Dispensing and Monitoring Ozone in Open-Top Field Chambers for Plant-Effects Studies

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ABSTRACT

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The design and function of a system that dispenses and monitors ozone (O_3) in multiple field chambers are reported. The air velocity, O_3 distribution, temperature, light, and plant response in open-top chambers were determined. Once initial dispensing rates were set, the system automatically dispensed and monitored O_3 for set periods each day. The open-top chambers provided a mean air velocity of 2.5 km/hr in the plant growth area. Mean photosynthetic photon flux density (400–700 nm) in the chambers was 88% of ambient. Mean temperature during daylight hours was 0.71 C above ambient. The horizontal variation in O_3 concentration was less than 6, 12, and 14% of the mean, at heights of 30, 120, and 180 cm, respectively. The vertical variation in O_3 concentration was less than 6% of the mean between 30 and 120 cm and less than 19% of the mean between 120 and 180 cm. Studies with field corn (*Zea mays*) and spinach (*Spinacia oleracea*) showed that chambers affected plant growth and that plant growth in one portion of a chamber could differ from growth in another portion. When effects of O_3 on injury, growth, or yield were significant, however, there were no interactions between chamber position and the magnitude of these effects.

Additional key words: air pollution, methods.

Until recently, field research on the effects of air pollutants was done in closed chambers, in which temperature is higher and light is lower than ambient levels. The effects of environmental variation on plant sensitivity to ozone (O_3) have received increasing attemtion during the past 10 yr (5,6). Open-top field chambers (2,14) were developed primarily to decrease chamber effects on temperature, light, and humidity.

Previous studies with open-top chambers compared plants growing in air that was carbon-filtered (CF) or was not filtered (NF) (2,9,14,17). This comparison was presumed to represent the difference between growth in clean vs. ambient air, although chamber air is diluted with ambient air through the open top. The extent of this dilution depends on ambient wind speed (2). Oxidant concentrations in NF chambers usually are 10–15% less than ambient concentrations because O_3 degrades in the chamber air-handling system. The dilution of CF air and degradation of oxidants in the NF chamber air-handling system are major problems in areas where ambient oxidant levels are high (13) or where these levels are near the thresholds for significant effects (8,14). Studies that compare plant response in CF and NF chambers do little to determine threshold doses at which plants are injured or plant growth and yield are reduced, since the effects of only one pollutant dose can be studied. Information on more than one dose is needed to determine the concentrations of O_3 that affect crop production adversely (8).

Several systems for dispensing and monitoring pollutant gases have been described (3,7,10,14–16), but none has been reported for use with O_3 in open-top chambers. Two major limiting factors are the inability (i) to sample O_3 accurately at distances greater than 10 m from the chambers and (ii) to uniformly distribute O_3 within the chambers.

This article describes new methods for dispensing and monitoring O_3 in open-top field chambers for use in studying the effects of oxidants on plants. A system that semiautomatically dispenses and automatically monitors O_3 in multiple open-top field chambers at distances to 106 m from the chambers is described. Chamber effects on air velocity, light, temperature, O_3 distribution, and plant growth were determined.

DESCRIPTION OF SYSTEMS

Dispensing system. Ozone is produced by "silent arc" electric discharge in oxygen (O_2). The O_3 generator (Model 03B2-AR/0, Ozone Research and Equipment Corp., Phoenix, AZ 85019) (Fig. 1) has an output capacity of 38 g/hr. A timer controls a solenoid valve that regulates O_2 flow from a tank to the ozonizer at a rate of 2–4 L/min (LPM). Oxygen pressure and flow were adjusted with a two-stage pressure regulator and needle valve (Fig. 1). A variable-flow self-priming pump (R2 series, Flotec Inc., Norwalk, CA 90650) circulated cooling water at a rate of 15 LPM between a reservoir and the O_3 generator to prevent damage to the dielectrics of the generator while in operation.

The equipment was installed in a converted house trailer. A bathtub served as a water reservoir, and water was returned from the O_3 generator through the shower nozzle for air cooling. The cooling water pump and generator were controlled independently by time clocks. If either O_2 or cooling water pressure fell below requirements, safety switches in the O_3 generator stopped the operation automatically.

