Open-Air Fumigation System for Investigating Sulfur Dioxide Effects on Crops

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ABSTRACT

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An open-air fumigation system for treating large field plots of crop plants with sulfur dioxide (SO_2) has been designed and tested. The fumigation system consists of an array of pipes suspended over the field plots through which SO_2 gas is released at controlled rates. The data from 2 yr experiments (three plots in 1977 and five in 1978) were examined for temporal and spatial variations in SO_2 concentrations. The SO_2 concentrations in the plots fluctuated with time due to changing wind speed and turbulence, although the SO_2 concentrations could be controlled within given ranges by adjustment of the SO_2 release rates. This fluctuation in SO_2 concentrations resembled that occurring near point sources of pollution. Statistical analysis indicated that the SO_2 concentrations (1-min averages) were neither normally nor log-normally distributed, and generally appeared to be intermediate between the two. Effects of spatial differences in SO_2 concentrations in the plots were minimized by locating the experimental subplots centrally in each fumigation system. The technique is discussed with regard to its suitability for air pollutant-crop effects studies.

Additional key words: soybeans, air pollution effects.

Projected increases in coal-fired electrical power generation have caused renewed concern regarding the impact of sulfur dioxide (SO_2) emissions on agricultural productivity. Although numerous studies have related elevated SO_2 concentrations to plant injury and growth reductions, little of the available data can be used to define SO_2 concentrations that cause economically significant yield reductions. To date, most experimental work of this kind has been carried out in laboratory or greenhouse growth chambers where it is difficult to grow most common crop plants to harvest maturity. As a result, the effects of SO_2 at the seedling and early vegetative stages have been emphasized. These results usually cannot be related to yield, especially in grain crops, since the plants often compensate for injury that occurs early in their life cycles and do not exhibit significant yield reductions at harvest. In addition, pollutant-plant interactions in most growth chambers or greenhouses should not be used to predict field behavior, since the rate of pollutant uptake and the sensitivity of the plants to the pollutant are likely to be different than they would be in the field.

Field studies of air pollutant effects on crop yield have been conducted in a variety of field chambers (eg, 2–5,11,14). While these studies are more relevant to estimates of yield reductions or crop damage due to ambient pollutant episodes, there are still certain unresolved questions concerning field chamber effects on plant growth, sensitivity to the pollutant, and the rate of pollutant uptake. Such factors as temperature, relative humidity, solar radiation, and wind speed, all of which may be affected by chambers, can modify plant responses to a given pollutant concentration (1,6,7,13). Recent improvements in chamber design, and in particular the development of improved open-top chambers, have resulted in a more natural environment for plant growth during exposures to pollutants. But even in the improved open-top chambers there are measurable differences in environmental parameters such as light and temperature which apparently may result in altered plant growth (4). The characteristics of the air flow and turbulence are also different in the open-top chambers than under ambient conditions since the air is introduced at a steady rate and the flow generally is upward through the chambers. In some cases, investigators have used movable field chambers, which were in place only during actual fumigation of the plants (2). While this reduces the chamber effect on growth, the problem of environmental modification during exposure to the pollutant remains. For example, Ashenden and Mansfield (1) found that the growth of S23 ryegrass was reduced by 0.11 ppm SO_2 at a wind speed of 25 m min^{-1} but not at 10 m min^{-1}. This was attributed to differences in leaf boundary layer resistance at the two wind speeds affecting the rate of pollutant uptake and clearly illustrates the importance of environment during exposure to pollutants.

In view of the problems inherent in the interpretation of results obtained from growth chamber and field chamber studies, an open-air field fumigation technique similar to that described by Lee et al (10) was developed for use with crop species. The technique was tested in a soybean field in 1977 and 1978, and this report describes its performance and evaluates its suitability for field studies of SO_2 effects on crops. Another article in this journal deals with the effects of the fumigations on soybean seed yield and quality (12).

