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‘Valencia’ Orange Fruit Yield with Ambient Oxidant or Sulfur Dioxide Exposures

D.M. Olszyk[1], G. Kats, C.L. Morrison, P.J. Dawson, I. Gocka, J. Wolf, and C.R. Thompson
Statewide Air Pollution Research Center, University of California, Riverside, CA 92521

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Abstract. **Three-year-old ‘Valencia’ orange *[Citrus sinensis* (L.) Osbeck] trees were exposed to air pollutants for 4 years in open-top field chambers to determine the chronic effects of ambient oxidants (primarily ozone) or sulfur dioxide (SO_2) on fruit yield and quality and tree growth. Ozone concentrations averaged 0.012,0.040, and 0.075 ppm for 0800 to 2000 HR during April to October for filtered, half-ambient, and full ambient oxidant chambers. Sulfur dioxide was applied continuously at 0.09 ppm. Oxidant and SO_2 effects were only marginally significant, as there was considerable variability in response among individual trees and between years. Across two “on” production years, yields were 31% lower with ambient oxidants, 11% lower with half-ambient oxidants, and 29% lower with sulfur dioxide compared to filtered air. Number of fruit per tree was reduced by ambient oxidants and SO_2. Individual fruit weights were reduced by ambient oxidants, but no other fruit quality characteristics showed definite responses to ambient oxidants or SO_2. Ambient oxidants had no effect on yield or quality of fruit during one “off’ production year. Neither ambient oxidants nor SO, affected tree growth.**

During the late 1950s and early 1960s, researchers conducted pioneer studies on the chronic (low-level, long-term) effects of photochemical oxidants on navel oranges and lemons near Los Angeles (Thompson et al., 1967; Thompson and Taylor, 1969). These studies showed reduced water use, increased leaf drop, and very substantial reductions in yields of both species due to photochemical oxidants. Losses in production occurred even though there were few easily observed leaf injury symptoms on the trees.

The sensitivity of orange trees to ambient pollutants in the previous studies, however, may have been different from that of outside trees since the experiments were conducted in closed, plastic-covered greenhouses. The trees were exposed only to filtered or ambient air, with little accurate air monitoring data for the different treatments. Thus, it was not possible to produce accurate dose-response models to describe the relationship between oxidant dose (measured as ozone, O_3) and yield. Such models have become necessary for interpreting current oxidant and orange yield data for loss assessments (Olszyk et al., 1988).

The susceptibility of oranges to long-term, low-level chronic exposure to sulfur dioxide (SO_2), as could occur near oil refineries and other point sources, has not been well-documented. Thomas (1961) cited results of O’Gara who reported citrus to be very resistant to acute foliar injury by SO_2 compared to 100 other crop, ornamental, or forest species tested. Matsushita and Harada (1964, 1966) found that exposures of three species of l-year-old citrus to 1 and 5 ppm SO_2 for 2 hr·day^{-1} for 40 days caused no foliar injury. However, we found no reports detailing chronic long-term exposures with low concentrations of so*.

Therefore, a study was initiated in 1983 to investigate growth and yield responses of ‘Valencia’ orange trees to ambient oxidants or added SO_2 to address carefully the effects of chronic air pollutants on citrus using state-of-the-art exposure techniques.

Materials and Methods

Tree culture. ‘Valencia’ orange trees were grown at the citrus experiment station at the Univ. of California, Riverside. Trees were planted during July 1983 and exposed to air pollutants from May 1984 through August 1988. The trees, grafted on ‘Troyer’ citrange (C. x *Citroncircus* Webberi) rootstock, were selected at a nursery based on uniform stem diameters of =3.2 cm. Trees were grafted =2 years previously and had set a few fruit in Spring 1983. These fruit were picked from the trees on 15 Nov. 1983 so that the highly variable number of fruit per tree would not affect flowering in Spring 1984. Trees flowered in Spring 1984. Trees flowered in Spring 1984 but did not set fruit.

