Effects of Ozone and Sulfur Dioxide on Yield of Winter Wheat

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ABSTRACT

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In studies conducted in consecutive years, winter wheat was exposed to O_3 alone and to O_3 and SO_2, alone and in combination, to evaluate impacts on yield. In both years, exposure to O_3 resulted in significant reductions in yield, although the shapes of the response curves were different. The variation in the curves for the 2 yr may be attributable to differences in precipitation and subsequent effects on the growth of the plants and their sensitivity to O_3. Sulfur dioxide, either alone or in combination with O_3, had no effect on yield even after multiple intermittent exposures at 0.363 ppm.

Winter wheat (*Triticum aestivum* L.), a major crop in the United States, is planted on more than 43 million acres with an annual value to producers of more than $6 billion (17). Because winter wheat is widely grown, it is potentially subject to elevated concentrations of ozone (O_3) of anthropogenic origin over portions of its range. Little is known of the impact of O_3 on wheat production under field conditions (9). Shannon and Mulchi (14) exposed the cultivars Arthur-71 and Blueboy during anthesis to 0.20 ppm O_3 for 4 hr/day for 7 days in growth chambers and found yield reductions of 30 and 23%, respectively. Using open-top chambers, Heagle et al (6) exposed 11 wheat cultivars to O_3 for 4 wk to determine their relative sensitivity and conducted long-term field exposures with four cultivars to evaluate dose-response relationships. They found that yields of plants exposed for 54 days to 7-hr average O_3 concentrations of 0.10 and 0.13 ppm were 16 and 33% lower, respectively, than yields of plants grown at 0.03 ppm O_3.

The objective of this study was to evaluate the effects of long-term exposures to both O_3 alone and in combination with sulfur dioxide (SO_2) on the yield of hard red winter wheat. The study was conducted as part of the National Crop Loss Assessment Network (NCLAN) program. Complementary research evaluating the relationship between whole-plant photosynthesis and yield is presented in a companion paper (1). The cultivar Vona was selected because of its economic importance. The 25,756 acres of certified Vona seed grown in 1982 constituted about 11% of the acreage of certified hard red winter wheat seed produced that year (2).

MATERIALS AND METHODS

Cultural practices. Studies were conducted in the field during the 1982 and 1983 growing seasons. Soils in the experimental field are Hapludalfs in the Collamer and Niagara series and described as silt loams (3). Cultural practices employed during both years were similar. Seed of Vona was planted with a drill in late summer at a rate of 100–112 $kg \cdot ha^{-1}$ in rows 17.5 cm apart and banded with 10-20-20 (NPK) fertilizer at about 280 $kg \cdot ha^{-1}$. In the spring, the field was top-dressed with ammonium nitrate at about 120 $kg \cdot ha^{-1}$. Plant density ranged from 120 to 170 tillers per meter-row. During both years of the study, the field was sprayed with dinocap (Karathane) in May to control powdery mildew (*Erysiphe graminis*).

Pollutant treatments and monitoring. In both years of the study, plants placed in open-top chambers were exposed to controlled levels of pollutants. The design of the open-top chambers followed that described by Heagle et al (4), and the methods of distributing and monitoring the pollutants were similar to those presented by Heagle et al (5). In 1982, 24 plots were selected on the basis of uniform stand density, and soil conditions and treatments were randomly assigned to six plots in four blocks. The five O_3 treatments in open-top chambers were charcoal-filtered air (CF), nonfiltered air (NF), and NF to which 0.03, 0.06, or 0.09 ppm O_3 was added (NF + 0.03, NF + 0.06, and NF + 0.09, respectively). An ambient plot not enclosed by an open-top chamber was also included in each block. The addition of O_3 was initiated on 18 May, as the tightly rolled flag leaf was emerging, and terminated on 17 July, after the kernels were fully ripe and the straw dead. All plots were harvested on 22 July. Ozone was added daily for 7 hr (1000–1500 hours EDT) except when precluded by rain or technical difficulties. To facilitate dew formation within the chambers, chamber fans were turned off between 2300 and 0500 hours EDT.