MATERIALS AND METHODS

Description of the open-air fumigation technique. The open-air fumigation technique utilizes arrays of pipes (fumigation systems) suspended over the plant canopy, through which diluted SO_2 is released at controlled rates to the experimental plots. This treatment technique is similar in concept and construction to the Zonal Air Pollution System (ZAPS) used by Lee et al (10), but differs in that the individual fumigation systems are smaller and the pipes are arranged in a parallel fashion which allow the system to be more easily used with row crops. In 1977 each fumigation system consisted of five 29-m sections of release pipes extending at 6.7-m intervals from a 27-m baseline pipe (Fig. 1). In 1978 only three release pipes were used, corresponding to the three southernmost pipes illustrated in Fig. 1. The release pipes were drilled with 0.08-cm holes at 0.76-m intervals on alternating sides of the pipe and oriented as nearly horizontal as possible when the system was assembled in the field. The baseline pipe was not drilled and served only as a delivery line for the release pipes. The pipe used in the construction of the fumigation systems was 2.54-cm (1-inch) inside diameter, threaded, schedule 40 aluminum with aluminum elbows and couplings. Each system was suspended approximately 30 cm above the plant canopy by attaching the pipes to metal fence posts which were placed in the ground. The connectors used for attaching the pipe to the fence posts allowed the pipe to be raised as the plants increased in height.

Field site. The site of the 1977 studies was a 4-ha section of a soybean (*Glycine max* [L.] Merr. 'Wells') field in Kendall County, Illinois. The site was virtually flat and the soil was a relatively uniform Martinton silt loam. Further details concerning the site and crop are given elsewhere (12).

Yield subplots. In 1977 four yield subplots, each consisting of four 6.1-m rows (1-m row spacing) were located centrally in the fumigation systems since preliminary experiments indicated this to be the area of maximum spatial uniformity of SO_2 concentrations (Fig. 1). Control subplots were located about 10 m west of each fumigated system and fumigations were not conducted during easterly winds to prevent their fumigation.

In 1978 the treated subplots again were located as shown in Fig. 1, but the two northernmost pipes in the diagram were eliminated. The control subplots were located to the south of the fumigation systems. These changes were made since it was decided to fumigate only on days having southerly winds which are predominant in the study area; thus, the two northernmost pipes were superfluous. In both years the fumigation systems were placed at least 40 m apart in the field to prevent control subplots from being affected by the adjacent systems. Further details concerning the yield subplots may be found elswhere (12).

Delivery and measurement of SO_2. Bottled anhydrous SO_2 was used as the SO_2 source and was introduced into the SO_2 delivery pipes downstream from the compressors (Fuji Model UFC 201P) in the SO_2 delivery sheds (Fig. 1). The flow rate of the SO_2 was regulated by means of adjustable rotameters (Matheson Model 7642T). As a safety feature, a solenoid valve was placed between the pressure regulator on the SO_2 tank and the rotameters. This valve was indirectly controlled by the SO_2 monitor in the field trailer through a relay switch which closed the solenoid valve if the SO_2 concentration exceeded a set level. Since the valve was open only when energized, the SO_2 flow also stopped if electrical failure occurred. These features insured that the field plots were not exposed to excessively high SO_2 concentrations.

Sampling and measurement of SO_2. The SO_2 concentrations in the center of the yield subplots (Fig. 1) were monitored by pumping air from near the top of the soybean canopy through 0.635-cm (¼-inch) I.D. polyethylene tubing to the field trailer with a vacuum pump. All of the sample lines were continuously pumped and sequentially diverted to the SO_2 monitors (Thermoelectron Model 43, Meloy S160A and Meloy S285A) by a timer-controlled electrical sequencer in conjunction with three-way solenoid valves. (Details of the design are available from the senior author.) Each of the four SO_2 sampling points in each plot was monitored for 2 min every 16 min and thus each plot was monitored one-half of the time. Tests indicated that the time required to transport an air sample from the most distant plot to the field trailer was less than 45 sec and sorption of SO_2 in the sample lines and loss through the lines was less than 5%. Before starting the SO_2 measurements on each day, the flow through the sample lines was reversed for an hour or more to evaporate any condensation in the sample lines.