Tree culture followed general maintenance practices for the Riverside area. Trees received foliar zinc sulfate sprays (1 g-liter^{-1}) after major flushes of growth had just expanded, usually twice a year. Trees were watered via furrow irrigation whenever Irrometers (Irrometer Corp., Riverside, Cal if.) buried in the soil at a depth of 46 cm read – 0.5 MPa or leaves began to wilt. At each irrigation, trees received a nutrient solution containing 57 g N over an approximate 14.3-m^2 soil surface beneath each tree. Trees received chemical insecticide sprays for a variety of insects following commercial recommendations for ‘Valencia’ oranges (Olszyk, 1989).

Pollutant exposure. Pollutant exposures were conducted in open-top field chambers of a dome-shaped design specifically developed for this study (Kats et al., 1985). Each chamber consisted of a hemispherical vinyl plastic dome 2.03 m high and 4.27 m in diameter, with a 2.44-m diameter open area at the top and reinforced with sheet metal piping. Each dome was placed on a 0.91 x 4.27 m (height/diameter) cylindrical base consisting of a sheet metal frame covered by opaque fiberglass, resulting in a total chamber volume of 41.6 m^3. A 559-W (3/4 hp) motor with propeller fan moved air into the chamber to provide =1.4 air exchanges/rein from 0600 to 2000 HR daily. A speed controller Parajust Model Y (Parametric Corp., Orange, Calif.) was used to reduce the air flow to =0.5 air ex-

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[1]To whom reprint requests should be addressed. Present address: US EPA/ERL-C, 200 SW 35th St., Corvallis OR 97333.

changes/min at night to simulate low nighttime wind speeds typical for orchards.

A gradient of ambient oxidant exposures was achieved by removing various amounts of pollutants with activated charcoal filters in the incoming air streams of the chambers. The three oxidant treatments were: (a) charcoal-filtered; (b) half-ambient, half of the incoming air passing through charcoal filters;" and (c) ambient. All chambers had particulate filters before the air entered the blower box.

Sulfur dioxide exposure was achieved by adding a metered amount of gaseous SO_2 to incoming air after it had passed through charcoal filters. The control consisted of charcoal-filtered air without SO_2 addition. The SO_2 dispensing system consisted of a temperature-controlled tank of liquid SO_2, a heatless air dryer to provide" carrier air for the SO_2, a flowmeter for each chamber, and dispensing lines. Flow of SO_2 was reduced at night to compensate for the reduced air flow into the chambers.

Pollutant monitoring focused on O_3 because it was considered to be the most phytotoxic gas in the photochemical oxidant mixture (Olszyk et al., 1989) and on SO_2 because it was added to some chambers. Ambient air quality data for nitric oxide (NO), nitrogen dioxide (NO,), and peroxyacetyl nitrate (PAN) were available from a nearby site for part of the study (Olszyk et al., 1989). The O_3 and SO_2 monitoring system consisted of Teflon sample lines, a scanning valve time sharing system, Dasibi Model 1003 AH O_3 analyzer (Dasibi Environmental Corp., Glendale, Calif.), TECO Model 43 SO_2 analyzer (Thermoelectron Corp., Hopkinton, Mass.), and microcomputer data collection system. Air samples from each chamber were drawn through the O_3 analyzer then through the SO_2 analyzer. Electronic signals from both SO_2 and O_3 analyzers were then fed into a Cyborg ISAAC (Cyborg Corp., Newton, Mass.) data acquisition system, which converted analog signals to digital signals and then processed and stored the data in an Apple II computer (Apple Computer, Cupertino, Calif.). Air was sampled at a height of =1 m to the south of the tree canopy.

There were seven trees for each of the four pollutant treatments and seven outside (control) trees (Olszyk, 1989), for a total of 35 trees. Because "only a 24-channel scanning value system was available for the study, it was not possible to monitor air quality for each tree. Thus, more trees were sampled from those treatments that were expected to have more variable pollutant concentrations, i.e., all seven trees each for the half-ambient and SO_2 treatments, four of seven trees for the filtered and ambient treatments, and two of seven trees for the outside treatment.

