Effects of Increasing Doses of Sulfur Dioxide and Ambient Ozone on Tomatoes: Plant Growth, Leaf Injury, Elemental Composition, Fruit Yields, and Quality

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ABSTRACT

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Jet star, an indeterminant tomato cultivar, was exposed to 0.011, 0.059, 0.118, 0.235, and 0.468 ppm SO_2 in open-top field chambers supplied with nonfiltered (NF) air and to 0.005, 0.113, and 0.466 ppm SO_2 in chambers with charcoal-filtered (CF) air. Treatments were given 5 hr/day, 5 days/wk, for a total of 57 days during July, August, and September. Ripe fruit yields were decreased 16% by O_3 in NF compared with CF air. The highest dose of SO_2 given in CF air reduced fruit yield by 18%. Ambient O_3 and the SO_2 treatments were additive in their effects on fruit yields. Significant reductions in fruit numbers were observed. Fruit quality was not measurably altered. A negative linear response for ripe fruit yield vs. SO_2 exposure dose was demonstrated. As the SO_2 dose was increased, sulfur (S) content of the leaves increased linearly. In NF air, S content ranged from 1.62 to 2.56%. In both CF and NF air, S content of fruits was 0.24%; and, the SO_2 treatments did not cause measurable changes. Foliar concentrations of other elements were changed significantly by leaf position and harvest date, but not by SO_2 treatments.

Additional key words: air pollution, *Lycopersicon esculentum*.

Phytotoxic concentrations of ozone (O_3) commonly occur in the United States and have significant impact on crop productivity (8,14,22). Sulfur dioxide (SO_2) may be a problem downwind of large industrial sources that burn fossil fuels (14). The possibility that losses may be potentiated by pollutant interactions is a concern (14,17,18,26).

Ambient O_3 has been shown to reduce the yields of two fresh market tomato (*Lycopersicon esculentum* Mill.) cultivars in southern California (19,20). A 23% yield reduction was predicted for cultivar 6718VF at an O_3 exposure dose of 10 ppm-hrs; i.e., about 100 hourly averages $\geqslant$0.1 ppm (19). However, exposure of an apparently ozone-tolerant processing tomato cultivar in chambers with 75% nonfiltered (NF) and 25% charcoal-filtered (CF) air (83 ppm-hrs O_3 dose) did not cause a significant decrease in yield (18). Yields in plots without chambers were reduced 66%, indicating a large "chamber effect." In the same experiment, a 6-hr exposure to SO_2 on five successive days each week over a 10-wk period revealed that exposure to 0.10 and 0.20 ppm SO_2 reduced yields about equally. No interaction was observed between SO_2 and O_3 at these exposure doses. Fruit quality was not adversely affected. A more than additive decrease in the fresh weights of the largest fruits in each tomato cluster, but no change in total fruit weight per plant, was found after exposure to 0.20 ppm of O_3 and SO_2 twice each week for 8 wk (23). Exposure to 0.11–0.12 ppm SO_2 alone for 10 wk (72-hr week), did not reduce tomato yields or fruit quality (16).

Extensive data are available on the sulfur (S) content of leaves because of its importance as a plant nutrient (3,4,27) and S uptake following exposure of plants to SO_2 in polluted air (15). However, no data are available on S accumulation from long-term experiments involving the addition of SO_2 to open-top chambers, or on other mineral elements in tomato plants exposed to increasing doses of SO_2. Tomato plants are efficient S accumulators (4). A comparison of average background S levels of 34 crop and tree species in southern Ontario, Canada, revealed tomato foliage contained the highest S content (15).

The objectives of the present research were: to evaluate the impact of ambient O_3 and increasing doses of SO_2 in ambient (NF) air on tomato fruit yields, leaf injury, height growth, fruit quality, and mineral composition of leaves and fruits; to compare impact of SO_2 in NF and CF air; and, to evaluate the possibility of an interaction between SO_2 and ambient O_3. An abstract was previously published (10).

MATERIALS AND METHODS

The research site was located at the USDA Agriculture Research Center, Beltsville, MD. The soil type was a Codorus silt loam containing about 65% sand, 11% clay, and 24% silt (13). Lime was added to bring the soil to about pH 6.5. Before planting, 560 kg/ha of 5-10-5 NPK fertilizer was applied. At transplanting, a soluble fertilizer was used, 1.2 g/L 20-20-20 NPK (1.2 L per plant). Weeds were controlled without the use of herbicides.

The cylindrical open-top chambers have been described previously (7). Six plants of indeterminant tomato cultivar Jet Star were transplanted on 30 May in each chamber in a circular pattern with an open section on the south side to facilitate leaf sampling, fruit harvest, and data recording. Except on the south side, the plants were spaced 0.6 m apart. They were contained within wire mesh cylinders (1.4 m high, 0.5 m diameter) to provide support. The tomato branches were kept within the cylinders until they grew out the tops.