The average SO_2 concentrations from the last minute of each 2-min monitoring period were used for computing mean SO_2 exposures. Arithmetic means ($\bar{x}$), geometric means ($\bar{x}_g$), and standard geometric deviations (S_g) were calculated for each fumigation, and for all fumigations combined for each monitor location. The $\bar{x}_g$ and S_g were calculated as

$$\bar{x}_g = \exp\left(\frac{1}{n}\sum_{1}^{n} \ln x_i\right)$$

$$S_g = \exp\left(\left[\frac{1}{n-1}\left(\sum_{1}^{n} (\ln x_i)^2 - \frac{1}{n}\left(\sum_{1}^{n} \ln x_i\right)^2\right)\right]^{1/2}\right)$$

where the x_i's are individual 1-minute readings.

Fumigations. In 1977, between 13 July and 24 August, 24 fumigations were performed with three fumigation systems for an average of 4 hr-44 min with minimum and maximum durations of 3 hr-0 min and 6 hr-40 min. In 1978 there were 18 fumigations with five fumigation systems between 19 July and 27 August, ranging from 1 hr-3 min to 6 hr-10 min, for an average of 4 hr-10 min. Fumigations were not administered for uniform time periods nor at set intervals because they depended on suitable meteorological conditions, although they always were conducted between 0900 and 1600 hours CST. Fumigations were not performed under conditions when the SO_2 would impact the control yield subplots, so in 1978 the winds had to be generally southerly while in 1977 they had to be southerly or northerly. Also, the fumigations were not started until the dew had evaporated from the leaf surfaces in the morning, and were terminated in case of rain to prevent SO_2 sorption on the wet plant surfaces which might result in acid-burn of the tissues.

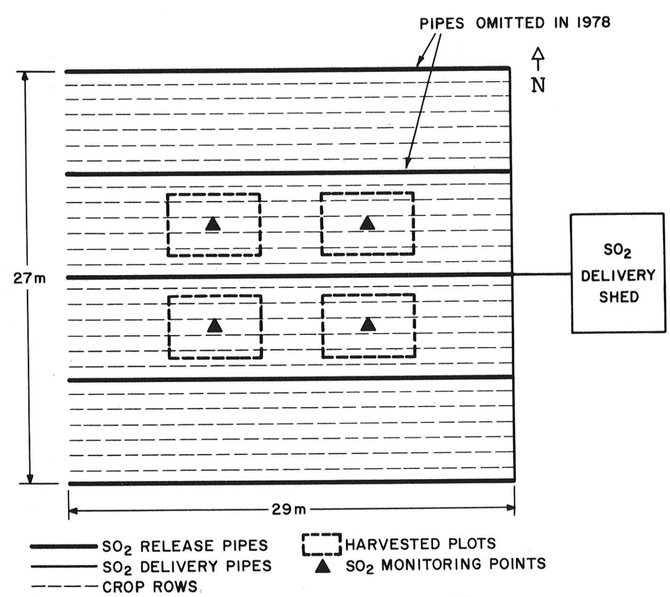

Fig. 1. Schematic diagram of an open-air fumigation system used for SO_2 treatment of soybeans.

RESULTS AND DISCUSSION

Temporal fluctuations in SO_2 concentrations. The arithmetic mean SO_2 concentrations ($\bar{x}$) obtained in the treated plots during fumigation periods were 0.12, 0.30, and 0.79 ppm in 1977 and 0.09, 0.10, 0.19, 0.25, and 0.36 ppm in 1978 (Table 1). As expected, the SO_2 concentrations continually fluctuated during fumigations due to normal changes in wind speed and turbulence over the plant canopy. This temporal fluctuation in SO_2 concentrations in the treated plots appears to be similar to that of actual SO_2 fumigation episodes, as illustrated by comparison to data obtained near a point source (Fig. 2). This characteristic of the open-air fumigation system is therefore a positive feature if the purpose is to acquire information on SO_2 effects under conditions closely simulating actual SO_2 fumigation events. More extensive fluctuations of concentrations would have occurred on days when wind speeds changed substantially, but in such cases the SO_2 flow rates were adjusted to prevent excessively high peaks and to maintain the SO_2 concentrations within the desired ranges.