Each channel was sampled for 5 rein, with only the signal from the last minute recorded by the computer. Since there were 24 channels each monitored for 5 rein/cycle, each channel was sampled once every 2 hr. This resulted in the following numbers of samples per hour per treatment: sulfur dioxide (three-four), half-ambient (three-four), ambient (two), filtered (two), and outside (one). Only data from two channels per hour were used from each of the sulfur dioxide and half-ambient treatments, so that there was an equal number of values per hour for all pollutant treatments. Rarely, only one value per hour was available from chamber treatments due to instrument malfunctions, line clogging, or short-term power failures.

Sulfur dioxide treatments began on 15 May 1984 and terminated on 22 Oct. 1987. Filtered, half-ambient, and ambient treatments began in Apr. 1984 (chambers came on line over a period of several weeks) and continued until 10 Aug. 1988. However, O_3 monitoring ended on 22 July 1988 as the O_3 instrument began to malfunction.

Yield and quality measurements. Yield was determined as weight and number of mature fruit per tree picked over l-day harvests on 8 May 1986, 20 May 1987, and 23 May 1988. Fruit quality was measured in terms of size, rind thickness, rind color, individual weight, total soluble solids (TSS, percent by weight), and titratable acidity (percent by weight) for 10 fruit per tree in 1986 and 30 fruit per tree in 1987 and 1988. Size was calculated from height and width measurements for individual fruit. Fruit circumference was determined as π x d, where d was the 'average of height and width. Rind thickness was measured with a ruler to the nearest millimeter. Rind color was rated on a 3 (green) to 13 (orange) scale according to a commercial color chart. To ensure uniformity in color evaluations, all ratings were done by the same individual in all 3 years and under similar light conditions.

Juice quality was assessed using the criteria of percent TSS and percent acid by weight. Juice was obtained with a home juicer (Sunkist Corp., Los Angeles, Calif.) from 10 (1986) or 30 (1987, 1988) fruit per tree, was pooled, and strained through cheesecloth. The TSS was determined using a refractometer and tables relating the index of refraction to TSS. Titratable acid content was determined for a mixture of 10 ml of strained juice, 50 ml of water, and two drops of phenolphthalein by titrating with 0.1562 N NaOH. Percent citric acid was calculated as: (milliliters of NaOH used x N NaOH)/milliliters of juice x specific gravity of juice).

Large fruit dropping from the trees were collected periodically and represented unseasonable loss of fruit that could have contributed to the final yield. Fruit loss was averaged from May of the "set" year through April of the following "harvest" year to represent fruit drop relevant to harvest.

Fruit remaining on the tree after the treatments ended in July 1988 were harvested in June 1989. Total number and weight of fruit on the trees were measured and did not differ with treatment. However, these data were not used due to the large effect of the chambers on tree growth after the blowers were turned off, as discussed in Olszyk (1989).

Growth measurements. Growth was determined by nondestructive measurements of tree size in Spring 1984, 1986, and 1988 using a meter stick. Leaf drop, which is normal for citrus trees and also increases with environmental stress, was measured monthly from about Dec. 1984 through Aug. 1988. The leaves falling to the ground beneath each tree were picked up and placed in covered buckets alongside each tree. On about the 10th of each month, the leaves were transferred to paper bags, dried in fiberglass greenhouses for 1 to 2 weeks, and weighed. Both total dry weight per tree and weight of a subsample of 10 or 30 leaves were determined. The individual leaf weight was an indicator of the relative size of individual leaves per treatment.

Statistical analysis. The seven replicates for each of the five treatments were randomly assigned among 35 trees. Analysis of variance (ANOVA) (Steel and Torrie, 1960) was used to detect pollutant treatment effects with degrees of freedom assigned to sources of variation as follows: treatment – 4 (filtered, half-ambient, ambient, SO_2, outside); error -30, total -34. Treatment effects were assigned to contrasts as follows: linear oxidant – 1; quadratic oxidant – 1; filtered vs. SO_2 – 1; and ambient vs. outside – 1. The results from the ambient vs. outside comparisons are discussed elsewhere in a more extensive analysis of the impacts of the chambers themselves on tree productivity and growth (Olszyk, 1989).

When more than one set of measurements was included in an evaluation, factors for year or month of collection, interaction (e.g., year x treatment), and an additional error term were added to the ANOVA (Olszyk, 1989). Linear regression analysis was used to determine the relationships between O_3 concentrations and yield.

