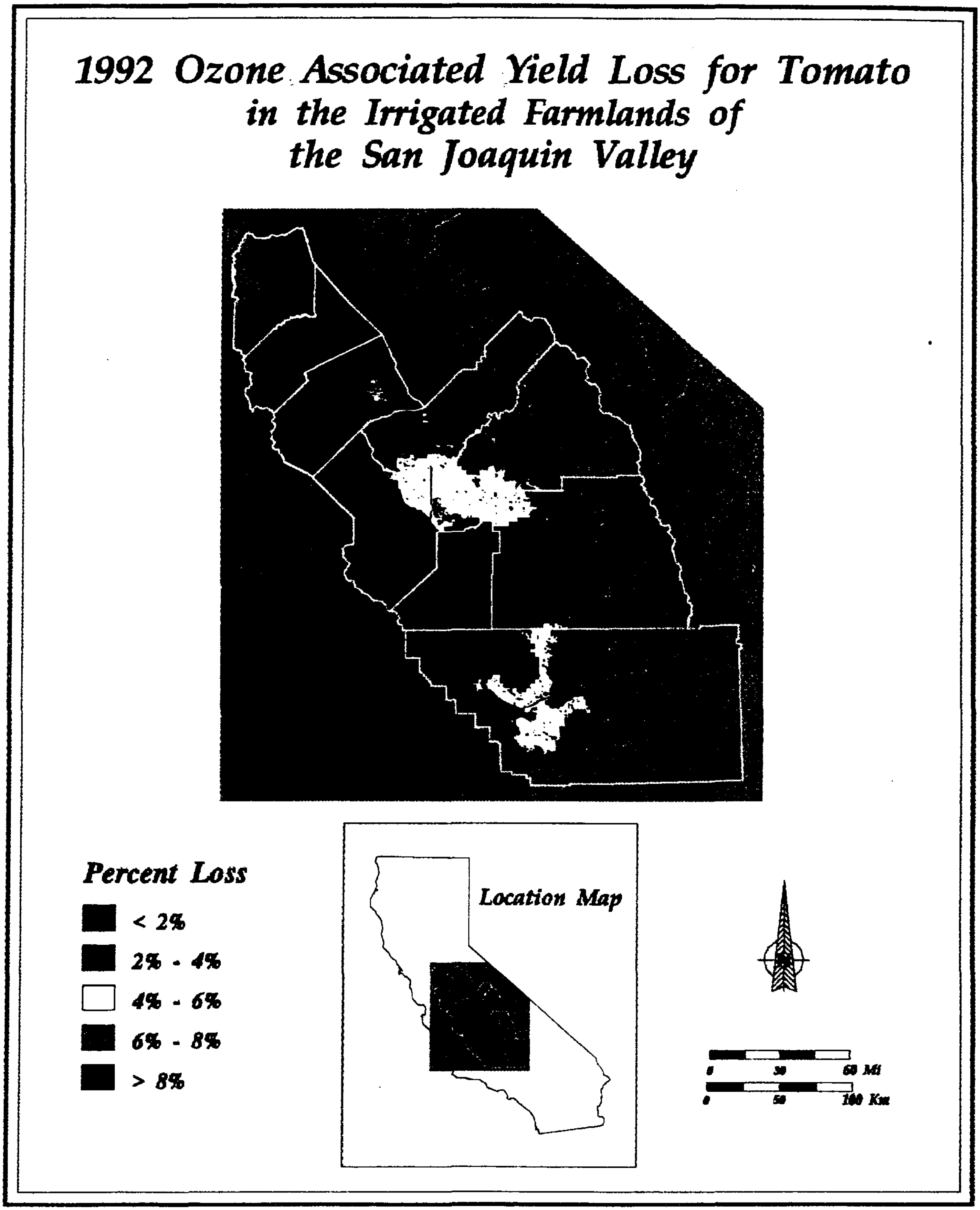

1992 Ozone Associated Yield Loss for Tomato
in the Irrigated Farmlands of
the San Joaquin Valley
Percent Loss
< 2%
2% - 4%
4% - 6%
6% - 8%
> 8%
Location Map
0
30
60 Mi
0
50
100 Km

Figure 38.