Because the SO_2 concentrations in the fumigated plots are highly variable, unlike those in most fumigation chamber experiments, mean SO_2 concentrations alone do not adequately characterize the fumigation regimes. Since it is widely believed that occasional extreme SO_2 concentrations may be more damaging to plants than prolonged exposure to low levels, some parameter expressing the magnitude, frequency, and duration of fluctuations is required to completely describe the experimental treatments and to permit comparison with other experiments and with ambient pollution regimes.

Frequency distributions, as illustrated for two of the 1977 plots

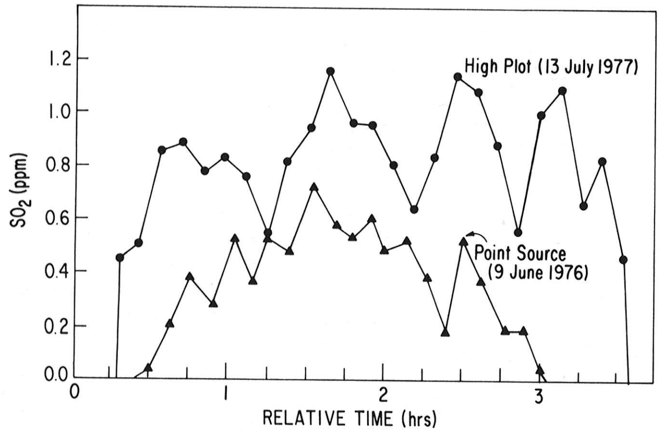

Fig. 2. SO_2 concentration versus time in the high-SO_2 plot (13 July 1977) and 3 km from a point source of SO_2 (9 June 1976).

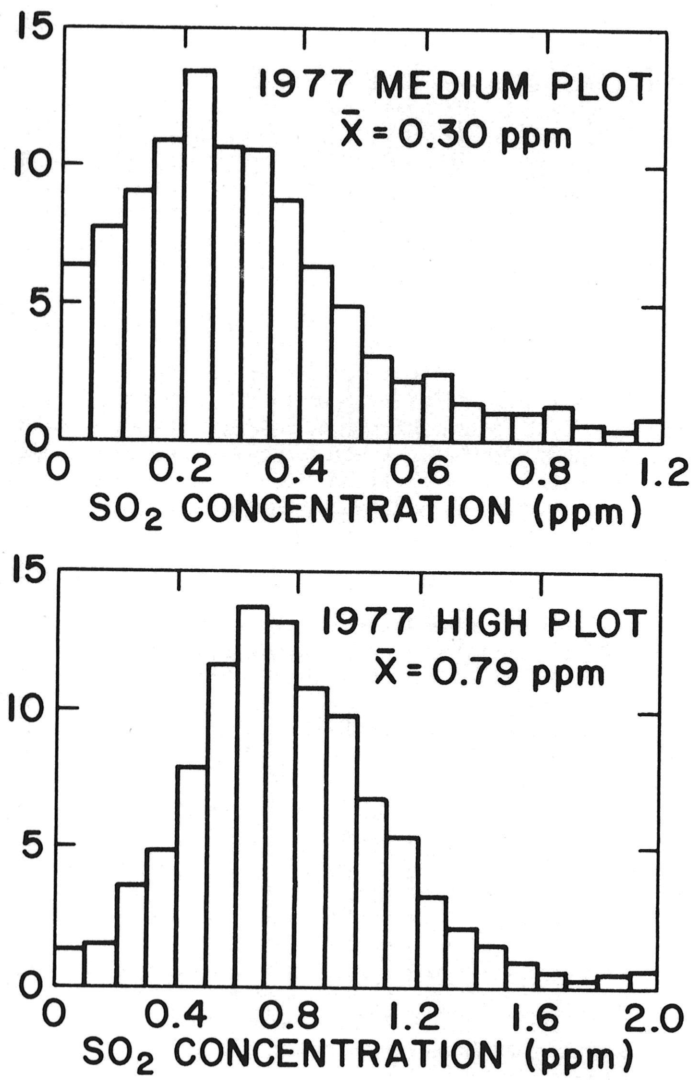

Fig. 3. Frequency distributions of SO_2 concentrations during fumigation periods in the 1977 medium and high-SO_2 plots. All monitoring locations within a plot were combined.