Results and Discussion

Pollutant treatments. The exposure chambers were effective in providing pollutant exposures near the target concentrations. Ozone, the surrogate for all ambient oxidants, averaged 0.075 ppm in outside air during the day and over the growing seasons (Olszyk, 1989) (Table 1). The chambers themselves removed a small amount of O_3, likely due to deposition on the blower and ‘walls, as shown by the 8% lower O_3 concentration for the ambient chamber vs. outside treatment. The half-ambient treatment was successful in providing an average O_3 concentration 50% of that in outside air. The filtered chamber treatment was very successful in removing O_3, with an average concentration 92% lower than outside air.

The daylight growing-season average concentrations did not fully characterize the O_3 exposures to which the trees were subjected in the different treatments. Diurnal patterns, peak concentrations, frequency of peak concentrations, respite times between peaks, and annual averages may all have been important (Hogsett et al., 1988). However, the daylight growing-season averages have been considered to be the most important for determining plant response in most recent National Crop Loss Assessment Network studies (Heck et al., 1984). Thus, averages were still used in regression equations with the yield data in this study.

Diurnal patterns of O_3 concentration were similar for all four growing seasons. Ozone concentrations were normally close to zero until 0700 HR, were at their maximum by 1500 HR, and then decreased rapidly to below 0.02 ppm by 2000 HR. Therefore, at Riverside, the 12-hr daylight concentration from 0800 to 2000 HR includes nearly all of the daily O_3 exposure for the trees.

Measurements of other important ambient oxidants, NO, NO_2, and PAN, were made during 1987 near the site. Concentrations of NO and NO_2 in outside air were high during the growing season (Olszyk et al., 1989). Hourly averages for NO_2 normally peaked at =0.06 ppm at 0800 HR, falling to below 0.03 ppm during midday. The 0800 to 2000 HR 12-hr growing season average for NO_2 was =0.038 ppm. Hourly averages for NO normally peaked at =0.09 ppm at 0600 HR, falling rapidly to <0.01 ppm by midday. The 0800 to 2000 HR 12-hr growing season average for NO was very low (0.01 ppm). Averages for PAN were normally <0.002 ppm, except during rare PAN pollution episodes when hourly averages reached up to 0.009 ppm.

Concentrations of NO_2 probably were reduced in the charcoal-filtered and half-ambient vs. ambient chambers by 70% as shown for ozone (Olszyk et al., 1989). Nearly all of the PAN would have been removed by charcoal filters. Concentrations of NO in all chambers would have been about the same as in outside air, as charcoal does not remove this pollutant. Despite the fact that relatively large concentrations of NO and NO_2 were likely present in the chambers, these pollutants were not considered in the pollutant exposure-plant response analysis. Available literature indicates that neither NO nor NO_2 affects agricultural crops at the concentrations likely during this study (U.S. Environmental Protection Agency, 1982).

Sulfur” dioxide concentrations averaged 0.08 to 0.09 ppm during 3 years (Table 1). This range was for the daylight growing-season average, but concentrations were about the same on a 24-hr and yearly average basis. The concentration of SO_2 in this study was several times higher than the mean annual average of 0.01 to 0.02 ppm found in orange growing areas of California, such as Kern County. However, hourly averages of up to 0.07 ppm have occurred in some other areas of the San Joaquin Valley. Thus, the average SO_2 concentrations used in this study should be considered only to represent the worst-case situation if SO_2 emission controls were to be relaxed and concentrations were to rise in California. However, while high SO_2 concentrations currently are not found in California, high concentrations are likely found in Mexico, where oranges are also grown.

Oxidant effects. For both “on” productivity years, 1986 and 1987, yield of oranges per tree was highest in the charcoal-filtered chambers, medium in half-ambient chambers, and lowest in ambient chambers (Fig. 1). The reduction in yield with increasing oxidants was statistically significant for 1986 but not 1987, based on ANOVA. However, when the yield data were compared to daylight growing-season oxidant concentrations (as a surrogate for total oxidants), there were significant regression equations for each year and across both years (Table 2).