To permit development of dose-response functions, the targeted SO_2 concentrations in the chambers were: 0, 0.06, 0.12, 0.24, and 0.48 ppm in NF air and 0, 0.12, and 0.48 ppm in CF air. The actual SO_2 values for NF air shown in the tables listing treatments were

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within 2% of the targeted values. The eight chamber treatments and an unchambered ambient air (AA) plot were randomized in each of three complete blocks. The SO_2 exposures were given 5 hr/day (1000-1500 hours EDT), 5 days/wk except on days with rain. The chamber air was sampled through Teflon tubing (0.64 cm OD). The air sampling tube intakes were positioned at midheight for the lower air inlet panels (i.e., 60 cm above the ground). The air intakes were placed on the west side of each chamber equidistant between the panel and the tomato foliage.

Sulfur dioxide was monitored with a TECO Model 43 pulsed fluorescence SO_2 analyzer (Thermo Electron Corp., Hopkinton, MA). A TECO Model 143 SO_2 permeation tube calibrator system was used for calibration. Each chamber was monitored in rotating sequence for 3-min intervals. The pollutant dispersing and monitoring system was patterned after that described by Heagle et al (7). To achieve a rapid response in monitoring SO_2 and O_3 concentrations in each chamber a sampling manifold constructed of glass tubing (0.64 cm OD) was used. Ozone was monitored with a Bendix Model 8002 analyzer (Bendix Corp. Lewisburg, WV) and a Dasibi Model 1003 PC (Dasibi Environ. Corp., Glendale, CA). A Dasibi 1003 PC, ultraviolet calibrator, was used for O_3 calibration. The Environmental Protection Agency audited the SO_2 and O_3 monitors at the field site and all instruments met EPA accuracy and performance standards.

The chamber air blowers were turned off at night between 2100 and 0500 hours EST to allow dew formation on the plants. Soil water potentials were measured with tensiometers (Irrometer Co. Inc., Riverside, CA) positioned at depths of 0.25 and 0.45 m. Between 1.2 and 1.4 cm of water was applied on days when soil water potentials at the 0.25-m depth reached −0.06 MPa. Lower water potentials would indicate possible soil moisture stress. Rainfall was 50% above the long-term average precipitation for July; but, only one-third of average precipitation in August and September. A total of 10.8 and 13.3 cm of irrigation water were applied in August and September, respectively.

Seasonal ambient O_3 concentrations were high, particularly during August 1980, with 21 hr $\geq$ 0.10 ppm, which was more than measured at Beltsville, MD, in any month since 1972 (11). The seasonal 7-hr O_3 average (1100-1800 hours EST) monitored in the NF chambers was 0.056 ppm. The highest daily 7-hr average was 0.11 ppm. The highest hourly average was 0.15 ppm on 4 August at 1500 hours.

Plant response variables. Plant height was measured biweekly. After the final fruit harvest, plants were cut at ground level and fresh and dry (at 60 C) weights determined. Senescent leaves that remained on stems were included in these measurements.

Beginning 28 July, ripe fruits were harvested by plant each week for 10 wk. The fruits were weighed individually to assess yield reductions attributable to both fruit size and fruit numbers. To evaluate fruit quality we determined total acidity, pH of the expressed juice, reduced ascorbic acid contents, color, texture, and taste quality of the ripe fruits (28).

Leaf injury and senescence were visually rated at 2-wk intervals beginning in mid-July, 2 wk after SO_2 treatments were initiated. Leaf injury due to a late season outbreak of leaf blight caused by *Septoria lycopersici* Speg. was also visually rated.

Multielement analyses were conducted on leaves sampled on 4 August, 1 September, and 29 September. Several leaflets were collected from the top, middle, and the lowermost strata of the plant canopy. Senescent leaves with necrotic tissue were avoided. A foliage sample of approximately 5 g (dry weight) was taken in each plot at each leaf position and harvest date. The unwashed leaves were air-dried and ground in a laboratory mill to pass a 1-mm mesh sieve. Fruit samples were taken on 29 September, sectioned to obtain subsamples, lyophilized, and also ground to pass a 1-mm mesh seive. On 12 September, soil samples were taken to determine content of S and other elements at 0–30 and 30–60-cm depths. The soil was air-dried and ground in a hammer mill to pass a 2-mm mesh sieve.

Plant tissue samples were analysed by X-ray fluorescence (EDXRF) as described by Knudsen et al (12). The following elements were measured: Al, Ca, Cl, Cu, Fe, K, Mg, Mn, P, S, and Zn. Total N was determined by the Kjeldahl procedure (2). Analytical precision was monitored using control samples included in each run.