Ozone flowed from the generator into a cylindrical aluminum manifold (10-cm diameter, 30-cm length) (Fig. 1) with 20 individual dispensing ports. Ozone passed from the manifold to 20 dual-float rotameters (Brooks, 0–.10 LPM; 0–.43 LPM, Emerson Electric Co., Hatfield, PA 19440) that regulated O_3 flow rates to the chambers through 0.53-cm ID thick-walled (0.075 cm) Teflon tubing (TFE, flexible, Dupont Corp.). The rotameter settings were pressure-dependent, requiring a stable pressure in the O_3 manifold. Stable pressure was provided by routing excess O_3 through a sealed cylindrical glass reservoir (120 cm × 5-cm diameter) partially filled with water (Fig. 1). Pressure was adjusted by changing the amount of water in the reservoir. Flow rate through the reservoir was

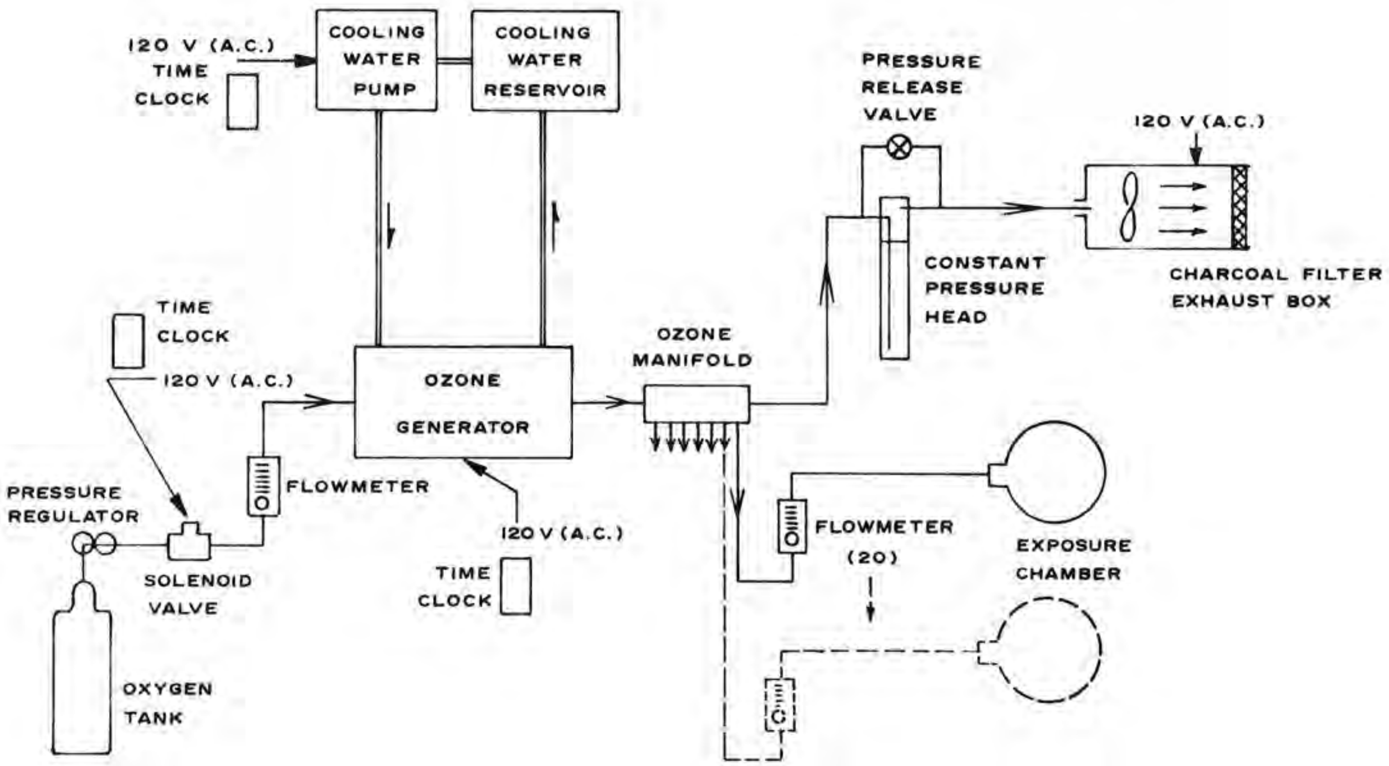

Fig. 1. Schematic diagram of ozone dispensing system.