For these data, regression analysis was considered to be more appropriate than ANOVA, as the specific O_3 concentrations could be considered as a dependent variable. The O_3 concentrations were based on data for the growing season 2 years before harvest (e.g., Apr. through Oct. 1984 for May 1986 harvest) because we hypothesized that O_3 affected yields primarily via the potential of the tree to support fruit set, as determined by the impact of O_3 on starch reserves accumulated during the previous growing season (Olszyk, 1989).

While some are statistically significant, all of the *r* values in Table 2 are low due to the large amount of variability within treatments. Thus, while the results indicate a trend in reduced orange yield due to oxidants, many more data would be needed to conclusively indicate a highly significant oxidant effect.

Reduced total weight of fruit with oxidant exposure was associated both with reduced fruit number and, to some extent, with reduced individual fruit weight based on ANOVA (Table 3) (Olszyk, 1989). More importantly, there was a significant regression for numbers of fruit in 1987 and across both 1986 and 1987, the two “on” years of production (Table 2).

Ambient oxidants had no effect on fruit yield in 1988, an “off” year. The total weight per tree and number per tree were about the same across the filtered, half-ambient, and ambient treatments (Fig. 1). There were no significant regression equations for 1988 yields (Table 2).

Table 1. Representative O_3 and SO_2 concentrations for the ‘Valencia’ orange study. Ranges of daylight (0800 to 2000 **HR,** PST) growing-season (April-October) averages for 1984-1988[z].

Type of chamber	SO_2 (ppm)	O_3 (ppm)
None (outside)	0-0.002	0.071-0.078
Ambient air	0-0.002	0.065-0.073
Half-ambient air	0-0.002	0.032-0.047
Filtered air	0-0.002	0.008-0.016
SO_2-enriched	0.081-0.090	0.009-0.015

[z]Data collection for June 1984 through July 1988 for O_3, and June 1984 through Oct. 1987 for SO_2.

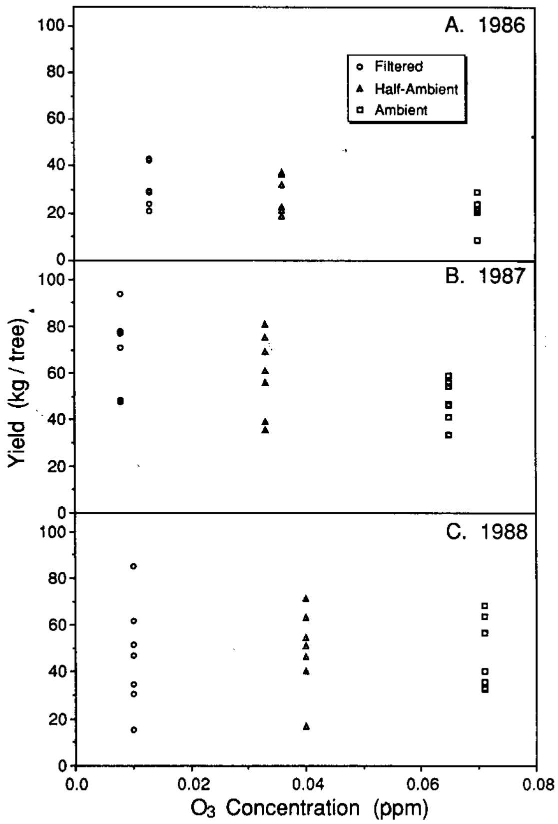

Fig.1. Scatter plots for fruit per tree in 1986, 1987, and 1988. Ozone concentrations are for 0800 to 2000 HR (PST) for April through October 2 years before the harvest year.

There was no direct evidence that off-season fruit drop played a role in the yield losses due to oxidants (Olszyk, 1989). An average of 161, 30, and 24 fruit per tree were lost during the year. before the harvests in 1986, 1987, and 1988, respectively, across all three oxidant treatments. No consistent oxidant effects were found on weights of off-season fruit drop.