(Fig. 3), provide a useful and complete description of the fumigation concentrations. It can be seen that the shape of the distributions varied somewhat between plots, largely due to differences in the degree of control of the SO_2 concentrations that was attempted. In 1977 the SO_2 concentrations in the low and medium plots were not extensively adjusted during the fumigations and the frequency distributions were strongly skewed, with a relative excess of very high concentrations compared to a normal distribution. The 1977 high plot was controlled to prevent excessively high concentrations and thus the frequency distribution was less skewed. In 1978 an attempt was made to prevent the SO_2 concentrations from exceeding certain limits in all plots and in most cases the skewing was less pronounced.

Although frequency distributions provide a very complete characterization of the fumigation regime, they are rather unwieldy and are not readily adaptable for comparisons between experiments. It would be convenient if one of two parameters could be used to convey the important characteristics of a fumigation in the same way that the mean and standard deviation convey the critical information from a normally distributed variable. With ambient air pollution monitoring data, statistics appropriate to a log-normally distributed variable (eg, geometric mean and standard geometric deviation) are commonly used to characterize the pollutant concentration (8), although it has been pointed out that the data often are not actually log-normally distributed (9). To determine if either log-normal or normal statistics could be used to express the fluctuations in the experimental plot SO_2 concentrations, log-normal and normal distributions were generated by using the experimental plot means, standard deviations (S), and standard geometric deviations (S_g) listed in Table 1. A chi-square goodness-of-fit test of the experimental plot data to the log-normal and normal distributions rejected the hypothesis of log-normality or normality with 99.5% confidence in all cases. Thus, statistics assuming either distribution may not be strictly applied to the experimental fumigation data. However, in the plots in which the SO_2 concentrations were not extensively regulated the frequency distributions did more closely resemble log-normal distributions, so that for these plots the $\bar{x}_g$ and S_g convey most of the important information about the fumigation regime. Previous studies by Lee et al (10) who used a similar type of fumigation technique did result in a distribution of SO_2 concentrations that approached log-normality. This is probably due to the fact that they released the gas continuously and did not attempt to maintain the concentrations within a given range, resulting in concentration patterns more comparable to ambient conditions.

No completely satisfactory parameter for describing the variation in the field plot pollutant concentrations has been found. One parameter which may be useful, and which makes no assumptions about the distribution of the data, is the percentage of time during the fumigations that the concentrations exceed some multiple of the mean. This value is especially relevant if one assumes the higher concentrations to be the most damaging to the plants rather than the mean exposure concentrations. A value of two and one-half times the mean was arbitrarily selected for the experimental plot concentration data and is presented in Table 1. While this information has not been published for other experiments or for ambient monitoring data, it can easily be calculated if the data have some definable distribution. For example, values of a normally distributed variable with coefficient of variation equal to 50 would exceed two and one-half times the mean 0.14% of the time, while a log-normally distributed variable with $S_g = 2.0$ would exceed this level 4.8% of the time.

The mean SO_2 concentrations obtained in the individual plots also varied from day to day as shown for the 1978 data in Fig. 4. While the gas release rates were adjusted depending on the conditions, the days having brisk winds generally had the lowest SO_2 concentrations. With light and intermittent winds the higher concentrations were obtained. Greater uniformity of the means could be obtained by constant attention to the gas release rates, although the day to day variation does more closely simulate actual SO_2 pollution.

Spatial variations in SO_2 concentrations. In addition to the observed fluctuations of SO_2 concentrations with time, horizontal concentration gradients within the individual treatment plots also occurred. The northeast yield subplots generally had higher mean SO_2 concentrations than those to the southeast, undoubtedly because most of the fumigations were conducted with winds from the southwest quadrant resulting in a buildup of SO_2 to the northeast. However, these concentration differences averaged over all fumigations were only about 18% at most and did not result in significant yield differences between the subplots (12). Thus, the concentration differences between individual subplots are probably not a serious drawback to the open-air fumigation technique, especially since the concentration differences are known.