Statistical analyses. This experiment with nine treatments used a randomized complete block design with three replications (Table 1). Analysis of variance procedures were used to analyze several dependent variables. Except for the multielement analyses individual plant data were included to assess chamber position effects. Variance due to SO_2 in the NF treatment was partitioned using orthogonal polynomials to characterize the response (linear, quadratic, and cubic). Regression techniques were then used to define the yield effects and foliar S accumulation due to increasing SO_2 exposure levels. The interaction between O_3 and SO_2 exposure effects was tested using data from CF and NF chambers with targeted SO_2 levels 0, 0.12, and 0.48 ppm. A 2×3 factorial analysis was employed. Mean differences within and between the CF, NF, and AA treatments were tested by the method of least significant difference (LSD). The analysis of variance for mineral composition data included sources of variation for leaf position, leaf sampling date, and their interactions.

TABLE 1. Design of the experiment, which had nine treatments, showing SO_2 exposure levels[a]

Chambers	SO_2 additions (ppm)[b] 0	0.06	0.12	0.24	0.48
Charcoal-filtered air	X		X		X
Nonfiltered air	X	X	X	X	X
Ambient air, no chamber	X				

[a]Three replications of each treatment.
[b]Targeted ppm values.

RESULTS

Leaf injury attributable to O_3 and SO_2 increased as the season progressed (Table 2). The symptoms of injury were primarily general chlorosis and leaf senescence. Significantly less leaf injury occurred in CF than in NF air plots with comparable SO_2 exposure concentrations. Increases in SO_2 up to 0.235 ppm in NF air caused little additional leaf injury, indicating the pollutants in ambient air, primarily O_3, were more important than the added SO_2 at these concentrations. Injury indices were higher on 6 and 15 August in unchambered plots subjected to ambient winds and natural conditions than in the chambers with NF air with approximately the same concentrations of SO_2. However, by 10 September the indices were equivalent.

Plants continued to elongate throughout the season (Fig. 1). At final fruit harvest plants within the CF and NF chambers averaged

TABLE 2. The effects of increasing SO_2 dose in charcoal-filtered (CF) and nonfiltered (NF) air on tomato leaf injury

Treatments: Chambers[b]	SO_2[c] (ppm)	O_3[d] (ppm)	Indices (%)[a] 6 Aug	15 Aug	10 Sept
CF	0.005	0.015	0	21	31
CF	0.113	0.015	2	19	26
CF	0.466	0.015	7	30	40
NF	0.011	0.056	12	33	42
NF	0.059	0.056	12	34	44
NF	0.118	0.056	22	40	45
NF	0.235	0.056	20	40	46
NF	0.468	0.056	37	42	62
AA	0.011	0.056	33	44	48
LSD ($P = 0.05$)			17	7.4	9.8

[a]Percentage of leaves with visible injury.
[b]CF = charcoal-filtered air, NF = nonfiltered air, and AA = ambient air, no chamber.
[c]SO_2 means 5 hr/day, 5 days/wk between 2 July and 29 September.
[d]O_3 7-hr average (1100–1800 hours EST), July, August, and September 1980.

TABLE 3. Mean square comparisons for tomato fruit yield, numbers, and plant mass for the five nonfiltered air treatments with increasing dose of SO_2[a]

		Means squares[b]				
		Ripe fruit/plant		Ripe and green fruit/plant		Plant mass[c] fresh/plant
Variable	DF	(kg)	(no.)	(kg)	(no.)	(kg)
SO_2 (linear)	1	36.9*	759	85.2*	4,095	137.8*
SO_2 (quadratic)	1	13.8	804	12.5	1,628	7.1
SO_2 (cubic)	1	0.7	7	7.3	294	8.1
Rep × SO_2 (error a)[d]	9	4.7	215	10.7	1,073	15.3
Plant (Pl)	5	49.1**	2,529**	130.3**	11,126**	201.4*
SO_2 × Pl	20	2.2	129	5.0	579	9.8
Rep × SO_2 × Pl (error b)	50	1.4	61	4.9	389	8.9
R-square		0.85	0.86	0.80	0.81	0.77
Coefficient of variation (%)		12.8	12.0	15.6	14.5	16.1

[a]This analysis includes three replications of five treatments in nonfiltered air with 0.011, 0.059, 0.118, 0.235, and 0.468 ppm SO_2, 5 hr/day, 5 day wk from 2 July to 29 September.
[b]Asterisk, **, $P = 0.01$; and *, $P = 0.05$.
[c]Fruits and stems with attached senescent leaves.
[d]Error a = Rep × SO_2 + higher order SO_2 polynomial.