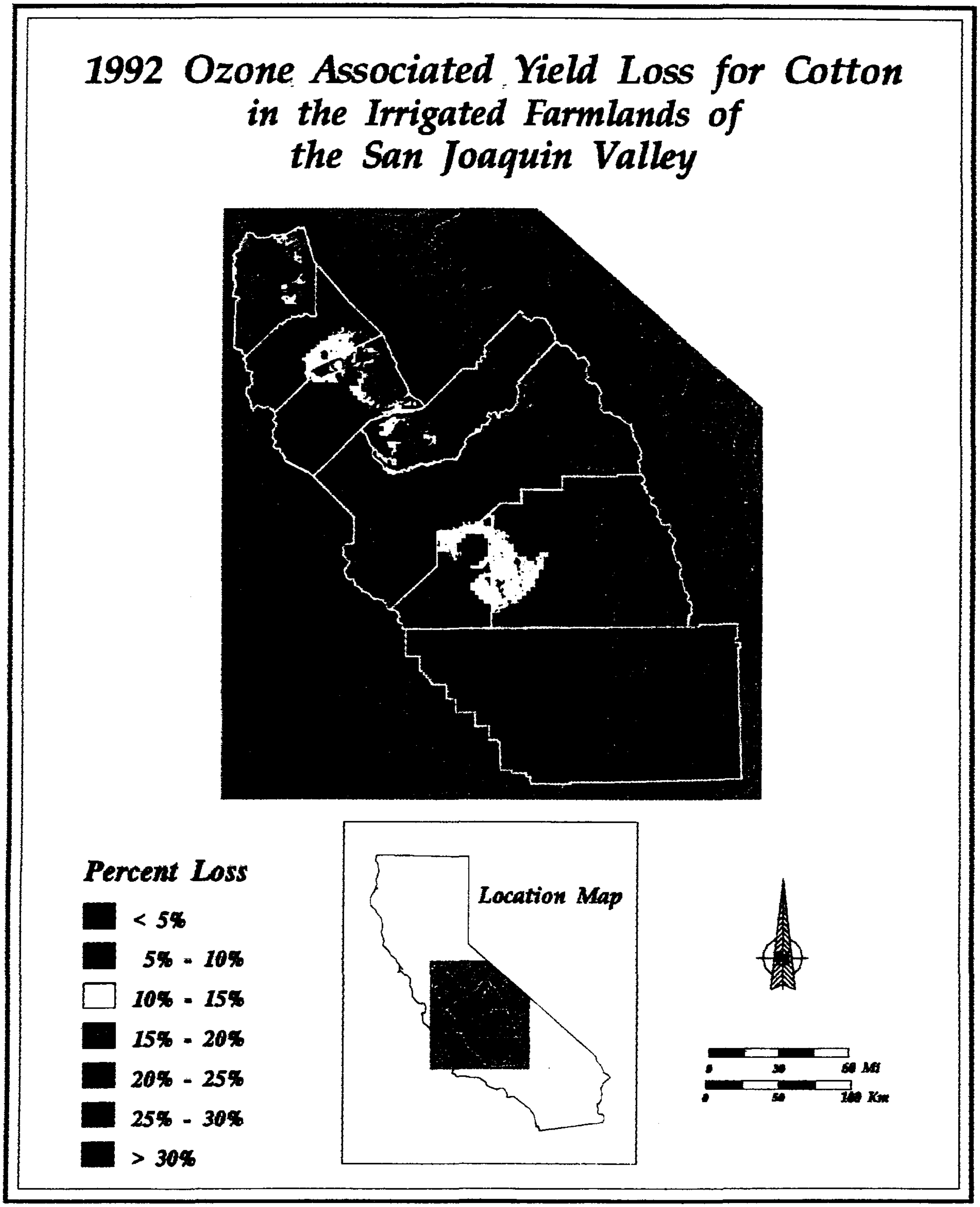
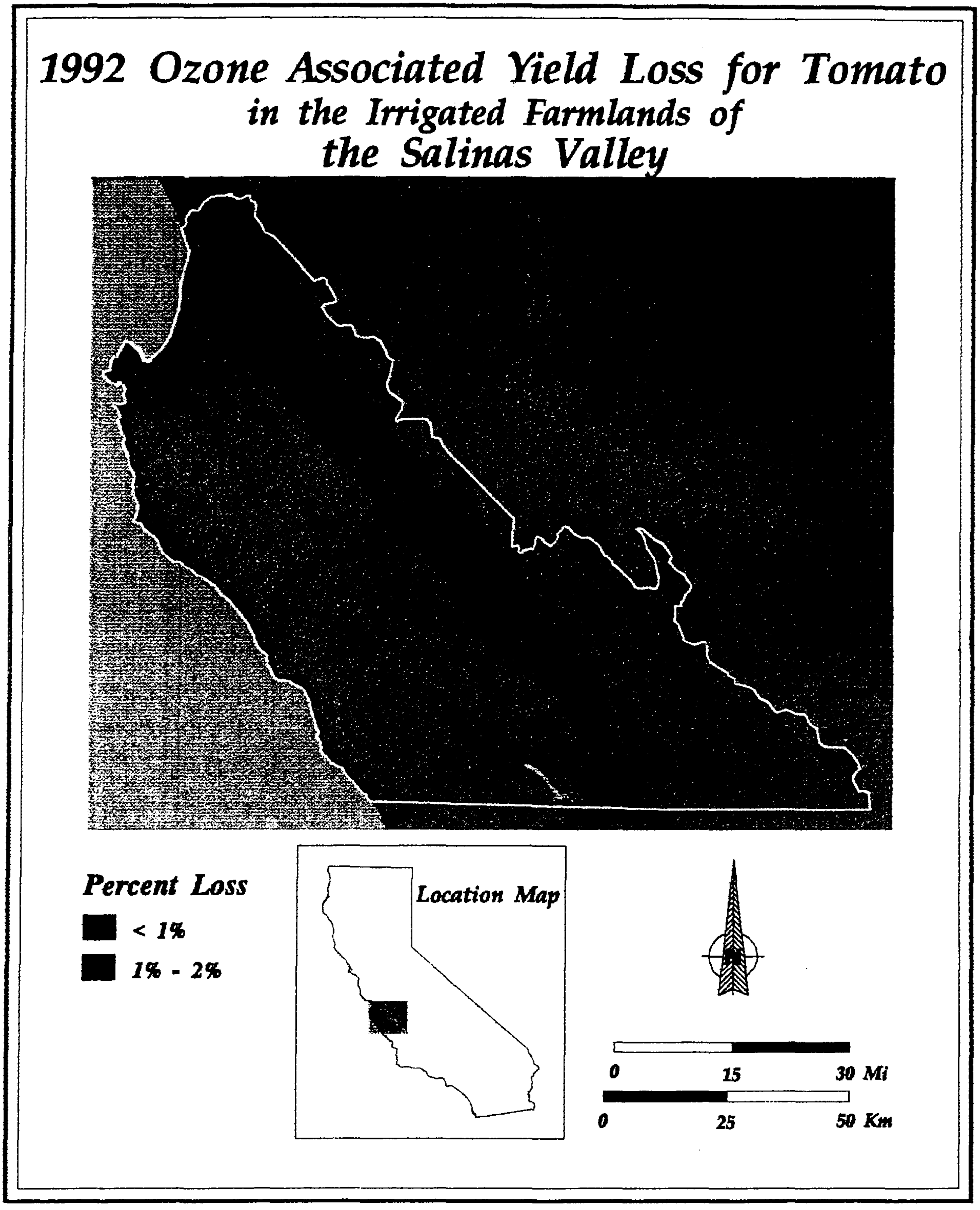
