EFFECTS OF SO_2 ON GROWTH AND YIELD OF WINTER CROPS GROWN IN CALIFORNIA

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ABSTRACT

The sulfur dioxide sensitivity of California crop plants grown during the winter was tested using lettuce (*Lactuca sativa* cv Empire) and wheat (*Triticum aestivum* cv Yecoro Rojo). The plants were grown in soil inside open top field chambers for 79 (lettuce) and 150 (wheat) days. Treatments include nonfiltered ambient air without added sulfur dioxide; filtered ambient air with 0, 79, 183 and 393 $\mu g\ m^{-3}$ added sulfur dioxide; and outside plots. Two harvests were made for each species: after 14 and 47 days of exposure for lettuce, and after 47 and 118 days for wheat. The results clearly indicated that winter exposures to sulfur dioxide can injure California crops. For wheat, sulfur dioxide at 183 $\mu g\ m^{-3}$ decreased wheat height by 5% and leaf area by 14% at the first harvest. Sulfur dioxide significantly reduced wheat yields at the final harvest. Sulfur dioxide at 393 $\mu g\ m^{-3}$ reduced total seed weight by 26%; and at 79 $\mu g\ m^{-3}$ and above, reduced 100 seed weight by 8% or more. Sulfur dioxide had no overall effect on lettuce plants at either harvest. Ambient oxidants had no overall effect on growth of lettuce or wheat. All chamber grown plants in general showed greater growth and yield than outside plants, indicating that the air pollutant sensitivity may be different for chamber-grown versus field-grown plants.

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SUMMARY AND CONCLUSIONS

California is a major U. S. producer of winter cereal and vegetable crops. Wheat is grown in over 1.1 million acres in the state with a value of approximately $309 million. The crop is planted in the fall and harvested the following summer. Lettuce is grown in approximately 148,000 acres in California, and has a value of $469 million. Lettuce is planted from November through January with harvests from April through May. Major wheat and lettuce production areas in California have relatively low winter oxidant levels, but there is a possibility for occasional sulfur dioxide exposures from current or potential point sources such as fossil fuel electrical generating stations.

In general, studies have not been conducted on the effects of air pollutants on crops growing during the winter in regions of the United States such as California which have mild winter environmental conditions. The vast majority of field air pollutant studies have been conducted with crops exposed under late spring to fall growing conditions, especially during the warmest months. This lack of winter crops research may be in part due to the generally lower air pollutant levels (especially oxidants) in winter than summer. However, plants are more sensitive to air pollutants under the lower light and higher humidity conditions of winter than summer, indicating that the importance of winter exposures should not be ignored for crops.

The sensitivity of crops to sulfur dioxide may be much greater in winter than summer. Perennial ryegrass exhibited reduced yield with continuous exposure to a minimum of 52 $\mu g\ m^{-3}$ sulfur dioxide for six months during the winter compared to 105 $\mu g\ m^{-3}$ required for the effect during the summer. More research is needed to interpret these results, but the current literature suggests that crops are injured more in the winter than previously suspected, with cereal crops being especially sensitive.

Information concerning the sensitivity of wheat and lettuce to air pollutants in the field is very sketchy. No results have been reported on the effects of sulfur dioxide on wheat during any time of the year from anywhere in the United States. Lettuce yield was actually increased by 30% with exposure to 786 $\mu g\ m^{-3}$ sulfur dioxide for 75 days during the winter. The study was conducted using plants grown in pots and exposed in open-top chambers in the field. Wheat yield was decreased by 10-16% when exposed to 196 versus 59 $\mu g\ m^{-3}$ ozone for seven weeks in late spring. Lettuce yield was decreased by 50% when exposed to 196 versus 78 $\mu g\ m^{-3}$ in late summer.

The objectives of this study were to determine the sensitivity of wheat and lettuce to sulfur dioxide or ambient oxidants when plants are exposed under California winter growing conditions, and to obtain dose response information from these exposures. Important California cultivars of the crops and commercial growing practices were used. The response of the crops to the air pollutants was evaluated in terms of commercially important yields, and in terms of growth and physiology.

The study was conducted in the ARB open-top field chambers at the University of California at Riverside. The chambers were cylindrical, 3 m in diameter by 2.43 m in height according to the National Crop Loss Assessment Network design with a baffle added at the top. Sulfur dioxide gas was dispensed into the chambers from a pressurized tank of liquid sulfur dioxide. Oxidant treatments were achieved by either filtering or not filtering the air entering the chambers. All sulfur dioxide treatments received filtered air. There were five chamber treatments: nonfiltered air and no sulfur dioxide, filtered air and no sulfur dioxide, filtered air plus approximately 79, 183 or 393 $\mu g\ m^{-3}$ sulfur dioxide. One treatment consisted of outside control plots. All treatments were replicated in four chambers or outside plots.

Wheat was planted directly into the chamber or outside soil on 12/15-16/83. Lettuce was started in an artificial medium in charcoal-filtered greenhouses on 11/29/83 and transplanted into the soil on 12/19-21/83. The pollutant treatments began on 1/18/84. Plants were watered, fertilized, and received pesticide sprays as needed.

A first harvest of lettuce was made on 2/1-2/84 after approximately 14 days of exposure. Parameters measured were planar leaf area, stomatal conductance, net photosynthesis, fresh weight, dry weight and leaf area. A first harvest of wheat was made on 2/9-10/84 after 22 days of exposure. Parameters measured were height, dry weight, fresh weight, leaf area, number of tillers, chlorophyll content, leaf injury, buffering capacity and total sulfur content. The final harvest of lettuce was on 3/13-19/84 after 47 days of exposure. Parameters measured were total fresh weight, head weight, total dry weight, plant diameter and head circumference. The final harvest of wheat was on 5/15-16/84 after 118 days of exposure. Parameters measured were stomatal conductance, net photosynthesis, leaf injury, total dry weight, ear weight, total seed weight, 100 seed weight and number of ears.

Sulfur Dioxide Effects. Sulfur dioxide produced significant decreases in wheat growth and yield. Significant effects occurred with as low as 79 $\mu g\ m^{-3}$. At the first harvest, sulfur dioxide at 183 $\mu g\ m^{-3}$ produced small reductions of 5% and 14% in plant height and leaf area, respectively. Sulfur dioxide produced visible chlorotic injury on wheat leaves at 183 and 393 $\mu g\ m^{-3}$ early in the growing season. Plants in these treatments also had a significant increase in leaf total sulfur content compared to control or low sulfur dioxide exposed plants. Even the lowest concentration of 79 $\mu g\ m^{-3}$ sulfur dioxide decreased the buffering capacity of leaves, indicating an altered plant metabolism. At the final harvest, the commercially important total seed weight was reduced by 26% at 393 $\mu g\ m^{-3}$. One hundred seed weight was reduced by 8, 12 and 29% by 79, 183 and 393 $\mu g\ m^{-3}$ sulfur dioxide, respectively.

While the most important yield effects happened only at the highest sulfur dioxide concentration, the occurrence of effects with as low as 79 $\mu g\ m^{-3}$ sulfur dioxide indicated that wheat may be detrimentally affected at levels of sulfur dioxide that could occur in the field during the winter. The injury symptoms with as little as 183 $\mu g\ m^{-3}$ after only 22 days of exposure during the coolest part of the growing season indicated that wheat may be especially sensitive to sulfur dioxide in winter, as described previously for other cereals.

However, the sulfur dioxide effects during the winter are species specific. Lettuce showed no indication of any detrimental effects from sulfur dioxide on yield, growth or physiology at either harvest.

Oxidant Response. The ambient oxidants occurring between January and early May had little effect on either wheat or lettuce. Wheat had a 6% significant reduction in height at the first harvest and a 9% reduction in 100 seed weight at the final harvest in filtered compared to nonfiltered chambers. Both of these reductions were small and may have been artifacts instead of true effects. The economically important wheat total seed weight was not affected at the final harvest. Lettuce did not show any response to ambient oxidants at either harvest. The low oxidant levels throughout the study (an average of 80 to 90 $\mu g\ m^{-3}$ ozone) were likely associated with the lack of any observable ambient air effects.

Chamber Effects. The most dramatic growth effects observed in the study were not the result of any air pollutant treatment, but occurred between chamber grown and outside plants. For wheat there were significant increases in growth at the first harvest, i.e. 24% in height and 56% in leaf area for chamber versus outside plants. The number of tillers per plant was decreased by 40% in chamber versus outside plants. By the final harvest total seed weight, 100 seed weight and ear weight were increased by 53, 22 and 45%, respectively, for chamber versus outside plants. The senescence of flag leaves for chamber plants was much less than for outside plants. For lettuce at the first harvest there were very large increases of 196, 117 and 235% in fresh weight, dry weight and leaf area for chamber versus outside plants. At the final harvest lettuce head fresh weight was 62% greater for chamber than for outside plants. However, total fresh weight was similar and total dry weight was actually lower for chamber than for outside plants. The lettuce plants apparently grew faster in outside plots than in chambers during the final part of the study.

The dramatic chamber effects showed that open-top field chambers are not the best system for exposing winter-grown crops to air pollutants. The chambers themselves significantly increase plant growth, probably due to the higher chamber soil and air temperatures compared to outside plots.

In conclusion, this study clearly indicated the potential for adverse effects to winter crops in California from relatively low levels of sulfur dioxide. In contrast, ambient levels of oxidants do not appear to cause injury to plants in the winter. Additional research on winter crops in California is suggested according to the following recommendations:

(1) Conduct the sulfur dioxide exposures using a chamberless zonal air pollution (ZAP) system and not open-top field chambers. Open-top field chambers are not recommended as the dramatic increases in plant growth in chambers indicated that air pollution sensitivity may be quite different in chambers versus outside fields.

(2) Use a variety of winter-grown California crops representing different commercially valuable plant parts, i.e., roots versus leaves, and different plant families.

(3) Begin the winter crops exposures earlier in the fall, i.e., mid-November, in order to include more of the coolest part of the growing season.

(4) Develop the use of buffering capacity or other physiological parameters as early indicators of sulfur dioxide effects on winter crops.

I. INTRODUCTION

California is a major U. S. producer of winter cereal and vegetable crops. Wheat is grown in approximately 1.1 million acres in the State with a value of approximately $309 million. The crop is planted in the fall and harvested the following June through August with Imperial, Yolo, Fresno, Kings, and San Joaquin the leading producing counties (3). Wheat growth continues throughout the winter months, with earlier harvests in warmer climates such as the Imperial Valley.

Lettuce is grown in approximately 148,000 acres in California with a value of over $469 million. Lettuce is planted from November through January with harvests from April to May with Monterey, Imperial, San Luis Obispo, Riverside, and Fresno the leading producing counties (3).

Major wheat and lettuce production areas in California have relatively low winter oxidant levels, but there is a possibility for occasional sulfur dioxide exposures from current or potential point sources such as coal-fired generating stations.

The susceptibility of winter wheat and lettuce to low level "chronic" sulfur dioxide exposures under field conditions is not known. To date, only high "acute" sulfur dioxide levels (524-2096 $\mu g\ m^{-3}$) have been used in studies with wheat (14) and lettuce (19,20), with experiments conducted primarily under controlled environment or greenhouse conditions. In one field study 786 $\mu g\ m^{-3}$ sulfur dioxide significantly increased lettuce yield compared to unexposed plants (25). This increase in yield was attributed to a sulfur fertilization effect.

Oxidants have been shown to decrease both wheat and lettuce growth and yield for plants exposed in the field, but under conditions different from those found in California during the winter (8,9,10). Wheat yield was decreased by 10-16% when plants were exposed to 196 versus 59 $\mu g\ m^{-3}$ ozone (7). However, the exposures were conducted between 4/9 through 5/31 under the late spring environmental conditions of North Carolina which would be different from growing conditions in California. In North Carolina the summer day and night temperatures and relative humidity would have been higher than winter temperatures or humidity in California. In addition, the primary wheat cultivar grown in California was not among the four tested in North Carolina.

Lettuce yield was decreased by 50% when exposed to 196 versus 78 $\mu g\ m^{-3}$ ozone for plants of the most widely grown California cultivar (8). However, the exposures were conducted between 9/1 and 11/13 under the warmer conditions of fall compared to winter in California.

In general, studies have not been made on the effects of air pollutants on crops growing during the winter in regions of the U.S. which have mild winter environmental conditions such as California. The vast majority of field air pollution studies have been conducted with crops exposed under late spring to fall growing conditions, especially during the warmest summer months. This lack of winter crops research may be in part due to the generally lower air pollutant levels (especially oxidants) in winter than summer. However, plants are more sensitive to air pollutants under the lower light and higher humidity conditions of the winter than during the summer (6), indicating that the importance of winter exposures should not be ignored for crops.

The sensitivity of plants to sulfur dioxide may be much greater in winter than in summer. Bell et al. (2) reported that perennial ryegrass exhibited reduced yield with continuous exposure to a minimum 52 $\mu g\ m^{-3}$ sulfur dioxide for six months in the winter, compared to a minimum of 105 $\mu g\ m^{-3}$ sulfur dioxide in the summer. Research by Davies (5) indicated that this greater sensitivity may be associated with lower winter light intensities. More research is needed to interpret these results, but the current literature suggests that crops are injured more in the winter than previously suspected, with cereal crops being especially sensitive.

Open-top chambers have been shown to be an effective method for determining the effects of air pollutants on crops under more nearly ambient environmental conditions during the summer (8,10). We have maintained a set of chambers at the University of California, Riverside, under contract to the Air Resources Board. These chambers were available for immediate use and had the capability of providing either sulfur dioxide or ambient oxidant exposures.

However, open-top field chambers had not been tested for use during winter months in a climate such as California's. Thus, the reported study also was conducted using an alternative field exposure system to test whether the open-top field chambers themselves had any effect on plant response to air pollutants in the winter. Concurrent with the open-top field chamber study, an experiment was conducted using linear air exclusion systems to expose wheat and lettuce to sulfur dioxide or ambient oxidants as described in Appendix A. The air exclusion study had the same treatments and number of replicates as the open top chamber study. Results from this study are given in Appendix A, pages 4-17 through 4-39.

The objective of this study was to determine the sensitivity of wheat and lettuce to sulfur dioxide or ambient oxidants when plants are exposed under winter-growing conditions, and to obtain dose-response information for those exposures. This objective was investigated using important California cultivars and methods characteristic of commercial growing procedures. The sensitivity of the crops were assessed in terms of commercially important yield. Injury, growth and physiology data were obtained to understand the mechanism for the effects in order to increase the applicability of the results for other species and conditions.

II. METHODS

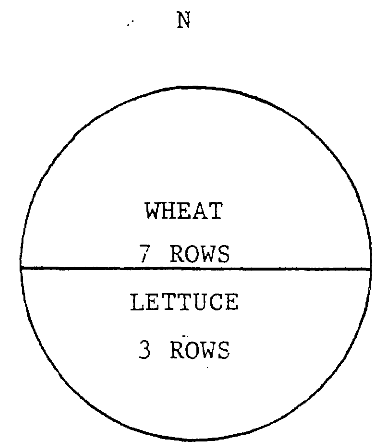
A. Pollutant Exposure and Monitoring

The open top field chambers were of the National Crop Loss Assessment (NCLAN) design (8,10) as modified by Kats et al. (12). The chambers were cylindrical, and 3 m in diameter by 2.43 m in height. They consisted of a rolled aluminum frame covered by clear PVC film. The cylinder was divided into an upper half covered by one layer of film, and a lower half covered by an inflatable double layer of film. The inner wall of the lower chamber was covered by 0.03 m diameter holes, positioned in 6 rows, with 0.15 m between holes in a row and 0.15 m between rows. The chamber had a cone-shaped baffle at the top (12), that effectively reduced the chamber opening by 50%. This baffle reduced entrance of ambient air into the chamber. Each chamber was equipped with a blower assembly consisting of a 1.52 x 0.60 x 0.62 m sheet metal blower box, 3/4 hp ILG propeller fans, fiberglass particulate matter filter, corrugated activated charcoal filters, and vinyl connecting duct between blower box and chamber.

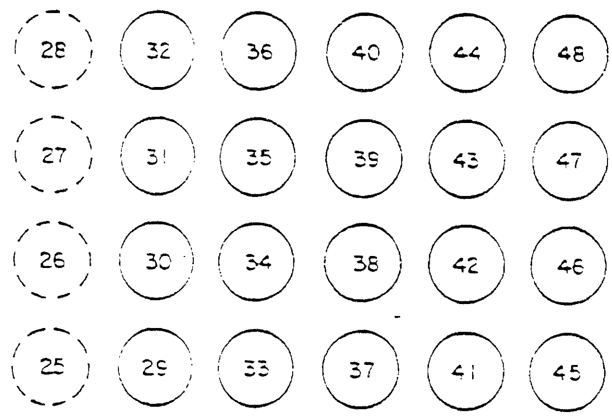
A sulfur dioxide dispensing system was built using a small cylinder with pressurized liquid sulfur dioxide as a gas source. This cylinder was kept at $38^{o}C$ inside an insulated galvanized trash can. The gas was dispensed at 7.037×10^{3} kg m^{-2} (10 PSI) through a line regulator (Matheson Model 71A), injected into the blower box, and carried into the chamber via the air stream. Sulfur dioxide was monitored by a Thermo Electron Corporation Model 43 sulfur dioxide analyzer from samples taken at 0.15 m above the ground in the center of the chamber or outside plots.

The overall experimental design for the sulfur dioxide gradient study is shown in Figure 1B with circular row plots used for comparison to open-top chambers. There were a total of 6 treatments in the study each replicated four times as shown in Figure 1B: 1) Chamber plus filtered air only, 2) Chamber plus filtered air and 79 $\mu g\ m^{-3}$ SO_2, 3) Chamber plus filtered air and 183 $\mu g\ m^{-3}$ SO_2, 4) Chamber plus filtered air and 393 $\mu g\ m^{-3}$ SO_2, 5) Chamber plus nonfiltered air, 6) Outside plots with ambient air. Exposures were initiated on 1/18/84 and continued until final harvest of wheat on 5/15-16/84. All exposures were continuous except when sulfur dioxide was turned off during brief periods of heavy rain or with

A



B



TREATMENTS

SYSTEM	AIR	SO_2 ($\mu g m^{-3}$)	PLOTS
Open Top Chamber	Filtered	0	29, 31, 32, 46
Open Top Chamber	Filtered	79	30, 35, 42, 43
Open Top Chamber	Filtered	183	36, 38, 39, 41
Open Top Chamber	Filtered	393	37, 40, 47, 48
Open Top Chamber	Nonfiltered	0	33, 34, 44, 45
Outside-Circular	Nonfiltered	0	25, 26, 27, 28

Figure 1. Diagram of plot layout for winter crops study. (A) indicates location of plants in plots, (B) indicates location of treatments.

high wind speeds early during the year. These off periods amounted to 10% of the hours during the experiment. Target versus actual concentrations of sulfur dioxide obtained with the exposures are shown in Table 1.

Concentrations over the entire wheat exposure period from 1/18 to 5/16/84 (119 days) were similar to the shorter lettuce exposure period from 1/1 to 3/19/84 (61 days) [Table 1]. Filtered zero chamber treatments had sulfur dioxide concentrations approximately 25% of ambient chambers or outside plots. Apparently some ambient sulfur dioxide which was not excluded by the carbon filters, or some ambient sulfur dioxide entered the top of the chambers to result in actual sulfur concentrations of 7 or 5 $\mu g\ m^{-3}$ in the zero sulfur dioxide treatments.

There were relatively low ambient ozone concentrations throughout the experimental period (Table 2). The raw data used to obtain these values are given in Appendix B. The open chambers effectively excluded 73% of the ambient ozone during both the lettuce and wheat growth periods (Table 2, column 5). This percentage exclusion was similar to the 75% of the ambient ozone effectively excluded by open top field chambers within outside ozone concentration exceeding 300 $\mu g\ m^{-3}$ (Appendix A, Figure 2-7).

The chambers were turned on immediately following lettuce planting. The ambient air or filtered treatments were initiated at that time, with the sulfur dioxide treatments beginning approximately four weeks later.

B. Plant Culture

1. Wheat

Wheat (cultivar Yecora Rojo) was planted directly into the soil on 12/15-16/83. Seeds were placed in seven concentric half-circle rows in chambers and circular open plots (Figure 1A). Two seeds were planted together with 0.05 m between pairs of seeds and 0.18 m between rows. Thus, there were approximately 1600 wheat seeds per chamber or circular open plot. Wheat was thinned to one plant every 0.025 m during the first week in January, 1984, or approximately three weeks after planting.

Plants were watered as needed via a drip irrigation system using irrigation water supplemented with a fertilizer solution (full strength North Carolina State University Phytotron solution) weekly. The plant received sprays of Orthene® and Sevin® as needed to control insects. A first harvest of wheat was made on 2/9-10/84 after 22 days of exposure. The final harvest was made on 5/15-16/84 after 118 days of exposure.

Table 1

TARGET AND ACTUAL SULFUR DIOXIDE CONCENTRATIONS FOR OPEN TOP FIELD CHAMBERS AND OUTSIDE PLOTS

Treatment		Sulfur Dioxide ($\mu g\ m^{-3}$)+	
Air	Target Sulfur Dioxide	Lettuce	Wheat
Filtered	0	7 ± 6	5 ± 9
	79	81 ± 7	79 ± 14
	183	180 ± 16	181 ± 22
	383	382 ± 24	385 ± 43
Nonfiltered	Ambient	25 ± 20	18 ± 18
Outside	Ambient	31 ± 20	24 ± 26

+Values are means ± SD of four replicate plots, except for two replicates for outside circular plots. Sampling height of 0.25 m. Data from one day each for seven and fourteen weeks for lettuce and wheat, respectively, averaged over 24-h per day.

Table 2

OZONE CONCENTRATIONS DURING WINTER STUDY+

Species	System	Ozone ($\mu g\ m^{-3}$) Filtered	Nonfiltered	Ozone/ Exclusion(%)$
Lettuce‡	Open top	18 ± 13 (53)	66 ± 42 (163)	73
	Outside	-	72 ± 41 (163)	-
Wheat&	Open top	21 ± 14 (53)	77 ± 46 (243)	73
	Outside	-	81 ± 46 (223)	-

+Values are means ± SD of four replicate plots between 0800 and 2000 for one day per week. Sampling height of 0.25 m. Peak values are indicated in parentheses. Diurnal peaks occurred between 1200 and 1800.

‡Average for seven weeks.

&Average for 14 weeks.

$Determined by the formula: {[(Nonfiltered - filtered)/nonfiltered] x 100}.

Wheat height was measured for four plants per plot beginning 1/20/84 and continuing for eight weeks until 3/23/84. The tallest point on the plant was measured whether it was the top of the awns or the tip of an upright flag leaf. The extent of heading of four wheat plants per plot was determined weekly between 3/2 and 3/23/84 at which time all plants had headed.

For the first wheat harvest four subsamples of at least eight plants each were taken randomly from among all rows of each plot. The fresh weight of six plants from each subsample was determined immediately and saved for dry weight and total sulfur determinations. Two plants were removed from each subsample and measured for number of tillers and leaf area and all leaves were rated for air pollutant injury on a 0 (no injury) to 10 (100% injury) scale. The dried tissue from four plants per plot was ground to a powder and analyzed for total sulfur content by X-ray fluorescence at Crocker Nuclear Laboratory of the University of California at Davis. The leaves from two plants from each plot were saved for chlorophyll concentration according to the absolute ethanol extraction procedure of Knudson et al. (13).

Buffering capacity (a measure of sulfur dioxide induced acidity) was measured for one frozen wheat sample per plot according to the procedure of Scholz and Reck (22). Samples were from the first harvest.

Important gas exchange parameters: stomatal conductance and net photosynthesis, were measured on wheat between harvests in mid March during a period of rapid vegetative growth. Stomatal conductance was measured with the LI-1600 steady state porometer. Two plants per plot were measured for each species. Net photosynthesis was measured with the ^3H and ^{14}C dual isotope porometer (1), on the same plants as the LI-1600 measurements. Only the ^{14}C data was used for analysis. The ^3H data was not used as questions exist as to whether the ^3H_2O uptake against H_2O concentration gradient accurately indicates H_2O transpiration out of leaves. Net photosynthesis was calculated according to the following formulae:

1. ^{14}C uptake = DPM ^{14}C/(leaf area x sample time)
2. ^{14}C tank constant = DPM ^{14}C/sample volume

3. CO_2 conductance = ^{14}C uptake/^{14}C tank constant

4. Net photosynthesis = CO_2 conductance x atmospheric CO_2 (340 ppm or 1.39×10^{-2} mol m^{-3}) x $\frac{P_{exp}}{P_o} \times \frac{T_o}{T_{exp}}$, where $T_o = 298^oK$ and P_o = 101.33 kPa.

A second rating of wheat (0-10 scale) was made on 4/4/84 to evaluate injury to plants during the important grain filling period. Four plants per plot were selected at random and all leaves on the plant were rated for injury. There were approximately four to six leaves per plant, however, the flag leaf nearest the developing head is the most important to produce photosynthate for grain filling.