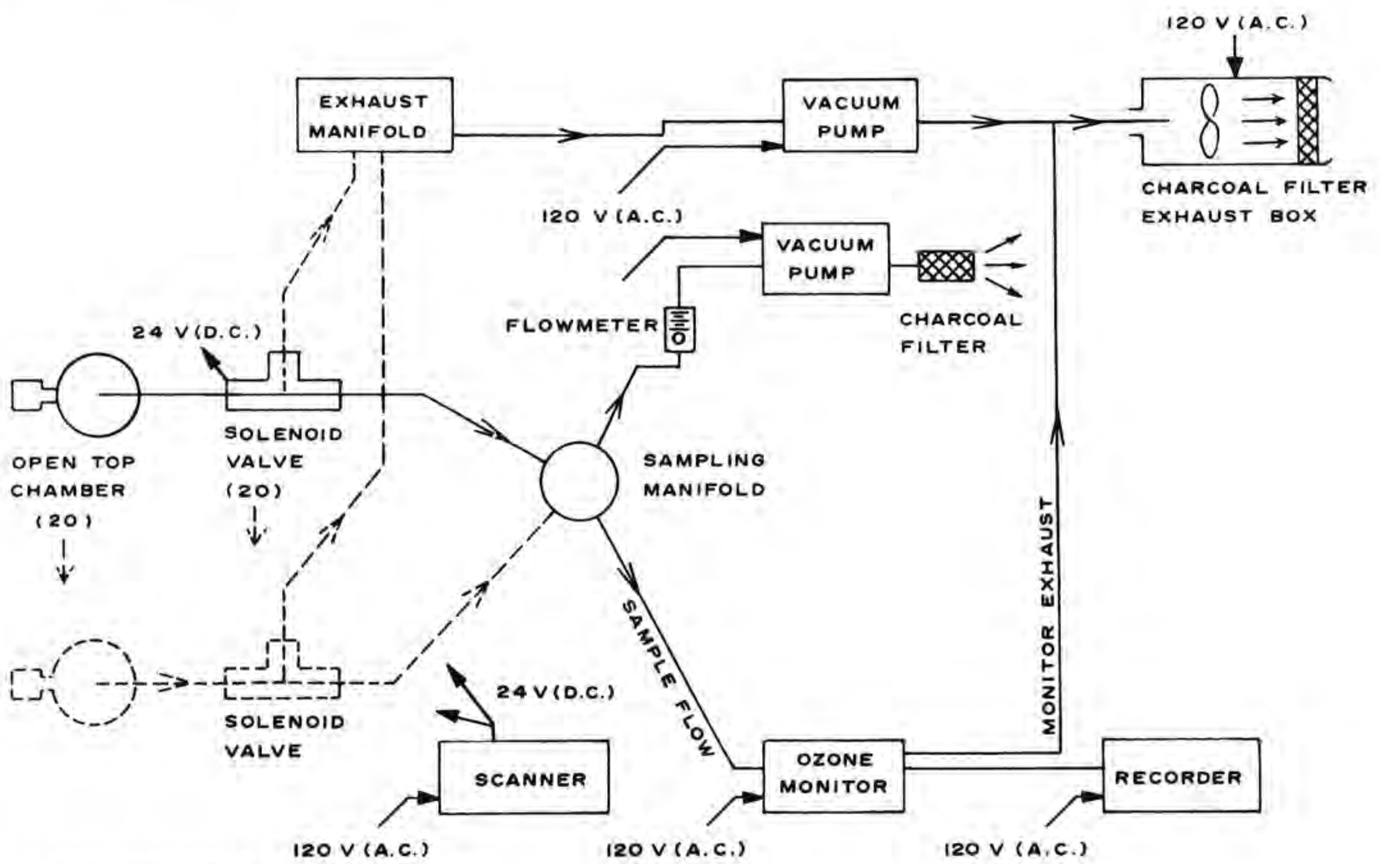

Fig. 2. Schematic diagram of ozone monitoring system.

adjusted with a control valve that bypassed the reservoir (Fig. 1).