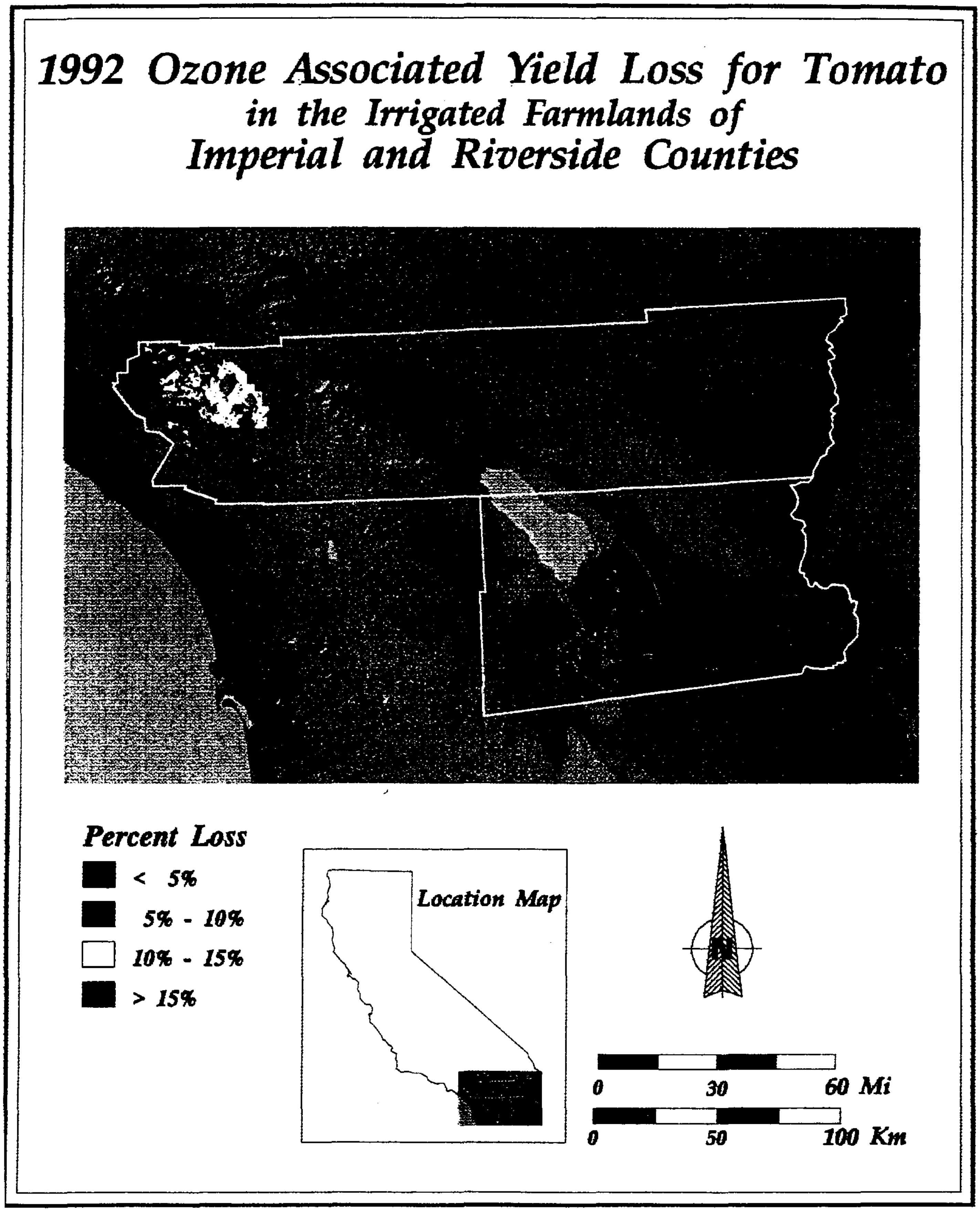