At the final harvest subsamples of 10 plants each were taken on 5/15-16/84 and air-dried for approximately one month. Subsamples were taken only from the middle rows. Two to five subsamples were taken from each of the four middle rows for a total of approximately 11 subsamples per plot. After drying, subsamples were measured for total dry weight, number of ears, ear weight, seed weight and 100 seed weight.

2. Lettuce

Lettuce (cultivar Empire) were grown from seed. Lettuce seed pelleted in Endrin® insecticide was planted on 11/29/83 in trays placed in a charcoal-filtered chamber. The seeds were planted in a commercial fir-bark-redwood shavings-peat-sand medium (Supersoil®) and were treated with a pelleted fertilizer (Osmocote®). The seedlings were transplanted into the ground in the plots on 12/19-21/83.

Lettuce plants were placed in three rows in one-half of each chamber or circular open control plots, with seedlings placed 0.13 m apart within rows and 0.25 m apart between rows. There was a total of approximately 40 seedlings planted in each chamber or circular open plot (4 inner row, 18 middle row, 18 outer row). A first harvest of lettuce was made on 2/1-2/84 after 14 days of exposure. The final harvest was on 3/13-19/84 after approximately 47 days of exposure.

During the early part of the exposures growth of lettuce was monitored by nondestructive methods. Lettuce planar area was determined for four plants per plot, or 16 per treatment, by placing a transparent acetate sheet imprinted with a grid over the plant and then counting the grid intersections directly over leaf tissue (19). Measurements were initiated before beginning the sulfur dioxide exposures. Measurements were continued for six weeks through 2/3/84. At that time the plants were over 0.5 m^2 in area, and too large to determine planar area by counting 0.0068 m^2 cells on the grid.

For the first harvest every other lettuce plant was removed from the middle row in chambers and outside areas. This resulted in 8-10 plants per plot. Lettuce plants were cut off at soil level and total fresh weight measured immediately. Leaf area was measured for four plants selected randomly from the harvested plants. Two plants per plot were reserved for total sulfur analysis and the rest dried at 32°C in forced-air driers to obtain dry weights. The plants were inspected for air pollutant injury, but no symptoms representative of sulfur dioxide or ozone injury were found on any plants. Between the first and final harvests stomatal conductance and net photosynthesis were measured for lettuce as previously described for wheat.

At the final harvest all remaining lettuce plants were used from the inner and middle rows in open-top chambers or circular outside areas. Plants in the outer row of open-top chambers were discarded as guard row plants whose growth was affected by the adjacent chamber wall. This resulted in 12 to 14 plants per plot. Total plant and head fresh weights were determined immediately. Measurements were made of plant diameter and head circumference. A rating of leaf tip burn was made per plant and plants were again rated for air pollutant injury. As at the first harvest, no air pollutant injury was found. Four plants per plot were saved for dry weight determinations.

C. Environmental Measurement

Five parameters were measured to determine differences in environment which could affect plant response to air pollutants in the chambers versus outside plots: air speed over plant canopy, air temperature, soil temperature, leaf temperature, and dew formation.

Air speed was determined with a hand-held directional anemometer (Kurz Air Velocity Meter Model 441S). Measurements were made at the top of the canopy over individual plants that were used for stomatal conductance measures. Air speed was measured coincident with stomatal conductance measurements.

Temperature was measured continuously using iron-constantin thermocouples attached to strip chart recorders. Thermocouples were positioned at a standard height of 0.15 m within the plant canopy.

Soil temperature also was measured using thermocouples connected to recorders. A standard depth of 0.05 m was used with some additional measurements at 0.10 m.

Leaf temperature was measured for lettuce by attaching fine wire thermocouple to leaves. The thermocouple was attached to the leaf with perforated surgical tape. Leaf temperature was also obtained from the fine wire thermocouple inside the cuvette of the Lambda Instruments Company LI-COR 1600 steady state porometer.

Ratings of relative dew formation and guttation were made on wheat plants for all plots on three early winter dates, 1/16, 1/18 and 1/20/84. Each plot was visually rated on a scale with 0 = no dew or guttation water and 5 = all leaves covered with dew or a large drop of guttation water on the tips of all wheat leaves.

D. Statistical Analysis

Statistical analysis procedures were adapted from Steel and Torrie (24) and Snedecor and Cochran (23). The statistical design was a completely randomized design for wheat at the final harvest and lettuce at both harvests. A randomized complete block system was used for wheat at the first harvest with four rows within chambers as blocks. At each harvest the initial analysis was with a one-way analysis of variance. The analysis considered 0, 79, 183 and 393 $\mu g\ m^{-3}$ SO_2; nonfiltered, and outside control treatments as factors. More detailed analysis included one-way analysis of variance with the four SO_2 levels as fixed factors, and using Duncan's Multiple Range Test to compare differences between treatment means. A 't' test also was used to compare outside versus ambient chamber treatments, and ambient versus filtered chamber treatments. In the tables 'SD' indicates standard deviation for either individual plants or for plots (chambers or outside).

III. RESULTS AND DISCUSSION

A. Sulfur Dioxide Exposures

1. Wheat

General results from statistical analysis of wheat data are summarized in Table 3. Sulfur dioxide only had an apparent statistically significant effect on plant height and leaf injury at the first harvest. At the final harvest sulfur dioxide had a statistically significant effect on total seed weight and one hundred seed weight.

a. First Harvest

At the first harvest there were scattered treatment effects on wheat due to sulfur dioxide (Table 4). Sulfur dioxide had an apparent statistically significant inhibitory effect on height and leaf area at 183 $\mu g\ m^{-3}$ sulfur dioxide. However, since no sulfur dioxide growth effects were apparent at the higher concentration 393 $\mu g\ m^{-3}$ the response at the medium concentration is likely an artifact.

Wheat height was the same with all sulfur dioxide treatments based on measurements on weeks 5 through 7 (Figure 2). Exposure to both 183 and 393 $\mu g\ m^{-3}$ sulfur dioxide definitely caused leaf chlorosis. The leaf injury followed relatively cool and short days and was not seen later during the exposures indicating that the winter environmental conditions may have increased the sensitivity of plants to sulfur dioxide as reported by Bell et al. (2) and Davies (4). The chlorophyll measurements, however, did not correlate with the visual observations of injury as there were no statistically significant differences in chlorophyll concentration between sulfur dioxide concentrations (Table 4).

There was a lower buffering capacity in open-top chamber wheat plants exposed to sulfur dioxide than in control wheat plants (Table 5). This indicated that sulfur dioxide was affecting the overall ionic composition of plants, likely resulting from an increase in acidic sulfur compounds in leaf tissues with uptake of sulfur dioxide. This altered ionic composition could affect photosynthesis or other metabolic processes directly linked to growth or yield, however, the relationship between buffering capacity and plant metabolism has not been studied. Up to now, buffering capacity has only been measured by other researchers as an indicator of general plant stress due to air pollutants, and has not been evaluated in terms of its potential link to the physiology of air pollution injury.

Table 3

RESULTS FROM ANALYSIS OF VARIANCE FOR WHEAT DATA

Harvest	Factors[+]	Fresh Wt	Dry Wt	Ear Wt	Seed Wt	100 Seed Wt	No. Tillers	No. Ears	Leaf Area	Height	Leaf Injury
First	T_1-SO_2	ns[‡]	ns	-	-	-	ns	-	*	**	***
	T_2-O_3	ns	ns	-	-	-	ns	-	ns	*	ns
Final	T_1-SO_2	-	ns	ns	*	***	-	ns	-	-	-
	T_2-O_3	-	ns	ns	ns	**	-	ns	-	-	-

[+]T = treatments: T_1-SO_2 for 0, 79, 183 and 393 $\mu g\ m^{-3}$ sulfur dioxide, T_2-O_3 for filtered versus nonfiltered air.

[‡]***, ** and * = statistically significant at $p<0.005$, 0.01 and 0.05, respectively.

Table 4

WHEAT RESPONSE TO SULFUR DIOXIDE AND OXIDANT EXPOSURES AT FIRST HARVEST+

Response	Outside		Nonfiltered		Sulfur Dioxide ($\mu g\ m^{-3}$) 0	79	183	393
Dry weight (g)	3.0 ± 0.9	ns	3.5 ± 0.9	ns	4.0 ± 1.0	4.0 ± 1.3	3.4 ± 1.0	3.8 ± 0.9
Fresh weight (g)	17.5 ± 4.8	ns	20.4 ± 5.8	ns	21.6 ± 4.4	20.5 ± 6.0	19.3 ± 6.7	23.0 ± 6.6
Height (m)	0.29 ± 0.04	*	0.36 ± 0.04	*	0.38 ± 0.03 b	0.39 ± 0.04 b	0.36 ± 0.05 a	0.39 ± 0.05 b
Leaf area (cm^2)	26.8 ± 8.8	*	41.9 ± 9.1	ns	42.6 ± 11.1 b	42.6 ± 12.2 b	36.6 ± 10.7 a	45.2 ± 14.6 b
Tillers (#)	3.5 ± 1.6	*	2.1 ± 1.2	ns	2.0 ± 1.5	1.9 ± 0.9	1.5 ± 1.2	1.9 ± 1.6
Chlorophyll ($mg\ g\ dry\ wt^{-1}$)	6.5 ± 2.3	ns	8.5 ± 1.9	ns	8.7 ± 2.9	7.0 ± 1.7	9.3 ± 1.3	9.6 ± 6.6
Leaf Injury (0-10 scale)	0.4 ± 0.7	ns	0.5 ± 0.9	ns	0.2 ± 0.03 a	0.6 ± 0.8 a	2.5 ± 1.3 b	3.5 ± 1.1 c

+Values are means ± SD for 32 replicates (plants, eight from each of four plots) for height, leaf area, tillers and leaf injury; and eight replicates for chlorophyll concentration (plants, two from each of four plots). Values are means ± SD for 16 replicates (plants, four from each of four plots) for dry and fresh weights. Individual chambers and outside plots were the experimental units for the analysis of variance. Pairs of outside versus nonfiltered or nonfiltered versus 0 means separated by a "*" are significantly different at $p<0.05$ level according to a t test. Means for sulfur dioxide concentrations followed by different letters are significantly different at $p<0.05$ level using Duncan's Multiple Range Test.

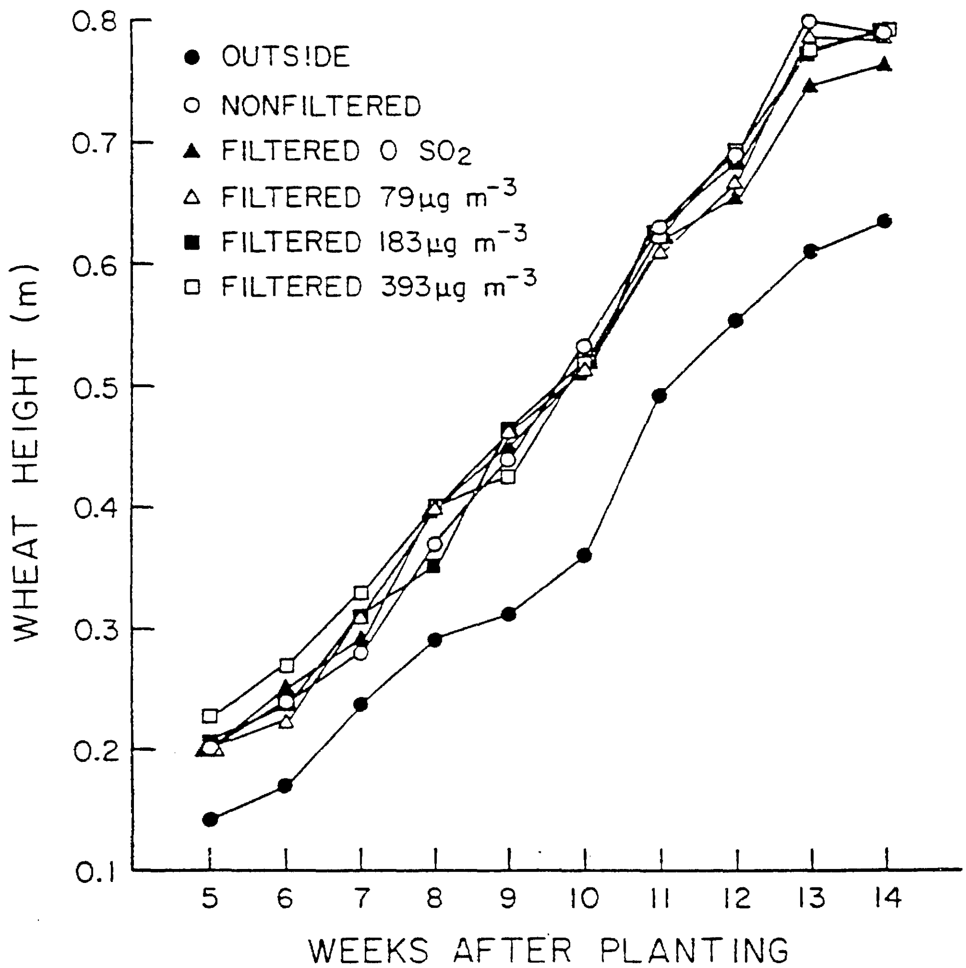


Figure 2. Wheat height with different treatments over time. First harvest was on February 9-10, 1984, or seven weeks after planting.

Table 5

BUFFERING CAPACITY AND TOTAL SULFUR CONTENT FOR WHEAT PLANTS EXPOSED TO SULFUR DIOXIDE+

	Sulfur Dioxide ($\mu g\ m^{-3}$)			
Response	0	79	183	393
Buffering Capacity‡	2.29 ± 0.12b	1.90 ± 0.06a	1.87 ± 0.06a	1.67 ± 0.06a
Total Sulfur Content&	4.0 ± 1.1a	4.4 ± 0.9a	6.3 ± 1.1b	7.8 ± 1.6c

+Values are means ±SD for four replicates (plants, one from each plot) for buffering capacity. Values are means ±SD for 16 replicates (plants, four from each plot) for total sulfur content. Individual plants are the experimental units for the analysis of variance. Values for sulfur dioxide concentrations in the same row followed by different letters are significantly different at $p<0.05$ using Duncan's Multiple Range Test.

‡In (ml 0.017N HCl) (g fresh weight)$^{-1}$ (ph unit change)$^{-1}$.

&In (mg sulfur) (g dry weight)$^{-1}$.

Total sulfur content analysis indicated that the wheat plants not only took up sulfur from the sulfur dioxide exposures (Table 5), but that the highest sulfur content levels corresponded to the treatments producing leaf injury (Table 4). There also was a statistically significant decrease in leaf guttation at 79 $\mu g\ m^{-3}$ compared to 0, 183 or 393 $\mu g\ m^{-3}$ on 1/20/84 (Table 6). However, this was likely just a spurious effect as leaf guttation was not affected by sulfur dioxide on the other two dates.

b. <u>Final Harvest</u>

Wheat plants continued to grow rapidly between 2/10/84 and harvest on 5/15-16/84. Plants were approximately the same height in all sulfur dioxide treatments (Figure 2, weeks 8-14). Porometer measurements on 3/12/84 indicated that stomatal conductance was similar in wheat plants grown in all sulfur dioxide treatments (Table 7). Net photosynthesis also was unaffected by sulfur dioxide treatment (Table 8). The net photosyntheses values were quite variable, with SD's often greater than the treatment mean. Thus, the dual isotope porometer procedure may not be

Table 6

GUTTATION ON WHEAT LEAVES WITH DIFFERENT EXPOSURE SYSTEMS+

Leaf Guttation (0-5.0 scale)‡

			Sulfur Dioxide ($\mu g\ m^{-3}$)			
Date	Outside	Nonfiltered	0	79	183	393
1/16/84	5.0±0 *	2.3±1.0 ns	2.8±0.5	2.5±0.6	2.0±0	1.8±0.5
1/18/84	5.0±0 *	1.5±0.6 ns	1.5±0.6	1.8±0.5	1.5±0.5	2.5±1.0
1/20/84	5.0±0 *	2.8±2.8 ns	2.0±0.8 ab	1.5±0.6 a	2.5±0.8 b	2.8±0.5 b

+Values are means ±SD of four replicates (plots). Individual chambers and outside plots were the experimental units for the analysis of variance. Pairs of outside versus nonfiltered, or nonfiltered versus 0 sulfur dioxide values separated by a "*" are significantly different at $p<0.05$. Values for sulfur dioxide concentrations in the same row followed by different letters are significantly different at $p<0.05$ using Duncan's Multiple Range Test.

‡Guttation rated on 0 to 5 scale where 0 = no beads of water at tips of any wheat plants in the plot and 5 = beads of water at tips of all plants in plot.

appropriate for determining net photosyntheses when only a limited number of plants are measured. Furthermore, the relatively low net photosynthesis rates in wheat (especially compared to lettuce), indicated the sensitivity of the instrument may have been reduced due to instrument malfunction.

During the time of grain filling, the leaves of wheat plants gradually became chlorotic and then necrotic as senescence progressed. The injury was most severe on lower leaves and least severe on flag leaves which lie just below the wheat heads. These flag leaves contribute most of the photosynthate transported to the developing grains. There were no differences in leaf injury attributable to sulfur dioxide (Table 9).

At the final harvest sulfur dioxide resulted in statistically significant reductions in wheat yield (Table 10). Total seed weight was reduced with 183 and 393 $\mu g\ m^{-3}$ sulfur dioxide. Reduced individual seed weight was the primary cause for the decreased yield as one hundred seed

Table 7

STOMATAL CONDUCTANCE FOR WHEAT AND LETTUCE EXPOSED TO SULFUR DIOXIDE AND AMBIENT OXIDANTS+

Stomatal Conductance (cm s^{-1})					
		Sulfur Dioxide ($\mu g\ m^{-3}$)			
Outside	Non-filtered	0	79	183	393
		Wheat			
0.21±0.12	0.27±0.16	0.31±0.19	0.35±0.11	0.30±0.16	0.27±0.12
		Lettuce			
0.36±0.06	0.23±0.08	0.25±0.10	0.24±0.06	0.27±0.10	0.23±0.05

+Values are means ± SD for eight replicates (plants). Individual plants (two per chamber or outside plot) were the experimental units for the analysis of variance. There were no significant differences between sulfur dioxide concentrations, between filtered and nonfiltered treatments or outside and nonfiltered treatments or outside and nonfiltered treatments at $p<0.05$ except that for lettuce there was a significant difference between nonfiltered chambers and outside plots at $p<0.05$ according to a t test.

weight was reduced for all sulfur dioxide treatments whereas number of ears was unaffected. There were no statistically significant differences between sulfur dioxide treatments in total plant or ear dry weight. However, there was a trend toward a lower ear weight with increasing sulfur dioxide concentrations, thereby reflecting the sulfur dioxide induced reduction in seed weight.

2. Lettuce

Results from statistical analysis of lettuce data are shown in Table 10. There were no statistically significant effects from sulfur dioxide at either harvest.

a. First Harvest

There were no differences in growth or physiological response between sulfur dioxide treatments during the period leading up to the first harvest. Lettuce planar area was not affected by sulfur dioxide

Table 8

NET PHOTOSYNTHESIS FOR WHEAT AND LETTUCE EXPOSED TO SULFUR DIOXIDE AND AMBIENT OXIDANTS[+]

Net Photosynthesis ($\mu mol\ m^{-2}\ s^{-1}$)					
		Sulfur Dioxide ($\mu g\ m^{-3}$)			
Outside	Non-filtered	0	79	183	393
		Wheat[‡]			
0.88±0.81	0.77±0.63	2.45±2.24	1.23±0.86	2.01±3.32	1.57±1.30
		Lettuce			
7.35±4.53	6.32±2.04	4.75±3.64	4.95±1.19	6.67±3.65	6.84±3.65

[+]Values are means ±SD of eight replicates (two plants from each of four plots). Individual plants were the experimental units for the analysis of variance. There were no statistically significant differences between any treatments.

[‡]Wheat data is not compatible with lettuce data due to change in instrument sensitivity between measurements for the two species.

Table 9

INJURY TO WHEAT LEAVES EXPOSED TO SULFUR DIOXIDE OR AMBIENT OXIDANTS[+]

Leaf Injury (0-10 scale)					
		Sulfur Dioxide ($\mu g\ m^{-3}$)			
Outside	Non-filtered	0	79	183	393
		Whole Plant			
5.9±1.5	4.8±2.1	4.7±1.5	5.3±2.2	5.9±1.5	6.4±1.1
		Flag Leaf			
3.3±2.2	0.9±0.8	0.9±0.5	0.9±0.8	0.9±0.7	1.5±0.8

[+]Values are means ±SD for 16 replicates (four plants from each of four plots). Individual plants were the experi mental units for the analysis of variance. There were significant differences between outside plots and non filtered chambers for flag leaves according to a t test. The other differences were not significant.

Table 10

WHEAT RESPONSE TO SULFUR DIOXIDE AND OXIDANT EXPOSURES AT FINAL HARVEST[+]

			Sulfur Dioxide ($\mu g\ m^{-3}$)			
Response	Outside	Nonfiltered	0	79	183	393
Dry weight (g)	11.3 ± 0.5 ns	13.8 ± 2.1 ns	12.9 ± 1.6	13.4 ± 2.1	12.5 ± 2.2	11.2 ± 1.4
Ear weight (g)	6.7 ± 2.4 *	9.7 ± 1.3 ns	9.6 ± 1.2	9.8 ± 1.7	9.1 ± 1.4	7.5 ± 8.7
Total seed weight (g)	4.7 ± 0.2 *	7.2 ± 1.0 ns	7.2 ± 0.9 b	7.5 ± 1.2 b	6.8 ± 1.0 ab	5.3 ± 0.6 a
100 seed weight (g)	0.37 ± .004 *	0.45 ± 0.02 *	0.49 ± .003 c	0.45 ± 0.01 b	0.43 ± 0.03 b	0.35 ± 0.1 a
Ears (#)	4.9 ± 0.4 ns	4.1 ± 0.07 ns	3.6 ± 0.5	4.5 ± 0.7	4.3 ± 0.8	4.4 ± 0.7

[+]Values are means ± SD for four replicates (plots). Individual chambers and plots were the experimental units for the analysis of variance. There were 11 observations per plot with 10 plants per observation. Pairs of outside versus nonfiltered, or nonfiltered versus zero means separated by a "*" are significantly different at $p<0.05$ according to a t-test Means for sulfur dioxide concentrations followed by different letters are significantly different according to Duncan's Multiple Range Test.

during the period up to six weeks after planting (one week before the first harvest) [Figure 3]. Stomatal conductance was not affected by sulfur dioxide treatments (Table 6). Net photosynthesis was also similar across all sulfur dioxide treatments (Table 8).

At the first harvest there were no statistically significant responses for lettuce attributable to sulfur dioxide (Table 12). Leaf area appeared to be greater at 79 $\mu g\ m^{-3}$ than 0, 183 or 393 $\mu g\ m^{-3}$ sulfur dioxide, but the mean for 79 $\mu g\ m^{-3}$ was not significantly different from the other treatments. A slight growth stimulation at the lowest level of sulfur dioxide is possible due to a fertilization effect, which may have been negated by any toxic effects of sulfur dioxide at the higher concentrations.

b. Final Harvest

Sulfur dioxide had no statistically significant effects on lettuce growth or yield (Table 13). There was an apparent, but not statistically significant, trend towards higher leaf fresh weights with exposure to sulfur dioxide. However, in contrast, there was also a lower dry weight. Thus, there was an apparent decrease in percent dry weight, i.e., increase in water content for sulfur dioxide-treated versus control lettuce plants. The percentage dry weight averaged 4.6, 4.0, 4.0 and 4.2% for the 0,79, 183 and 393 $\mu g\ m^{-3}$ sulfur dioxide treatments, based on the treatment means shown in Table 13. However, no actual measurements of leaf water content were made for the lettuce plants.