Average weight per fruit decreased with increasing oxidants, but only in 1988 (Table 3). In 1987 fruit were larger for the half-ambient treatment than for either the ambient or filtered-air treatment. This half-ambient response was also statistically significant in the combined 1987 and 1988 data. The large fruit size with the half-ambient treatment was associated with increased rind thickness. Fruit color tended to be less orange with increasing oxidants, but only when the data were pooled across 1986 plus 1987, 1986 plus 1988, or 1987 plus 1988.

Neither juice TSS nor titratable acid concentrations were affected by oxidants in any year. The TSS and acids (by weight) were 11.970 and 1.2%, respectively, across three oxidant treatments and all years.

Yields in our experimental orchard were lower than those expected for commercial 'Valencia' orchards of the same age in southern California. For example, in 1986, we only had the equivalent of one or two boxes per tree (at 20 kg/box), whereas similar aged commercial trees normally produce five or six boxes of oranges. In 1987, we still had only two to four boxes of fruit per tree for the highest yielding trees. This lower yield for trees in chambers may have been related to their much greater vegetative growth compared to outside trees (Olszyk, 1989).

Overall, oxidants did not affect growth of the orange trees. None of the canopy size measurements were significantly different between the three oxidant treatments for any year (0lszyk, 1989). Canopy volumes averaged 2.5, 5.8, and 21.0 m^3 in 1984, 1986, and 1988, respectively. Oxidants also had no effect on the total weight of leaves dropped from the trees, which averaged 290 g dry weight per month per tree across all treatments and 45 months of collection. The average total production of leaves varied by <4% among the filtered, half-ambient, and ambient treatments across all months. Data for individual months did not indicate any clear pattern of early senescence of leaves in our study (Olszyk, 1989), in contrast to the oxidant stimulation of leaf drop reported earlier for navel oranges (Thompson and Taylor, 1969).

Oxidants tended to result in decreased individual leaf weights, especially during the growing-season months of April through

Table 2. Results from regression analysis of ambient O_3 and 'Valencia' orange yield data from three harvest years'.

Harvest year	df	*r*	Intercepts different	Common slope	Regression equation[y]
			Total wt/tree		
1986	17	−0.489*	N/A	N/A	Y = 34.2 − (188.9 X)
1987	21	−0.459*	N/A	N/A	Y = 69.3 − (317.3 X)
1988	21	0.012^NS	N/A	N/A	N/A
1986, 1987	36	−0.452**	**	*	Y = 53.7 − (261.1 X)
1986, 1988	36	−0.121^NS	***	NS	N/A
1987, 1988	40	−0.207^NS	***	NS	N/A
1986, 1987, 1988	56	−0.248^NS	***	NS	N/A
			Total no./tree		
1986	17	−0.252^NS	N/A	N/A	N/A
1987	21	−0.477*	N/A	N/A	Y = 372 − (1769 X)
1988	21	0.108^NS	N/A	N/A	N/A
1986, 1987	36	−0.394**	***	*	Y = 283 − (1245 X)
1986, 1988	36	−0.015^NS	***	NS	N/A
1987, 1988	40	−0.197^NS	***	NS	N/A
1986, 1987, 1988	56	−0.205^NS	***	NS	N/A

[z]Ozone exposure is 0800–2000 HR daylight, April–October growing season average for year, 2 years before harvest (June–Oct. 1984, for 1986 harvest).
[y]Equation where Y is the projected yield and X is the O_3 exposure in ppm.
NS,*,**,***Nonsignificant or significant at P = 0.05, 0.01, or 0.001, respectively.

Table 3. Effects of ambient O_3 or SO_2 on ‘Valencia’ orange fruit number and quality.’