1992 Ozone Associated Yield Loss for Cotton
in the Irrigated Farmlands of
the San Joaquin Valley
Percent Loss
< 5%
5% - 10%
10% - 15%
15% - 20%
20% - 25%
25% - 30%
> 30%
Location Map
0
30
60 Mi
0
50
100 Km

Figure 39.



1992 Ozone Associated Yield Loss for Tomato
in the Irrigated Farmlands of
the Salinas Valley
Percent Loss
< 1%
1% - 2%
Location Map
0
15
30 Mi
0
25
50 Km

Figure 40.



1992 Ozone Associated Yield Loss for Tomato
in the Irrigated Farmlands of
Imperial and Riverside Counties
Percent Loss
< 5%
5% - 10%
10% - 15%
> 15%
Location Map
0
30
60 Mi
0
50
100 Km

Figure 41.

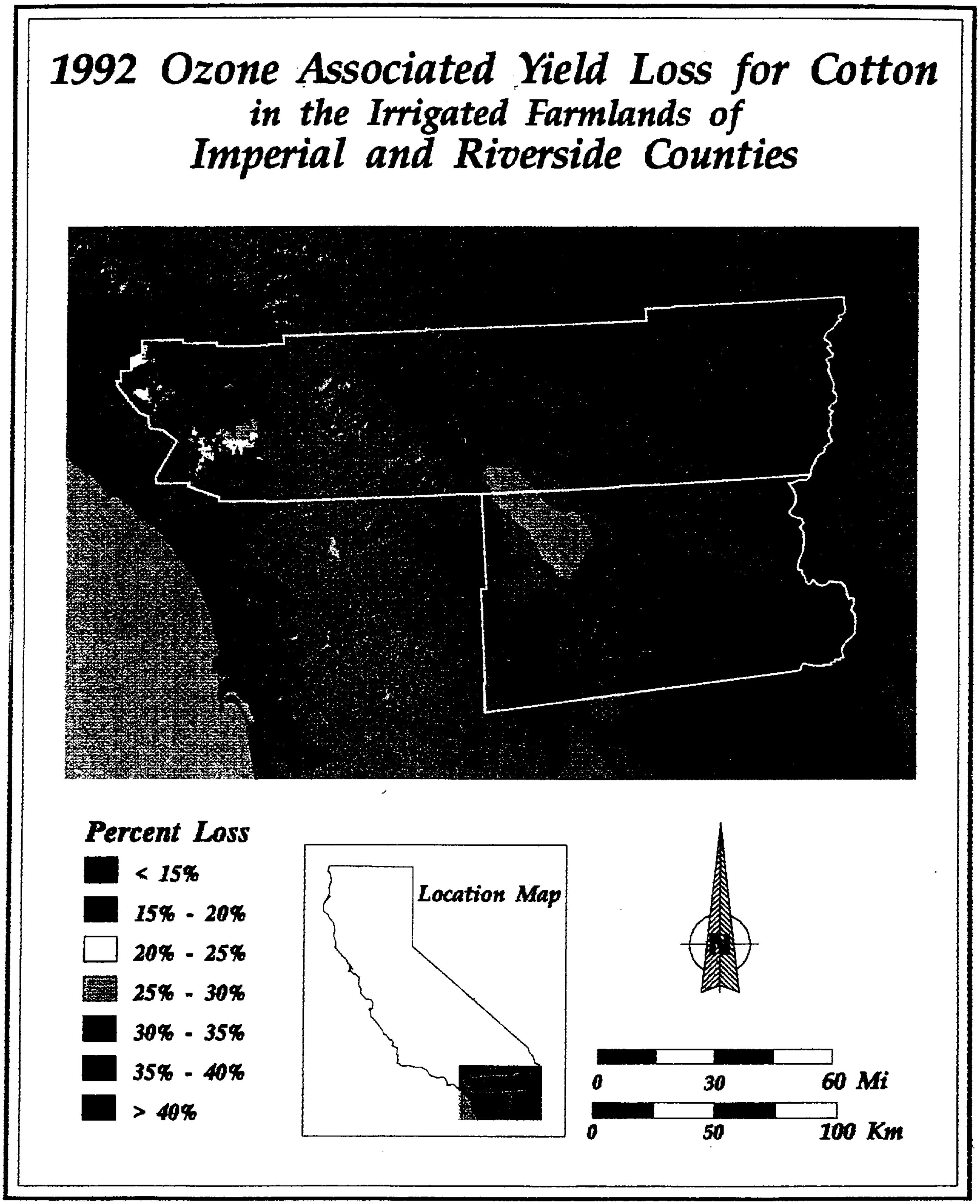

1992 Ozone Associated Yield Loss for Cotton
in the Irrigated Farmlands of
Imperial and Riverside Counties
Percent Loss
< 15%
15% - 20%
20% - 25%
25% - 30%
30% - 35%
35% - 40%
> 40%
Location Map
0
30
60 Mi
0
50
100 Km

Table 9. Leaf Ozone Injury Ratings of Acala SJ-2 Cotton at Ten Locations in the San Joaquin Valley, 1992.*

Location No.	D	I	G	Injury Rating**	WI+	Yield (lbs/acre)	Ozone++
1	9.8	5.0	5.8	0.72	9.29	1,240	7.8
2	7.8	4.8	10.8	0.53	5.58	1,918	5.9
3	7.8	2.6	10.0	0.51	5.40	1,474	5.9
4	9.6	0.4	11.4	0.47	3.97	1,335	6.1
5	8.8	1.4	11.2	0.48	4.33	1,438	6.9
6	6.6	1.2	11.6	0.41	3.76	1,252	4.8
7	6.0	1.8	11.6	0.40	3.81	1,735	6.9
8	5.2	1.2	12.2	0.37	3.10	1,210	5.8
9	6.8	2.0	11.4	0.43	4.13	1,735	6.9
10	7.8	2.4	9.8	0.50	5.46	1,710	5.8

* Values are the mean of five plants, where D, I and G are dropped leaves, injured leaves and green leaves, respectively. Larger values reflect greater ozone injury.

** Injury Rating = (D + I)/(D + I + G). Values from original data, and may vary slightly from the data in the table due to rounding.

\+ WI = {10 + [(0.14)D + (0.35)I + (0.66)G]}. WI = Weighted Injury based on the relative contribution of each component to the observed variability in plant ozone injury among locations, based on principal component analysis.