TABLE 4. Linear regression parameters (a,m) and correlation coefficients (r) for tomato fruit yield, plant mass, and sulfur in leaves following exposure to SO_2 in nonfiltered (NF) and charcoal-filtered (CF) air[a]

	$Y = a + m\,[SO_2]$[b]					
	NF			CF		
Variable	a	m	r	a	m	r
Ripe fruit (kg/plant)	9.86	−3.89	−0.62	12.26	−4.67	−0.73
Ripe and green fruit (kg/plant)	15.23	−5.96	−0.65	17.37	−5.70	−0.54
Plant mass[c] (kg/plant)	19.83	−7.59	−0.68	21.89	−6.65	−0.55
Sulfur in leaves (%)	1.62	2.06	0.87	1.69	2.36	0.87

[a]Plants exposed 5 hr/day, 5 days/wk, total 275 hr from 2 July to 29 September. Five hour mean exposure concentrations: NF, 0.011, 0.059, 0.118, 0.235, and 0.468 ppm SO_2; CF, 0.005, 0.113 and 0.466 ppm SO_2.
[b]Linear regression equation, $[SO_2]$ = ppm SO_2.
[c]Fresh weight of fruits and stems with attached senescent leaves.

2.2 m in height and those grown without chambers (AA) averaged 1.8 m. Over the concentration range studied, increasing the SO_2 exposure dose did not have a significant effect on height growth. Only the height of plants in AA plots were significantly different from plants receiving the other treatments.

Regression analyses for the five NF air treatments revealed that weights of fruit and plant mass decreased linearly after the exposure to increasing SO_2 exposure doses (Table 3). This indicates that all the SO_2 exposure doses over the range tested reduced fruit yield and plant mass. Regression parameters and correlation coefficients for the yield of ripe, ripe plus green, and total plant mass in NF and in CF air are summarized in Table 4.

Interactions between O_3 and SO_2 concerned with the effects on fruit yields and plant mass were evaluated by analysis of variance. Three exposure treatments, 0, 0.12, and 0.48 ppm SO_2, in CF and NF air were included in the analysis (Table 5). According to the

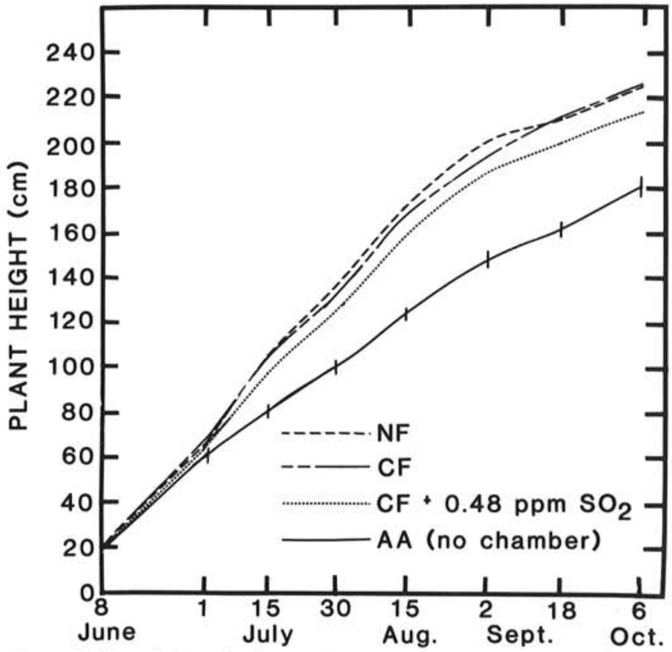

Fig. 1. Height of plants in four of the nine treatments taken at biweekly intervals. Vertical bars represent one standard error of mean. Differences between the treatments without bars are not statistically significant.

TABLE 5. Mean square comparisons for weight and numbers of ripe, ripe and green tomato fruits, and plant mass[a]

		Mean squares[b]				
		Ripe fruit/plant		Ripe and green[c] fruit/plant		Plant mass[d] fresh/plant
Variable	DF	(kg)	(no.)	(kg)	(no.)	(kg)
Rep.	2	1.2	23	2.2	225	5.9
SO_2	2	37.1*	1,626*	63.1	3,855	98.4
O_3	1	111.9**	3,594**	110.2	2,124	116.7
SO_2 × O_3	2	1.1	135	1.4	87	0.8
Rep. × SO_2 × O_3 (error a)	10	7.4	367	24.6	1,740	32.6
Plant (PL)	5	82.4**	3,456**	212.5**	14,342**	332.8**
SO_2 × PL	10	2.2	113	3.7	355	5.9
O_3 × PL	5	2.0	69	4.1	170	6.0
SO_2 × O_3 × PL	10	2.0	107	6.6	840*	11.5
Rep × SO_2 × O_3 × Pl (error b)	60	2.3	99	5.3	373	8.8
R-square		0.84	0.84	0.84	0.83	0.83
Coefficient of variation (%)		14.7	13.8	15.0	13.7	15.1

[a]This analysis includes three replications and six treatments, (charcoal-filtered and nonfiltered air with 0.0, 0.12, and 0.48 ppm SO_2 added). This ANOVA permits a test of significance of interactions between SO_2 and O_3.
[b]Asterisks **, $P = 0.01$, *, $P = 0.05$.
[c]Total fruit harvest at end of season.
[d]Fruits plus stems with the attached senescent leaves.