Characteristic	Harvest year	Air in chamber: SO_2-enriched	Filtered	Half-ambient	Ambient
No./tree	1986	140 ± 79	139 ± 72	134 ± 78	97 ± 70
	1987	229 ± 150[y]	376 ± 72	279 ± 81	246 ± 113
	1988	214 ± 23	256 ± 32	228 ± 19	215 ± 26
Wt/fruit (g)	1986	167 ± 33	193 ± 10	195 ± 30	166 ± 20
	1987	220 ± 64	179 ± 29	215 ± 16	179 ± 32
	1988	256 ± 32	256 ± 19	236 ± 19	228 ± 19[x]
Rind thickness (mm)	1986	4.3 ± 0.9	5.0 ± 0.6	4.8 ± 1.0	5.8 ± 1.0
	1987	5.1 ± 1.0	4.5 ± 0.6	5.1 ± 0.6	4.3 ± 0.5[w]
	1988	---	5.3 ± 1.5	5.6 ± 2.0	4.9 ± 1.3
Circumference (mm)	1986	222 ± 12	232 ± 9	234 ± 13	239 ± 13[v]
	1987	236 ± 31	219 ± 20	236 ± 10	212 ± 11[w]
	1988	---	248 ± 23	246 ± 24	240 ± 21
Color (3 to 13)	1986	11.0 ± 0.3	11.3 ± 0.3	11.1 ± 0.4	9.7 ± 2.1
	1987	11.4 ± 1.0	12.1 ± 0.2	11.9 ± 0.2	11.9 ± 0.3
	1988	---	11.0 ± 1.7	10.4 ± 2.4	10.8 ± 1.8

‘Values are means ± SD for seven trees, except for five (ambient) or six (SO_2, filtered, half-ambient) for 1986 for number of fruit and weight per fruit. For other characteristics, values are means ± **SD** of 50 to 60 observations (10 per tree) in 1986 and 210 observations (30 per tree) in 1987 and 1988. Statistical significance is reported only for individual year effects.
Significant difference between SO_2 and filtered treatments, $P < 0.05$.
‘Significant linear O_3 effect across filtered, half-ambient, and ambient treatments, $P < 0.05$.
‘Significant quadratic O_3 effect with highest value for half-ambient treatment, $P < 0.05$.
‘Significant quadratic O_3 effect with highest values in ambient and half-ambient treatment, $P < 0.005$.

October. Thirty leaf weights averaged 9:6 ± 3.6, 9.1 ± 3.3, and 9.2 ± 3.3 g for the filtered, half-ambient, and ambient treatments, respectively, across 27 months during 4 years. There was a significant linear oxidant effect at $P < 0.05$, with leaves exposed to ambient air weighing slightly less (5%) than leaves exposed to filtered air. The reduced leaf weight was probably associated with smaller leaf size since specific leaf area (a measure of weight per unit of leaf surface) was not affected by oxidants (Olszyk, 1989).

Sulfur dioxide effects. Yield per tree was 24.3 ± 9.9 or 31.4 ± 9.4 kg for SO_2 or filtered trees (n = 6), respectively, in 1986, and 42.9 ± 21.4 or 66.3 ± 18.3 kg for SO_2 or filtered trees (n = 7), respectively, in 1987. Yields for the SO_2-treated trees were 23% and 35% lower compared to trees in filtered air in 1986 and 1987, respectively. This difference was statistically significant *($P < 0.05$) in 1987* and across both years. The number of fruit per tree was similar and 39% lower with SO_2 as compared to filtered air in 1986 and 1987, respectively (Table 3). This result indicated that the yield loss was associated with reduced fruit size in 1986 but reduced fruit number in 1987.

The predicted 1988 orange yield for the SO_2-treated trees based on a Nov. 1987 fruit picking and counting was about the same as for the filtered-air trees (Table 3). The number of oranges per tree was not significantly different between trees in SO_2-enriched and filtered air, based on an unpaired *t* test. Nevertheless, the 1988 data for the SO_2 treatment did show the large variability and lower yield in 1987, which indicates an “off” year in 1988 compared to 1986 and 1987.

Sulfur dioxide-exposed trees tended to have larger fruit than trees in filtered air (Olszyk, 1989). The response occurred for fruit circumference across both years but not for the individual years (Table 3). The larger fruit may have been due to the greater availability of reserves to the fewer fruit with the SO_2 exposure, similar to that for trees exposed to oxidants. No other external fruit quality characteristics were affected by SO_2 (Table 3).

Neither juice TSS nor titratable acid concentrations were affected by SO_2 in any year. The TSS and acids (by weight) were 11.8% and 0.8%, respectively, across 1986 and 1987 for the SO_2-exposed trees.