++ 7-hr mean ozone concentration for the growing season (April to September).

Multivariate Analysis - Yield versus Agronomic Factors Plus Ozone. Results from the step-wise regression with P to enter set at 0.15 indicated that ozone did not become a significant predictive variable of yield until ten other variables were included and the R^2 exceeded 0.95 (Table 10). The P value of June ozone was 0.1304. However, if the traditional significance level of 0.05 was used instead of the $P = 0.15$ to enter set point, June ozone would not have been significant. Furthermore with 10 independent variables already included and an $R^2 > 0.95$, the probability is high that the correlation was random and not necessarily related to the physiological function of the plant.

To test whether the indirect effects of ozone were manifested in important plant growth parameters measured, plant height and number of nodes (height-related) were omitted as independent variables and the regression was rerun. After the fourth run, only density, density sq, planting date, and petiole Zn proved significant; ozone was not. Backward regressions were also used with the full suite of variables and selected omissions to test for indirect effects. The analysis proceeded until seven variables remained, each with a significance of $P < 0.05$. They were density, density sq, pH1, petiole N, petiole K, soil K, and June ozone. The regression coefficient for June ozone was positive (i.e., yield stimulating). However, the effects of the high correlation ($R^2 > 0.96$) between the monthly ozone values were of concern. Thus, all monthly ozone values were excluded except June ozone, and the analysis was rerun. June ozone fell out of the regression at an early step; it needed the other monthly ozone values to "hold" it in long enough to attain a $P < 0.05$.