Monitoring system. Air samples from 20 points (field chambers or ambient air) were drawn continuously through 0.53-cm ID thick-walled (0.075 cm) Teflon tubing and through the exhaust ports of solenoid valves (3-way, 24 VDC, stainless steel and Viton, Versa Products Co. Inc., Englewood, NJ 07631) to the exhaust manifold with a vacuum pump (Model MB-302, Metal Bellows Co., Sharon, MA 02067) (Fig. 2). Airflow was maintained at 2.5 LPM per sample tube. Sequential activation of each of 20 solenoid valves by a timer (scanner) caused the air sample to be delivered separately to a glass sampling manifold, while all other samples were exhausted. The sampling manifold was a 250-ml sphere to which 15-mm screw fittings were attached. Bored closure caps with Teflon-covered squeeze washers provided gastight seals. Samples were drawn through the sampling manifold at a flow rate of 2.5 LPM by a small vacuum pump (Model MB-41, Metal Bellows Co.).

Ozone was monitored continuously from the sampling manifold by a chemiluminescence analyzer (Model 8410A, Monitor Labs Inc., San Diego, CA 92121) calibrated with the 1% neutral buffered potassium iodide method (1,12). Ozone concentrations were recorded on a strip chart recorder.

Field chambers. Cylindrical open-top field chambers, 3 m in diameter and 2.4 m high, (Fig. 3) were used (2). Air was drawn by a 0.5-HP axial blade fan at 70.8 m^3/min (2,500 cfm) through a particulate filter and inflated a 1.2-m wide air duct that encircled the lower half of the chamber. Air passed from the duct into the chamber through 250 holes (2.5-cm diameter) located in six rows on 15-cm centers (Fig. 3).

MATERIALS AND METHODS

Dispensing and monitoring ozone. Ozone concentrations of 0.02, 0.06, or 0.10 ppm (0.10 ppm = 196 $\mu g/m^3$ at 25 C and 760 mm Hg) were dispensed to the plant growth area of 15 open-top field chambers at distances to 106 m. The tests began in June and ended in October 1976. The monitoring system automatically sampled the O_3 concentrations in ambient air and in the chambers through Teflon tubes ranging in length from 30 to 106 m.

The efficiency of each sampling line was determined with a portable O_3 generator, which produced a stable O_3 output by UV irradiation of clean air flowing through a quartz tube. The O_3 generator was similar to that described by Hodgeson et al (11). The O_3 output from the portable generator was drawn separately through each of the 20 sampling lines on four dates at 3-wk intervals to determine sampling efficiencies.

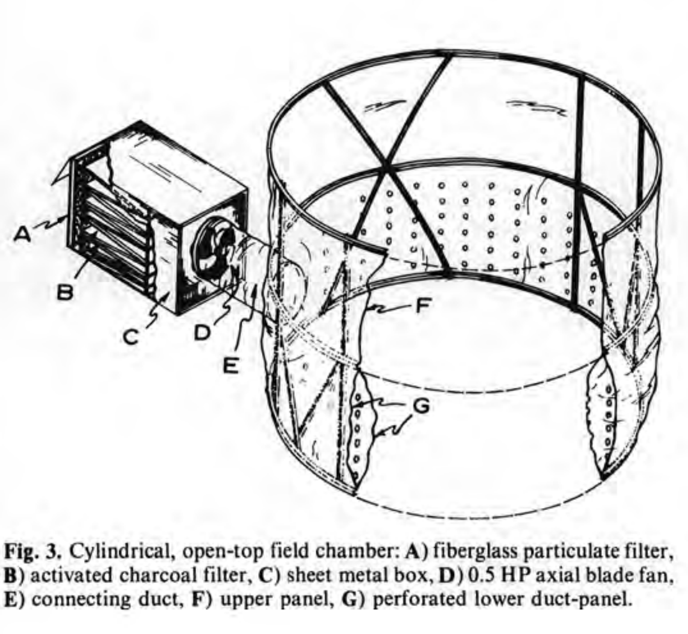

Fig. 3. Cylindrical, open-top field chamber: **A)** fiberglass particulate filter, **B)** activated charcoal filter, **C)** sheet metal box, **D)** 0.5 HP axial blade fan, **E)** connecting duct, **F)** upper panel, **G)** perforated lower duct-panel.