The 1983 experiment evaluated the effects of O_3 and SO_2, both alone and in combination, on yield. Four levels of O_3 and four levels of SO_2 were provided in open-top chambers and replicated. The four O_3 treatments in the open-top chambers were CF, NF, and NF in which the O_3 levels were maintained at 1.4 and 1.8 times the ambient concentration by adding O_3. In contrast to the experiment in 1982, the concentrations of the O_3 additions were not constant but varied as the ambient concentration of O_3 changed. A custom-built electronic controller, directed by an ambient O_3 monitor, was used to alter the output of the O_3 generator and produce the proportional additions. The duration and time period for the O_3 additions and the still air period at night were the same as in 1982. The four SO_2 treatments in the chambers were NF and NF to which 0.10, 0.30, and 0.60 ppm SO_2 were added. The SO_2 additions were 4 hr in duration and conducted three times each week (minor variations in exposure duration and frequency occurred because of weather conditions and equipment problems). Ambient plots that were not enclosed by chambers constituted a fifth treatment for both O_3 and SO_2. The 4×4 factorial experiment was conducted in two randomized complete blocks.

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TABLE 1. Treatment-level concentrations of O_3 (ppm) and the number of hours exceeding the concentrations associated with the past and present National Ambient Air Quality Standards for O_3 for exposures in winter wheat studies at Ithaca, NY, in 1982 and 1983

Year	Treatment	7-hr Average	Maximum 7-hr	Average daily 1-hr max.	Maximum 1-hr	Hours >0.08	Hours >0.12
1982	Filtered	0.022	0.042	0.038	0.074	0	0
	Ambient	0.044	0.074	0.054	0.088	2	0
	Nonfiltered	0.042	0.079	0.054	0.088	5	0
	Nonfiltered + 0.03	0.062	0.098	0.074	0.109	109	0
	Nonfiltered + 0.06	0.082	0.128	0.094	0.146	256	42
	Nonfiltered + 0.09	0.096	0.161	0.118	0.180	309	186
1983	Filtered	0.027	0.068	0.044	0.076	0	0
	Ambient	0.057	0.118	0.069	0.128	55	5
	Nonfiltered	0.054	0.096	0.068	0.116	54	0
	1.4 × Ambient	0.076	0.150	0.093	0.153	122	23
	1.8 × Ambient	0.096	0.168	0.121	0.199	182	76

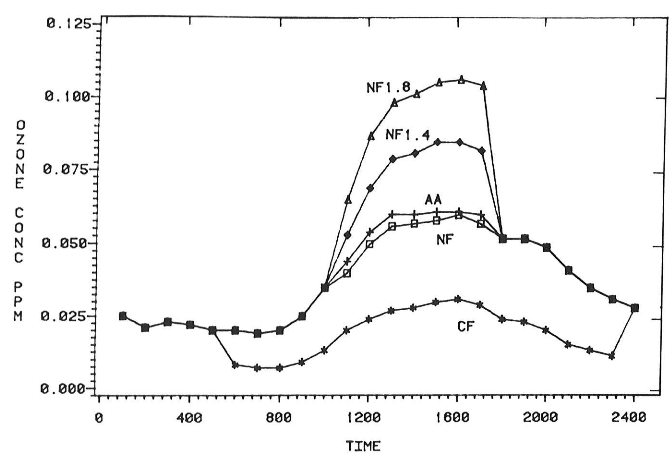

Fig. 1. Diurnal pattern of concentrations of O_3 for each treatment during the exposure period in the 1983 winter wheat study at Ithaca, NY.

In 1983, O_3 exposures were initiated on 12 June and terminated on 17 July. At the time exposures to O_3 began, the heads were about three-quarters emerged and flowering had not started. Exposures to SO_2 were initiated on 22 June and terminated on 15 July. Flowering was completed when the SO_2 treatments began. The kernels were fully ripe when the exposures were terminated and all plots were harvested on 18 and 19 July.