ANOVA, both SO_2 and ambient O_3 reduced yields of ripe fruits. Their effects were additive. However, yields of ripe plus green fruit were not significantly reduced by the pollutants, nor was plant mass.

The cumulative weekly harvest data given in Figure 2 shows that the highest concentration of SO_2 (0.48 ppm) in CF air reduced yields about the same amount as the O_3 present in the ambient air (NF vs. CF). Relative differences among the four treatments remained essentially constant after the fourth weekly harvest.

Effects of the eight SO_2 chamber treatments and the no chamber treatment on fruit yields and plant mass are summarized in Table 6. The LSD values indicate significant differences for ripe fruit weight and numbers occurred between the two CF and NF air treatments with lowest SO_2 exposure doses. Fruit numbers were significantly less in the AA plots than in any plots with chambers. Yields of ripe and ripe plus green fruits in AA plots were less than in the NF chamber plots without added SO_2.

Considering all treatments, the greatest percentage (26%) of the harvested fruits was in the 120–154-g size class (Table 7). Size classes 95–119 and 155–199 g each contained 21% of the fruit. The AA plots produced the highest percentage of large fruits. However, because total fruit numbers were less (Table 6), there was no net increase in the number of large fruits.

Elemental composition. Foliar S (percentage of dry weight) increased linearly ($r = 0.87$) in both NF and CF air as a result of SO_2 exposure (Table 4). The range was from 1.6 to 2.6% in NF and 1.8 to 2.8% in CF air (Table 8). The regression equations are presented in Table 4. The fruit and soil contained mean S contents of 0.24 and 0.05%, respectively. The SO_2 treatments studied caused no measurable change in fruit or soil S levels (Table 8). The leaf N:S ratio decreased in response to the increase in SO_2 exposure dose because the nitrogen content was about the same in leaves from all treatments (Table 9). The N:S ratios for chamber treatments ranged between 1.4 and 2.5. They were lowest in CF and NF chambers treated with the highest SO_2 exposure concentration.

Significant differences also occurred between treatments in the leaf contents of Al and Zn (Table 9). Al was highest in two CF air

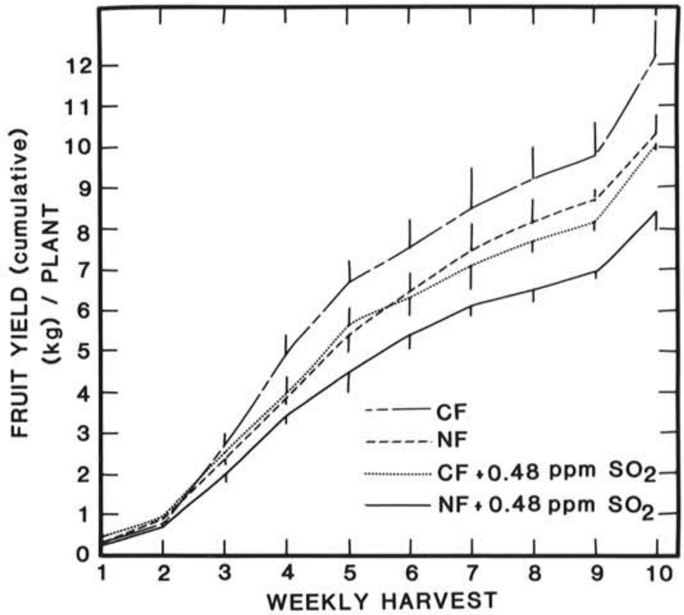

Fig. 2. Cumulative yield of ripe fruits at weekly intervals for CF and NF air with and without the targeted 0.48 ppm SO_2 added. Vertical bars represent one standard error of the mean.