For this data, ozone was not a significant predictor of yield variability in cotton across 21 locations in the San Joaquin Valley in 1990. Agronomic and environmental associated factors accounted for approximately 95% of the observed variability. Although ozone was insignificant for this data set, it does not preclude its possible importance for other years or crops. The results indicate that the 7-hr mean exposure index response models as developed by NCLAN and similar research may be inadequate. Furthermore, these results point to a serious shortcoming in much of the experimental results describing plant response to ozone stress; there has been no field validation of experimental results using actual farm data. Until such time that agronomic variables are fully integrated into predictive models, yield losses based on ozone alone should be considered as rough estimates at best.

Table 10. Results of a Step-wise Regression of 21 Independent Variables on Cotton Yield from 21 Locations in the San Joaquin Valley in 1990.

Step	R^2	Significant Variables	F	Prob > F
1	0.56	Density	10.71	0.0045
		Density sq	9.8	0.0061
		Plant Height	8.49	0.0097
2	0.72	Density	11.21	0.0041
		Density sq	10.33	0.0054
		pH1 -- A Horizon	9.16	0.0080
		Plant Height	18.19	0.0006
3	0.77	Density	15.01	0.0001
		Density sq	13.35	0.0015
		Soil pH1	12.75	0.0024
		Petiole K	3.71	0.0021
		Plant Height	24.54	0.0002
4	0.85	Density	24.94	0.0002
		Density sq	23.21	0.0003
		Soil pH1	20.74	0.0005
		Petiole K	8.51	0.0113
		Petiole N	7.36	0.0168
		Plant Height	34.87	0.0001
5	0.90	Density	31.57	0.0001
		Density sq	28.71	0.0001
		Soil pH1	14.61	0.0021
		Petiole K	17.58	0.0011
		Petiole N	7.04	0.0199
		Petiole Zn	6.46	0.0246
		Plant Height	47.76	0.0001
6	0.92	Density	37.69	0.0001
		Density sq	34.41	0.0001
		Soil pH1	18.92	0.0009
		Zn1	3.09	0.1041
		Petiole K	19.05	0.0009
		Petiole Zn	8.08	0.0148
		Plant Height	56.13	0.0001

Table 10 (Continued). Results of a Step-wise Regression of 21 Independent Variables on Cotton Yield from 21 Locations in the San Joaquin Valley in 1990.

Step	R^2	Significant Variables	F	Prob > F
7	0.94	Density	46.15	0.0001
		Density sq	41.92	0.0001
		Soil pH1	23.92	0.0005
		Zn1	5.31	0.0448
		Zn2	3.09	0.1063
		Petiole K	24.72	0.0004
		Petiole N	13.32	0.0038
		Petiole Zn	12.45	0.0047
		Plant Height	44.44	0.0001
8	0.95	Density	56.01	0.0001
		Density sq	51.17	0.0001
		Soil pH1	25.86	0.0005
		Zn1	8.55	0.0152
		Zn2	5.51	0.0408
		Petiole K	27.61	0.0004
		Petiole N	17.60	0.0018
		Petiole Zn	9.77	0.0108
		Plant Height	39.39	0.0001
		June Ozone	2.72	0.1304

REFERENCES

Adaros, G., H. J. Weigel, and H. J. Jargan. 1990. Effects of incremental ozone concentrations on the yield of bush beans. Gartenbanwissenschaft 55:162-167.

Bender, J., H. J. Weigel, and H. J. Jaeger. 1994. Regression analysis to describe yield and metabolic responses of beans *Phaseolus vulgaris* to chronic ozone stress. Angew. Bot. 64:329-344.

Brewer, R. F. 1978. The Effects of Present and Potential Air Pollution on Important San Joaquin Valley Crops: Sugar Beets. Final Report, California Air Resources Board, Contract No. A6-161-30.

Brewer, R. F. 1982. The Effects of Ozone and Sulfur Dioxide on Cotton Growth and Quality. Final Report, California Air Resources Board, Contract No. A3-047-33.

Brewer, R. F. 1983. The Effects of Ambient Air Pollution on Thompson Seedless Grapes. Final Report, California Air Resources Board, Contract No. A1-132-33.

California Air Resources Board. 1990. California Air Quality Data, Technical Support Division, Sacramento, CA.