Ozone was produced from oxygen with a Griffin Model 1A generator (Griffin Corp., Lodi, NJ), and individual Aalborg Model FM 112-02 flow meters (Aalborg Instruments, Monsey, NY) controlled the distribution of the pollutant to each chamber. Ozone monitoring was conducted with Monitor Labs Model 8410 instruments (Monitor Labs Inc., San Diego, CA). Sulfur dioxide was produced from a tank of anhydrous SO_2 and metered into a manifold with a Brooks Model 5850 mass flow controller (Brooks Instruments, Hatfield, PA). Distribution to the chambers was regulated with individual Aalborg Model FM 102-05 flow meters (Aalborg Instruments and Controls Inc., Monsey, NY). Monitoring was conducted with TECO Model 43 SO_2 analyzers (Thermo Electron Corp., Hopkinton, MA). Monitoring for both pollutants in each chamber was conducted on a time-sharing basis with an automated sequential sampling system. Each observation lasted 2 min, and the chambers were sampled two or three times each hour. The sample stream was split after passing through the sequencing valve and entered the O_3 and SO_2 monitors. Trials of the split-stream system showed no influence of one instrument on the efficiency or functioning of the other. In 1982, only O_3 was monitored in the chambers and the sample stream was not split. All sample lines were FEP Teflon. The efficiency of each sampling line was determined twice during the study and taken into account during exposure and subsequent reduction of monitoring data. Monitoring data were recorded with an HP Model 85 computer and an HP Model 3497A data acquistion unit (Hewlett-Packard, Palo Alto, CA) with strip-chart backup.

Determination of yield. Two 1-m row sections were harvested from each of the two center rows of each plot. Plants were cut near the soil surface, and the heads were separated from the stems and counted. The heads and straw were dried at 75–80 C for 48 hr and weighed separately. The heads were threshed and the dry weight of grain measured. Dry weights of 100-seed lots of grain were determined as indices of seed size. The moisture content of the grain after drying was about 10%. Data were evaluated using analysis of variance. Dose-response functions for yield were determined by regression analysis using linear, quadratic, and Weibull models. Regardless of whether a linear or quadratic model provided an adequate fit to the data, NCLAN analytical procedures stipulate that the Weibull model also be used so that response functions will be presented in a consistent format for comparison (7).

RESULTS

Pollutant treatments and monitoring. Data characterizing the O_3 exposure regimes for each treatment in 1982 and 1983 are presented in Table 1. During the 61-day exposure period in 1982, there were 8 days on which O_3 was not added because of rain or technical difficulties. In 1983, there were 2 days during the 36-day period on which O_3 was not added. The 7-hr seasonal average concentrations of O_3 show good agreement between ambient and NF treatments. The data also indicate that CF treatment reduced the O_3 level to about 50% of that in the NF treatment. In both years, the O_3 additions produced distinct treatment levels (Table 1). The two highest O_3-addition treatments resulted in relatively high single-event concentrations of O_3 and numerous occasions when the 1-hr average concentrations of 0.08 and 0.12 ppm associated with the initial and revised air quality standard for O_3 were exceeded.

The diurnal pattern of the average hourly concentrations of O_3 in 1983 for each treatment during the exposure period is presented in Figure 1. The effect of the proportional controller in producing O_3 additions that are multiples of the ambient concentration is evident at the beginning of the daily exposure period; however, termination of the exposure produced a rapid decrease in the concentration of O_3 in the pollutant-added treatments.

Ambient O_3 concentrations were quite different during the 2 yr of the study. In 1982, the maximum 1-hr concentration of O_3 was 0.088 ppm with five hourly averages above 0.08 ppm and none above 0.12 ppm. In contrast, the maximum 1-hr concentration of O_3 in 1983 was 0.128 ppm and was accompanied by 55 hourly averages above 0.08 ppm and five above 0.12 ppm.

In 1983, SO_2 exposures were conducted on 12 days during the 36-day period. The average concentrations for each treatment were somewhat below the target values but produced distinct levels as the exposure regime characteristics indicate (Table 2). Ambient SO_2 was extremely low, with detectable levels (>0.005 ppm) occurring in only 50 hr of the 864-hr study period. The maximum 1-hr ambient SO_2 concentration monitored was 0.025 ppm. As a result of these low levels of SO_2, the ambient and NF treatment concentrations were essentially zero.

Determination of yield. Data collected at harvest in 1982 included the number of heads and dry weights for straw, heads, grain, and 100-seed lots (Table 3). Analysis of variance indicated that effects of treatments were significant for all harvest variables except number of heads (Table 4). Comparisons of the percent reductions in seed dry weight and 100-seed weight for each treatment show that they are similar, indicating that the primary effect of O_3 was on size rather than number of seeds. Regression analyses were conducted using quadratic and Weibull models to characterize relationships between yield and the seasonal 7-hr concentrations of O_3. Plot-level yield and O_3 data were used in the analyses. Dose-response functions for winter wheat exposed to O_3 at Ithaca, NY, in 1982 and 1983 are as follows (yield in $kg \cdot ha^{-1}$ and O_3 exposure is 7-hr average in ppm):