Chamber performance. *Air velocity*. An open-top chamber was installed in an enclosed building to determine air velocity characteristics. A particulate filter was used on the chamber air-inlet during all measures. Velocity was measured (with and without a charcoal filter) with a precision omnidirectional thermoanemometer (Model B-27, Teledyne-Hastings-Raydist Inc., Hampton, VA 23661). Air velocity was measured in the chamber at heights of 45 and 135 cm at 15-cm intervals from the chamber center (0–75 cm) along four transects (toward points A, B, C, D) (Fig. 4). Air velocity also was measured at heights of 15, 45, 75, 105, and 135 cm at eight locations (28-cm intervals) in each of two rows (Fig. 4).

Light transmission. The effects of the clear polyvinyl chloride (Krene, KDA 2244, 8 mil, Union Carbide Corp.) chamber covering on the photon flux density in the region of photosynthetically active radiation (PAR, 400–700 nm) was measured in the chambers with a quantum sensor (LI-185, Lambda Instruments Corp., Lincoln, NE 68504). Direct comparisons between PAR in the open and in a chamber were made at heights of 45 and 135 cm at each of five positions (Fig. 4). To avoid possibly confounding effects of momentary changes in cloud cover, readings were considered valid only when two successive comparisons at each position showed the same degree of difference. Readings were taken at 0800, 1000, 1200, 1400, and 1600 hours EDT on three sunny and two overcast days between 24 August and 21 September.

Temperature. Temperature was monitored continuously during August and September at heights of 45 and 135 cm at each of nine positions in a chamber (Fig. 4) and at one position in the open, with 20 shielded Type T thermocouples. Tall fescue, *Festuca*

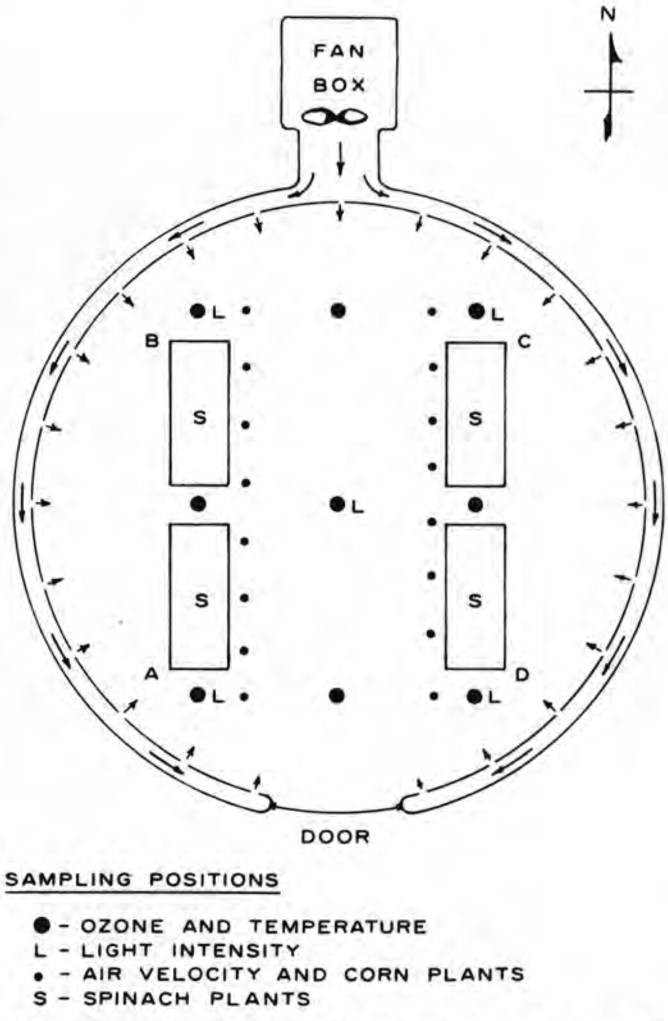

Fig. 4. Schematic diagram of sampling positions for ozone, temperature, light intensity, air velocity, and growth and yield of corn and spinach in open-top field chambers.

arundinacea (Shreb.), growing in the chamber, was watered as required and maintained at a height of 5–10 cm. Temperature data from four sunny and four cloudy days were selected for statistical analyses.