California Air Resources Board. 1991. California Air Quality Data, Technical Support Division, Sacramento, CA.

California Air Resources Board. 1992. California Air Quality Data, Technical Support Division, Sacramento, CA.

Eckey-Kaltenbach H., D. Ernst, W. Heller, and H. Sanderman. 1994. Biochemical plant responses to ozone. IV. Cross-induction of defensive pathways in parsley (*Petroselinum crispum* L.) plants. Plant Physiol. 104: 67-74.

Environmental Systems Research Institute. (ESRI) 1992. ARC/INFO Geographical Information System, Redlands, CA.

Fangmeier A., S. Brunschon, and H. J. Jager. 1994a. Time course of oxidant stress biomarkers in flag leaves of wheat exposed to ozone and drought stress. New Phytol. 126:63-69.

Fangmeier A., U. Brockerhoff, U. Gruters, and H. J. Jager. 1994b. Growth and yield responses of spring wheat (*Triticum aestivum* L cv. Turbo) grown in open-top chambers to ozone and water stress. Environ. Pollut. 83:317-325.

Fuhrer, J., A. Grimm, W. Tschannen, H. Shareat-Madari. 1992. The response of spring wheat to ozone at higher elevations. New Phytol. 121:211-219.

Goldstein, M. and W. R. Dillion. 1983. Multivariate Analysis: Methods and Applications. Wiley, New York.

Gumpertz, M. L. and J. O. Rawlings. 1992. Nonlinear regression with variance components: Modeling effects of ozone on crop yield. Crop Sci. 32:219-224.

Heagle, A. S., W. W. Heck, V. M. Lesser, J. O. Rawlings, and F. L. Mowry. 1986. Injury and yield response of cotton to chronic doses of ozone and sulfur dioxide. J. Environ. Qual. 15:375-382.

Heck, W. W., W. W. Cure, J. O. Rawlings, L. J. Zaragosa, A. S. Heagle, H. E. Heggestad, R. J. Kohut, L. W. Kress, and P. J. Temple. 1984a. Assessing impacts of ozone on agricultural crops. J. Air Pollut. Control Assoc. 34:729-735.

Heck, W. W., W. W. Cure, J. O. Rawlings L. J. Zaragosa, A. S. Heagle, H. E. Heggestad, R. J. Kohut, L. W. Kress, and P. J. Temple. 1984b. Assessing impacts of ozone on agricultural crops: II. Crop yield functions and alternative exposure statistics. J. Air Pollut. Control Assoc. 34:810-817.

Kats, G., P. J. Dawson, A. Bytnerowicz, J. W. Wolf, C. R. Thompson, and D. M. Olszyk. 1985. Effects of ozone or sulfur dioxide on growth and yield of rice. Agric., Ecosys. & Environ. 14:103-117.

Kerby, T. A. 1990. 1989 Pima Testing Program. University of California Cooperative Extension, Shafter, CA.

Kohut, R. and J. A. Laurence. 1983. Yield response of red kidney bean to incremental ozone concentrations in the field. Environ. Pollut. 32:233-240.

Kress, L. W. and J. E. Miller. 1985. Impact of ozone on field-corn yield. Can. J. Bot. 63:2408-2415.

Lee, E. H., D. T. Tingey, and W. E. Hogsett. 1988. Evaluation of ozone exposure indices in exposure-response modeling. Environ. Pollut. 53:43-62.

McCool, P. M., R. C. Musselman, R. R. Teso, and R. J. Oshima. 1986. Determining crop yield losses from air pollutants. Calif. Ag. 40(7-8):9-10.

Miller, P. R., M. H. McCutchan, and B. C. Ryan. 1972. Influence of climate and topography on oxidant air pollution concentrations that damage conifer forests in southern California. In: Fume Damage to Forests. Forestry Commission Research and Development, Paper 82, October, 1971.

Mortensen, L. M. 1992. Effects of ozone concentration on growth of tomato at various light, air humidities, and carbon dioxide levels. Scientia Horticulturae 49:17-24

Mutters, R. G. and M. R. Guzy. 1993. Crop Losses from Air Pollutants. Final Report, California Air Resources Board, Contract No. A033-174.

Olszyk, D. M., A. Bytnerowicz, G. Kats, P. J. Dawson, J. Wolf, and C. R. Thompson. 1986. Crop effects from air pollutants in air exclusion systems vs. field chambers. J. Environ. Qual. 15:417-422.

Olszyk, D. M. 1989. Mechanistic Basis for the Growth and Yield Effects of Ambient Ozone on Valencia Oranges. Final Report, California Air Resources Board, Contract No. A733-088.