1982: Quadratic

$$\text{Yield} = 7{,}703.0 - 124{,}928.5\,(O_3) + 614{,}582.7\,(O_3)^2$$

Weibull

$$\text{Yield} = 9{,}103.82 \exp - (O_3/0.04)^{0.853}$$

1983: Linear

$$\text{Yield} = 5{,}393.2 - 31{,}808\,(O_3)$$

Weibull

$$\text{Yield} = 4{,}420.38 \exp - (O_3/0.109)^{2.735}.$$

Analysis of the harvest data for 1983 indicated that only O_3 had a significant effect on yield; the effects of SO_2 and $O_3 \times SO_2$ were not significant (Table 5). Examination of the treatment-level yield values (Table 6) illustrates the reduction attributable to O_3 and the lack of an SO_2-induced effect. Because there were no significant SO_2 or $O_3 \times SO_2$ interaction effects, the 7-hr average concentrations of O_3 for each plot were used with the linear and Weibull models to produce dose-response functions.

TABLE 2. Treatment-level concentrations of SO_2 (ppm) for exposures of winter wheat at Ithaca, NY, in 1983[a]

Treatment	4-hr Fumigation average	Max. 1-hr	Average fumigation 1-hr max.	Peak:mean ratio
Ambient	0.000	0.025	0.000	···
Nonfiltered	0.000	0.025	0.000	···
Nonfiltered + 0.10	0.039	0.069	0.051	1.3
Nonfiltered + 0.30	0.166	0.266	0.196	1.2
Nonfiltered + 0.60	0.363	0.509	0.428	1.2

[a]Data are for fumigation days only.

DISCUSSION

The response of Vona wheat in 1982 indicated that it was highly sensitive to O_3. Compared with the CF treatment at 0.022 ppm, yield reductions from expected yield ranged from 33% in the NF treatment (0.042 ppm) to 73% in the highest O_3 addition (0.104 ppm). The 33% reduction at 0.042 ppm was particularly striking, because Heagle et al (6) found the soft red winter wheat cultivar Holly required a much higher exposure to achieve the same reduction: 0.13 ppm O_3 for 7 hr/day for about 1 mo.

In 1983, the O_3-induced reductions from expected yield for Vona were less than those measured in 1982. The dose-response curve in 1982 was concave and had a Weibull distribution with an estimate of 0.853 for the C parameter, whereas in 1983, the curve was slightly convex with an estimate of 2.735 for the C parameter (Fig. 2). Similarly, the best regression for the 1982 dose-response data was a quadratic function, whereas a linear function fit the 1983 data. The change in the shape of the dose-response curve is not readily explainable, although two factors deserve comment: First, the exposure period in 1983 was 25 days shorter than that in 1982 because of the expansion of the exposure facilities to include SO_2. Although exposures to O_3 were initiated before heading was completed and continued through grain maturation, the earlier period of vegetative growth occurred in the absence of charcoal filtration or O_3 additions. Second, precipitation during May and

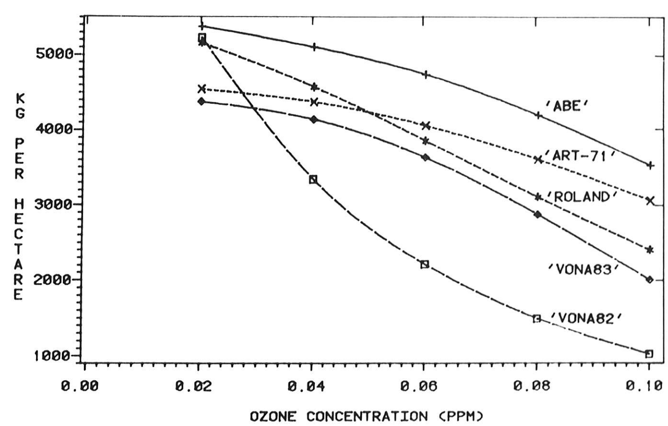

Fig. 2. Dose-response curves for the effects of O_3 on yield of winter wheat for three cultivars (Abe, Arthur-71, and Roland) evaluated in studies at Argonne National Laboratory in 1982 and Vona used in studies at Ithaca, NY, in 1982 and 1983. Curves were produced using the Weibull function.