B. Oxidant Exposures

1. Wheat

The general results are shown in Table 3 for statistical analysis of nonfiltered versus filtered chamber data (T_2-O_3). In these comparisons, any differences between the two treatments were attributed to the oxidants removed by the charcoal filters.

a. First Harvest

Wheat height was significantly lower in nonfiltered chambers than in filtered chambers (Table 4). However, the reduction in height was only 5%. This difference is likely an artifact, or if real, had no biological importance as there were no other differences in growth, chlorophyll content, or leaf injury between filtered and nonfiltered

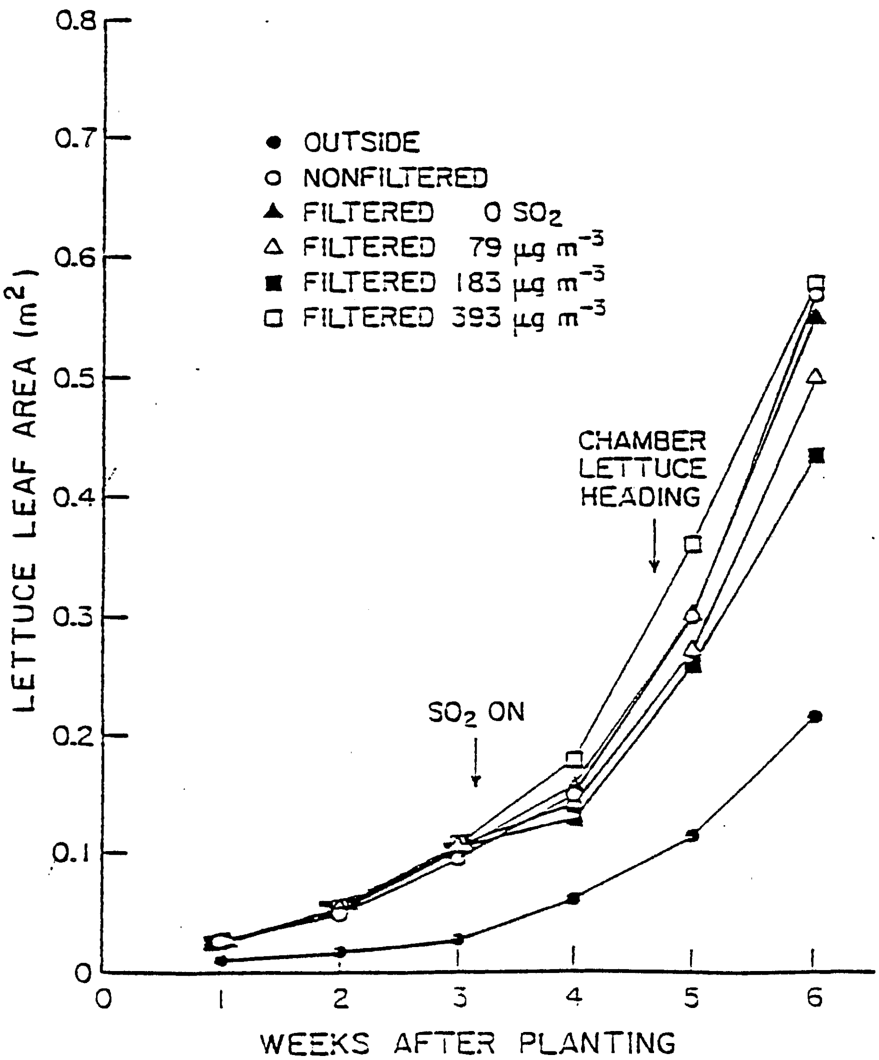


Figure 3. Lettuce planar area with sulfur dioxide and oxidant exposures in open top chambers. Each point represents the mean of 16 plants, four in each of four plots. First harvest was one week after termination of the planar area measurements, e.g., seven weeks after planting.

chamber plant. Furthermore, there were no significant differences between filtered and nonfiltered chambers in terms of weekly wheat height (Figure 2), or guttation (Table 6).

b. Final Harvest

During the growth period leading up to the final harvest there were no differences between filtered and nonfiltered chamber wheat plants in terms of stomatal conductance (Table 6), net photosynthesis (Table 7), or leaf injury for either whole plants or flag leaves (Table 8). At the final harvest there was a significantly lower (8%) 100 seed weight for nonfiltered compared to filtered chamber plants (Table 9). However, the plants apparently compensated for the lower individual seed weights in terms of number of seeds as total seed weight was the same for nonfiltered versus filtered chamber plants. Furthermore, there were no differences in terms of ear weight, number of ears, or total plant dry weight between nonfiltered and filtered wheat plants.

2. Lettuce

Results are shown in Table 11 from statistical analysis of lettuce nonfiltered versus filtered chamber data. There were no significant differences attributable to oxidants (T_2-O_3) at either harvest.

Table 11

RESULTS FROM ANALYSIS OF VARIANCE FOR LETTUCE DATA

Harvest	Factors[+]	Total Fresh Weight	Head Weight	Total Dry Weight	Leaf Area	Plant Diameter	Head Circumference
First	T_1-SO_2	ns [‡]	–	ns	ns	–	–
	T_2-O_3	ns	–	ns	ns	–	–
Final	T_1-SO_2	ns	ns	ns	–	ns	ns
	T_2-O_3	ns	ns	ns	–	ns	ns

[+]T = treatments: T_1-SO_2 for 0, 79, 183 and 393 $\mu g\ m^{-3}$ sulfur dioxide, T_2-O_3 for filtered versus nonfiltered air.

[‡]There were no statistically significant growth or yield effects for lettuce at either harvest.

Table 12

LETTUCE RESPONSE TO SULFUR DIOXIDE AND AMBIENT OXIDANT EXPOSURES AT FIRST HARVEST+

			Sulfur Dioxide ($\mu g\ m^{-3}$)			
Response	Outside	Nonfiltered	0	79	183	393
Fresh weight (g)	20.2 ± 2.8 *	59.8 ± 20.2 ns	53.0 ± 16.6	62.6 ± 34.1	48.7 ± 21.2	63.1 ± 24.8
Dry weight (g)	1.2 ± 0.3 *	2.6 ± 0.8 ns	2.4 ± 0.8	2.8 ± 1.5	2.4 ± 0.9	2.8 ± 0.7
Leaf area (m^2)	0.29 ± 0.40 *	0.97 ± 0.36 ns	0.85 ± 0.24	1.13 ± 0.65	0.81 ± 0.28	0.98 ± 0.22

+Values are means ± SD for four replicate (plots). Each plot had 8 to 15 observations (plants). Individual chambers and outside plots were the experimental units for analysis of variance. Pairs of outside versus nonfiltered, or nonfiltered versus zero means separated by a "*" are significantly different at $p<0.05$. No sulfur dioxide concentrations are significantly different.

Table 13

LETTUCE RESPONSE TO SULFUR DIOXIDE AND AMBIENT OXIDANT EXPOSURES AT FINAL HARVEST+

					Sulfur Dioxide ($\mu g\ m^{-3}$)			
Response	Outside		Nonfiltered		0	79	183	393
Total fresh weight (g)	578 ± 100	ns	677 ± 114	ns	586 ± 118	639 ± 114	626 ± 131	628 ± 90
Head fresh weight (g)	313 ± 61	*	509 ± 114	ns	443 ± 86	493 ± 96	466 ± 103	488 ± 79
Total dry weight (g)	32.2 ± 6.5	*	26.6 ± 6.4	ns	27.2 ± 9.1	25.7 ± 6.3	25.1 ± 7.5	26.6 ± 6.9
Plant diameter (m)	0.35 ± 0.02	ns	0.36 ± 0.02	ns	0.34 ± 0.02	0.34 ± 0.02	0.33 ± 0.03	0.34 ± 0.02
Head circumference (m)	0.33 ± 0.02	ns	0.36 ± 0.03	ns	0.36 ± 0.02	0.36 ± 0.02	0.36 ± 0.03	0.36 ± 0.02

+Values are means of ± SD of four replicates (plots) per treatment for statistical analysis for all para meters except total dry weight. Each plot mean had 12 to 14 observations (plants) For total dry weight each mean ± SD is for 16 observations, four from each of four plots per treatment. Individual chamber and outside plots were the experimental units for analysis of variance Pairs of outside versus nonfiltered, or nonfiltered versus zero means separated by a "*" are significantly different at $p<0.05$ using a t-test. No sulfur dioxide concentrations are significantly different at $p<0.05$.

a. First Harvest

There were no significant differences in growth or physiological responses attributable to ambient oxidants during the period leading up to the first harvest. Lettuce planar area (Figure 3), stomatal conductance (Table 7), and net photosynthesis (Table 8) were similar for nonfiltered and filtered treatments. At the first harvest, fresh weight, dry weight, and leaf area were all similar for nonfiltered versus filtered treatments (Table 12).

b. Final Harvest

There were no statistically significant differences between nonfiltered and filtered chambers for any parameter at the final harvest (Table 13).

C. Chamber Effects

There were significant increases in growth and yield for chamber-grown plants for both wheat and lettuce at either harvest, as indicated by the responses for ambient chamber versus outside plants. Responses also were different for chamber versus outside plants for some of the physiological parameters.

1. Wheat

a. First Harvest

Wheat seedlings emerged on approximately 12/22/83 in chambers and a few days later in outside plots. The earlier germination was likely due to warmer temperatures in chambers than in outside plots. The soil also stayed more moist in chambers than outside, presumably due to lack of convective drying of soil by wind. Enhanced growth of wheat in chambers was maintained over time as indicated by the greater plant height compared to outside areas (Figure 2). There was an average 35% greater height for chambers versus outside plots over the 10 weeks of measurement.

There clearly was less guttation at the tips of wheat leaves in chambers compared to outside plots (Table 6). Air speed over the plants may be an important factor in guttation. The most guttation was in the nighttime still air outside plots, with less guttation in the chambers which had a constant flow over the plants during the night.

Growth was considerably different for wheat plants in nonfiltered chambers versus outside at the time of the first harvest (Table 4).

Chamber plants were larger than outside plants with statistically significant greater height (24%) and leaf area (56%). Plant weight was not affected by the chamber to the same extent as height and area. Dry and fresh weights were only 17% greater for chamber than outside plants, and the differences between the two treatments were not statistically significant. Chamber plants were much less prolific in tillering than outside plants, producing 40% fewer additional stems per plant. The large increase in growth and decrease in tillering, but not in biomass for chamber versus outside plants, indicated that the chamber plants were morphologically different from outside plants during early stages of growth.

There was an apparent 31% greater chlorophyll content in leaves from nonfiltered chamber versus outside plants (Table 4). However, this difference was not statistically significant. There was no difference in chlorotic or necrotic leaf injury to chamber versus outside wheat plants.

b. Final Harvest

Wheat plants continued to be much taller in the chambers than in outside plots over the period leading up to the final harvest (Figure 2). Porometer measurements showed no difference in either stomatal conductance (Table 7) or net photosynthesis (Table 8) for nonfiltered chamber versus outside plants.

There was much less injury to flag leaves from nonfiltered chamber compared to outside plants based on measurements during the time of grain filling (Table 9). This delay of senescence was most evident for the flag leaves and was not significant on a whole plant basis. The retention of photosynthetic activity usually associated with delayed senescence may be at least in part responsible for the higher yields for chamber versus outside wheat plants.

Yield was much greater for chamber than outside wheat plants at the time of the final harvest. The economically important total seed weight was 53% greater for nonfiltered chamber than for outside plants (Table 10). However, individual wheat seeds averaged only 22% larger for chamber versus outside plants, as shown by the 100 seed weights. This increase in individual seed size was not adequate to explain all of the increase in total seed weight. Thus, increased seed number per plant also probably played a role in the increased chamber yield. The increased seed weight was reflected in the 45% greater ear weight for chamber versus outside plants.

At the final harvest the increased dry matter production for chamber plants was primarily only in terms of reproductive (seed) growth and not vegetative growth. There was only a 22% greater total dry weight for non-filtered chamber versus outside plants, and no difference in vegetative dry weight when total seed weight was subtracted from dry weight. There was no difference in number of ears between chamber and outside plants. Apparently the chamber plants grew extra tillers after the first harvest as they equalled the number on the outside plants at the time of the second harvest. This increase in tillers for chamber plants was necessary to produce the equal number of ears for both chamber and outside treatments as each tiller on a plant produces one ear. Thus the morphological differences between chamber and outside plants at the first harvest were likely more closely related to delayed development for outside versus chamber plants, than to any real difference in growth form.

2. Lettuce

a. First Harvest

Lettuce growth was much greater in chambers than outside plots during the period leading up to the first harvest. Lettuce planar area was 168% greater for nonfiltered chambers than for outside plots by 6 weeks after planting (Figure 3). At the time of the first harvest lettuce fresh weight, dry weight and leaf area were 196, 117 and 235%, respectively, greater in chambers than in outside plots (Table 12). All of the nonfiltered chamber means were highly statistically significantly different from outside plot means.

Stomatal conductance was significantly lower (36%) for nonfiltered chamber compared to outside lettuce plants (Table 7). A cause for this lower chamber conductance is not known, and is contrary to the higher stomatal conductance which may have been expected for the rapidly photosynthesizing, fast-growing chamber plants. There was no difference in net photosynthesis for the chamber versus outside plants.

b. Final Harvest

At the final harvest there was a statistically significant difference between nonfiltered chamber and outside treatments for the economically significant head fresh weight (Table 13). However, the 62% greater head fresh weight for chambers versus outside plots was not reflected by the other response parameters. Total fresh weight was only 17% greater for chamber versus outside plots, and the difference was not statistically significant. Total plant dry weight was actually significantly lower (17%) for chamber compared to outside plots. Plant and head diameters were approximately the same for both chambers and outside plots. Apparently, the plants in the outside plots grew more rapidly than the chamber plants over the 33 days between the first and final harvests. The lettuce plants are apparently more adapted to the cooler outside temperatures than to chamber temperatures for later growth, compared to more rapid growth under warmer chamber versus outside temperatures during the early part of the growing season.

The general pattern of larger lettuce heads with a greater percentage of total plant fresh weight likely was associated with earlier maturation in the chambers versus outside plots. Increases in air and soil temperature as documented for the chambers, have been shown to enhance lettuce head formation (16,17,27). Head formation is associated with folding of inner leaves back a into tight unit and accelerated twisting and drying of outer leaves (16,17). This process results in a shift of relative plant biomass from total plant to head. The proportional increase in relative water content in chamber versus outside plants also is likely associated with earlier head maturation. As the inner leaves fold toward the center of the plant their transpiration is likely decreased due to high inner head humidity. Therefore, fewer leaves were turned outward for chamber versus outside plants, and, thus, rapidly losing water.

3. Environmental Variability

The significant differences in plant growth, yield and physiology between chambers and outside plots may be largely explained by differences in environmental conditions between chambers and outside plots. These chamber versus outside differences are described below.

a. Air Speed

During the sulfur dioxide gradient study, air speed was considerably lower in open-top chambers than in outside plots (Table 14). The measurements were made during the day when there were brisk winds. At still times, the chambers would have greater air speeds than outside plots.

Table 14

AIR SPEED FOR SULFUR DIOXIDE AND AMBIENT OXIDANT STUDY+

Air Speed ($m\ s^{-1}$)					
		Sulfur Dioxide ($\mu g\ m^3$)			
Outside	Nonfiltered	0	79	183	393
1.27±0.43 *	0.57±0.08 ns	0.53±0.07	0.50±0.07	0.55±0.06	0.58±0.10

+Measurements made over the lettuce canopy. Values are means SD of eight replicates (measurements), two from each of four replicate plots. Individual observations were the experimental units for the analysis of variance. There was a significantly greater air speed in outside versus nonfiltered plots at $p<0.05$.

b. Air Temperature

During the study the air temperature pattern changed over the growing period (Table 15). During most of the winter, air temperatures were slightly higher in open top chambers than in outside plots. As spring progressed, air temperature became similar in chambers and outside plots. Figure 4C illustrates the diurnal pattern in air temperature for chambers and outside plots on a typical winter day.

c. Soil Temperature

During the winter soil temperature at the 0.05 m level, open top chambers had higher soil temperatures than in outside plots at night (Figure 4B). Soil temperature at the 0.10 m level in chambers was slightly greater than for outside plots over the entire day (Figure 4A).

d. Leaf Temperature

Open top chambers had up to 3°C warmer leaf temperatures than outside plots during early morning, and similar temperatures at mid-day (Figure 4D).

e. Dew Formation

Dew did not form within open-top chambers on any date (Table 16). In contrast, nearly all plants had substantial dew accumulation in outside plots. Still air at the plant canopy level apparently was not the only factor encouraging water condensation; the conductance of heat from plant leaves to a clear night sky also plays a major role in dew formation.

Table 15

AVERAGE DAILY AIR TEMPERATURE FOR SULFUR DIOXIDE-OXIDANT STUDY IN 1984+

Date	Air Temperature (°C) Open Top Chamber	Outside‡
2/3/84	21.0 ± 4.1	19.9 ± 3.4
2/11/84	17.5 ± 3.2	17.8 ± 5.4
2/17/84	15.8 ± 4.3	14.8 ± 4.9
2/24/84	21.8 ± 5.5	17.4 ± 4.8
3/2/84	21.2 ± 4.9	20.0 ± 5.9
3/9/84	19.9 ± 4.3	19.8 ± 5.0
3/21/84	23.4 ± 4.9	22.3 ± 5.0
3/30/84	21.1 ± 5.8	20.1 ± 4.7
4/6/84	19.2 ± 3.3	19.2 ± 3.3
4/13/84	32.7 ± 5.9	31.4 ± 7.0
4/20/84	23.5 ± 5.0	23.3 ± 4.9
4/27/84	16.7 ± 4.6	16.0 ± 5.2
5/4/84	30.9 ± 5.5	29.1 ± 6.0

+Values ±SD for hours 0800-2000, except for 0900-2000 on 2/17/84 and 1100-2000 on 4/6/84.

‡Circular plot.

Table 16

DEW ON WHEAT LEAVES+

Date	Nonfiltered Chamber		Outside
1/16/84	0	*	3 ± 0
1/18/84	0	*	3 ± 0.8
1/20/84	0	*	5 ± 0‡

+Values are means ±SD of four observations, one from each of four plots. Individual observations were the experimental units. Pairs of nonfiltered and outside values separated by a "*" are significantly different at $p<0.05$. Dew rated at 0-5 scale where 0 = no dew on any plant and 5 = entire leaf surfaces of all plants covered with dew.

‡Dew had solidified to frost.

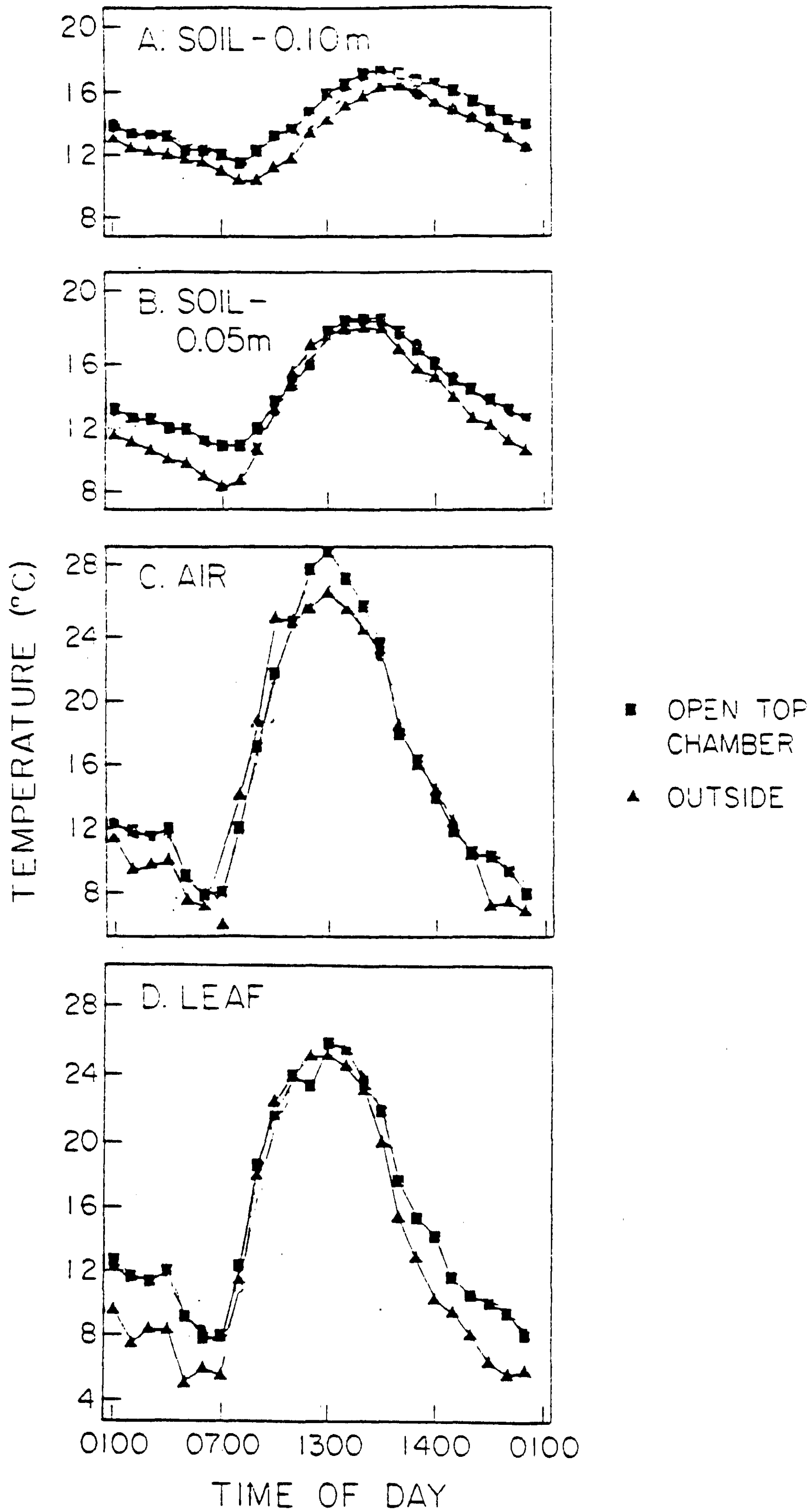


Figure 4. Diurnal temperatures on 2/4/84. Data is for (A) soil at 0.10 m depth, (B) soil at 0.05 m depth, (C) air at 0.15 m height, and (D) abaxial surface of lettuce leaves.

D. Applicability of These Findings

The results with wheat clearly indicated that exposure to relatively low average concentrations of sulfur dioxide can adversely affect winter grown crops in California. Exposure to a minimum of 183 $\mu g\ m^{-3}$ for 22 days can produce leaf injury to young vegetative plants, and as little as 79 $\mu g\ ^{-3}$ over the growing season may reduce individual seed weight. The leaf injury was observed during the coolest part of the growing season. This reinforced the hypothesis that cool weather increases the sulfur dioxide sensitivity of crops. The lack of sulfur dioxide effects on lettuce showed that the winter injury effect may be highly species specific. Thus additional screenings are necessary to evaluate the sulfur dioxide sensitivity of a wide range of California winter crops.

The sulfur dioxide concentration producing yield losses to wheat in this study (393 $\mu g\ m^{-3}$) is similar to the concentrations shown to affect other cereal or grass crops. Roberts (21) analyzed all available data sets including data from both field and laboratory chambers collected in both winter and summer. He concluded, based on linear regression analysis, that from 330 to 440 $\mu g\ m^{-3}$ sulfur dioxide produced an approximately 10 to 20% reduction in yield for ryegrass, the species most often studies. For six other species, sulfur dioxide produced effects ranging from a 15 % increase in yield to a 57% decrease in yield with concentrations between 162 and 472 $\mu g\ m^{-3}$. The variable response depended not only on species, but also on exposure system and procedure for determining pollutant concentration.

The observed decrease in wheat yield during winter months fulfilled the predicted response based on previous studies with grasses. Colvill et al. (4), Whitmore and Mansfield (28), and Bell et al. (2) all reported maximum sensitivity of grasses to sulfur dioxide during winter months in England from December into April. Colvill et al. (4) and Whitmore and Mansfield (28) demonstrated 30 to 50% decreases in yield in late winter for ryegrass and Kentucky Bluegrass compared to no decreases in yield during the summer. Bell et al. (2) showed that the concentration of sulfur dioxide required to produce growth reductions in ryegrass during the winter was only one-half that required to reduce growth during the summer.

Roberts summarized available response theories to conclude that the greater sulfur dioxide effects during the winter were associated with slower plant growth rates in the winter than summer (21). Thus, the different environmental conditions in the winter compared to summer, i.e., cooler temperatures, lower light intensity, and shorter days, may not be having direct effects on pollutant sensitivity of plants via specific interactions with physiological detoxification mechanisms (18). However since these same environmental conditions also directly decrease plant growth rates, their indirect effects on plants are still important.

The sulfur dioxide effects may have been more significant if the sulfur dioxide exposures had been initiated earlier during the winter period. Planting on about 11/1 instead of mid-December would have resulted in more of the exposure period occurring during the coolest part of the year in Riverside. In addition, early 1984 was warmer and drier than average, thus possibly reducing the pollutant sensitivity of the plants.

Additional studies are needed to more definitively document the effects of sulfur dioxide on winter crops. Earlier planting and/or a cooler climate exposure site likely would produce results more applicable to the agricultural environment. Open-top field chambers such as in this study are not recommended for future air pollutant winter crop research as the small environmental differences between chambers and outside plots dramatically increased plant growth in chambers.

Air exclusion systems would alleviate much of the environmental variability with chambers as described in Appendix A, pages 3-1 through 3-13. However, air exclusion systems would still increase plant growth somewhat compared to outside plants during the coolest part of the winter. The results with air exclusion systems also were somewhat different than with open top chambers. The high concentration of 393 $\mu g\ m^{-3}$ sulfur dioxide apparently increased wheat growth in air exclusion systems compared to decreased growth (Appendix A, Table 4-17, page 4-32) in open-top chambers.

A portable, chamberless zonal air pollutant (ZAP) system may be a better system for winter exposures (26). The ZAP system has a major drawback of potentially confounding background pollutant concentrations when used during the summer "smog" season. However, this problem would be insignificant in the winter due to low ambient ozone and sulfur dioxide levels in most areas.

The lack of general ozone effects in the winter was expected as ambient ozone concentrations are generally quite low. The predicted yield loss for the wheat is only 0.8 to 6.9% for 7-hour ozone concentrations of 78 to 98 $\mu g\ m^{-3}$ (9,11). These small differences would be very difficult to detect in a field situation. The previous results were from the NCLAN studies which used eight cultivars of winter wheat.