TABLE 6. Tomato fruit yields and plant mass after exposure to increasing SO_2 dose in open-top chambers with either charcoal-filtered or nonfiltered air

	Treatment		Ripe fruit/ plant		Ripe & green fruit/plant		Plant mass[a] fresh/plant
Chambers[b]	SO_2[c] (ppm)	O_3[d] (ppm)	(kg)	(no.)	(kg)	(no.)	(kg)
CF	0.005	0.015	12.3	87	17.1	157	21.6
CF	0.113	0.015	11.7	77	17.0	146	21.5
CF	0.466	0.015	10.1	70	14.7	133	18.7
NF	0.011	0.056	10.3	72	15.4	146	19.8
NF	0.059	0.056	9.7	68	15.2	144	19.6
NF	0.118	0.056	9.3	64	14.5	136	19.1
NF	0.235	0.056	8.2	60	12.9	125	17.2
NF	0.468	0.056	8.4	63	12.8	128	16.6
AA	0.011	0.056	7.6	45	11.3	101	14.3
LSD ($P = 0.05$)			1.7	12	3.1	26.4	3.6

[a] Fruits and stems with attached senescent leaves at last fruit harvest.
[b] CF = charcoal-filtered air; NF = nonfiltered air; AA = plots without chambers.
[c] Daily SO_2 means, 5 hr/day, 5 days/week, between 2 July and 29 September (total 275 hours).
[d] 7-hr average (1100–1800 hours EST), July, August, and September 1980.

TABLE 7. Effects of increasing SO_2 dose in charcoal-filtered and nonfiltered air on the size of ripe fruits[a]

	Treatments		Fruits within different size classes (%)						
Chambers[b]	SO_2[c] (ppm)	O_3[d] (ppm)	0–69 g	70–94 g	95–119 g	120–154 g	155–199 g	200–249 g	250 + g
CF	0.005	0.015	6	13	20	27	20	10	5
CF	0.113	0.015	3	9	21	28	22	12	6
CF	0.466	0.015	4	12	22	27	22	9	4
NF	0.011	0.056	5	13	22	25	21	9	5
NF	0.059	0.056	3	13	22	29	18	10	5
NF	0.118	0.056	4	12	19	28	23	10	4
NF	0.235	0.056	7	15	25	24	18	7	4
NF	0.468	0.056	5	16	22	28	19	9	2
AA	0.011	0.056	5	7	13	20	27	17	13
Average			5	12	21	26	21	10	5

[a] Means of six plants per plot, three replications.
[b] CF = charcoal-filtered air; NF = nonfiltered air; AA = ambient air.
[c] Means, 5 hr/day, 5 days/wk between 2 July and 29 September.
[d] 7-hr average (1100–1800 hours EST), July, August, and September 1980.

treatments with lowest concentrations of SO_2, but Zn was lowest in these two treatments (Table 9). The SO_2 and O_3 exposure treatments had no effect on the leaf composition of the other elements studied.

The leaf position and sampling dates affected leaf mineral contents (Table 10). An analysis of variance showed highly significant differences between leaf position and sampling dates for all elements except Mg for sampling dates. Leaves from the top of the plant were higher in content of N, P, K, Cl, and Cu than those from the bottom of the plant canopy. At the first sampling date, 4 August, foliar N, P, and K levels were higher than in the fall (29 September). Chloride and Mn content increased as the season progressed.

TABLE 8. The effects of increasing SO_2 dose in nonfiltered and charcoal-filtered air on sulfur content in leaves, fruit, and soil

Treatments		Sulfur content (%)			
Chambers[a]	SO_2[b] ppm	Leaves	Fruit	Soil	Leaves N:S ratio
NF	0.011	1.62	0.23	0.05	2.5
NF	0.059	1.70	0.24	0.05	2.3
NF	0.118	1.94	0.23	0.05	2.1
NF	0.235	2.15	0.25	0.05	1.8
NF	0.468	2.56	0.25	0.05	1.7
CF	0.005	1.76	0.24	0.06	2.2
CF	0.113	1.91	0.21	0.05	2.0
CF	0.466	2.81	0.23	0.06	1.4
AA	0.011	1.45	0.24	0.05	2.7
LSD ($P = 0.05$)		0.48	NS	NS	NS

[a] NF = nonfiltered air; CF = charcoal-filtered air; AA = no chamber.
[b] Means, 5 hr/day, 5 days/wk between 2 July and 29 September.

DISCUSSION

Ambient O_3 at Beltsville, MD, which is 10 km northeast of Washington, D.C., reduced yields of ripe tomato fruit by 16% (from 12.3 to 10.3 kg per plant, or from 123 to 103 MT/ha). This was based on a comparison of yields in CF and NF air without added SO_2. Fruit yields in the chambers were about the same as recently reported (11.6 kg per plant) for greenhouse tomatoes (24). Yields in the AA-no chamber plots (7.6 kg per plant) were lower than in any chambered plots. The AA plots were included in this and other experiments in the EPA-sponsored National Crop Loss Assessment Network (NCLAN) to test chamber effects (8). The AA plot yield data were not used in developing SO_2 exposure dose-response functions but were included in other analyses to estimate experimental error. Greater yields in the open-top chambers than in the AA plots may be due to higher air temperatures (0–3 C) and to slower mean air velocity in the wind-protected chambers (7,11). The extent of chamber effects vary with experimental species. Five years' experience with three snap bean (*Phaseolus vulgaris* L.) cultivars showed that yields in the AA plots were about the same as in NF chamber plots (11). The assumption is made here that plant response to the pollutants in plots with and without open-top chambers are similar (8).

