Ozone Injury to Plants as Influenced by Air Velocity During Exposure

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ABSTRACT

Oat, tobacco, bean, and cucumber seedlings were exposed to ozone in paired fumigations to determine whether varying air velocities near the levels used in experimental exposures affects the amount of subsequent ozone injury. The velocities of 0.26 vs. 0.82 km/hr (0.16 mph vs. 0.51 mph) and 0.26 vs. 1.1 km/hr (0.16 mph vs. 0.71 mph) were compared during 1- and 3-hr exposures.

Air velocities during exposure had little or no effect on ozone injury to oat and cucumber. Tobacco was often injured more at the high air velocity, but the differences were usually not significant. Bean was more severely injured at the high than at the low velocity, and the results were often significant. The effects of air velocity on the severity of plant injury were greatly influenced by plant species. Phytopathology 61:1209-1212.

Additional key words: Avena sativa, Nicotiana tabacum, Phaseolus vulgare, Cucumis sativum.

Reports on the effects of air pollution on plants usually contain descriptions of exposure time and the concentration of a given pollutant. Less commonly, temperature, humidity, light, airflow rates, air velocity, or other factors are included in descriptions of exposure conditions.

Recently, Brennan & Leone (1) reported that, when identical concentrations of sulfur dioxide or ozone were circulated over tomato and cucumber plants at 9.1 cfm (0.26 m^3/min) or 16.6 cfm (0.47 m^3/min) in exposure chambers (0.28 m^3), plants were more severely injured at the higher flow rate. These authors gave no quantitative measure of the extent of injury differences or important details of the experimental design. Hill (3) found increased ozone uptake by oat plants with increasing linear air velocities up to 4.8 km/hr (3 mph), but did not report the effect of velocity on plant injury during exposure.

Since air velocity effects appear to be poorly understood, it was considered necessary to determine whether different air velocities during greenhouse exposures significantly affect plant injury. This paper reports the quantitative effects on subsequent injury when plants were exposed to ozone administered at different air velocities.

MATERIALS AND METHODS.—Oats (*Avena sativa* L. 'Clintland 64'), tobacco (*Nicotiana tabacum* L. 'Bel W_3'), bean (*Phaseolus vulgare* L. 'Pinto'), and cucumber (*Cucumis sativum* L. 'Ashley') were planted in a 1:1 peat-perlite potting mix in 10-cm plastic pots, and grown in a polyethylene plastic-covered greenhouse. Plants were watered daily with half-strength Hoagland's solution (4).

A specially designed exposure chamber system (Fig. 1) designed to dispense ozone at different airflow rates was installed in the greenhouse. Each chamber (size, 0.6 × 0.6 × 0.6 m), was covered with clear 5-ml Teflon plastic film. Air was drawn into the chamber system through a particulate filter (Fig. 1-A) and an activated charcoal filter (Fig. 1-B) prior to ozonation which occurred as shown (Fig. 1-C). The ozonized airflow was split and transferred through the duct (Fig. 1-D) into the top of the two chambers (Fig. 1-E), over the plant area, and through perforated plates in the base of each chamber to the exits. Each airstream passed through a metering orifice (Fig. 1-F) and flow-control valve (Fig. 1-G). This method of air entry into the chambers produced a circular airflow through them. The perforated plate at the base of the chamber had sufficient pressure-drop across it to insure uniform airflow through the plate. This arrangement produced a linear air velocity across leaf surfaces at least equal to the average linear velocity through the chamber. The two airstreams combined and were exhausted via a centrifugal blower (Fig. 1-H). The airflows were calculated by knowing the calibration of the orifices and measuring the pressure drop across them with a Magnehelic pressure meter. Air velocity was calculated from air flow rates through the chambers, considering chamber size. Actual air velocity at plant height at a given position is not necessarily directly proportional to the amount of air passing through the chambers. Therefore, actual velocities were measured with a Hastings air meter (Model G-11) at 9 positions at plant height within each chamber. The calculated linear velocity in the chambers, using the calibrated orifices and pressure drop across them, was 0.05, 0.19, and 0.37 km/hr (0.03, 0.12, and 0.23 mph) for the 0.28, 1.1, and 2.3 m^3/min (10-, 40-, and 80-cfm) chambers, respectively. The measured velocity values using the air-velocity meter averaged 0.26, 0.82, and 1.1 km/hr (0.16, 0.51, and 0.71 mph) for the 10-, 40-, and 80-cfm chambers, respectively. We will refer to the 10-, 40-, and 80-cfm chambers as the 0.16-, 0.51-, and 0.71-mph chambers, respectively. The ozone was produced with an ultraviolet mercury arc lamp inserted directly into the airstream (Fig. 1-C). Ozone concentration was adjusted to desired concentrations (±39 μg/m^3) with a variable