Leaf buffering capacity may provide a good indication of the occurrence of sulfur dioxide effects to plants even before the appearance of visible injury symptoms. As little as 79 $\mu g\ m^{-3}$ sulfur dioxide for 22 days altered the buffering capacity of wheat plants. The other physiological indicators, i.e., stomatal conductance, net photosynthesis, and chlorophyll content, were not affected by sulfur dioxide. However, these parameters were measured only once over the course of the study. Repeated measurements may have more accurately reflected changes in wheat metabolism leading to the growth reductions.

IV. RECOMMENDATIONS

In conclusion, this study demonstrated that relatively low sulfur dioxide concentrations can detrimentally affect winter crops such as wheat in California. In contrast, ambient oxidants are not likely to affect winter crops. However, additional research is needed to provide information as to the scope of potential losses from sulfur dioxide for California winter crops. The following criteria are recommended for this research:

(1) Conduct the sulfur dioxide exposures using a chamberless zonal air pollution (ZAP) system. Open-top field chambers are not recommended as the dramatic increases in plant growth in chambers indicate that the air pollution sensitivity may be quite different in chambers versus outside fields. The ZAP system could be used successfully in most areas of California that are not near current sulfur dioxide sources.

(2) Use a variety of winter-grown crops representing different types of economic yield, e.g., leaves versus roots, and different plant families. Prospective crops include broccoli, carrots, barley or potatoes.

(3) Begin the winter crops exposure earlier during the late fall in order to include more of the coolest part of the growing season for the winter crops. The exposures should be approximately during the period from mid-November through early March.

(4) Develop the use of buffering capacity or other physiological parameters as early indicators of sulfur dioxide effects on winter crops.

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APPENDICES

Appendix A

A Field Air-Exclusion System for Measuring
the Effects of Air Pollutants on Crops
Final Report to EPRI
August, 1985

Appendix B

Raw Ozone Data for Outside Plots and Chambers

APPENDIX A

A Field Air-Exclusion System for Measuring the Effects of Air Pollutants on Crops

EA-4203
Research Project 1908-3

Final Report, August 1985

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REPORT SUMMARY

SUBJECT	Air quality
TOPICS	Air pollution Crops Ozone Sulfur dioxide
AUDIENCE	Environmental scientists / R&D managers

A Field Air-Exclusion System for Measuring the Effects of Air Pollutants on Crops

In two years of field testing, an electronically regulated prototype proved more realistic for southwestern conditions than conventional systems for exposing plants to controlled amounts of pollutants. A mobile version of the experimental system, developed on the basis of the test results, is transportable to remote sites.

BACKGROUND Accurate estimates of crop or forest losses from air pollutants require experimental systems that expose plants to known pollutant dosages under near-ambient environmental conditions. Because the relative humidity within the open-top exposure chambers used at present exceeds ambient conditions, such systems can overestimate potential losses.

OBJECTIVES

- To design, build, and test a prototype air-exclusion system for controlled exposure of plants to air pollutants.
- To compare plant response to exposure in that system and in open-top field chambers.

APPROACH In their design, the project group aimed at replicating ambient air temperatures, light intensities, airflow, and relative humidity in a system capable of excluding air or emitting controlled amounts of pollutants over the plant canopy. Their prototype consisted of an air-filter module, a blower for air supply, a manifold for air distribution, and perforated ducts to deliver air in target areas. Computer controls regulated and monitored air pollutant concentrations. After carbon monoxide testing had identified optimal operating parameters, they tested the system's ability to filter out ambient oxidants by comparing alfalfa grown in air-exclusion systems, open-top systems, and outside plots—four crops in 1983 and three in 1984. After modifying the prototype to provide a linear gradient, they grew winter wheat and lettuce in three levels of sulfur dioxide. They used the test results in designing a mobile air-exclusion system.

RESULTS The prototype air-exclusion system proved an effective alternative to open-top field chambers for controlled exposure of plants to air pollutants. It performed as effectively as an open-top chamber in both oxidant exclusion and sulfur dioxide addition. Environmental conditions within the systems were similar as well. Moreover, the air-exclusion system displayed several additional advantages over the open-top chambers:

- Simplicity of design and construction
- Mobility
- Ease of altering airflow over plants
- Air pollutant monitoring
- High airspeed to ensure high conductances from leaf boundary layers
- Essential similarity to outdoor plots in light intensity and relative humidity, as well as air, soil, and leaf temperatures in summer and fall
- Environmental conditions nearer to outside plots in winter and early spring
- Ability to control dew and fog deposition and guttation on leaves by altering airflow over the plant canopy

EPRI PERSPECTIVE Other projects in EPRI's subprogram on the ecological effects of atmospheric deposition have considered the effects of sulfur deposition in the Southeast, Midwest, and Northeast (RP1908-1, RP1908-2, and RP1812). A suitable experimental system has been lacking, however, for a study of the effects of sulfur deposition in the Southwest, where those effects seem to be dominated by ozone. The air-exclusion system developed in this effort now makes possible an assessment of the impact of sulfur emission in that region.

PROJECT RP1908-3
EPRI Project Manager: John Huckabee
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ABSTRACT

An air exclusion system was designed, constructed and tested to determine its effectiveness in plant air pollution studies. The system provided both reductions in ambient oxidants and additions of sulfur dioxide to a plant canopy. The system design included particulate and activated charcoal filters, pressure-type blowers, a mixing manifold, and perforated inflatable ducts which were positioned between rows of plants. Carbon monoxide tests indicated optimal system parameters for air exclusion including: air flow of at least 0.944 $m^3 s^{-1}$ within the ducts, three or four rows of holes on the side of each duct pointing 45° upward, 90° to the side, and 45° downward from the center of the duct, four ducts per system, and a hole size that provided an air velocity of 0.5 to 1.8 $m s^{-1}$ over the plant canopy.

Oxidant exclusion studies indicate that 70% reductions in ambient ozone could be achieved with the air exclusion system, which was comparable to the exclusion achieved with either open-top or closed-top chambers. The percentage oxidant exclusion could be altered by designing a system with three sections each with different sized holes. This configuration provided a linear gradient in ozone concentrations within a single system.

Alfalfa studies encompassing four harvests in 1983 and three in 1984 indicated that overall plants responded similarly in the two systems to ambient oxidants. Filtering ambient oxidants in general increased plant growth in both air exclusion systems and open top chambers. Plant growth was similar between non-filtered air exclusion systems, open top chambers and outside plots during summer harvests. In the fall, alfalfa growth was greater in open top chambers than outside plots.

Sulfur dioxide was added to a modified linear gradient system to provide treatments of 0, 79, 183 and 393 $\mu g\ m^{-3}$ sulfur dioxide for winter wheat and lettuce exposures. The sulfur dioxide as well as nonfiltered air and outside plot treatments were simultaneously repeated in open top field chambers. Scattered growth

responses attributable to sulfur dioxide were found at two harvests for each crop, however, the major plant response was substantially increased growth in open top chambers than in outside plots. Plant growth was moderately increased in air exclusion chambers compared to outside plots.

No large environmental differences were found between air exclusion systems and open top chambers versus outside plots in the summer. In the fall and winter open top chambers had higher air, leaf and soil temperatures than air exclusion systems or outside plots. Air speed over the plant canopy was higher with the air exclusion system than in open top chambers or outside plots.

Based on the previous tests a smaller mobile air exclusion was designed and tested for use at remote sites. This system provided for oxidant exclusion of alfalfa plants comparable to the exclusion with the fixed systems, but at lower cost and with greater flexibility for use.

Overall the air exclusion was shown to be an effective alternative to open top field chambers for controlled exposures of plants to air pollutants. Little environmental modification, simple maintenance and low cost further emphasized the air exclusion system as a useful technique for air pollutant studies.

ACKNOWLEDGMENTS

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The open top chambers were used with the cooperation of the California Air Resources Board, who also funded the open top chamber portion of the sulfur dioxide linear gradient study under contract A3-057-33.

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SUMMARY

An air exclusion system was designed to reduce ambient air pollutants over a plant canopy and/or to provide a means for supplying controlled levels of air pollutants to plants. The system provides an effective alternative to the use of closed or open top chambers, thus minimizing the "greenhouse effect." The system consisted of a cabinet type, positive pressure blower, particulate and activated charcoal filters, a mixing manifold, and perforated, inflatable plastic ducting. The ducting was anchored between rows of test plants. The air exclusion system was tested by adding up to 115 mg m^{-3} of carbon monoxide to the incoming airstream and determining the degree of dilution within the canopy of test plants at three different heights, 0.05, 0.25 and 0.41 m. The carbon monoxide can be determined with an accuracy of ±2.0 mg m^{-3}. The addition of this easily measured tracer gas provided much more precise measurement of either ambient air exclusion or the amount of pollutant dilution expected than is possible with ambient pollutants because the concentration of tracer is orders of magnitude greater.

Trials with the system showed that optimal parameters for ambient air exclusion with ducts 0.32 m diameter were: air flow of at least 0.944 m^3 s^{-1} within the ducts, three or four rows of holes on the side of each duct pointing 45° upward, 90° to the side, and 45° downward from the center of the duct, four ducts per system, and a hole size that provided an air velocity of 0.5 to 1.8 m s^{-1} over the plant canopy.

Oxidant exclusion studies indicate that 70% reductions in ambient ozone could be achieved with the air exclusion system, which was comparable to the exclusion achieved with open-top chambers and very nearly that with closed-top chambers. Inability to achieve 100% exclusion of ambient ozone in all systems is caused primarily by the failure of the carbon filters to effect complete removal of the pollutant. Vertical, turbulent incursion of air from outside with ducts or open top chambers was of lesser significance.

The percentage oxidant exclusion could be altered by designing a duct system with three sections each with different sized holes. This configuration provides a linear gradient in ozone concentrations within a single system where ambient oxidant occurs. To compare the performance of plants in the air exclusion system with open top chambers, alfalfa was grown for two seasons.

Four harvests in 1983 and three in 1984 indicated that, overall, plants responded similarly in the two systems to ambient oxidants. Filtering out ambient oxidants increased plant growth in both air exclusion systems and open top chambers. Plant growth was similar between nonfiltered air exclusion systems or open top chambers and in outside plots during summer harvests. In the fall, alfalfa growth was greater in open top chambers than in outside plots probably because of the higher temperatures in chambers.

The air exclusion system was modified to provide a linear gradient by injecting sulfur dioxide in three successive sections of filtered air ducts to provide 0, 79, 183 and 393 $\mu g\ m^{-3}$ between the ducts. Winter wheat and lettuce were grown for 150 and 79 days, respectively. Responses of the wheat and lettuce to these levels of sulfur dioxide were compared to plants grown in open top chambers. Plants also were grown in nonfiltered ambient air in the exclusion system or open top chambers, and outside plots. Moderate growth responses were caused by the sulfur dioxide. Low levels caused some stimulation of growth in the air exclusion system but the highest level reduced growth in the open top chambers. The greatest increase in growth was for open top chambers as compared to outside plots or air exclusion systems. Growth also was moderately greater with the air exclusion systems than in outside plots.

No large environmental differences were found between air exclusion systems and open top chambers versus outside plots in the summer. In the fall and winter open top chambers had higher air and soil temperatures than air exclusion systems or outside plots. Air speed over the plant canopy was higher with the air exclusion system than in open top chambers or outside plots when wind speeds were less than $1.8\ m\ s^{-1}$.

Based on the previous tests a smaller mobile air exclusion system was designed and tested for use at remote sites. This system provided for oxidant exclusion on alfalfa plants comparable to the exclusion with the fixed systems, but at lower cost and with greater flexibility for use.

Overall the air exclusion was shown to be an effective alternative to open top field chambers for controlled exposures of plants to air pollutants. Little environmental modification, simple maintenance and low cost emphasize the air exclusion system as a useful technique for further air pollutant studies.

Section 1

INTRODUCTION

Accurate estimates of crop or forest losses from air pollutants require experimental systems which provide known pollutant treatments under near-ambient environmental conditions. Recent ozone (O_3), sulfur dioxide (SO_2), and pollutant mixture studies have been based largely on the use of large open top field chambers to provide the pollutant treatments (1,10-15,19,21,25,32,33).

Open top field chambers provide a relatively realistic environment for pollutant exposures, however, small changes in environmental conditions have been documented. In general, open top chambers have slightly higher air temperatures, lower light intensities, and a different air flow pattern over the plant canopy compared to outside areas (8,9,15,19,21,25,36). Chamber air flow is generally low, but constant. Boundary layer conductance of gases between the atmosphere and stomata on leaves can be low if chamber air flow rates are high enough to provide for leaf flutter and prevention of large air temperature increases. Under optimum conditions boundary layer conductances in chambers may actually be greater than in outside areas (34-35).

Relative humidity has been suspected to be higher in open top chambers than outside areas, however, there has been little experimental data to address this concern. Olszyk et al. (21) found water vapor evaporation to be 10% lower in chambers than outsdie areas, suggesting that there may be more water vapor in chambers than outside. In contrast Weinstock et al. (36) reported a 5-10% lower relative humidity in open top chambers than outside areas, possibly related to a higher chamber air temperature.

Relative humidity is of particular concern as previous studies have shown that increased humidity can double the amount of injury caused by either ozone or sulfur dioxide with a given exposure (6,23,28). This finding is important as the amount of crop damage suffered in the humid eastern United States, where levels of ozone are much lower than in the more arid West but degree of injury is similar. This information suggests that open top chamber studies can overestimate losses if relative humidities do not reflect ambient conditions. Comparisons of crop yield in nonfiltered chambers versus outside areas have demonstrated a "chamber effect" on plant response which can confound the determination of pollutant effects in controlled studies. In the United States Environmental Protection Agency's National Crop Loss Assessment (NCLAN) studies, peanuts showed a significant reduction in yield and wheat and turnips showed significant increases in yield in open top chambers versus outside plots (11,12).

Use of various modified open top structures in an attempt to reduce the "chamber effect" represents at best a partial solution. A fluid dynamic study of several chamber configurations, funded by the U. S. Department of Energy, tried to define factors which control the ingress of outside air into various shaped structures and devise means of minimizing this effect while attempting to attain field conditions (16). This work defined some of these parameters and found that a number of tradeoffs exist; (a) total exclusion of outside pollutants is virtually impossible in open top walk-in cylinders because the energy of wind is several fold greater than air which can be injected at the bottom by reasonably sized fans; (b) reducing the size of top opening of cylinders excludes outside air but defeats the original purpose; (c) wall effects occur in these structures as in conventional chambers; and (d) culture of plants in either pots or these restricted areas is different from the field. Modifications of the top of the chamber with baffles, truncated cones or horizontal strips showed that by increasing the chamber height of an open 3 m dia cylinder by 0.6 m with a "snow fence" of vertical plastic ribbons reduced the ingress of outside air much better than the other designs but maintained the open top structure.

Because of the limited success of these prior efforts, a nonchamber exclusion system was utilized by Jones et al. (7), Shinn et al. (29) and Laurence et al. (18) in attempts to overcome several of the problems of either closed top or open chambers. Jones et al. (7) attempted to exclude sulfur dioxide ladened air from soybeans by installing plastic, perforated tubes between the crop rows. Carbon filtered air was then blown out through and over the plants to protect from sulfur dioxide during periods when a power plant plume came to ground level. Shinn et al. (29) used the same design with pinto beans but increased the size of holes in the ducting continuously along the ducts. There were small holes near the blower and gradually enlarged holes farther down the duct to provide a "linear gradient" of exposure to the plants. Shinn et al. (29) also used a vertical plastic wall around the plots 0.6 m high but this had little effect on air exclusion. Laurence et al. (8) and Reich et al. (24) used perforated polyethylene tubes placed between rows of plants subjected to ozone, sulfur dioxide or hydrogen fluoride exposures.

None of the previous above "air exclusion" systems were developed to its full capacity as a technique for air pollutant studies. Jones et al. (7) had only limited success in excluding ambient sulfur dioxide throughout the soybean canopy in part because most of the air was directed up and over the plants. Bennett et al. (4) and Shinn et al. (29) used air exclusion systems primarily to expose plants to a mixture of carbon dioxide, hydrogen sulfide, methane, and nitrogen, and did not develop their systems to fully exclude ambient pollutants. Laurence et al. (18) also used an air exclusion system primarily to provide sulfur dioxide or hydrogen fluoride exposures. Their group did use an air exclusion system in a limited study of different levels of ambient oxidant exclusion versus sulfur dioxide addition. However, flow rates with different sized holes for variable air exclusion were not fully investigated. None of the previous research groups have reported large scale air pollutant studies using the air exclusion system in spite of its potential for research. Instead, all three groups have terminated further air exclusion system design studies.

Thus there is a great need to develop optional air pollutant exposure systems for both evaluation of the true chamber effect with open top field chambers, and as an alternative exposure system for specific vegetation needs. Air exclusion systems also have the potential for greater mobility and lower cost than open top chambers. In particular, an alternative air exclusion system could be used in fact to "calibrate" the air pollutant crop response curves generated as part of the NCLAN study. In this respect, air exclusion systems could be used not to necessarily replace open top chambers in NCLAN research, but rather to provide a means for evaluation of the precision of the NCLAN crop loss functions.

Air exclusion systems could also provide a standard procedure for air pollution studies with plants growing in environments where chamber effects would be accentuated for open top chambers. For example, open top chambers would have relatively warm temperatures under summer desert conditions or during cool winter months compared to outside plots. Chambers could also have unusual moisture deposition patterns under dew, mist or rain.

In order to investigate the full feasibility of an air exclusion system for air pollutant studies, a two-year research project was carried out by the Statewide Air Pollution Research Center of the University of California, Riverside, under contract to the Electric Power Research Institute. Primary objectives of the project were to:

1. To design, build and test a prototype air exclusion system based on the original design of Jones et al. (7).

2. Determine the maximum extent of air exclusion possible for the system.

3. Compare air exclusion rates and physical environmental conditions for air exclusion systems versus NCLAN design open top chambers.

4. Evaluate plant response with air exclusion system versus open top field chamber exposures.

5. Determine feasibility of using the air exclusion system to provide a linear gradient of ambient oxidant pollutant levels or a linear gradient of added sulfur dioxide pollutant concentrations.

6. Compare air exclusion systems to closed top chambers utilized by the California Department of Food and Agriculture in their California Crop Loss Study.

7. Evaluate physiological responses of plants with air exclusion versus chamber air pollutant exposures.

8. Design a prototype mobile air exclusion system for use at remote sites.

Information relative for objectives 1, 2, 3 and 5 is presented in Section 2 of this report; for objectives 3 and 6 in Section 3; for objectives 4, 5, 6 and 7 in Section 4; and for objective 8 in Section 5.

Section 2

AIR EXCLUSION SYSTEM DESIGN AND TESTING

All of the system design studies focused on procedures for ensuring a high enough air flow around plants to exclude ambient air pollutants and, thus, provide a known "control" or close to zero pollutant background treatment. Different levels of air exclusion and addition of sulfur dioxide all were added upon this "zero" pollution background to provide desired known pollutant concentration exposures. In order to optimize the degree of exclusion of the ambient pollutants, a number of air flows and configurations of perforations were tested.

METHODS

Air Exclusion System Construction

The air exclusion system consisted of four major components: a module containing the filters, a blower for air supply, a manifold for air distribution, and perforated air ducts to deliver the air in the target area (Figure 2-1).

The filter module was fabricated of galvanized sheet metal and constructed to contain three Barnebey Cheney 7M activated carbon filters (Figure 2-2). These filters (corrugated design), measured 0.61 l x 0.61 w x 0.22 h m and contained 20.4 kg of 6 mesh coconut charcoal. The carbon filters were protected from dust with glass furnace filters and strainer mats.

The blower was a 2 hp, three-phase Peerless Electric utility blower, Model 150. The blower wheel had a diameter of 0.8 m and backward curved blades. The motor pulley was adjustable to vary rates of air delivery. Free air delivery was between 0.944 and 1.888 m^3 per second.

For the initial test of the system the manifold consisted of a 1.82 x 0.61 x 0.61 m box with three short galvanized exhaust ports for attaching the plastic ducts. Butterfly valves were installed in the exhaust port to equalize the flow rate in the three ducts.

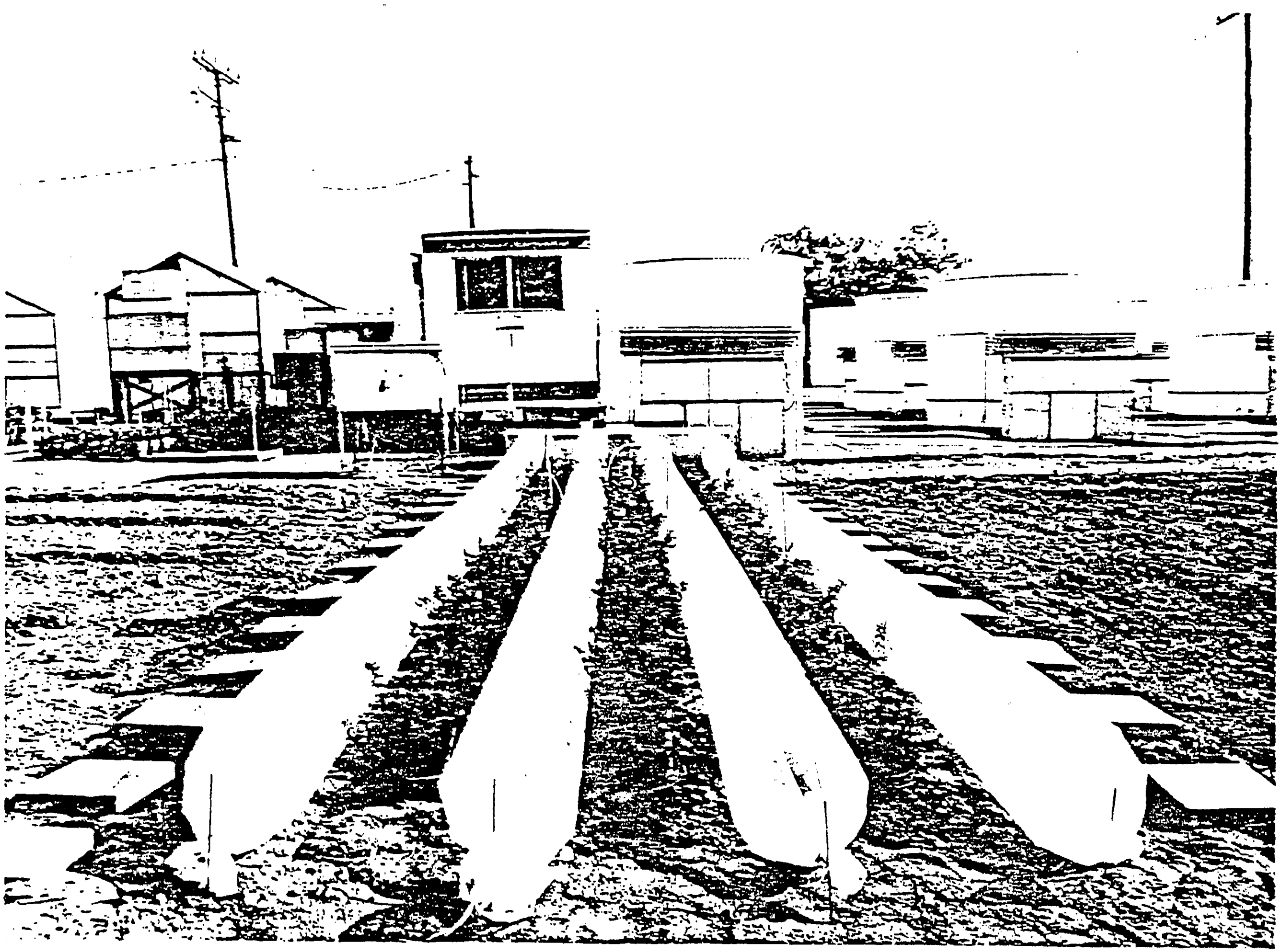


Figure 2-1. Photograph is of four-duct system in foreground, with blower box and trailer with instruments in background.

The air ducts consisted of 0.254 m flat diameter Layflat® polyethylene tubing with a material thickness of 0.0001 m. Perforations of 0.022 m diameter were cut using an electrically heated nichrome loop while the ducts were inflated. The ducts were stabilized in place by laying a piece of 0.02 m diameter galvanized steel tubing lengthwise within each duct. This prevented flapping of the inflated ducts in the wind even under high (>13.4 m s^{-1}) wind speed. The ends of the ducts were tied with string to create a horizontal balloon when inflated.

The physical parameters of the system (e.g., flow rate, number of perforations and placement of the holes) were varied during the test period aiming for maximum exclusion of outside pollutants. The duct systems were oriented perpendicular to the westerly prevailing wind at Riverside, California.