Olszyk, D. M., G. Kats, C. L. Morrison, P. J. Dawson, I. Gocka, J. Wolf, and C. R. Thompson. 1990. Valencia orange fruit yield with ambient oxidant on sulfur dioxide exposures. J. Am. Soc. Hortic. Science 115:878-883.

Pell, E. J., N. S. Pearson, and C. Vinten-Johansen. 1988. Qualitative and quantitative effects of ozone and/or sulfur dioxide on field-grown potato plants. Environ. Pollut. 53:171-186.

Pliejel, H., L. Sharby, K. Ojanpera, and G. Selldan. 1992. Yield and quality of spring barley, *Hordeum vulgare L.*, exposed to different concentrations of ozone in open-top chambers. Agric. Ecosys. Environ. 38:21-29.

Reinert, R. A., J. A. Dunning, W. W. Heck, P. S. Benepal, and M. Rangappa. 1984. Screening of bean (*Phaseolus vulgaris*) for sensitivity to ozone. HortScience 19:86-88.

Retzlaff, W. A., T. M. DeJong, and L. E. Williams. 1992. Photosynthesis and growth response of almond to increased atmospheric ozone partial pressures. J. Environ. Qual. 21:208-216.

Sakaki T., K. Tanaka, and M. Yamada. 1994. General metabolic changes in leaf lipids in response to ozone. Plant Cell Physiol. 35:53-62

Sanders, G. E., A. D. Robinson, P. A. Geissler, and J. J. Colls. 1992. Yield stimulation of a commonly grown cultivar of *Phaseolus vulgaris* L. at near-ambient ozone concentrations. New Phytol. 122:63-70.

Slaughter, L. H., C. L. Mulchi, and E. H. Lee. 1993. Wheat-kernel growth characteristics during exposure to chronic ozone pollution. Environ. Pollut. 81:73-79.

Snyder, R. G., J. E. Simon, R. A. Reinert, M. Simini, and W. W. Heck. 1988. Effects of air quality on foliar injury, growth, yield, and quality of muskmelon. Environ. Pollut. 53:187-196.

Takemoto, B. K., D. M. Olszyk, A. G. Johnson, and C. R. Parada. 1987. Yield responses of field-grown crops to acidic fog and ambient ozone. J. Environ. Qual. 17:192-197.

Temple, P. J., O. C. Taylor, and L. F. Benoit. 1985a. Effects of ozone on yield of two field-grown barley cultivars. Environ. Pollut. 39:217-225.

Temple, P. J., O. C. Taylor, and L. F. Benoit. 1985b. Cotton yield responses to ozone as mediated by soil moisture and evapotranspiration. J. Environ. Qual. 14:55-60.

Temple, P. J., O. C. Taylor, and L. F. Benoit. 1986. Yield response of head lettuce (*Lactuca sativa* L.) to ozone. Environ. Exp. Bot. 26:53-58.

Temple, P. J., L. F. Benoit, R. W. Lennox, C. A. Reagan, and O. C. Taylor. 1988. Combined effects of ozone and water stress on alfalfa growth and yield. J. Environ. Qual. 17:108-113.

Temple, P. J. 1990a. Growth and yield responses of processing tomato (*Lycopersicon esculentum* Mill.) cultivars to ozone. Environ. Exp. Bot. 30:283-291.

Temple, P. J. 1990b. Growth form and yield responses of four cotton cultivars to ozone. Agron. J. 82:1045-1050.

Temple, P. J., T. E. Jones, and R. W. Lennox. 1990. Yield loss assessments for cultivars of broccoli, lettuce, and onion exposed to ozone. Environ. Pollut. 66:289-300.

Thompson, C. R. and O. C. Taylor. 1969. Effects of air pollutants on growth, leaf drop, fruit drop, and yield of citrus trees. Environ. Sci. Technol. 3:934-940.

Thompson, C. R. and G. Kats. 1970. Ambient oxidants reduce grape yield reductions from photochemical smog. Calif. Ag. 24:12-13.

Thompson, C. R., G. Kats, and J. W. Cameron. 1976. Effects of ambient photochemical air pollutants on growth, yield, and ear characters of two sweet corn hybrids. J. Environ. Qual. 5:410-412.

Tonneijck, A. E. 1994. Effects of various ozone exposures on the susceptibility of bean leaves (*Phaseolus vulgaris* L.) to *Botrytis cinera*. Environ. Pollut. 85:59-65.

Van Camp, W. H. Willekens, C. Bowler, M. Van Montagu, D. Inze, P. Reupold-Popp, H. Sandermann, and C. Langebartels. 1994. Elevated levels of superoxide dismutase protect transgenic plants against ozone damage. BioTechnology 12:165-168.

Appendices

TABLES