TABLE 3. Measures of yield of winter wheat exposed to O_3 in 1982

Treatment	Straw wt ($g \cdot m\text{-}row^{-1}$)	Head wt ($g \cdot m\text{-}row^{-1}$)	Number of heads	Seed weight $kg \cdot ha^{-1}$	Seed weight % Loss	100-Seed weight g	100-Seed weight % Loss
Filtered	70.7	118.5	124.3	5,331.0	···	3.26	···
Ambient	71.5	96.5	137.8	4,049.8	24	2.32	29
Nonfiltered	60.0	84.2	111.9	3,552.1	33	2.47	24
Nonfiltered + 0.03	64.3	72.0	115.1	2,322.3	56	1.77	46
Nonfiltered + 0.06	51.3	46.3	117.4	1,698.8	68	1.41	57
Nonfiltered + 0.09	43.4	38.8	100.0	1,430.0	73	1.30	69

TABLE 4. Analysis of variance for measures of yield in the winter wheat study conducted with O_3 in 1982[a]

Source of variation	df	Mean squares: Straw wt	Head wt	Head no.	Seed wt	100-Seed wt
Block	3	1,087.8	2,089.2	656.0	559.4	0.12
Treatment	4	1,843.1*	16,277.8**	1,271.4	12,550.7**	10.69**
Linear	1	6,481.1**	61,781.4**	3,035.2	44,863.4**	38.92**
Quadratic	1	111.1	2,433.9*	139.8	5,294.2**	3.77**
Cubic	1	96.4	5.6	1,909.2	23.0	0.03
Treat × block	12	300.9	473.3	1,231.9	239.8	0.18

[a]F values determined by the ratio of the block or treatment mean square to the treatment × block (error) mean square. * = $P(\text{value} > F\text{critical}) = 0.05$ and ** = $P(\text{value} > F\text{critical}) = 0.01$.

TABLE 5. Analysis of variance of grain yield data for winter wheat exposed to O_3 in 1983

Source of variation	df	Sum of squares	Mean source	F
Block	1	8,070.5	8,070.5	0.02
O_3	3	23,400,789.6	7,800,263.2	18.29**[a]
SO_2	3	246,285.2	82,095.1	0.19
$O_3 \times SO_2$	9	6,476,453.8	719,605.9	1.69
Error	15	6,395,611.2	426,374.1	

[a]** = Significant $P = 0.01$.

TABLE 6. Treatment-level yields of grain ($kg \cdot ha^{-1}$) for winter wheat exposed to O_3 and SO_2, alone and in combination, in open-top chambers at Ithaca, NY, in 1983

Sulfur dioxide	Ozone (7-hr av. ppm)				
(4-hr average ppm)	0.027	0.057	0.076	0.096	Mean
0.000	4,893	3,834	2,789	2,041	3,389
0.039	3,411	4,359	3,569	2,500	3,460
0.166	4,559	3,872	2,036	2,089	3,139
0.363	4,577	3,464	2,879	2,582	3,379
Mean	4,360	3,882	2,818	2,303	

June of the 1983 growing season was less than in 1982: 13.36 vs. 22.35 cm (10,11). This decrease was probably an important factor in reducing the yield in the CF treatment from 5,331 $kg \cdot ha^{-1}$ in 1982 to 4,360 $kg \cdot ha^{-1}$ in 1983, even though the concentrations of O_3 were similar for both years. Plants exposed to O_3 under conditions of reduced soil moisture show a greater degree of stomatal closure than do plants exposed under well-watered conditions (12,13). The response limits the uptake of O_3 by the moisture-stressed plants. The differences in the dose-response curves in these studies may be largely the result of the effects of soil moisture on limiting plant growth and yield and on reducing the uptake of O_3 during exposure. The dose-response curve for Vona in 1983 is similar to those produced for other cultivars at Argonne National Laboratory (Fig. 2); however, Vona appears to be more sensitive to O_3 than the cultivars Abe, Arthur-71, and Roland used in that study (8).

Sulfur dioxide, either alone or in combination with O_3, had no effect on yield. The SO_2 exposures were initiated after flowering and could only affect seed fill but not seed set or vegetative growth. It is possible that SO_2 would have influenced yield if exposures had been initiated earlier. The absence of reduction in yield of wheat in response to exposure to SO_2 is consistent with the limited information available in the literature (15,16). The highest SO_2 treatment level, 12 4-hr exposures at an average concentration of 0.363 ppm, represents a series of fumigations that is greater than the maximum exposures expected to occur in the vicinity of a modern coal-fired power plant.

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