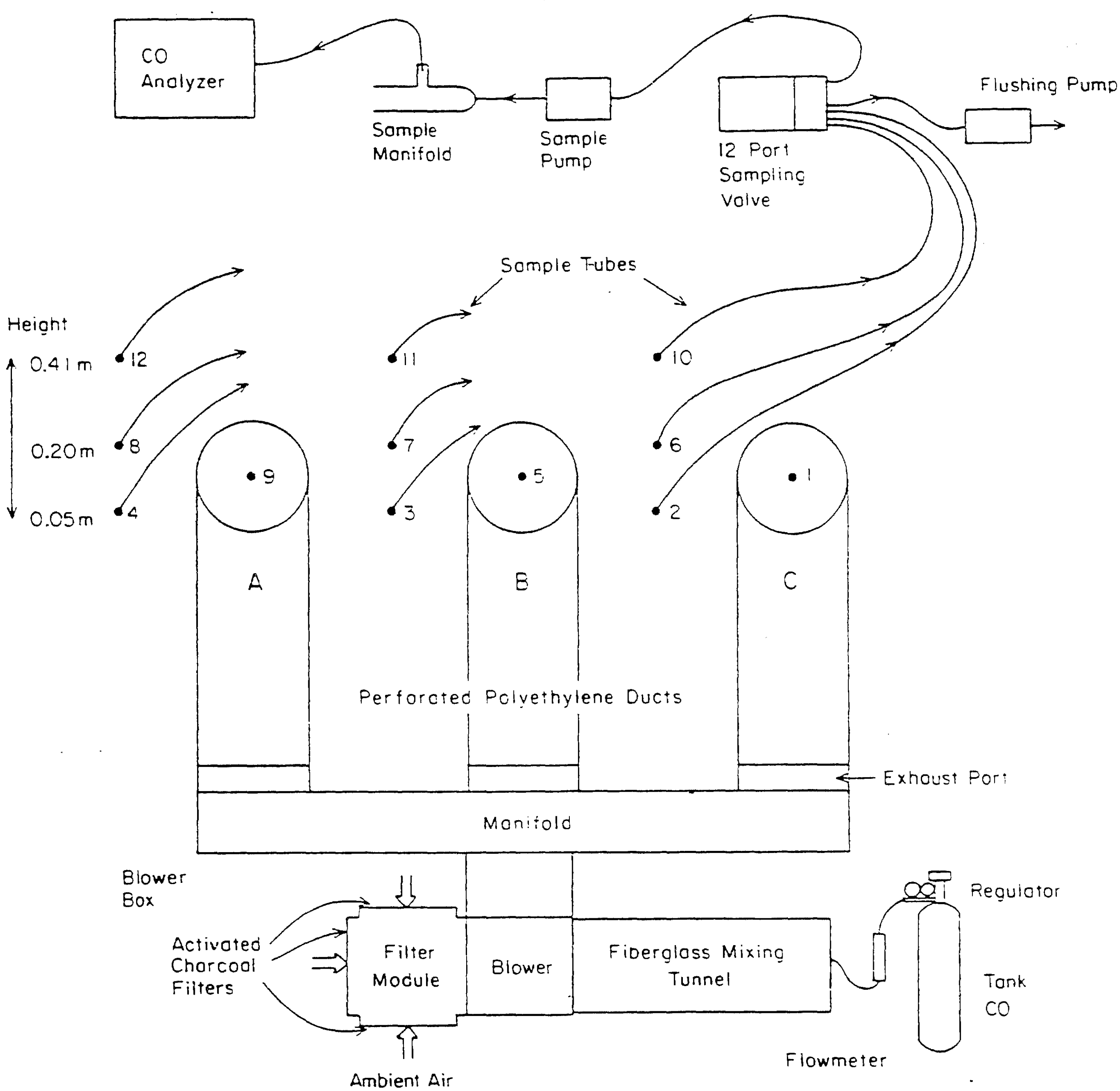


Figure 2-2. Diagram of three duct air exclusion system and pollutant sampling system. Ducts A, B and C correspond to ducts 1, 2 and 3 in Figure 2-3, A through E.

Carbon Monoxide Test Procedure

Since a polluted atmosphere was not always available or concentrated enough to test the system, a method using carbon monoxide (CO) as a tracer gas was developed. Carbon monoxide was convenient because it is cheap, readily available in large cylinders, easy to measure, and the site where we were operating had a low background ambient concentration of this pollutant. Carbon monoxide (99.5%

purity from Liquid Carbonic Co.) was metered through a flow meter; FP-1/4-10-G-5 (Fisher and Porter) into the air stream upstream from the blower. After dilution with the incoming air, the concentration of carbon monoxide was measured inside the ducts with a carbon monoxide analyzer (Ecolyzer Model 2700 UC, Energetics Science, Inc.). The quantity of carbon monoxide metered into the blower was adjusted before a system test so the duct concentration would be in the upper part of the 0-115 mg m^{-3} scale.

The carbon monoxide concentration was measured in each duct to guarantee that the carbon monoxide had properly mixed with the air before entering the ducts. If not equal the point of injection was increased upstream of the blower using a fiberglass tunnel. Since the rate of detection is proportional to the rate of air flow, the following equation was applied for the determination of the flow rate:

$$C = \frac{B}{A}$$

where

A = Carbon monoxide concentration in target area e.g., duct (mg m^{-3})

B = Carbon monoxide flow injected from into system through mixing tunnel (mg s^{-1})

C = Air flow rate (m^3 s^{-1})

The quantity B is determined by multiplying the flowmeter measurement (m^3 s^{-1}) x tank concentration of carbon monoxide (1.15 kg m^{-3} x 0.995 purity). All carbon monoxide concentration values were originally measured in ppm units.

Once the duct concentration of carbon monoxide was known, the percent depletion of carbon monoxide in ambient air could be determined by the formula:

$$\text{Carbon monoxide depletion (\%)} = \frac{\begin{array}{c}\text{Carbon monoxide}\\ \text{concentration at sampling point}\end{array}}{\begin{array}{c}\text{Carbon monoxide}\\ \text{concentrations in duct}\end{array}}$$

The carbon monoxide concentration in the duct was the average of carbon monoxide at points 1, 5 and 9 inside the ducts (Figure 2-2). The carbon monoxide depletion was equal to the percentage exclusion of atmospheric oxidants with filtered air, assuming that dilution of air between the ducts of the added carbon monoxide was the same as dilution of ambient oxidants.

The speed for air leaving each hole ($m\ s^{-1}$) was estimated by dividing the duct flow rate ($m^3\ s^{-1}$) by the hole area per meter of duct (m^2).

A sample system was constructed to continuously measure the critical carbon monoxide levels in this system (Figure 2-2). Twelve sample points were established: three inside the ducts and three groups of three between the ducts. Outside samples upwind were taken before and after tests. These background levels were subtracted from those measured in the ducts but were often less than one microgram per m^3. The three sample points between the ducts were at 0.05, 0.20 and 0.41 m above the ground. All sample points were sequentially sampled using a 12 point valve (Samplivalve by Scanivalve). The valve controller could be programmed to sample continuously at any interval desired. Sampling time per point was at least 300 s. A flushing pump kept all lines flushed continuously and a sample pump was used to lead a sample to a small manifold and subsequently to the analyzer.

SINGLE LEVEL SYSTEM

Initial Carbon Monoxide Tests

Initially three polyethylene ducts were installed and perforated with holes of 0.022 m diameter. The number of holes and the pattern of the perforations varied between tests. The different hole orientations used are illustrated in Figure 2-3. The flow rate through the system was always approximately 0.944 $m^3\ s^{-1}$. The flow rates per unit length of duct was varied by varying the length of the ducts. The initial length of the duct was 32.0 m with holes starting 1.52 m from the beginning of the ducts. The sampling points were located in the center of the ducts. Testing took place only when the prevailing wind was perpendicular to the direction of the ducts. The ducts were 0.254 m in diameter when inflated.

Tables 2-1 through 2-4 indicate percent ambient air exclusion for different tests. The tests were carried out using different numbers of holes, different orientation of the holes and different flow rates per unit length of duct. Each configuration was tested two to six times when ambient wind speed was 0 to 2.2 m s^{-1} with representative runs shown in the tables.

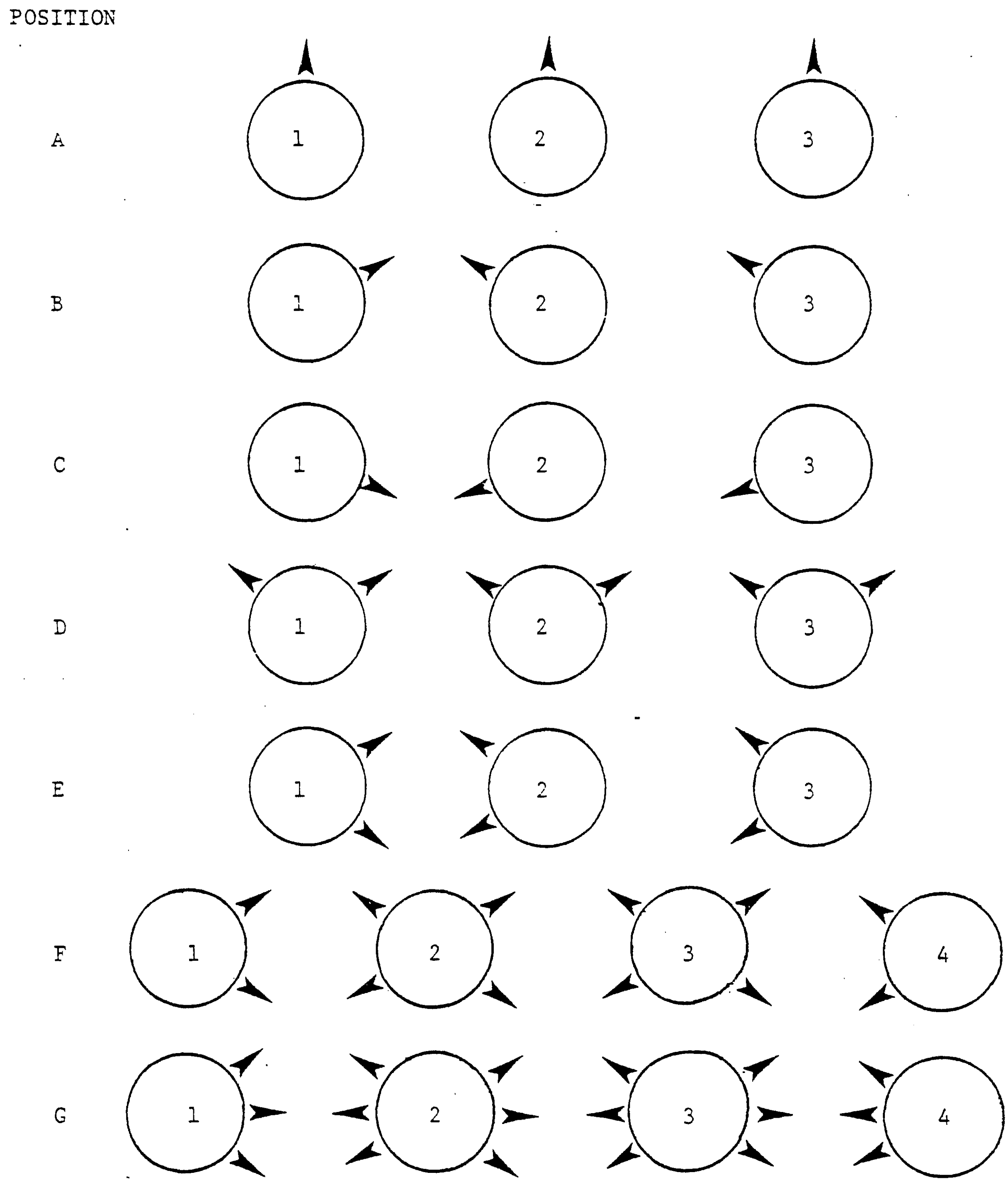


Figure 2-3. Diagram of hole positions for seven different duct configurations. Positions A-E were for 3-duct system, positions F and G for four-duct system. Each ▲ indicates a direction of air flow from holes.

Table 2-1

AIR EXCLUSION CARBON MONOXIDE TEST RESULTS USING ONE ROW OF HOLES 0.15 m APART PER DUCT

	In Duct			Air Exclusion (%)		
Hole Position[a]	Flow rate[b] ($m^3\ s^{-1}$)	Carbon Monoxide[c] ($mg\ m^{-3}$)	Sampling Height (m)	Outside Duct 1	Between Ducts 1+2	Between Ducts 2+3
A	0.010	77	0.05	3	5	2
			0.20	3	5	3
			0.41	5	5	0
B		84	0.05	8	7	1
			0.20	7	7	1
			0.41	3	1	3
C		87	0.05	7	37	39
			0.20	7	28	13
			0.41	7	3	1
B	0.016	91	0.05	6	15	10
			0.20	10	18	6
			0.41	6	9	0
C		87	0.05	15	59	26
			0.20	13	53	16
			0.41	13	13	7

[a]As shown in Figure 2-3.

[b]Per linear meter of duct. Air speed per hole was 4.09 and 6.21 m s^{-1} for flow rates of 0.010 and 0.016 $m^3\ s^{-1}$, respectively.

[c]Average of sampling points 1, 5 and 9 within ducts 1, 2 and 3, respectively.

Table 2-2

AIR EXCLUSION CARBON MONOXIDE TEST RESULTS USING ONE ROW OF HOLES 0.076 m APART PER DUCT

	In Duct			Air Exclusion (%)		
Hole Position[a]	Flow rate[b] ($m^3\ s^{-1}$)	Carbon Monoxide[c] ($mg\ m^{-3}$)	Sampling Height (m)	Outside Duct 1	Between Ducts 1+2	Between Ducts 2+3
A	0.010	82	0.05	13	4	10
			0.20	4	14	13
			0.41	9	11	17
B		81	0.05	11	4	11
			0.20	10	21	16
			0.41	6	4	1
C		87	0.05	20	53	33
			0.20	21	43	21
			0.41	16	15	13
A	0.016	82	0.05	14	6	14
			0.20	10	16	9
			0.41	11	14	13
B		79	0.05	17	9	17
			0.20	19	41	23
			0.41	21	9	0
C		81	0.05	27	63	33
			0.20	21	50	13
			0.41	29	16	4

[a]As shown in Figure 2-3.

[b]Per linear meter of duct. Air speed per hole was 1.99 and 3.10 m s^{-1} for flow rates of 0.010 and 0.016 $m^3\ s^{-1}$, respectively.

[c]Average of sampling points 1, 5 and 9 within ducts 1, 2 and 3, respectively.

Table 2-3

AIR EXCLUSION CARBON MONOXIDE TEST RESULTS USING TWO ROWS OF HOLES 0.076 m APART PER DUCT IN 45° UPWARD POSITION[a]

In Duct			Air Exclusion (%)		
Flow rate[b] ($m^3\ s^{-1}$)	Carbon Monoxide[c] ($mg\ m^{-3}$)	Sampling Height (m)	Outside Duct 1	Between Ducts 1+2	Between Ducts 2+3
0.043	100	0.05	14	31	30
		0.20	16	29	29
		0.41	23	36	37

[a]As shown in position D, Figure 2-3.

[b]Per linear meter of duct. Air speed per hole was 4.34 $m\ s^{-1}$.

[c]Average of sampling points 1, 5 and 9 within ducts 1, 2 and 3, respectively.

Table 2-4

AIR EXCLUSION CARBON MONOXIDE TEST RESULTS USING TWO ROWS OF HOLES 0.15 m APART PER DUCT IN 45° UPWARD AND DOWNWARD POSITIONS[a]

In Duct			Air Exclusion (%)		
Flow rate[b] (m^3 s^{-1})	Carbon Monoxide[c] (mg m^{-3})	Sampling Height (m)	Outside Duct 1	Between Ducts 1+2	Between Ducts 2+3
0.010	78	0.05	12	47	29
		0.20	16	29	19
		0.41	10	9	7
0.016	84	0.05	14	53	34
		0.20	11	52	23
		0.41	18	8	15
0.020	94	0.05	17	70	61
		0.20	13	49	37
		0.41	18	24	17
0.039	99	0.05	17	83	48
		0.20	24	79	51
		0.41	23	64	38

[a]As shown in position E, Figure 2-3.

[b]Per linear meter of duct. Air speed per hole was 2.01, 3.04, 4.02 and 7.73 m s^{-1} for flow rates of 0.010, 0.016, 0.020 and 0.039 m^3 s^{-1}, respectively.

[c]Average of sampling points 1, 5 and 9 within ducts 1, 2 and 3, respectively.

The results indicated that air exclusion was low with a single row of holes oriented straight up or at a 45° angle up (hole position A or B, respectively, in Tables 2-1 and 2-2). The maximum exclusion of 14 to 41% was obtained at the medium (0.20 m) sampling points between ducts 1 and 2 or 2 and 3. This was considerably less than the 85% exclusion claimed by previous researchers (7). Jones et al. (7) had used a similar design duct system with 0.025 m diameter holes placed 0.305 m apart in three rows per duct. The rows were oriented toward the top and 45° up on the ducts, i.e., a combination of positions A and O on Figure 2-3. However, their exclusion tests were made with a high level of added sulfur dioxide (1100 to 3670 μg m^{-3}) emitted into ambient air near the systems.

There was no determination of percent air exclusion with the lower ambient sulfur dioxide concentrations which occurred during actual field usage of the system.

Downward facing holes (Position C in Figure 2-3) resulted in greater air exclusion than upward facing holes. Near the ground surface (0.05 m), air exclusion reached as much as 63% (Tables 2-1 and 2-2). The percent exclusion decreased with increasing height to 4 to 29% at 0.41 m. Thus, downward facing holes apparently can alleviate the trapping of air pollutants near the ground surface which results from the use of upward facing holes (7).

Two rows of upward facing holes per duct resulted in up to 37% air exclusion between ducts (Table 2-3). The percent exclusion did not vary greatly with height either between or outside of the ducts.

The combination of downward and upward facing holes resulted in the greatest air exclusion (Table 2-4). The air exclusion system achieved up to 64 and 83% exclusion at heights of 0.41 and 0.05 m, respectively, with the highest in duct flow rate.

The percent air exclusion increased greatly with increased in-duct air flow rate. Air exclusion was at least doubled with an increased flow rate from 0.010 0.016 m^3 s^{-1} and one row of 0.15 m apart holes (Table 2-1). Air exclusion also was increased with increased flow rate in 0.076 m apart ducts, however, the increase averaged only about 50% (Table 2-2). With two rows of upward and downward holes percent air exclusion increased approximately 40, 100 and 175% between ducts with 60, 100 and 390% increases in flow rate above 0.010 m^3 s^{-1} (Table 2-4). Air exclusion did not increase as much outside duct 1 as between ducts 1+2 or 2+3.

More holes per linear meter of duct resulted in an increase in air exclusion, even though the flow speed per hole was reduced. Air exclusion generally was doubled with 0.076 m apart holes (Table 2-2), compared to 0.15 m apart holes (Table 2-1).

1983 System Tests. Based on the results from the initial CO tests, a more permanent air exclusion system was designed for use with alfalfa plants. A number of changes were made in the system using the earlier results as a guideline. The blower and filter module remained the same. This time four blower units were used in order to employ four systems for field testing. New manifolds were designed and fabricated from 20 gauge galvanized sheat metal. Each manifold consisted of a rectangular box of 0.46 x 0.46 x 0.24 m with four 15.0-m long exhaust tubes with an inflated diameter of 0.318 m. The distance between the tubes was 0.41 m. Baffles were installed inside the manifold to promote a more symmetric air flow to the ducts. The new ducts were made from Layflat polyethylene tubing with a material thickness of 1.016×10^{-4} m.

The duct design used holes 0.15 m apart within and between rows, resulting in 19.7 holes per linear m of duct. This hole number allowed for a more uniform flow of filtered air into the canopy than either single or double row systems, even with a lower frequency of 0.076 m between holes. The air flow within the ducts was adjusted at the manifold to provide the same air flow speed from holes in each duct. This necessitated a flow rate twice as high in center ducts 2 and 3 than outside 1 and 4 (Figure 2-3, F and G), because the number of holes was twice as high in the center versus outside ducts.

Initially two rows of holes, facing 45% upward and 45% downward were used (Figure 2-3, F). With a flow rate of 0.023 m s^{-1} in the duct, 35 to 77% air exclusion was achieved with this configuration (Table 2-5).

The final system design had three rows of holes. The previous pattern of two rows of holes, facing 45° upward and 45° downward, respectively, was used; with

Table 2-5

AIR EXCLUSION CARBON MONOXIDE TEST RESULTS USING A FOUR DUCT, TWO ROW SYSTEM[a]

Carbon Monoxide[b] (mg m^{-3})	Height (m)	Air Exclusion (%) Between Ducts 1+2	Air Exclusion (%) Between Ducts 2+3	Air Exclusion (%) Between Ducts 3+4
79	0.05	61	77	59
	0.25	42	55	45
	0.41	35	38	37

[a]As shown in Figure 2-3, F. Approximate flow rates are 0.023 and 0.046 m^3 s^{-1} in ducts 1, 4 and 2, 3, respectively. Air speed per linear meter of duct. Air speed per hole was 4.61 m s^{-1}.

[b]Average of four sampling points, each of ducts 1 through 4.

the addition of another row in between facing 90^{o} in relation to the normal (Figure 2-3, G). Within the rows the holes were spaced at 0.15 m as previously. The outside ducts 1 and 4 had three rows and B and C six rows of holes. The most important reason for this alteration was to enhance diffusion of the air flowing through the plant canopy and to alleviate any pollutant trapping near the ground.

The exclusion potential of this system was tested using three different air velocities per unit length of duct. The different velocities were established by varying the length of the ducts between tests. In an initial test carbon monoxide was injected in each of the four ducts of a system and the concentration measured at an adequate distance in order to guarantee complete mixing.

By calculation of the dilution rate it was established that the flow rate within each of the four ducts was proportional to the number of perforations. Duct 2 and 3 had twice the flow rate when compared to ducts 1 and 4 (Figure 2-3, G).

To determine the exclusion characteristics of the system a network of sample points was established. Four sample points were inside the ducts and between each row were three points at 0.05, 0.20 and 0.41 m height.

The results of Table 2-6 show that at a flow rate of 0.023 $m^3\ s^{-1}$ per linear m of duct the performance is quite similar to that of the three duct system at 0.020 $m^3\ s^{-1}$ as previously described. Increasing flow rates again resulted in increasing exclusion, at a rate similar to that with the two row system. However, air diffusion over the canopy was better when using three rows of holes instead of two rows. Therefore a blower system as described using four ducts with an effective length of 9.1 m and three rows of holes on the effective side of the ducts was used in the following experiments.

For the oxidant exclusion tests an experiment was designed comparing alfalfa plant responses in filtered versus nonfiltered air exclusion systems, filtered versus nonfiltered open top chambers, and outside plots (Figure 2-4). Outside plots were of two designs, linear rows of pots buried in the ground to correspond to air exclusion treatments, and linear rows raised above the ground and surrounded by wood shavings to correspond to the open top chamber treatments. Each treatment was replicated in two plots. The experiment was continued over three summer harvests, and a fourth fall harvest which was part of the oxidant linear gradient study (Table 2-7).

Table 2-6

AIR EXCLUSION CARBON MONOXIDE TEST RESULTS USING A FOUR DUCT, THREE ROW SYSTEM[a]

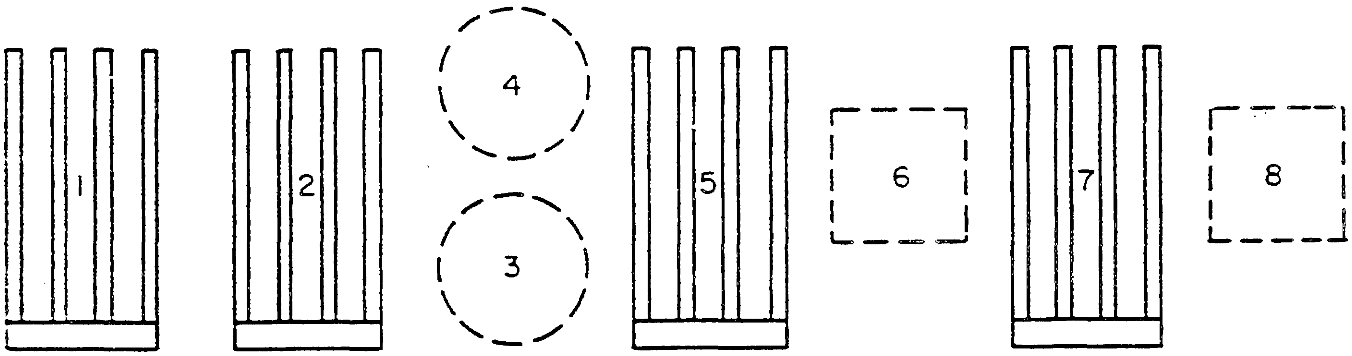
Flow Rate[b] ($m\ s^{-1}$)	Carbon Monoxide[c] ($mg\ m^{-3}$)	Height (m)	Air Exclusion (%) Between Ducts 1+2	Between Ducts 2+3	Between Ducts 3+4
0.025	72	0.05	71	65	68
		0.25	58	52	52
		0.41	36	32	29
0.035	78	0.05	79	82	77
		0.2	75	68	68
		0.41	47	47	41
0.044	73	0.05	83	82	79
		0.25	86	70	69
		0.41	51	53	60

[a]As shown in Figure 2-3, G.