To determine if significant spatial variations in SO_2 concentrations occurred horizontally within individual subplots, concentrations were monitored for several days at four locations on a perpendicular line between two of the SO_2 release pipes within a yield subplot. While the SO_2 concentrations were sharply elevated at the buffer row immediately downwind of the pipe, the daily mean SO_2 concentrations differed by only 5–10% across the four rows of the yield subplot. This indicates that a single monitor located in the center of a subplot gave a reasonable representation of the exposure history of that subplot. Preliminary experiments indicated relatively uniform SO_2 concentrations in a line parallel to the pipes within the area of a single subplot if the fumigation was conducted with NE to NW or SE to SW wind directions. However, with E or W winds the SO_2 dispersed down the pipelines and did not uniformly impact the subplots, so fumigations were not performed under these conditions.

To determine if the SO_2 was penetrating into the canopy after being released from the pipes, the SO_2 concentrations were monitored at four heights from the surface of the canopy to ground level when the plants were fully grown. The mean SO_2 concentrations were highest at the canopy surface and dropped only 15% halfway down the canopy. The SO_2 concentrations were approximately 34% less at 10 cm from ground level. Thus, the SO_2 readily penetrated the canopy and it is apparent that monitoring SO_2 concentrations at the surface of the canopy satisfactorily represented the exposure history of the upper half of the canopy, which includes the most physiologically-active portion of the plants. The vertical gradient in SO_2 concentrations was not appreciably different with wind speeds between 2 and 10 $m \cdot sec^{-1}$.

SUMMARY

The open-air fumigation technique embodies several important features which contribute to its value in experimental field studies of plant-SO_2 interactions. The experimental plants are grown under typical agricultural practice and the microenvironment of the plants is minimally altered by the SO_2 delivery system, as evidenced by the lack of yield alteration in piped but unfumigated control plots (12). This eliminates possible chamber effects on pollutant uptake rates and the problems of interpretation of data from experiments with plants that may differ physiologically and morphologically from field grown plants because of the growth conditions. In addition, the SO_2 concentrations exhibit the