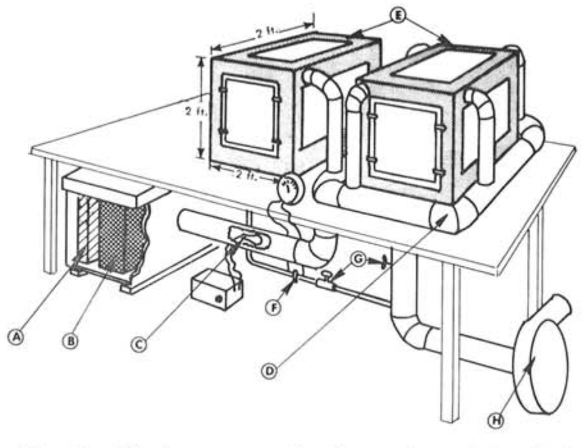

Fig. 1. Plant exposure chamber system designed to dispense ozone and supply air at different velocities. **A)** Particulate filter; **B)** activated charcoal filter; **C)** region of ozonation; **D)** duct connecting two chambers; **E)** chambers; **F)** metering orifice; **G)** flow control valve; **H)** centrifugal blower.

autotransformer on the primary of the high-voltage lamp transformer. Cool-white fluorescent lights were used during exposures, and light intensity within the chambers at plant height ranged from 700 to 2,000 ft-c, depending on ambient sunlight.

Plants were exposed to ozone in paired fumigations at air velocities of 0.16 versus 0.51 mph, and 0.16 versus 0.71 mph between 9 AM and 3 PM daily. Cucumbers were exposed for 3 hr, and the other species for both 1 and 3 hr. Ozone concentrations were determined by a Mast instrument, and the values corrected to 2% neutral KI. Specific ozone concentrations varied with the length of exposure and plant species (Tables 1-4). Two or three ozone concentrations producing slight to moderate plant injury were used for each type of exposure. Ozone levels differed by less than ± 1 pphm (19.8 μg/m^3) and temperature which varied with greenhouse conditions by less than ± 0.5 C between paired chambers during individual exposures. The relative humidity during fumigations varied between 30 and 70%, depending on external weather conditions, but was nearly identical in both chambers during a given exposure.

Oats (14-18 days old), tobacco (7-8 weeks old), and beans (14 days old) were exposed between November and April. Cucumbers (21-33 days old) were exposed in August and September. Depending upon plant species, each fumigation utilized 4-5 pots/chamber with 1-5 plants/pot. Each type of exposure was repeated 8-12 times (Tables 1-4). The percentage leaf area injured by ozone was recorded for each injured foliar leaf when ozone symptoms had sufficiently developed. The results were analyzed statistically, using the Keuls range test.

RESULTS.—The amount of injury which developed on a given plant species at a set ozone level and exposure time varied widely from exposure to exposure, often overshadowing the effect of the varying ozone concentrations used in these experiments. This is not surprising, as the amount of injury from ozone exposure is known to be affected by many environmental factors which commonly fluctuate in the greenhouse.

The different ozone concentrations did not appear to affect the action of different air velocities on the amount of subsequent plant injury. Therefore, injury data from exposures at different ozone levels have been combined for each velocity comparison. The combined average percentage of ozone injury on leaves of cucumber, oats, tobacco, and bean at different air velocities is shown in Tables 1-4.

The results indicate that no simple correlation exists between air velocity during ozone exposure and the resulting plant injury. Rather, the amount of injury to plants exposed at different velocities varied with plant species and age of leaf.