[b]Per linear meter of duct. Air speed per hole was 3.34, 4.68 and 5.88 $m\ s^{-1}$ for flow rates of 0.025, 0.035 and 0.044 $m\ s^{-1}$, respectively.

[c]Average of four sampling points, 1 in each of ducts 1 through 4.

The open top field chambers were of the National Crop Loss Assessment (NCLAN) design (8,10) as modified by Kats et al. (16). The chambers were cylindrical, and 3 m in diameter by 2.43 m in height. They consisted of a rolled aluminum frame covered by clear PVC film. The cylinder was divided into an upper half covered by one layer of film, and a lower half covered by an inflatable double layer of film. The inner wall of the lower chamber was covered by 0.03 m diameter holes, positioned in 6 rows, with 0.15 m between holes in a row and 0.15 m between rows. The chamber had a cone shaped baffle at the top (16), that effectively reduced the chamber opening by 50%. This baffle reduced entrance of ambient air into the chamber. Each chamber was equipped with a blower assembly consisting of a 1.52 x 0.60 x 0.62 m sheet metal blower box, 3/4 hp ILG propeller fans, fiberglass particulate filter, corrugated activated charcoal filters, and vinyl connecting duct between blower box and chamber.



TREATMENTS

SYSTEM	AIR	PLOTS
Air Exclusion	Filtered	1, 2
Air Exclusion	Nonfiltered	5, 7
Outside-Linear	Nonfiltered	6, 8
Chamber	Filtered	10, 11
Chamber	Nonfiltered	9, 12
Outside-Circular	Nonfiltered	3, 4

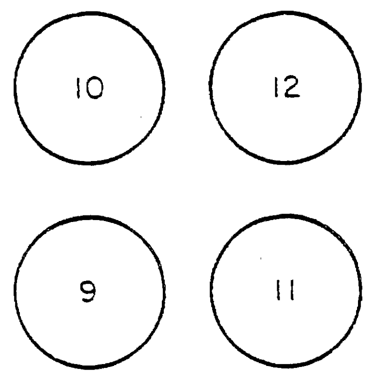


Figure 2-4. Diagram of experimental design for 1983 alfalfa single level air exlusion tests. There were three rows of 10 plants each per plot.

Photochemical oxidants were measured as ozone using a Dasibi Model 1003 AH ozone analyzer calibrated with a Dasibi Model 1003 AH transfer standard maintained by the California Air Resources Board in El Monte, California.

Oxidant exclusion ranged from approximately 50 to 75% in air exclusion systems depending on ambient ozone concentration (Table 2-7). For the first harvest there was the lowest percent air exclusion and relatively low ozone concentrations. The percent exclusion also was one-fourth lower in filtered air exclusion systems than filtered open top chambers. For the second and third harvests oxidant exclusion improved in the air exclusion systems and was as efficient as in open top chambers.

At the fourth harvest oxidant exclusion was approximately 70% in both air exclusion systems and open top chambers (Table 2-7). This high exclusion was apparent in exclusion systems even though ambient ozone was low, primarily because data for the comparisons was from the high flow portion of the linear gradient exclusion system.

Table 2-7

EXPERIMENTAL PARAMETERS FOR DIFFERENT ALFALFA HARVESTS

Harvest	Dates	System	Ozone[a] ($\mu g\ m^{-3}$) Filtered	Nonfiltered	Percent Exclusion[b]
			1983		
First	7/8-7/29	Air exclusion	51.0	103.9	51
		Open top	33.3	105.8	68
		Outside	-	103.9[c]	-
Second	7/30-8/23	Air exclusion	64.7	178.4	64
		Open top	62.5	170.5	65
		Outside	-	178.4[c]	-
Third	8/24-9/19	Air exclusion	52.9	174.4	68
		Open top	52.9	188.2	68
		Outside	-	167.6	-
Fourth	9/20-10/30	Air exclusion[d]	26.5	95.1	69
		Open top	22.5	93.1	74
		Outside	-	86.2	-
			1984		
First	6/4-6/18	Air exclusion	41.2	160.7	77
		Open top	43.1	150.9	76
		Closed top	37.2	156.8	79
		Outside	-	176.4	-
Second	6/19-7/12	Air exclusion	52.9	166.6	69
		Open top	33.3	135.2	81
		Closed top	37.2	164.6	78
		Outside	-	170.5	-
Third	7/13-8/7	Air exclusion	39.2	113.7	69
		Open top	29.4	117.6	77
		Closed top	21.6	103.9	83
		Outside	-	126.8	-

[a]Average ozone concentration between 0600 and 2200 in 1983, and 0800 and 2000 in 1984 for time period indicated. Outside nonfiltered average is used for all outside plots. Sampling height of 0.25 m in 1983 and 0.15 m in 1984.

[b]Filtered system versus outside.

[c]Used nonfiltered air exclusion data to indicate outside averages to indicate outside averages.

[d]Data is for high air flow air exclusion systems.

Oxidant exclusion in air exclusion systems decreased with increased sample height (Table 2-8). The greatest exclusion was always just above the ground surface, where ozone concentrations were always less than 30% of outside plots. The percentage air exclusion was decreased by at least one-third with increased sample height to 0.36 or 0.41 m.

Table 2-8

OXIDANT EXCLUSION FOR DIFFERENT SAMPLING HEIGHTS IN AIR EXCLUSION SYSTEMS

			Ozone Exclusion (%)[a]		
Harvest[b]	Sample Height (m)	Outside Ozone ($\mu g\ m^{-3}$)	West Row	Middle Row	East Row
1983 - First	0.05	176	56	78	67
	0.25	196	50	40	30
	0.41	196	50	50	60
1983 - Second	0.05	-	55	75	71
	0.25	179	46	64	55
	0.41	-	39	43	42
1983 - Third	0.05	-	-	71	-
	0.25	174	79	67	67
	0.41	-	-	50	-
1984 - First	0.05	-	-	77	-
	0.15	-	-	77	-
	0.25	137	-	69	-
	0.36	-	-	57	-
1984 - Second	0.05	-	-	73	-
	0.15	-	-	71	-
	0.28	192	-	59	-
	0.36	-	-	45	-
1984 - Third	0.05	-	-	73	-
	0.15	-	-	71	-
	0.25	157	-	61	-
	0.36	-	-	50	-

[a]Filtered air exclusion system.

[b]1983 data is for one system, 1984 data is for two systems.

Sample height had no effect on oxidant exclusion in the open top field chambers (Table 2-9). The oxidant exclusion was approximately the same at all three heights in the chambers, for both the third and fourth harvests in 1983.

Table 2-9

OXIDANT EXCLUSION FOR DIFFERENT SAMPLING HEIGHTS IN OPEN TOP CHAMBERS

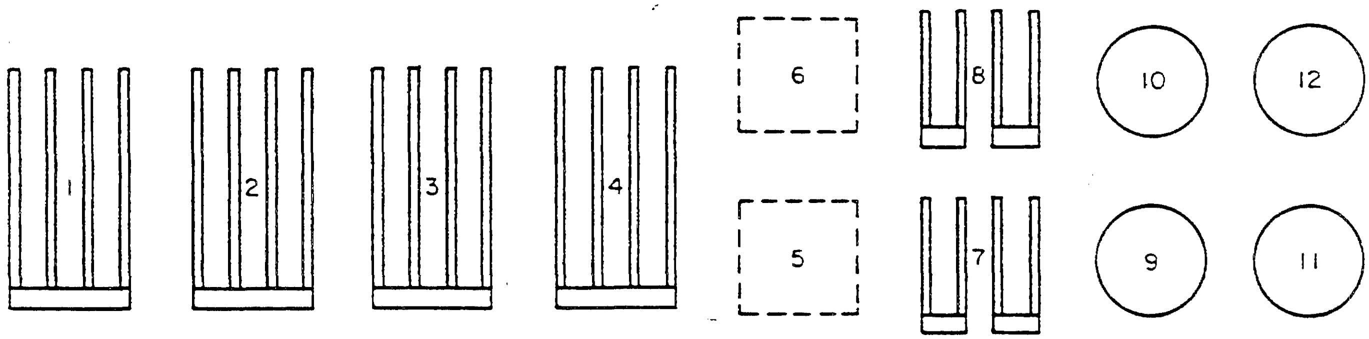
Harvest	Height (m)	Outside Ozone ($\mu g\ m^3$)	Ozone Exclusion (%)[a]
1983 - Third	0.05	-	75
	0.25	194	74
	0.41	-	75
1983 - Fourth	0.05	-	80
	0.25	98	78
	0.41	-	80

[a]For one filtered chamber or outside area.

1984 System Tests. For the 1984 oxidant exclusion tests an experiment was designed comparing alfalfa plant responses in filtered versus nonfiltered air exclusion systems, open top chambers, closed top chambers, and outside plots (Figure 2-5). Each treatment occurred in two plots. The experiment was continued over three harvests of alfalfa (Table 2-5).

The air exclusion systems had the same basic duct hole configuration as for the sulfur dioxide addition study (Figure 2-6, B). However, the metal baffles were removed leaving single 14.63 m long ducts with 0.91 m left without holes at the blower end.

With the assistance of a diecutting service (T.N.S. Diecutting Inc.), a simple die module was designed and fabricated to perforate ducts with large numbers of small holes according to our specifications. The total hole area per unit length of duct was calculated to be equal to that of the previously used ducts. The new pattern had four rows of holes with a diameter of 0.011 m. The outside rows were placed to point 45^{o} upward and 45^{o} downward, respectively, after inflation of the



TREATMENTS

SYSTEM	AIR	PLOTS
Air Exclusion – Fixed	Filtered	3, 4
Air Exclusion – Fixed	Nonfiltered	1, 2
Air Exclusion – Mobile	Filtered	7
Air Exclusion – Mobile	Nonfiltered	8
Outside	Nonfiltered	5, 6
Open Top Chamber	Filtered	9, 10
Open Top Chamber	Nonfiltered	11, 12
Closed Top Chamber	Filtered	13, 14
Closed Top Chamber	Nonfiltered	15, 16

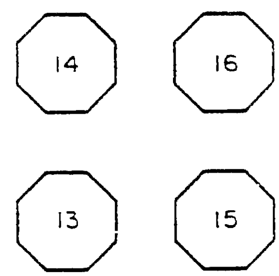


Figure 2-5. Diagram of experimental design for 1984 alfalfa single level air exclusion tests. There were three rows of seven plants each per plot.

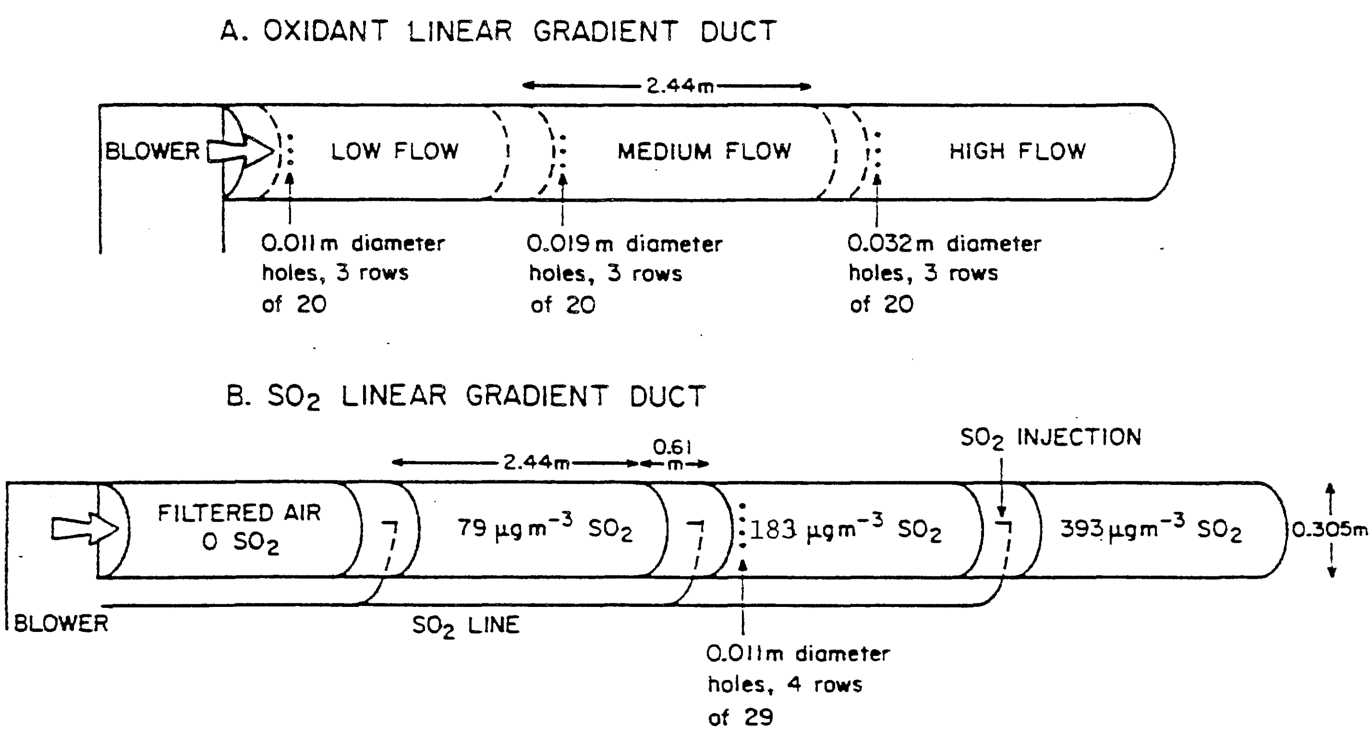


Figure 2-6. Diagram of hole positions for linear gradient ducts. Systems were designed for (A) oxidant linear gradient, and (B) sulfur dioxide linear gradient.

ducts. The other two rows were symmetrically placed in between. Using this principle the within row spacing was 0.084 m and the center to center hole spacing within the rows 0.057 m. A qualitative test placing plants between the ducts showed a visible improvement in the uniformity of air movement.

Outside plots only had pots buried in the ground in the same pattern as for air exclusion systems. There were no raised circular outside plots as in 1983. The open top field chambers were the same as in 1983, except that pots were buried in the soil and not raised above the surface.

Closed top chambers were the California Department of Food and Agriculture's Crop Loss Assessment design. The design was based on the Closed Stirred Tanks Reactor design of Rogers et al. (26). Each octagonal chamber was 2.44 m in diameter and 2.29 to 2.44 m high. The chambers were covered with Teflon film both on the sides and top. The top was slanted on a 4^{o} angle from north to south. Suspended from the top was an impeller blade to increase air mixing. Nonfiltered and filtered air were provided by central blowers which supplied 20 chambers via underground ducting. The ratio of filtered to nonfiltered air in the chamber was determined by adjusting their relative flows into a baffle for mixing before entering the chamber. The mixed air was directed up into the chamber towards the impeller for dispersal within the chamber.

Three exclusion tests were carried out using a grid of sample points. Flow rates per unit length of duct were 0.027, 0.036 and 0.052 $m^3\ s^{-1}$, with ducts of 12.2, 9.1 and 6.1 m length, respectively (Table 2-10). The results showed that at 0.036 $m^3\ s^{-1}$ or more, adequate exclusion can be expected. The higher degree of exclusion always meant reduction of usable duct length. Static pressures inside the ducts were measured near the beginning and the ends of the systems with the 9.1 m and 6.1 m long ducts. A pitot tube with a Magnehelic manometer was used (Dwyer Instruments, Inc.). The instrument readings were quite noisy due to the turbulence inside the ducts. Average readings ranged from 0.0048 to 0.0058 m H_2O in the 9.1 m ducts and from 0.0091 to 0.0104 m H_2O in the 6.1 m ducts.

Oxidant exclusion was between 69 and 77% for the air exclusion system over all three harvests (Table 2-7). At the first harvest the percent exclusion system was the same in air exclusion systems as in open and closed top chambers. At the second and third harvest the percent exclusion was approximately 10% lower in air exclusion systems than chambers. Open and closed top chambers had roughly the same exclusion at all harvests.

Table 2-10

AIR EXCLUSION CARBON MONOXIDE TEST RESULTS USING 0.011 m DIAMETER HOLES 0.057 m APART IN 1984[a]

Flow Rate[b] (m^3 s^{-1})	Carbon Monoxide[c] (mg m^{-3})	Height (m)	Air Exclusion (%) Between Ducts 1+2	Between Ducts 2+3	Between Ducts 3+4
0.027	75	0.05	51	49	62
		0.25	43	39	54
		0.41	20	27	27
0.036	78	0.05	73	78	77
		0.25	77	68	69
		0.41	57	55	57
0.052	81	0.05	90	88	93
		0.25	93	90	90
		0.41	81	86	81

[a]Hole configuration as shown in Figure 2-7, A; duct configuration as shown in Figure 2-3, F.

[b]Per linear meter of duct. Air speed per hole was 4.05, 5.40 and 7.80 m s^{-1} for ducts 1 and 4 at flow rates of 0.027, 0.036 and 0.052 m^3 s^{-1}, respectively; and 2.03, 2.70 and 3.90 m s^{-1} for ducts 2 and 3 at flow rates of 0.025, 0.036 and 0.052 m^3 s^{-1}, respectively.

[c]Average of four sampling points, one in each of ducts 1 through 4.

The percent oxidant exclusion decreased with sample height (Figure 2-7, Table 2-8). Oxidant exclusion decreased by 20 to 28%, with an increase in sampling height from 0.05 to 0.36 m.

The percent exclusion also increased as ambient ozone concentrations increased (Figure 2-7), probably because a constant low level of oxidant bypasses the carbon filters. This also occurs in the open and closed top chambers.

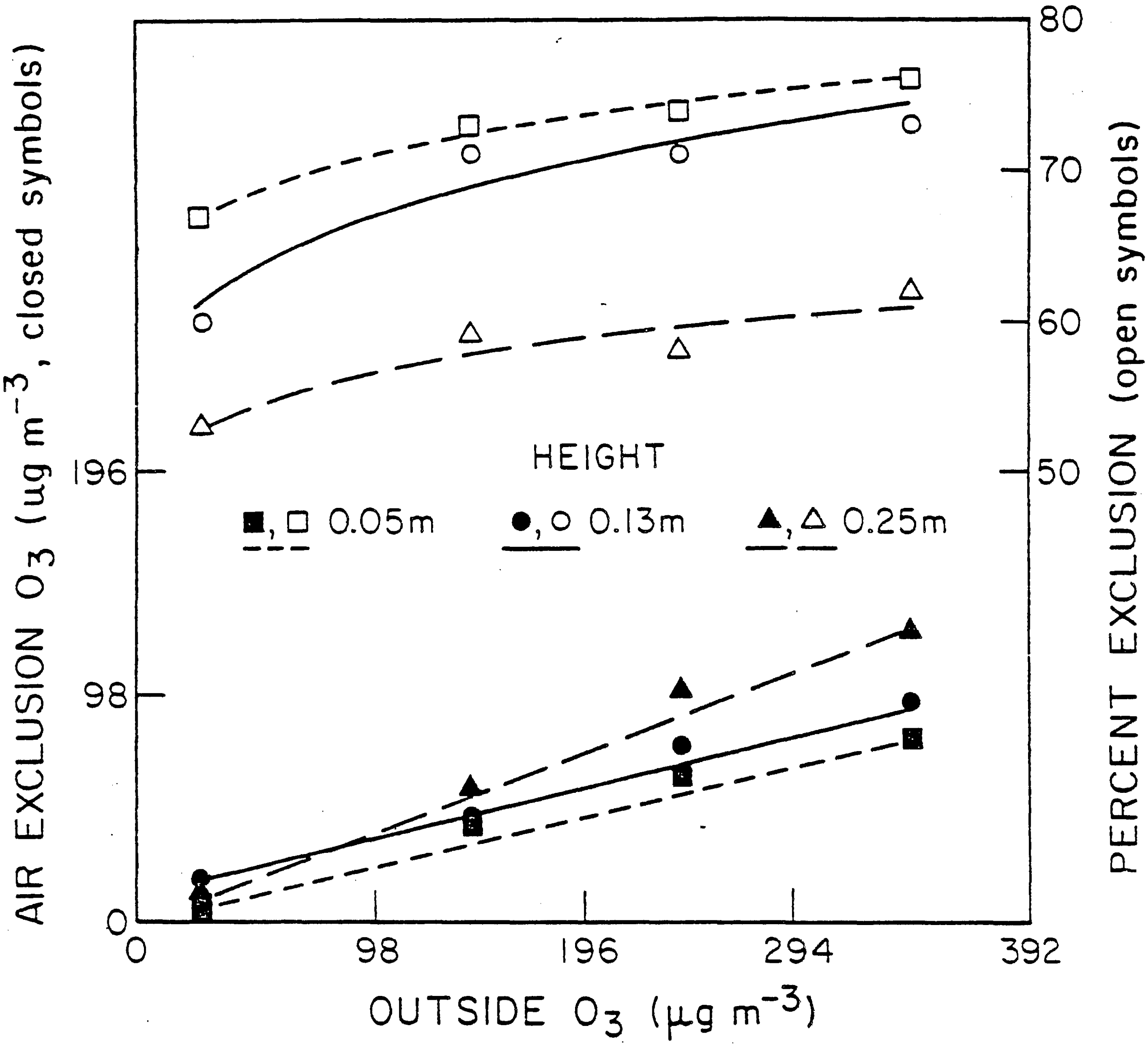


Figure 2-7. Ozone exclusion with different ambient ozone concentrations.

LINEAR GRADIENT SYSTEM

Oxidant Exclusion

A linear gradient in oxidant exclusion was achieved by modifying the single level air exclusion system. Holes of three sequentially increasing diameters were placed in three sections of duct (Figure 2-6, A). This resulted in increasing levels of air flow and subsequent air exclusion as the holes became further from the blower box. The basic 4 duct configuration shown in Figure 2-3, G was used, with ducts 9.1 m long. Three rows of holes were used in ducts 1 and 4 and six in ducts 2 and 3. Each duct was divided into three sections with a different hole size in each section. A hole area ratio of 1:3:9 was used while the cumulative hole area for each duct was kept the same as in a 9.1 m long duct with uniform holes of 0.022 m diameter. Hole diameters were 0.0106, 0.0185 and 0.0321 m. Three sample points were established in the center of each section between ducts 2 and 3 and one sample point inside each duct. The degree of exclusion was measured using carbon monoxide as a tracer gas.

To measure the flow rate in each individual duct carbon monoxide was injected at the begining of each duct one meter before the perforated area. The carbon monoxide concentrations near the ends of ducts 1, 2, 3 and 4 were 81, 35, 41 and 86 mg m^{-3} respectively relating to within duct flow rates of 1.0, 2.16, 2.28 and 1.09 m^3 s^{-1}. As previously, it shows an air flow ratio of 1:2:2:1.

An attempt was made to measure the incremental flow rates of each section within the duct. Since the mixing of the carbon monoxide within a short distance is probably incomplete, the results were considered to be unreliable. A ratio of 1:2:5 might only serve as a rough estimate. Table 2-11 lists the results of the carbon monoxide test.

Table 2-11

AIR EXCLUSION CARBON MONOXIDE TEST RESULTS FOR OXIDANT LINEAR GRADIENT STUDY[a]

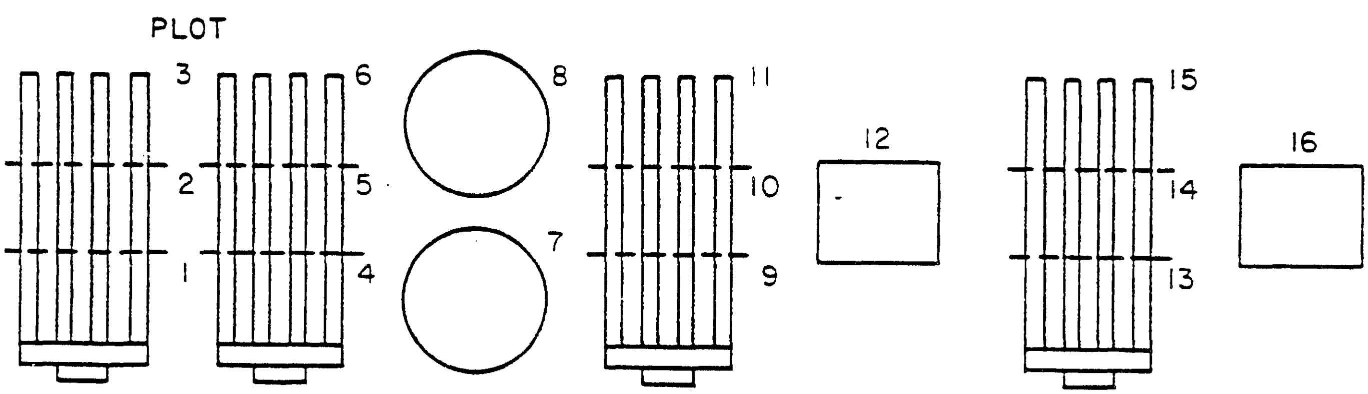
Carbon Monoxide[b] (mg m^{-3})	Height (m)	Air Exclusion (%)		
		Low Flow	Medium Flow	High Flow
85	0.05	38	68	95
	0.25	26	51	95
	0.41	11	31	81

[a]As shown in Figure 2-7, B. Approximate flow rates were 0.036 or 0.074 in ducts 1 and 4 or 2 and 3, respectively. Air speed per hole was approximately 20, 71, 6.80 and 2.26 m s^{-1} for low, medium and high flows, respectively.