Ozone distribution. Ozone sampling tubes, installed in inverted plastic funnels to prevent water intake, were used to monitor O_3 concentrations sequentially at each of nine chamber positions at three heights (30, 120, and 180 cm) (Fig. 4). On each of two dates, two chambers were used when ambient winds from the southeast were 5–10 km/hr and the mean ambient O_3 concentration was 0.08 ppm (v/v). Ozone was monitored at each of the 27 locations per chamber until 1 min after stability was attained (about 3–5 min). Field corn (*Zea Mays* L. 'Coker 16') growing in the chambers was 2.1 and 3.6 m tall in one chamber and 0.6 and 2.7 m tall in the other chamber on the first and second measurement dates, respectively.

Plant growth. Field corn was used during the summer and spinach (*Spinacia oleracea* L., 'Winter Bloomsdale' and 'Hybrid 7') during the fall to determine whether the chambers or the position of plants in the chamber affected growth and whether there were interactions between position and the effects of O_3. Field corn was planted in rows and eight potted spinach plants were located in each chamber quadrant (Fig. 4). Corn and spinach were grown in ambient air with no chamber (AA), in CF chambers, or in NF chambers with 0.02, 0.06, or 0.10 ppm of O_3 added for 7 hr each day. Ozone was added for 89 days in the corn study and for 35 days in the spinach study. Plants were watered as needed to prevent wilting and to provide uniform moisture conditions. Foliar injury, plant growth, and yield were measured.

TABLE 1. Effect of length of Teflon sampling tube on the concentration of ozone monitored from a stable source[a]

Sample tube length (m)	Number tested	Sampling efficiency[b] Mean (%)	$S\bar{x}$
30.5	3	93.5	± 0.81
45.7	8	92.8	± 0.51
61.0	2	91.3	± 1.06
76.2	3	89.0	± 0.90
91.4	2	90.4	± 1.32
106.7	2	85.6	± 1.40

[a]The indicated number of sampling tubes (0.53 cm ID) were tested on each of four dates.
[b]Sampling efficiency is defined as the percentage of the ozone concentration as monitored through a 3-m Teflon tube.

TABLE 2. Air velocity at different positions in an open-top field chamber

Height[a] (cm)	Velocity (km/hr)	$S_{\bar{x}}$	Position from frame[b] (cm)	Velocity (km/hr)	$S_{\bar{x}}$
15	2.77	± 0.26	45	2.54	± 0.32
45	3.04	± 0.24	75	2.36	± 0.29
75	3.07	± 0.13	105	2.18	± 0.19
105	1.95	± 0.07	135	2.24	± 0.22
135	1.47	± 0.06	135	2.38	± 0.31
			105	2.52	± 0.42
			75	2.60	± 0.50
			45	2.92	± 0.60

[a]Measures were made in a chamber installed in an enclosed building. Each value is the mean of 640 instantaneous measures (10 on each of 2 days at eight positions in each of two rows with and without a charcoal filter installed).
[b]Starting 45 cm from the frame nearest the fan box and ending 45 cm from the frame nearest the door. Each value is the mean of 400 instantaneous measures (10 on each of 2 days, in two rows, at five heights, with and without a charcoal filter installed).

RESULTS

Dispensing system. During the 4-mo test, the dispensing system functioned well in dispensing 0.02, 0.06, or 0.10 ppm of O_3 to the plant growth area of 15 open-top field chambers. The rotameter flow rates returned to the original rates at the start of each exposure, and O_3 was automatically dispensed at constant amounts for 7 hr/day. Routine maintenance of the dispensing system consisted of cleaning rotameter floats each month.