Separate harvest from each plant revealed significant within-chamber effects (Tables 3 and 5). Inspection of individual plant data (not presented) revealed that the two plants on the south side of each chamber produced somewhat higher fruit yields than the other four plants. This was probably due to more space between the two plants on the south side. Chamber effects may also occur because of environmental factors. In the NCLAN and other experiments involving more than one cultivar, the cultivars were placed at random in each quadrant of the chamber (8,11).

The treatments, particularly 0.24 ppm and 0.47 ppm SO_2 exposures for 5 hr/day and 5 days/wk, were higher than is

TABLE 9. Effects of increasing SO_2 dose in nonfiltered and charcoal-filtered air on leaf mineral contents

Treatment		Mineral elements[a]										
Chambers[b]	SO_2[c] (ppm)	Al (%)	Ca (%)	Cl (%)	Cu (ppm)	Fe (ppm)	K (%)	Mg (%)	Mn (ppm)	N (%)	P (%)	Zn (ppm)
NF	0.011	0.228	5.2	0.46	10.5	322	1.3	0.74	189	3.3	0.19	28.2
NF	0.059	0.258	5.2	0.48	10.1	428	1.4	0.79	209	3.1	0.19	33.8
NF	0.118	0.232	5.2	0.44	10.0	411	1.2	0.82	175	3.2	0.19	30.1
NF	0.235	0.263	5.4	0.43	9.0	421	1.0	0.85	156	3.2	0.19	37.5
NF	0.468	0.216	4.7	0.41	9.2	320	1.3	0.79	152	3.3	0.20	35.6
CF	0.005	0.311	5.6	0.52	10.3	551	1.1	0.88	191	3.1	0.17	24.4
CF	0.113	0.290	5.7	0.51	9.5	465	1.0	0.91	205	3.1	0.17	25.3
CF	0.466	0.279	4.8	0.42	9.9	497	1.1	0.96	196	3.2	0.18	36.1
AA	0.011	0.286	5.0	0.50	9.9	556	1.4	0.67	187	3.4	0.19	40.0
LSD ($P = 0.05$)		0.054	NS	NS	NS	NS	NS	NS	NS	NS	NS	9.9

[a] Combined means for three replications, three leaf positions, and three sampling dates.
[b] NF = nonfiltered air, CF = charcoal-filtered air, AA = no chamber.
[c] Means, 5 hr/day, 5 days/wk between 2 July and 29 September.

TABLE 10. Tomato leaf composition as related to leaf position and sampling date

		Leaf position[a]			LSD	Sampling date[b]			LSD
Element	Value	Top	Middle	Bottom	($P = 0.01$)	4 Aug	1 Sept	29 Sept	($P = 0.01$)
Al	%	0.15	0.20	0.43	0.03	0.26	0.31	0.22	0.04
Ca	%	3.43	5.81	6.21	0.17	5.11	5.05	5.36	0.18
Cl	%	0.52	0.45	0.42	0.04	0.39	0.45	0.54	0.03
Cu	ppm	17.9	6.8	5.1	0.7	9.8	11.2	8.5	0.7
Fe	ppm	211.7	262.0	843.4	102.2	466.7	527.4	331.6	115.0
K	%	1.78	0.99	0.36	0.09	1.45	1.20	0.97	0.07
Mg	%	0.63	0.91	0.92	0.06	0.82	0.82	0.83	NS
Mn	ppm	168.5	194.8	188.6	10.4	158.0	192.8	200.6	8.8
N	%	4.86	2.81	2.05	0.15	3.64	3.32	2.73	0.10
P	%	0.23	0.17	0.16	0.01	0.20	0.19	0.17	0.01
S	%	1.37	2.22	2.36	0.07	2.02	1.87	2.08	0.09
Zn	ppm	24.8	26.8	45.4	6.6	35.8	33.6	28.0	3.8
N:S	ratio	3.91	1.37	0.93	0.40	2.14	2.36	1.64	0.18

[a] Means for the nine treatments, three replications, and three sampling dates.
[b] Means for the nine treatments, three replications, and three leaf positions.

currently expected to occur in the ambient air in the United States (14). However, none exceeded the National Air Quality Standard (3-hr exposure to 0.50 ppm SO_2). The higher doses were included to develop the dose-response functions and they permitted a more effective assessment of the potential for SO_2 to alter the mineral composition of leaves and fruit quality.