[b]Average of four sampling points, 1 in each of ducts 1 through 4.

An experiment was designed comparing alfalfa plant responses in filtered versus nonfiltered air exclusion systems equipped with low, medium, and high air flow rates using the linear gradient air exclusion system (Figure 2-8). Outside plots and open top chambers were also included in the study to provide the 1983 fourth harvest comparison between filtered and nonfiltered systems, and between ambient systems and outside plots.

Oxidant exclusion rates of 31, 59 and 70% were achieved with the low, medium and high flow rates, respectively (Table 2-12). The differing air flow rates had little effect on ozone concentrations with nonfiltered systems. The percent oxidant exclusion was greatest at ground level with all three air flow rates (Table 2-13). However, a greater air exclusion rate was maintained with increasing sample height only with the high flow rate.



TREATMENTS	PLOTS
Air Exclusion-Low Flow, Filtered	1, 4
Air Exclusion-Medium Flow, Filtered	2, 5
Air Exclusion-High Flow, Filtered	3, 6
Air Exclusion-Low Flow, Nonfiltered	9, 13
Air Exclusion-Medium Flow, Nonfiltered	10, 14
Air Exclusion-High Flow, Nonfiltered	11, 15
Outside-Linear	12, 16
Outside-Circular	7, 8
Open Top Chambers, Filtered	18, 19
Open Top Chambers, Nonfiltered	17, 20

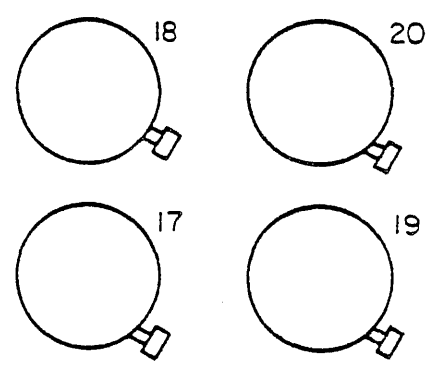


Figure 2-8. Diagram of experimental design for linear gradient oxidant exclusion test. There were three rows of seven plants each per plot.

Table 2-12

OZONE CONCENTRATIONS FOR LINEAR GRADIENT STUDY[a]

Air Exclusion[b]	Ozone ($\mu g\ m^{-3}$) Low Flow	Medium Flow	High Flow
Filtered	62	37	27
Nonfiltered	95	89	95

[a]Values are averages of two plots. Data is for 10/8 through 10/26/83, 0800 to 2000. Sampling height was 0.25 m.

[b]Ozone concentration in adjacent linear outside plots of 90 $\mu g\ m^{-3}$ averaged for two plots.

Table 2-13

OZONE EXCLUSION FOR DIFFERENT SAMPLING HEIGHTS IN LINEAR GRADIENT STUDY

Sample Height (m)	Ozone Exclusion (%)[a] Low Flow	Medium Flow	High Flow
0.05	43	71	84
0.25	39	71	82
0.41	23	41	76

[a]A single filtered air system versus outside plot ozone concentration of 90 $\mu g\ m^{-3}$.

Sulfur Dioxide Addition

Methods. For the sulfur dioxide addition experiment the air exclusion system was again modified to provide oxidant air exclusion plus four concentrations of sulfur dioxide (0, 79, 183 and 393 $\mu g\ m^{-3}$). Each sulfur dioxide duct consisted of four 2.44 m long sections separated by 0.61 m galvanized cresent shaped steel baffles (Figure 2-7, B). The outside ducts had holes only on their inner faces toward plants. The holes were 0.076 m apart in each row, with four rows per duct 0.076 m apart. Inner ducts had the same hole arrangement as outer ducts, but had holes positioned on both sides of the duct. The blower assembly and manifolds were as for the oxidant exclusion studies.

The size and orientation of the baffles was determined empirically and were inserted inside the polyethylene duct. Carbon monoxide was injected at the upstream side of the mixing duct and the concentration measured 1.52, 4.57 and 7.62 m downstream inside the polyethylene duct. If the concentration differences were within 5% of each other, mixing was considered adequate. Four 0.063 m high baffles placed alternatingly 0.18 m apart and perpendicularly to the air stream enhanced mixing sufficiently with a minimum effect on the flow rates in the duct. Installation of the three mixing ducts within each of the four polyethylene ducts did not have a measurable effect on the total flow rate of each duct. One test showed air flows of 0.033 and 0.058 $m^3\ s^{-1}$ for duct 1 or 4 and 2 or 3, respectively, and a total of 0.041 $m^3\ s^{-1}$ for the whole system. These values compare well with the flow rate of the system without mixing ducts. An attempt was made to measure the flow rate per unit length of duct for each individual section within the ducts. In the time frame permitted, only a trend could be established with a higher flow rate in the sections closest to the blower and the ones farthest removed.

A sulfur dioxide dispensing system was built using a small cylinder with pressurized liquid sulfur dioxide as a gas source. This cylinder was kept at $38^{o}C$ inside an insulated galvanized trash can. The gas was dispensed at 7.037 x $10^3\ m^{-2}$ (10 PSI) through a line regulator (Mathieson Model 71A), and a needle valve into a mixing Venturi filled with dry compressed air. The flow rate of the sulfur dioxide air mass was sufficient for transport through 0.0127 m diameter schedule 40 PVC pipes to a series of small manifolds. Each duct system required three manifolds with four branches each for the three groups of four mixing ducts. Each branch of the manifolds was equipped with a piece of hypodermic tubing of 22 gauge and a length of 0.0032 m diameter polyethylene tubing to the dispensing portion of the mixing duct. By varying the length of the hypodermic tubes at a constant gas pressure the gas dispensing rate could be regulated. Based upon the air flow rates in the mixing ducts and the desired ratio of concentrations, the lengths of the hypodermic tubes could be estimated. The desired proportionality within each duct was 0:1:2:4 distributed over the four sections. Once this was established the concentrations of sulfur dioxide could be controlled with the needle valve. Since the predicted ratio deviated considerably from the measured ratio, the tube lengths had to be adjusted accordingly. The tubes ranged from 1.2-2.4 m in length after adjustments.

The injection system was designed to provide the sulfur dioxide gradient by adding sulfur dioxide in increments until the cumulative effect produced 0, 79, 183 and 393 $\mu g\ m^{-3}$ sulfur dioxide in the ducts. The sulfur dioxide was monitored with a Meloy Model SA285 sulfur dioxide analyzer calibrated with a controlled temperature Metronics Corp. Dynacal sulfur dioxide permeation tube.

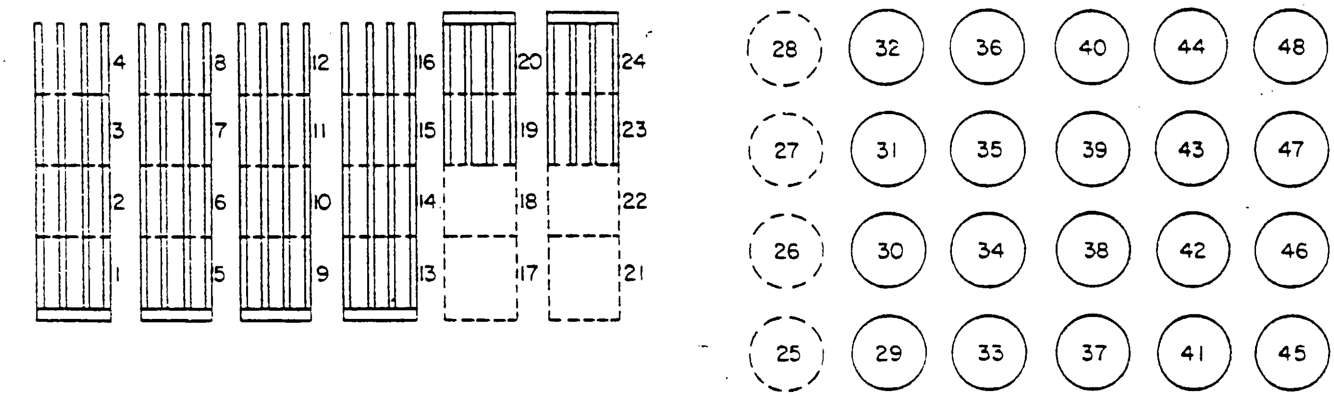
Each of the sulfur dioxide air exclusion systems used charcoal filtered air in the ducts. This resulted in a nonfiltered-zero sulfur dioxide treatment at the end of the ducts nearest the blowers (Figure 2-6B).

Nonfiltered air exclusion systems also were constructed in order to determine the effects of any ambient oxidants on the plants, and the effect of the air exclusion systems themselves on plant growth and pollutant sensitivity. These systems had 6.1 m long ducts half the length of the sulfur dioxide system ducts. Each duct system provided two nonfiltered plots. The hole configuration for the nonfiltered systems was the same as for filtered systems. The blower boxes for nonfiltered systems were of a slightly different dimension (1.89 x 0.62 x 1.73 m) versus the filtered systems, and were located on the opposite ends of the ducts.

The sulfur dioxide, nonfiltered and filtered air treatments were repeated in open top chambers as well as in air exclusion systems. Each treatment was performed in a single chamber (Figure 2-9). The same chambers were used as for the 1983 air exclusion studies, with the addition of sulfur dioxide injection tubes within the chamber baffles. The sulfur dioxide was supplied as for the air exclusion systems, but was monitored by a ThermoElectron Corporation Model 43 sulfur dioxide analyzer.

Two types of outside control plots were used for the study. Linear row plots were used for comparison to air exclusion systems. Circular row plots were used for comparison to open top chambers.

The overall experimental design for the sulfur dioxide-linear gradient study is shown in Figure 2-9. Each treatment had four replicates. Wheat and lettuce were the test plants. The study was conducted from 12/15/83 to 5/16/84.



TREATMENTS

SYSTEM	AIR	$SO_2 (\mu g m^{-3})$	PLOTS	SYSTEM	AIR	$SO_2 (\mu g m^{-3})$	PLOTS
Air Exclusion	Filtered	0	1, 5, 9, 13	Open Top Chamber	Filtered	0	29, 31, 32, 46
Air Exclusion	Filtered	79	2, 6, 10, 14	Open Top Chamber	Filtered	79	30, 35, 42, 43
Air Exclusion	Filtered	183	3, 7, 11, 15	Open Top Chamber	Filtered	183	36, 38, 39, 41
Air Exclusion	Filtered	393	4, 8, 12, 16	Open Top Chamber	Filtered	393	37, 40, 47, 48
Air Exclusion	Nonfiltered	0	19, 20, 23, 24	Open Top Chamber	Nonfiltered	0	33, 34, 44, 45
Outside linear	Nonfiltered	0	17, 18, 21, 22	Outside-Circular	Nonfiltered	0	25, 26, 27, 28

Figure 2-9. Diagram of experimental design for linear gradient sulfur dioxide addition test. Wheat was planted in the west (upper) half of each plot, and lettuce in the east half.

Carbon Monoxide Tests. The exclusion potential was tested by injecting carbon monoxide, and sampling between ducts 2 and 3. Three sample points were used, in the center of each section at 0.05, 0.25 and 0.41 m height. Table 2-14 lists the percent exclusion for each section with section closest to the blower. The lower percent exclusion between section 1 seems to contradict the higher flow rate monitored earlier.

Even though the exclusion potential was less than adequate the system was tested with sulfur dioxide as the pollutant gas. Only minor changes were necessary to establish these levels and reproducibility was excellent.

The system performed well but there are a number of serious drawbacks to consider. A system in the form as described is far from portable. Construction is time consuming and the effort spent on establishing sulfur dioxide flows dissappointing. Good exclusion would require larger blowers if four concentrations within a system is a condition. The zero concentration plot would always be closest to the blower so it is difficult to randomize for location. The other

Table 2-14

AIR EXCLUSION CARBON MONOXIDE TEST RESULTS FOR SULFUR DIOXIDE GRADIENT STUDY

Height (m)	Sulfur Dioxide Target Concentration ($\mu g\ m^{-3}$) 0	79	183	393
	Air Exclusion (%)			
0.05	56	70	67	76
0.25	41	57	46	67
0.41	21	40	48	43

option, as mentioned before, would be using small units with discrete concentrations. They would be portable and more flexible to use since the exposure levels would not be interrelated.

Sulfur Dioxide Gradient. The air exclusion system provided a linear gradient of sulfur dioxide exposures that were within 20% of the target concentrations of 79, 183 and 393 $\mu g\ m^{-3}$ (Table 2-15). In general, concentrations over the entire wheat exposure period from 1/18 to 5/16/84 tended to be lower than during the shorter lettuce exposure period from 1/1 to 3/19/84. There was some ambient sulfur dioxide which was not excluded by the carbon filters which resulted in actual sulfur concentrations of 10 or 12 $\mu g\ m^{-3}$ in the 0 sulfur dioxide treatments.

In general the air exclusion systems provided pollutant exposures that were the same as with open top field chambers (Table 2-16). Filtered zero chamber treatments had sulfur dioxide concentrations approximately 25% of ambient chambers or outside plots, presumably because of more effective air exclusion than with air exclusion systems. However, both ambient chambers and outside circular plots had higher sulfur dioxide concentrations than corresponding air exclusion plots. This indicated that the sensitivities of different sulfur dioxide analyzers for the chambers versus air exclusion systems may have played a role in the apparent differences between these low ambient sulfur dioxide concentrations.

Sulfur dioxide concentrations were relatively uniform between rows and at different sampling heights (Table 2-17). For the medium sulfur dioxide test plot, only the wheat, high sampling plot was greater than 15% from the target concentration.

There were relatively low ambient ozone concentrations throughout the experimental period (Table 2-18). The air exclusion system effectively excluded 60 and 53% of the ambient ozone during the lettuce and wheat growth periods, respectively. This was within the range for concurrent oxidant exclusion by open top chambers. With low ambient ozone levels relatively more pollutant passes the charcoal filters.

Table 2-15

TARGET AND ACTUAL SULFUR DIOXIDE CONCENTRATIONS FOR AIR EXCLUSION SYSTEM

	Sulfur Dioxide Target Concentration ($\mu g\ m^{-3}$)							
	0		79		183		393	
Replicate	Lettuce[a]	Wheat[b]	Lettuce	Wheat	Lettuce	Wheat	Lettuce	Wheat
	Actual System Concentration ($\mu g\ m^{-3}$)							
1	13	11	87	68	187	162	419	393
2	13	11	60	39	194	176	393	367
3	11	9	68	47	181	176	448	438
4	11	9	79	63	173	162	449	398
Average	12	10	74	54	184	169	427	399

[a]Data from 17 days, averaged over 24-h per day.

[b]Data from 53 days, averaged over 24-h per day.

[c]Sampling height of 0.25 m.

Table 2-16

TARGET AND ACTUAL SULFUR DIOXIDE CONCENTRATIONS FOR AIR EXCLUSION SYSTEMS, OPEN TOP FIELD CHAMBERS AND OUTSIDE PLOTS

Treatment		Sulfur Dioxide ($\mu g\ m^{-3}$)[a]	
Air	Target Sulfur Dioxide	Air Exclusion System[b]	Open Top Chamber[c]
	Lettuce		
Filtered	0	12	7
	79	74	81
	183	184	180
	383	427	382
Nonfiltered	Ambient	13	25
Outside	Ambient	13	31
	Wheat		
Filtered	0	10	5
	79	54	79
	183	169	181
	393	399	385
Nonfiltered	Ambient	11	18
Outside	Ambient	11	24

[a]Values are averages of four replicate plots, except for only one replicate for nonfiltered air exclusion systems and corresponding outside plots and two replicates for outside circular plots. Sampling height of 0.25 m.

[b]Data from 17 and 53 days for lettuce and wheat respectively, averaged over 24-h per day.

[c]Data from 7 and 14 days for lettuce and wheat, respectively, averaged over 24-h per day.

Table 2-17

SULFUR DIOXIDE CONCENTRATIONS FOR DIFFERENT ROWS AND HEIGHTS IN MEDIUM SULFUR DIOXIDE PLOT[a]

Sample Height (m)	Sulfur Dioxide ($\mu g\ m^{-3}$)		
	West Row	Middle Row	East Row
		Lettuce[b]	
0.36	-	194	-
0.25	176	181	183
0.15	-	183	-
		Wheat[c]	
0.36	-	136	-
0.25	162	176	155
0.15	-	181	-

[a]Plots No. 12 with a target sulfur dioxide concentration of 183 $\mu g\ m^{-3}$.

[b]Data from 17 days, averaged over 24-h per day.

[c]Data from 53 days, averaged over 24-h per day.

COMPUTER CONTROL SYSTEM

A computer control system was developed for the air exclusion with the capacity both to monitor and store data on air pollutant concentrations in the plots and to regulate the concentrations based on the system shown in Figure 2-2. The components of the system were:

1. Dasibi Model 1003AH ozone analyzer and Meloy Model SA285 sulfur dioxide analyzer.

2. Wind speed and direction. Heathkit wind and direction monitor.

3. 2-12 Port Scanivalve Corporation Scan Co. Model S2565/1P-12T scanning valves, and controller.

4. Cyborg Issac S91A interface with signals from ozone and sulfur dioxide analyzers as input and signal to computer as output.

5. Apple II+ computer with 64K memory, 2 disk drives, and monitor.

6. Brooks Mass Flow Controller Model 58-50, with range of 0-2000 SCM.

Table 2-18

OZONE CONCENTRATIONS DURING SULFUR DIOXIDE LINEAR GRADIENT STUDY[a]

Species	System	Ozone ($\mu g\ m^{-3}$) Filtered	Nonfiltered	Exclusion (%)
Lettuce[b]	Air exclusion[a]	26	61	63
	Open top	18	66	74
	Outside	-	70	-
Wheat[c]	Air exclusion	33	76	60
	Open top	21	82	74
	Outside	-	82	-

[a]Values are averages between 0800 and 2000 for one day per week. Sampling height of 0.25 m.

[b]Average for seven weeks.

[c]Average for 14 weeks.

A variety of computer software were developed for acquiring, storing and for controlling pollutant exposures. The following is a list of these programs including name and characteristics.

FLOWSCAN 24

- Controls an exposure.
- Collects data from 1 analyzer and 24 scanning valve sample points.
- Collects data on wind speed and direction.
- Tests a set point at a given pollutant concentration (e.g., 150 ppb) to set flow (e.g., sulfur dioxide).
- Regulates mass flow controller.

FLOWSCAN 24.2

- Controls an exposure.
- Same characteristics as FLOWSCAN 24, but with added capacity to receive signals from two analyzers and 24 scanning valve sample points.

ACQUIS

- Collects air monitoring and temperature data from up to eight channels including ozone, sulfur dioxide, nitrogen dioxide, wind speed, wind direction, dewpoint and air temperature.
- Generates 10 minute averages and stores them to disk.
- Stores daily instantaneous maximum valve for each channel.

HRLYMAX

- For use with ACQUIS.
- Reads raw data, calculates hourly averages for each channel.
- Calculates highest 10 minute average of day for each channel.
- Sorts data by channel number, by day, and by hour.
- Stores output in a "sums" file (ppb).

CHART DISK N.E.C

- For use with ACQUIS.
- Conversion factors applied for ppb to ppm, $\mu g\ m^{-3}$ or other units.
- Printout by pollutant by month.

AVEFLOWSCAN 24

- For use with FLOWSCAN 24.
- Prints out averages by channel number, number of points, minimum and maximum. Can request either all channels or a single channel.
- Can do averaging by plots.
- Outputs data into temporary "SUMS" file.

AVEFLOWSCAN 24E

- For use with FLOWSCAN 24.
- Does same procedures as AVEFLOWSCAN 24, and in addition can process data for different ranges of ppb.

AVE 24

- For use with AVEFLOWSCAN 24 or 24E.
- Reads output from "SUMS" file.

AVEFLOWIND 24

- For use with FLOWSCAN 24.
- Does same procedures as AVEFLOWSCAN 24, but for wind direction.

AVEWIND 24

- For use with AVEFLOWIND 24.
- Reads output from "SUMS" file.

AVEFLOWSCAN 24.2

- For use with FLOWSCAN 24.2.
- Does same procedures as AVE FLOWSCAN 24 for FLOWSCAN 24.

AVEFLOW 24.2

- For use with AVEFLOWSCAN 24.2.
- Reads output from "SUMS" file.

Section 3

ENVIRONMENTAL COMPARISONS BETWEEN EXPOSURE SYSTEMS

A wide variety of parameters were measured to determine differences in environment which could affect plant response to air pollutants in the different exposure systems: air speed over plant canopy, air temperature, soil temperature, leaf temperature, light intensity [measured as photosynthetic photon flux density (PPFD)], relative humidity and dew formation.

METHODS

Air speed was determined with a hand-held directional anemometer (Kurz Air Velocity Meter Model 441S). Measurements were made at the top of the canopy over individual plants that were used for stomatal conductance measures. Air speed was measured coincident with stomatal conductance measurements.

Temperature was measured continuously using iron-constantin thermocouples attached to strip chart recorders. Thermocouples were positioned at a standard height of 0.15 m within the plant canopy. Additional measurements at other heights were made to characterize temperatures from ground level to above plants. Air temperature was for all alfalfa, wheat and lettuce harvests.

Soil temperature also was measured using thermocouples connected to recorders. A standard depth of 0.05 m was used with some additional measurements at 0.10 m.

Leaf temperature was measured for lettuce by attaching fine wire thermocouple to leaves. The thermocouple was attached to the leaf with perforated surgical tape. Leaf temperature was also obtained from the fine wire thermocouple inside the cuvette of the Lambda Instruments Company LI-COR® 1600 steady state porometer.

Light intensity was determined as photosynthetic photon flux density between wavelenghts of 400 to 700 nm using the steady state porometer. Relative humidity was measured concurrently using the same instrument, but without any covering of the cuvette. These precautions were necessary for the porometer humidity sensor to stabilize at ambient conditions.

Dew formation on alfalfa leaves was measured as an indicator of relative night-time radiative cooling of leaves. Individual trifoliate leaves were removed from plants and placed between two pieces of Whatman No. 42 filter paper inside a preweighed and sealed plastic bag. The bags were then taken to a scale, the leaves removed, and the amount of dew absorbed on the filter paper determined by substraction (paper + bag + dew) - (paper + bag). Area of the leaves was then determined to express dew quantitatively as g H_2O m^{-2} leaf tissue (two-sided). Dew was determined on 10/6, 10/11 and 10/18/83.

AIR SPEED

Air speed for oxidant exclusion studies was consistently higher in air exclusion systems than all other treatments. For 1983 and 1984 alfalfa studies, air speed was generally over twice as fast in air exclusion systems than open or closed top chambers and outside plots (Table 3-1). Air speed for the oxidant linear gradient study was similar in low flow air exclusion systems and outside plots (Table 3-2). In medium and high flow plots air speed was up to 5 times that in outside plots.

Diurnal air speed was over 2-3 times as high in air exclusion chambers than in outside areas (Table 3-3). The air exclusion versus outside difference was greatest early in the morning when outside air was still, and smallest in the afternoon when outside winds had become stronger. Open top chamber air flow was greater than outside flow in the morning and less in the afternoon. Thus, open top chamber air flow was at a more constant rate than the more rapid and turbulent air flow from air exclusion systems, or diurnally changing outside air flow.

During the sulfur dioxide gradient study, air speed was similar in air exclusion systems and open top chambers (Table 3-4). Air speed was considerably lower in both systems than in outside plots.

AIR TEMPERATURE

Air temperature differences between systems varied with season (Table 3-5). During the first three (summer) harvests of 1983, air temperature was similar in air exclusion systems and outside plots, and $1^{o}C$ higher than in open top chambers as shown by the data for 7/26-27/83 (Figure 3-1A). During the fourth (Fall) harvest air temperature was $4^{o}C$ lower in air exclusion systems and outside plots than closed top chambers (Table 3-5). Air temperature was only measured during

Table 3-1

AIR SPEED FOR DIFFERENT EXPOSURE SYSTEMS FOR 1983 AND 1984 ALFALFA STUDIES

		Air Speed ($m\ s^{-1}$)[a]			
Year	Harvest	Air Exclusion	Open Top Chamber	Closed Top Chamber	Outside[b]
1983	3	1.01 b	0.94 b	-	0.51 a
	4	1.83 b	0.43 a	-	0.39 a
1984	3 am	1.03 c	0.40 a	0.78 b	0.58 ab
	3 pm	0.84 b	0.36 a	0.45 a	0.40 a

[a]Values are means of 12 (1984), 24 (1983-4) or 36 (1983-3), observations with three, six or nine plants, respectively, from each of four replicate filtered and nonfiltered plots. Values in a row followed by different letters are significantly different at $p<0.05$.

[b]Values are means of six observations, three from each of two replicate plots for 1984.