Slightly more injury occurred at the higher velocities in cucumber, but these differences were not significant (Table 1). The amount of injury in oats varied slightly with different treatments, but no consistent relationship to velocity was seen (Table 2). The only statistical difference in the amount of injury on oats occurred

TABLE 1. Ozone injury on leaves of cucumber exposed for 3 hr at different air velocities[a]

Leaf no.[c]	% Leaf injury/paired exposure[b]			
	0.16 mph	0.51 mph	0.16 mph	0.71 mph
1	8	9	5	8
2	11	13	8	11
3	7	6	7	8

[a] The average ozone concentration in the 0.16-mph vs. 0.51-mph exposures was 37 pphm. This is the average of 2, 2, and 5 exposures at 32, 35, and 40 pphm, respectively. The average ozone concentration in the 0.16-mph versus 0.71-mph exposures was 36 pphm. This is the average of 2, 3, and 3 exposures at 32, 35, and 40 pphm, respectively (1 pphm = 19.8 μg/m^3).

[b] Each figure is the average of 64-72 leaves from 8-9 individual experiments.

[c] The leaf number progresses from the oldest fully expanded leaf to the youngest.

TABLE 2. Ozone injury on oat leaves exposed for 1 and 3 hr at different air velocities[a]

Exposure time, hr	Leaf no.[b]	% Leaf injury/paired exposure[c]			
		0.16 mph	0.51 mph	0.16 mph	0.71 mph
1	1	1	1	1	1
	2	15	13	9	12
	3	19[d]	14	13	15
3	1	10	9	13	17
	2	9	9	13	15
	3	8	8	11	11

[a] The average ozone concentration in the 1-hr exposures was 50 pphm. The average ozone concentration in the 3-hr exposures was 34.5 pphm. This is the average of 5, 1, and 4 exposures at 30, 35, and 40 pphm ozone, respectively (1 pphm = 19.8 μg/m^3).

[b] The leaf number progresses from the oldest fully expanded leaf to the youngest.

[c] Each figure is the average of 200-250 leaves in 8-10 experiments.

[d] Injury on the third foliar leaf was significantly greater (5% level) on leaves exposed at 0.16 mph than at 0.51 mph.

TABLE 3. Ozone injury on tobacco leaves exposed for 1 and 3 hr at different air velocities[a]

Exposure time, hr	Leaf no.[b]	% Leaf injury/paired exposures[c] 0.16 mph	0.51 mph	0.16 mph	0.71 mph
1	1	21	30	33	45
	2	20	22	24	36[d]
	3	8	8	9	11
3	1	34	33	27	31
	2	23	21	21	24
	3	7	7	10	12

[a] The average ozone concentration in the 1-hr exposures was 45.5 pphm. This is the average of 3, 3, and 4 exposures at 40, 45, and 50 pphm, respectively. The average ozone concentration in the 3-hr exposures was 27.5 pphm. This is the average of five exposures at 25 pphm and 5 at 30 pphm (1 pphm = 19.8 μg/m³).

[b] The leaf number progresses from the oldest fully expanded leaf to the youngest.

[c] Each figure is the average of 40 leaves in 10 experiments.

[d] Injury was significantly greater from exposure in the 0.71-mph chamber than in the 0.16-mph chamber.

in a 1-hr exposure when the third foliar leaves were more severely injured at the low velocity (0.16 mph) than at the high velocity (0.51 mph).

Differences in the amount of injury at different velocities were greater in the 1-hr tobacco exposures than in the 3-hr exposures. More tobacco injury usually occurred at the high velocities than the low, but the only statistical difference was observed in relation to the second oldest leaf in the 1-hr exposures, where more injury was found at 0.71 mph than at 0.16 mph (Table 3). In two of the four types of exposures, significantly more injury occurred (5% level) on unifoliar pinto bean leaves at the higher than at the lower velocities (Table 4).