The precision with which O_3 concentrations were maintained in chambers at set levels above ambient concentrations was limited only by the degree of dilutiuon by ambient air. The inflow of ambient air through the open-tops became a greater problem as the difference between the desired chamber O_3 concentration and ambient concentration increased.

Monitoring system. The system provided continuous sequential monitoring of O_3 concentrations from 20 locations at distances to 106 m during the 4-mo test. Less than 2% of the 0.17 ppm of O_3 from the portable generator was lost while passing through a 3-m-long Teflon tube, the solenoid valves, and sampling manifold into the O_3 monitor. Sampling efficiency in the longer tubes directly related to sample tube length (Table 1). Efficiency ranged from 94% for 30.5-m tubes to 86% for 106-m tubes. Individual tubes tended to become slightly more efficient with use.

Chamber performance. *Air velocity*. Mean air velocity into the chambers through the 2.5-cm diameter holes was 31 km/hr. Apparent entrainment of surrounding air in the chamber by the individual airstreams caused turbulence that decreased air velocity at a short distance from the chamber walls. The mean velocity at the chamber center was 2.96 and 1.74 km/hr at heights of 45 and 135 cm, respectively. There were no trends toward changed air velocity from the center toward the periphery within the 1.5-m radius of measurement. Mean air velocity with a charcoal filter installed was 12% less (0.3 km/hr) than without a filter, but the filter did not affect airflow patterns.

Velocity varied little with height between 15 and 75 cm (2.77–3.07 km/hr) but decreased to 1.95 km/hr at 105 cm and to 1.47 km/hr at 135 cm (Table 2). Measurements at 30-cm intervals along two rows (Fig. 4) at five heights showed slightly greater air velocity near the chamber periphery than toward the center (Table 2).

TABLE 3. Light in an open-top field chamber at a different times and positions on sunny and cloudy days

Time of day or chamber position	Chamber PAR[a] (% of ambient)[b] Cloudy days 45 cm	Cloudy days 135 cm	Sunny days 45 cm	Sunny days 135 cm	Means
Hour, EST					
0800	79	89	75	92	84
1000	80	89	93	99	90
1200	82	93	101	101	94
1400	85	85	80	90	85
1600	86	94	78	88	87
Position or quadrant					
Northwest	80	89	87	94	88
Northeast	84	90	99	96	92
Center	83	90	90	91	89
Southwest	80	80	69	90	80
Southeast	85	95	82	99	90
Means	82	90	85	94	
LSD ($P = 0.05$)	3.2		4.3		

[a]PAR = photosynthetically active radiation. Photon flux density was measured in the PAR region of wavelengths (400–700 nm). Mean ambient PAR (0800 to 1600 hours EST) on sunny days was 1,345 microeinsteins/m^2/sec.
[b]Each value is the mean of 30 or 20 direct comparisons between chamber and ambient light (PAR) on 3 sunny or 2 cloudy days, respectively (10 comparisons per day).

TABLE 4. Temperature in an open-top field chamber during cloudy or sunny days with different ambient temperature ranges

Height of measure (cm)	Temperature increase in chamber[a]					
	Cloudy days[b]			Sunny days[c]		
	19–27 C	23–34 C	LSD ($P = 0.05$)	11–28 C	25–38 C	LSD ($P = 0.05$)
45	.37	.94	.29	1.19	.82	.32
135	.29	.62	.21	1.10	.32	.26

[a]Each value is the mean of 288 readings obtained by subtracting ambient air temperature from chamber temperature (nine chamber positions, 2 days, 16 hr, 0600 to 2100 hours EST).
[b]The mean ambient temperature for cloudy days (19–27 C and 23–34 C) was 22 and 27 C, respectively.
[c]The mean ambient temperature for sunny days (11–28 C and 25–38 C) was 22 and 33 C respectively.