Yield reduction due to SO_2 was linear (Table 3). However, under the conditions of the experiment, exposure to 0.24 ppm and 0.48 ppm SO_2 caused about the same yield reduction (Table 6). This occurred even though leaf injury values were significantly higher for the 0.48 ppm SO_2 treatment (Table 2), and S in the foliage also increased (Table 8). When snap bean cultivars were exposed to mixtures of O_3 and SO_2 with one cultivar even plants with no visible leaf injury showed significant yield losses (9). The use of leaf injury to predict yield losses can be misleading.

As reported by others for tomato (18,23,26), SO_2 did not interact with O_3 to potentiate yield losses (Table 5). Their effects were additive as shown by examination of data on leaf injury (Table 2) and ripe fruit yields (Table 6) for three of the nine treatments. That is, with CF air and 0.005 ppm SO_2 as the control, the increases in leaf injury caused by the NF treatment without SO_2 added and the treatment with 0.466 ppm SO_2 in CF air totaled about the same as the injury increase due to 0.468 SO_2 in NF air. The same treatment comparisons could be made for yield. The addition of 0.113 ppm SO_2 in CF air or 0.118 ppm SO_2 in NF air did not increase leaf injury compared with their CF and NF controls with no SO_2 added (Table 2).

Septoria leaf spot disease appeared in some plots late in the season, especially in CF chambers with no SO_2 added. By 19 September, most plants (80%) in CF air plots without SO_2 had 10% or more of their leaves with leaf spotting. In NF air only a few plants (17%) showed the leaf spot. Nevertheless, the injury was visibly less than on any plants in CF air. Injury was not found in plots with SO_2 added except on 11% of plants receiving CF air and the 0.11 ppm SO_2 exposure dose. Leaf spot development seemed to be restricted to treatments with most green foliage just before outbreak of the leaf spot.

The tomato fruit quality was not measurably affected even though yields declined as a result of the O_3 and SO_2 treatments. Although there was a linear increase in leaf S as SO_2 concentrations increased (Table 4), S content of the fruit remained unchanged (Table 8). The pH and percent soluble solids of the expressed juice were statistically equivalent for fruits sampled at the same stage of ripening (data not presented). No detectable differences in ascorbic acid contents of fruits relating to pollutant treatment were observed. An assessment of color and sensory quality (taste and texture), considered important in judging the quality of fresh market tomatoes (28), also did not reveal measurable differences due to the increasing SO_2 exposure doses.

Except for S, the increasing SO_2 exposure dose did not consistently alter other elements in the leaves. The elemental composition of the tomato foliage was compared, also, with values found in other reports (1,3–6,21,25,27). In general, leaf N and Cu were in the intermediate range; P and K were comparatively low. Other elements examined were present in relatively high concentrations.

Foliar Al was higher by a factor of 10 than expected for normal plants (3), 0.263 compared with 0.024%. The high values may be attributed to experimental error resulting from an enhancement by Si when determining Al by EDXRF (D. Knudsen, *personal communication*). Although the Al values are high, meaningful comparisons between treatments are possible. We have no explanation for the high foliar Al in the two CF treatments (Table 9), which produced highest yields of ripe fruits (Table 6).

The chamber treatments, which produce the smallest plant mass, had highest Zn in the foliage; i.e., AA plots and the CF and NF air chamber treatments with the highest SO_2 exposure dose (Tables 6 and 9). The CF plots with largest plant mass and highest fruit yield had lowest Zn in the foliage. A dilution factor may have been involved.

Foliar Mn was within a normal range for tomatoes (3). Foliar Cu in normal plants ranges from 5 to 20 ppm (3). Our mean value of 10 ppm was about the same as for tomatoes in a recent study (25). Calcium was lowest in the high dose SO_2 treatments, which caused most leaf senescence. Leaf N, P, Ca, and Mg levels were about the same as those reported by Halbrooks and Wilcox (6). Potassium levels were low in all treatments.

The effects of the SO_2 and O_3 treatments on elemental composition may be compared with the effects of leaf position and sampling dates (Table 10). Leaf position was more important than the sampling date in affecting foliar S, Al, Cu, and Mg concentrations and the N:S ratio. The greater accumulation of S in the lowermost leaves, 2.36 vs. 1.37% in top leaves, was probably due to longer exposures of these older leaves to SO_2. Foliar Ca increased as the season advanced, and the older bottom leaves had much more Ca (6.21%) than leaves from the top of the plant (3.43%). The Zn content of bottom leaves was almost double that of the leaves taken near the top of the plant.

Sulfur dioxide, even at concentrations much higher than expected in polluted air of the United States (14), was not very phytotoxic to Jet Star tomatoes. However, yield reductions were linear as SO_2 concentrations in NF and CF air were increased to 0.48 ppm. Measurable changes in fruit quality did not occur.

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