DISCUSSION.—Heck (2) reviewed the factors affecting plant sensitivity to air pollutants, and stressed the importance of many interacting variables. The influence of air velocity (wind) cannot be adequately assessed except in relation to other environmental factors and plant characteristics. The suggestion that increased air velocity increases plant injury from air pollutants presupposes an effect on the microenvironment of the leaf surface. A higher velocity should more readily disrupt the air boundary layer of the leaf surface. If this increased disruption results in a sustained higher pollutant level in the boundary layer, then more pollutant would be available for entry into leaves and greater injury should result. However, increased air velocity could also reduce the humidity at the leaf surface, possibly reducing plant sensitivity. The often observed increased sensitivity of greenhouse-grown plants near evaporative cooling pads could be a result of higher humidity conditions combined with more rapid replacement of pollutants due to higher air velocity, rather than merely to velocity alone. The importance of relative humidity in determining plant sensitivity has been emphasized by several workers (5, 6, 9) who found increasing plant susceptibility to ozone with increasing relative humidity. Recent results from our laboratory also show a marked effect of relative humidity.

TABLE 4. Ozone injury on unifoliar bean leaves exposed for 1 and 3 hr at different air velocities[a]

Exposure time, hr	% Leaf injury/paired exposure[b] 0.16 mph	0.51 mph	0.16 mph	0.71 mph
1	48	56	40	50[c]
3	25	32[c]	26	30

[a] The average ozone concentration in the 1-hr exposures was 49.2 pphm. This is the average of 1 exposure at 40 pphm and 11 exposures at 50 pphm. The average ozone concentration in the 3-hr exposures was 34 pphm. This is the average of one exposure each at 25, 30, and 40 pphm and 7 exposures at 35 pphm during the 0.16-mph vs. 0.71-mph exposures and 3, 6, and 1 exposures at 30, 35, and 40 pphm, respectively, during the 0.16-mph vs. 0.51-mph exposures (1 pphm = 19.8 μg/m³).

[b] Each figure is the average of 160-190 leaves in 10-12 experiments.

[c] Injury at the high flow rates was significantly greater (5% level) than at the low flow rates.

Brennan & Leone (1) suggest that the results of Menser et al. (7) and Miller et al. (8) support the theory that increased wind speed during exposure to pollutants increases plant injury. However, these experiments (7, 8) were not designed to determine whether wind speed affects injury. Neither the experimental design reported in this paper nor the one reported by Brennan & Leone (1) is adequate to test the hypothesis that increased ambient wind speeds during pollutant episodes increase plant injury. In the first place, we used air velocities in the range common to experimental pollutant exposures. The average linear velocity did not exceed 1.1 km/hr (0.7 mph), which is less than is commonly found in ambient air. Secondly, in both designs, airflow was not linear as commonly found in ambient air. Finally, set concentrations of pollutant were maintained within chambers, and plant densities were low. It is possible that increased ambient air velocity through dense plant stands could increase injury by interrupting the boundary layer, and by continually replacing pollutants absorbed by the plants. The constant ozone concentrations and low plant densities in greenhouse exposures, therefore, would tend to minimize this impact of air velocity on the boundary layer and result in little variation in plant response to the pollutant.

Our experiments were designed to determine whether different air velocities during routine greenhouse exposures significantly influence the amount of plant injury developing. We found that differences were greater with respect to unifoliar leaves of pinto bean than other plants tested, illustrating a variable response with different plant species. Age of the leaf, especially in tobacco, also influenced the effect of air velocity on injury. The results further indicate that plant injury due to ozone during experimental greenhouse exposures is less influenced by air velocities than has previously been indicated (1). Our greenhouse, laboratory, and field studies utilize calculated air velocities of 0.05 km/hr (0.03 mph) in chambers, 0.6 × 0.6 × 0.6 m capacity, 0.03 km/hr (0.02 mph) in chambers 0.6 × 0.9 × 1.2 m, and 0.17 km/hr (0.1 mph) in those of 2.4- × 2.4- × 1.95-m capacity. Since differences in the amount of injury developing on most plant species at 0.16 mph vs. 0.51 mph and 0.71 mph were in most cases small and insignificant, it appears unlikely that significant differences would occur during exposures at airflows which vary in the magnitude of ±0.1 mph.

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