Sulfur dioxide had no effect on overall tree growth as the average canopy volume and total weight of leaves dropped from SO_2-exposed trees was the same as for all trees in chambers (Olszyk, 1989). Sulfur dioxide exposure resulted in significantly lower *($P < 0.05$)* individual leaf weights when the data were averaged across all months, i.e., 30 leaf weights averaged 8.7 ± 3.3 and 9.1 ± 3.7 g for the SO_2 and filtered treatments, respectively, across 33 months during 3 years. The reduced leaf weight with SO_2 exposure was likely associated with smaller leaf size, as specific area was actually greater for SO_2-treated leaves.

Use of yield data to estimate crop losses from ozone. Only 3 years of reliable data were produced by this study, which is a very small amount of data with which to predict the response of trees in commercial orchards. Thus, these data should only be used with caution to indicate possible trends in crop yield losses from ambient O_3 as a surrogate for total oxidants. More precise crop loss estimates for ‘Valencia’ as well as other types of oranges would have required much more extensive experiments with many trees over more than 3 years.

However, because these are still the best available data with which to estimate general trends in effects on ‘ Valencia’ oranges from oxidants, they were used to develop equations to calculate at least general estimates of yield losses based on ambient O_3 concentrations following the general procedure described by Olszyk et al. (1988). The two “on” years had similar loss equations in terms of slope (the main determinant of percent loss) (Table 2). Thus, data from across the two “on” years were combined to produce a single “on” year O_3 exposure–yield loss equation: percent loss = $\{1 - [(a + (b \cdot X))]/[(a + (b \cdot X^B))]\} \times 100$, where a (53.7) was the average intercept for 1986 and

1987, b (261.1) was the average slope for the 1986 and 1987, X was the ambient O_3 concentration 2 years before harvest, and X^B was a background O_3 concentration used to estimate potential yield in clean air. An 0800 to 2000 HR growing season average concentration of 0.025 ppm, often has been used to represent X^B (Heck et al., 1984; Olszyk et al., 1988).

The question of which 'Valencia' orange yield loss equation to use was complicated by the fact that these trees exhibited the alternate-year pattern of bearing. Any general loss equation also had to consider the off-year on-year pattern of bearing, which varies among orchards across California. Therefore, even though its accuracy is unknown, for modeling purposes we assumed that off- and on-year orchards were distributed equally across the state as the pattern for orange yields varies between orchards, areas, and years. As a result, the percent loss equation could be modified to indicate that the estimated losses were less (e.g., only one-half) than those expected if all orchards were having an on year.

Use of results from this study to estimate the effects of ambient oxidants (or SO_2) on commercial orchards also was based on the assumption that trees in open-top chambers are as susceptible to air pollutants as outside trees. If chamber trees were more or less susceptible than outside trees, the calculated yield losses would over- or underestimate the actual losses in orchards. Thus, outside control trees were an important component of the study (Olszyk, 1989).

Comparison of yields and growth between the ambient chamber and outside trees indicated many significant chamber effects on" tree yield and growth as well as leaf physiology and biochemistry that could affect the reliability of the pollution response data. Yields were greater for the ambient chamber trees than for outside trees for all 3 years, with a statistically significantly difference at $P < 0.05$ between the two treatments for 1986 and 1988 (Olszyk, 1989). The average total fruit weight per tree for trees in chambers with ambient air and outside trees was 20.7 ± 7.5 and 1.0 ± 2.3 kg, respectively, in 1986; 48.3 ± 9:0 and 34.8 ± 18.4 kg in 1987; and 47.1 ± 15.3 and 22.9 ± 20.2 kg in 1988.

While some characteristics, such as the shade type leaf anatomy, suggested increased pollutant susceptibility for trees in chambers vs. outside, other criteria, such as decreased stomatal conductance and increased leaf starch concentration, suggested less pollutant susceptibility in chambers than outside (Olszyk, 1989). The net effect of these differences in responses between chamber and outside trees may well be no difference in susceptibility. However, this would need to be verified by further investigations of actual pollutant uptake and metabolism of trees in chambers vs. those outside to verify the accuracy of estimates of 'Valencia' orange yield losses from O_3 based on the data reported here.

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