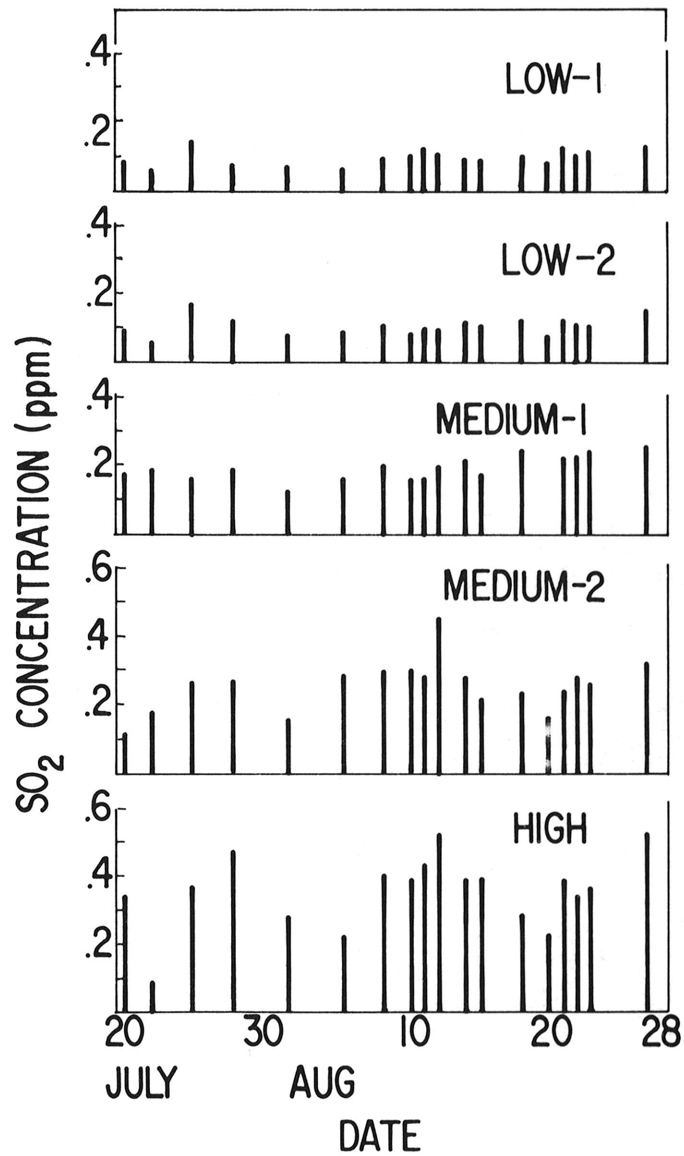

Fig. 4. Daily mean SO_2 concentrations during fumigation in all SO_2-treated plots in 1978.

TABLE 1. Characteristics of SO_2 fumigations with an open-air fumigation system in 1977 and 1978

Year/Plot[a]	Fumigations (no.)	Average duration (hr-min)	Arithmetic mean (ppm)[b]	Standard deviation[b]	Geometric mean (ppm)[b]	Standard geometric deviation[b]	Time $\geqslant 2.5 \cdot \bar{x}$ (%)[c]
1977	24	4-44					
Low			0.12	0.07	0.09	2.09	1.6
Medium			0.30	0.19	0.24	2.22	3.4
High			0.79	0.33	0.71	1.71	0.3
1978	18	4-10					
Low 1			0.09	0.05	0.08	1.73	0.3
Low 2			0.10	0.05	0.10	1.67	1.1
Medium 1			0.19	0.08	0.17	1.75	0.9
Medium 2			0.25	0.14	0.22	1.85	0.3
High			0.36	0.19	0.30	2.06	0.2

[a] The fumigations were performed between 13 July and 19 August in 1977 and between 19 July and 27 August in 1978.
[b] Values include all monitor locations within a plot.
[c] Values are the percent of time the SO_2 concentrations exceeded 2.5 times the arithmetic mean.

continual fluctuations that are characteristic of actual SO_2 pollution episodes. These fluctuations can be controlled to some extent by adjustment of the SO_2 flow rates into the delivery system, and thus the SO_2 concentrations can be maintained within specified concentration ranges.

Characterization of the SO_2 fumigation concentrations is more difficult than with previous studies, since the fluctuations in SO_2 concentrations and the periodicity of the treatments must be described. Frequency distributions in conjunction with the average duration and dates of exposure adequately characterize the fumigation history, although these are difficult to convey in a limited space and thus are less useful when reporting large volumes of data. The distribution of the data does not strictly lend itself to the use of normal or log-normal statistics for description of the SO_2 concentration variability. However, plant response to a given SO_2 treatment often will be quite variable since it is extensively modified by many factors and it is probably acceptable to report the mean concentrations and either the S_g or S along with some indication of the frequency and duration of exposures.

The open-air fumigation technique is not readily adaptable to studies in which control of environmental variables is essential. Two exceptions might be soil moisture and soil nutrition, in which cases irrigation and differential soil fertilization could be used. Other environmental parameters such as temperature, solar radiation, relative humidity, and the presence of other pollutant gases obviously cannot be regulated except by selecting dates for fumigations. However, data relating to environmental modification of pollution effects can be collected over a number of growing seasons in which conditions vary. In these types of studies extensive environmental monitoring should be conducted to characterize the experimental conditions for later comparisons.

Site selection is also an important criterion in open-air fumigation studies since subtle soil differences are known to result in dramatic yield differences. Since the fumigated plots are necessarily quite large and replication is difficult, the effects of soil variation on yield cannot readily be accounted for by experimental design. Thus, controls should be located as close as is practical to treated plots and soil samples from each plot should be analyzed in order to detect major differences in soil properties or nutrients.

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