TABLE 5. Ozone concentrations in open-top field chambers with ozone added to the air inlet when the mean ambient ozone concentration was 0.08 ppm and ambient wind velocity was 5–10 km/hr[a]

Height (cm)	O_3 concentration per row		
	West (ppm)	Center (ppm)	East (ppm)
30	0.167	0.163	0.167
120	0.157	0.160	0.160
180	0.133	0.150	0.140
LSD ($P = 0.05$) = 0.017 ppm			

[a]Ozone at 0.10 ppm was added to the chamber air. Each value is the mean of 12 observations (two chambers, three positions per row, on 2 days).

Light transmission. Light (PAR) in the chamber averaged 88% of ambient during the 5 days of measurement. The PAR at 0.45 and 1.35 m was 84 and 92% of ambient, respectively (Table 3). The southern positions averaged 85% of ambient and the northern positions averaged 90% of ambient. As expected, the changing angle of insolation and differential shading caused significant position × height effects for all hours. The PAR was greater than ambient at some chamber positions at certain times during sunny days due to reflection from the plastic walls.

Temperature. The mean temperature in the chamber was 0.56 and 0.86 C higher than ambient on cloudy and sunny days, respectively (Table 4). The maximum increase (<2.1 C) occurred at the 45-cm height between 0900 and 1200 hours on days with bright sun when the ambient temperature was >35 C. The effect of height was significant on sunny days but not on cloudy days. There were no significant position, position × height, or hour × height effects for either type of day.

Ozone distribution. Measurement of O_3 concentrations at different horizontal and vertical positions (Fig. 4) in the chambers showed no significant position or position × height effects (Table 5). Ozone concentration decreased significantly with height increase; the mean concentration at 120 and 180 cm was 4 and 16% less, respectively, than at 45 cm (Table 5), probably because of dilution with ambient air.

Biological measures. The mean height of corn plants grown in AA (0.03 ppm mean O_3 concentration) was 9% less than that in NF chambers (0.03 ppm mean O_3 concentration), and the differences were significant. Corn plants at the chamber sides were about 2% shorter than plants near the center, but the differences were not significant. Fresh weight of Winter Bloomsdale spinach grown in AA was the same as that in NF chambers. However, fresh weight of Hybrid 7 spinach in AA was only 72% of that in the NF chambers, and the difference was significant.

In NF chambers with the 24-hr mean O_3 concentration at 0.05–0.06 ppm, both corn and spinach had foliar injury and yield decrease. However, chamber position did not significantly affect the amounts of foliar injury, growth, or yield from exposure to O_3 for either species (4).

DISCUSSION

The O_3 dispensing and monitoring system used with open-top field chambers provided the means to study the effects of different doses of O_3 that follow the same general daily fluctuations as ambient concentrations. With minor modifications, other gaseous pollutants could be used. Dilution of chamber air by ambient air caused momentary fluctuations of O_3 concentration in chambers during periods when ambient winds exceeded 15 km/hr. Where ambient wind velocity regularly exceeds 15 km/hr, the use of the present system is limited. Successful control of O_3 concentrations in such areas can be achieved by adding a top of clear Teflon film (3).

A 0.6 × 4.5 m baffle installed at a 45° downward angle at the outer, upper chamber edge on the windward side of another open-top chamber design (13) has been partially effective in preventing ambient air ingress at ambient wind velocities of 32 km/hr in California.

Oxidant air pollution is pervasive in most areas; concentration gradients are small or nonexistent. Thus, exposure chambers are required to determine the effects of different doses of oxidants. With any chamber design, however, the chamber structure might possibly alter the environment in ways that change the sensitivity of plants to pollutants. Although open-top chambers affect the plant environment, these effects are less than those in closed chamber designs. In our 7-yr experience, the open-top chambers caused plants to grow slightly taller but rarely had significant effects on yield. Plants often grew differently in different parts of the chambers, but we did not find significant interactions between chamber position and the effects of O_3. The causes for chamber-induced growth effects may be related to slower mean air velocity, slightly higher temperature, or less light at some chamber locations than in the open. Previous studies have shown negligible chamber effects on relative humidity (2).

Large changes in the environment can change plant sensitivity to pollutants (6). There are no reports, however, that environmental changes of the magnitude caused by open-top chambers change plant sensitivity. Further work is needed to determine whether small long-term changes in environmental conditions significantly affect plant sensitivity to pollutants.

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