Table 3-2

AIR SPEED FOR OXIDANT LINEAR GRADIENT STUDY[a]

	Air Speed ($m\ s^{-1}$)		
Treatment	Low Flow	Medium Flow	High Flow
Filtered	0.42 a	1.11 b	2.18 c
Nonfiltered	0.36 a	1.16 b	1.49 b

[a]Values are means of 12 observations, six from each of two replicate plots. Values in a row followed by different letters are significantly different at $p<0.05$. Outside air speed was 0.39 $m\ s^{-1}$.

Table 3-3

LIGHT INTENSITY LEAF TEMPERATURE AND WIND SPEED FOR DIFFERENT EXPOSURE SYSTEMS ON 9/15/83[a]

	Light (μmol m^{-2} s^{-1})[b]			Leaf Temperature (°C)			Air Speed (m s^{-1})		
Time of Day	Air Exclusion	Open Top Chamber	Outside	Air Exclusion	Open Top Chamber	Outside	Air Exclusion	Open Top Chamber	Outside
0745	279	224	296	21.4	20.9	21.2	0.68	0.24	0.15
0845	604	548	703	23.0	23.6	23.0	0.85	0.19	0.09
1015	1043	728	949	26.6	26.3	26.9	1.14	0.26	0.13
1100	1236	773	932	29.2	29.9	29.5	1.07	0.17	0.20
1355	1384	834	1594	31.1	33.0	33.3	0.64	0.15	0.31
1445	1319	956	1561	34.1	32.9	33.7	0.60	0.14	0.28
1600	730	575	888	30.7	31.7	32.1	1.05	0.23	0.42
1645	441	590	756	30.9	31.4	31.6	0.73	0.17	0.28
1730	483	276	385	30.2	29.8	29.7	0.61	0.18	0.27

[a]Values are means of four observations (two from each of two plots).

[b]Photosynthetic photon flux density.

Table 3-4

AIR SPEED FOR SULFUR DIOXIDE AND AMBIENT OXIDANT STUDY[a]

	Air Speed (m s^{-1})[b]								
					Sulfur Dioxide (μg m^{-3})			
System	Outside		Nonfiltered		0	79	183	393
Air exclusion	0.95	*	0.54	ns	0.55 c	0.38 ab	0.33 a	0.41 b
Open top chamber	1.27	*	0.57	ns	0.53	0.50	0.55	0.58

[a]Measurements made over lettuce canopy. Value is mean of eight observations, two from each of four replicate plots.

[b]There was a significantly greater air speed in outside versus nonfiltered plots for both air exclusion systems and open top chambers at $p<0.05$. For air exclusion systems, air speeds at different sulfur dioxide concentrations followed by different letters are significantly different.

Table 3-5

AIR TEMPERATURE FOR OXIDANT AIR EXCLUSION STUDIES IN 1983 AND 1984[a]

Harvest	Dates	Air Temperature (^{o}C) Air Exclusion	Open Top Chamber	Outside
1983 - First	7/8-7/29	27.5	26.2	27.2
Second	7/30-8/23	29.6	28.9	29.4
Third	8/24-9/19	30.1	29.5	29.6
Fourth	9/20-10/30	19.6	23.7	19.5
1984 - Third	7/13-8/7	30.2	31.7	31.2

[a]Average for one system on two to six days between 0700 and 2000.

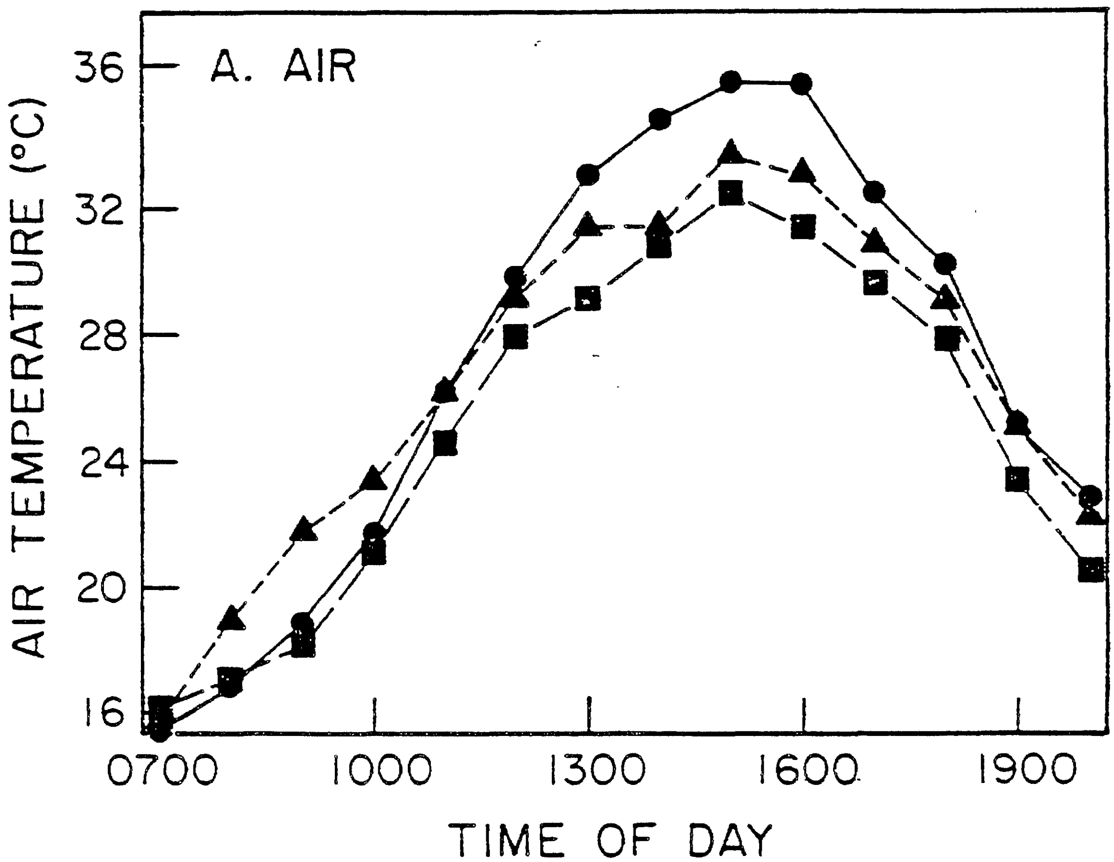
the third (summer) harvest of 1984, and at this time was $1^{o}C$ or more lower in air exclusion systems than open or closed top chambers and outside plots.

During the sulfur dioxide linear gradient study the air temperature pattern changed over the growing period (Table 3-6). During most of the winter, air temperatures were slightly higher in open top chambers than air exclusion systems, and both had warmer temperatures than outside plots. As spring progressed, air temperature became similar in all systems. Figure 3-2C illustrates the diurnal pattern in air temperature for chambers, air exclusion systems and outside plots on a typical winter day.

SOIL TEMPERATURE

Soil temperature was similar in air exclusion systems, open top chambers and outside plots over most of the day during the 1983 summer (Figure 3-1B). Open top chambers tended to be slightly warmer than outside plots in mid-morning. Air exclusion systems had a slightly lower than outside plots at this time.

During the winter soil temperature at the 0.05 m level was similar over the day for both air exclusion systems and open top chambers (Figure 3-2B). Air exclusion systems and open top chambers had higher soil temperatures than outside plots at night. Soil temperature at the 0.10 m level was the same for both systems and slightly greater than for outside plots over the entire day (Figure 3-2A).



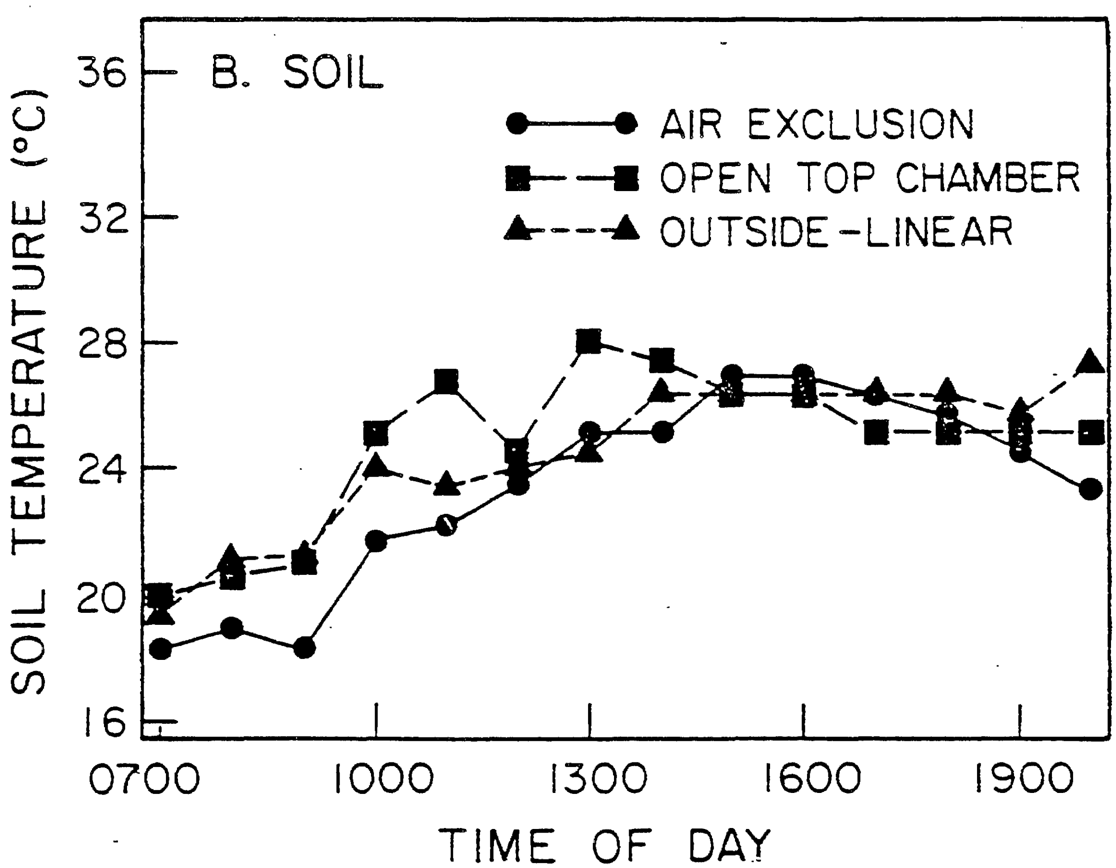


Figure 3-1. Diurnal temperatures on July 26-27, 1983. Data is averaged over two days for (A) air at 0.15 m height, and (B) soil at 0.10 m depth.

Table 3-6

AVERAGE DAILY AIR TEMPERATURE FOR SULFUR DIOXIDE-OXIDANT STUDY IN 1984[a]

	Air Temperature (°C)		
Date	Air Exclusion	Open Top Chamber	Outside[b]
2/3/84	21.3	21.1	19.8
2/11/84	17.7	17.5	17.8
2/17/84	15.1	15.8	14.8
2/24/84	16.9	21.8	17.4
3/2/84	19.9	21.2	20.0
3/9/84	20.0	19.9	19.8
3/21/84	22.1	23.4	22.3
3/30/84	19.9	21.1	20.1
4/6/84	21.4	19.2	19.2
4/13/84	29.1	32.7	31.4
4/20/84	21.5	23.5	23.3
4/27/84	15.1	16.7	16.0
5/4/84	27.5	30.9	29.1

[a]For hours 0800-2000, except for 0900-2000 on 2/17/84 and 1100-2000 on 4/6/84.

[b]Circular plot.

LEAF TEMPERATURE

During the winter leaf temperature was the same for air exclusion systems and open top chambers over most of the day (Figure 3-2D). Leaf temperature was 2°C higher at mid-day in air exclusion systems than open top chambers. The difference was most likely related to the higher light intensity in the air exclusion at mid-day. Both air exclusion systems and chambers had up to 3°C warmer leaf temperatures during early morning and 1 to 2°C cooler temperatures at mid-day.

Leaf temperature for alfalfa plants generally was the same in air exclusion systems as in open top chambers or outside plots. During diurnal measurements with the LI-COR® porometer in 1983, leaf temperature varied at most by 2°C between different treatments, which was within the confidence limits for the treatments (Table 3-3). In 1984 leaf temperature was again similar in air exclusion systems and outside plots (Figure 3-3). Open top chambers had leaf temperatures that were also the same as outside plots over most of the day, except for a 1°C higher

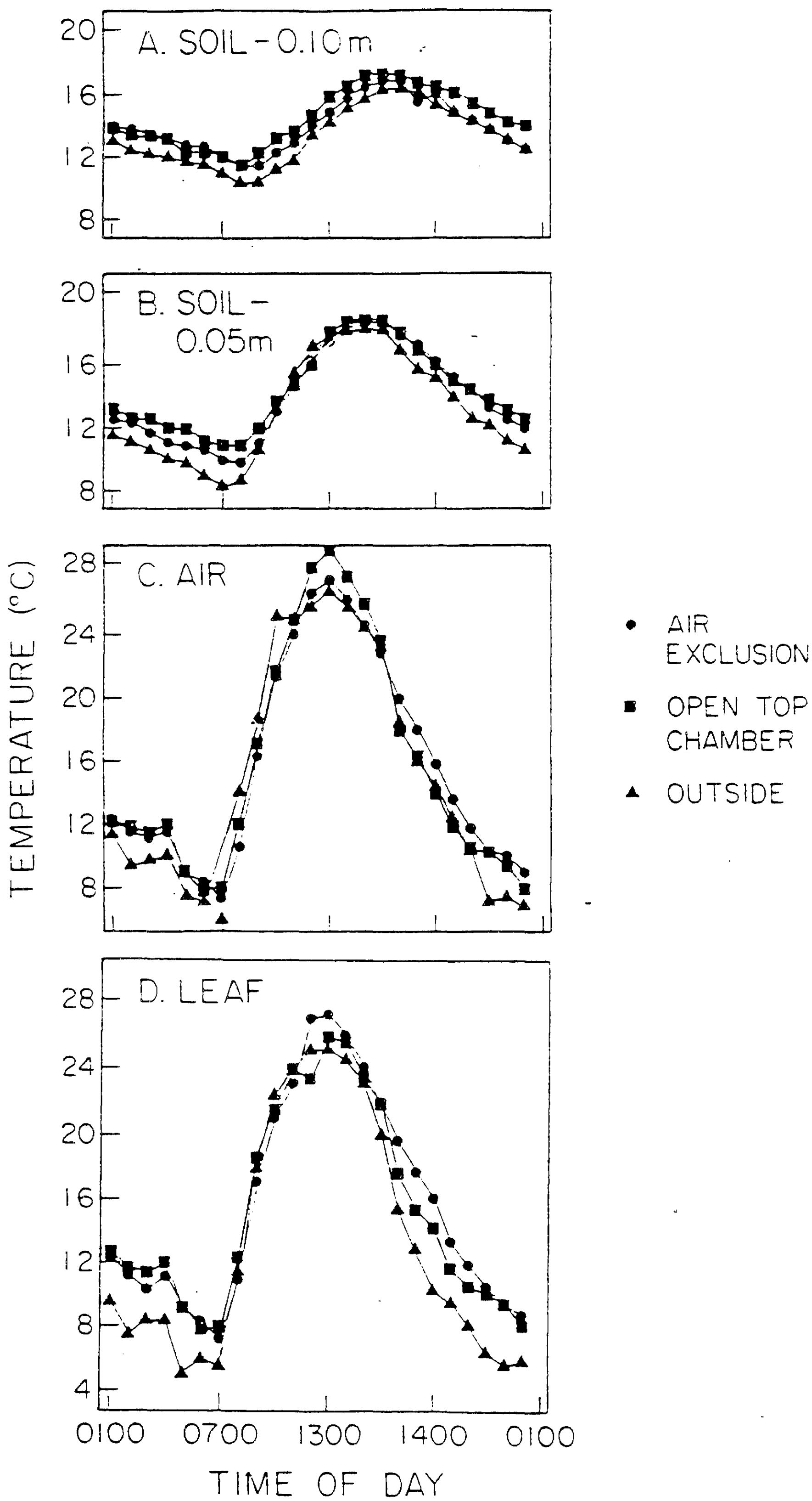


Figure 3-2. Diurnal temperatures on 2/4/84. Data is for (A) soil at 0.10 m depth, (B) soil at 0.05 m depth, (C) air at 0.15 m height, and (D) abaxial surface of lettuce leaves.

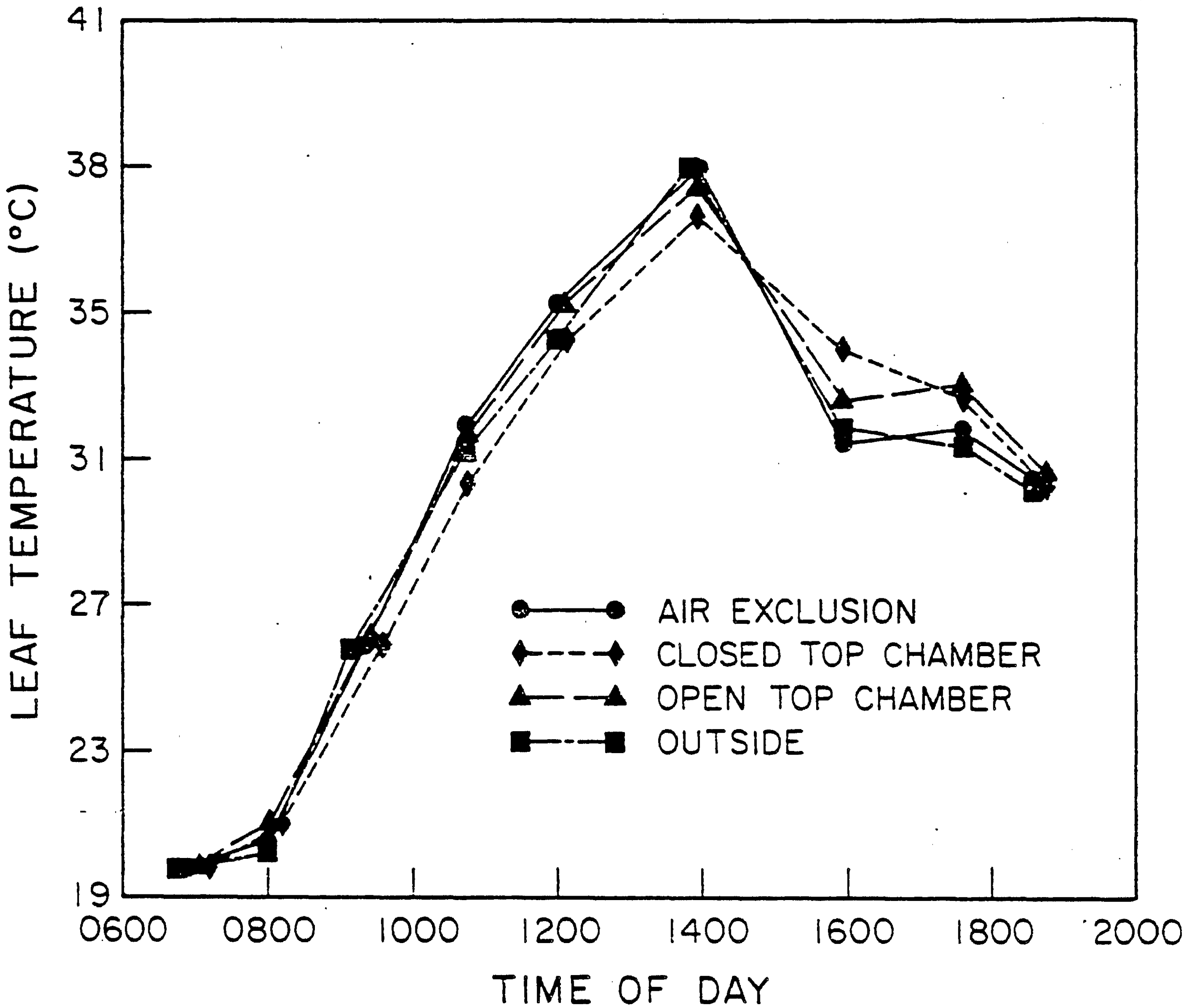


Figure 3-3. Diurnal leaf temperature on 8/2/84. Each value is the mean of two plots.

temperature than outside plots in the late afternoon. Closed top chambers had leaf temperatures that were about $1^{o}C$ lower than outside plots during late morning and 1^{o} higher than outside plots during late afternoon.

LIGHT INTENSITY

Light intensity in air exclusion systems was approximately the same as in outside plots and greater than in open or closed top chambers. In 1983, air exclusion chambers averaged only 4% lower light intensity than outside areas even though for some the air exclusion intensity was 33% higher to 42% lower than from average outside plots (Table 3-3). Open top chambers averaged 29% lower light intensity than outside plots. In 1984, air exclusion systems had a similar intensity as in outside plots, averaging only 6% lower over the day (Figure 3-4). Light intensity in open top and closed top chambers averaged 24 and 31% lower, respectively, than in outside plots.

RELATIVE HUMIDITY

Relative humidity was similar in air exclusion systems as in outside plots over a range of humidities and across an entire day (Figure 3-5). Open top and closed top chambers had higher relative humidities than outside plots at midday. However, the maximum differences were only about 3-4%.

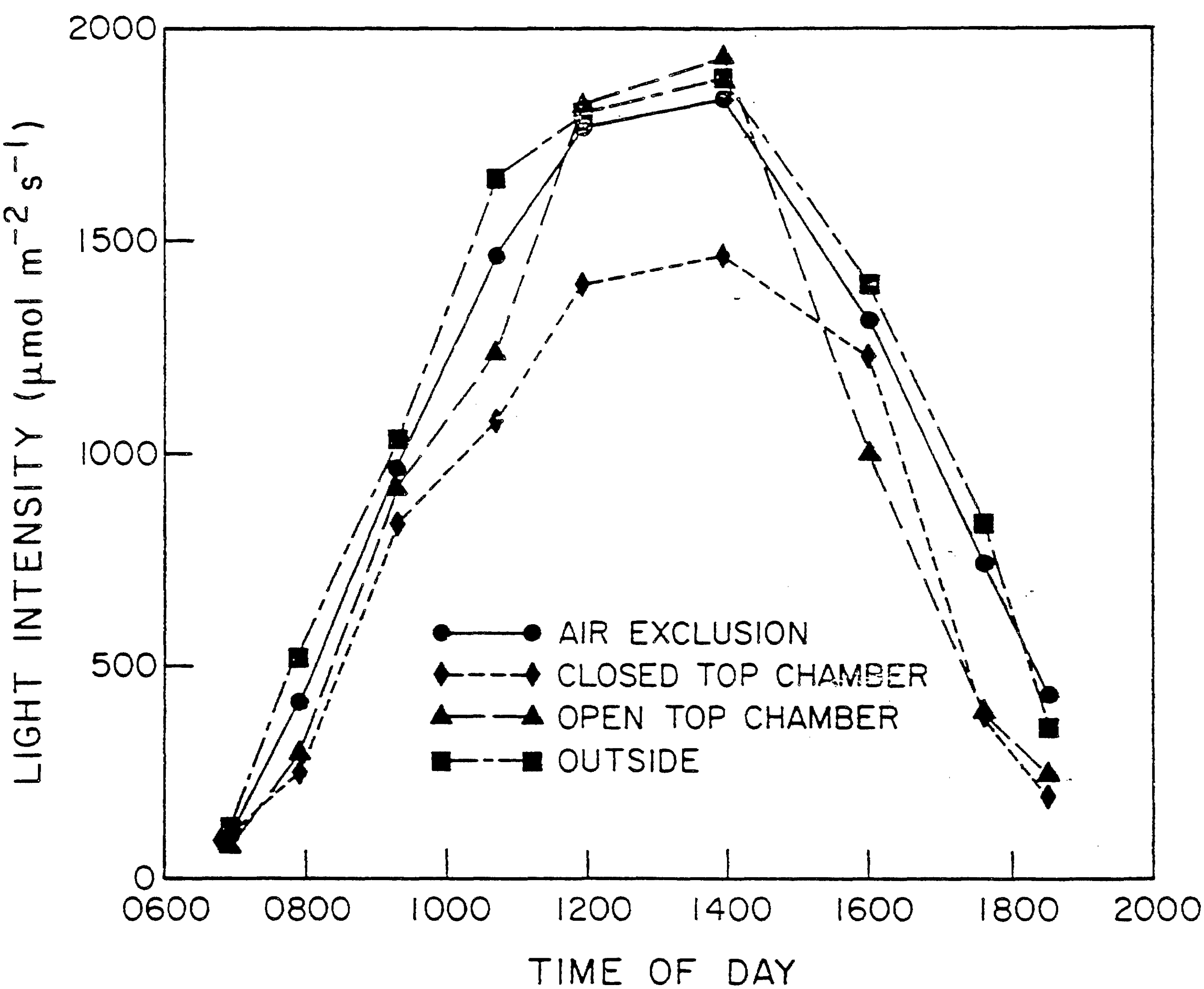


Figure 3-4. Diurnal light intensity on 8/2/84. Each value is the mean of two plots.

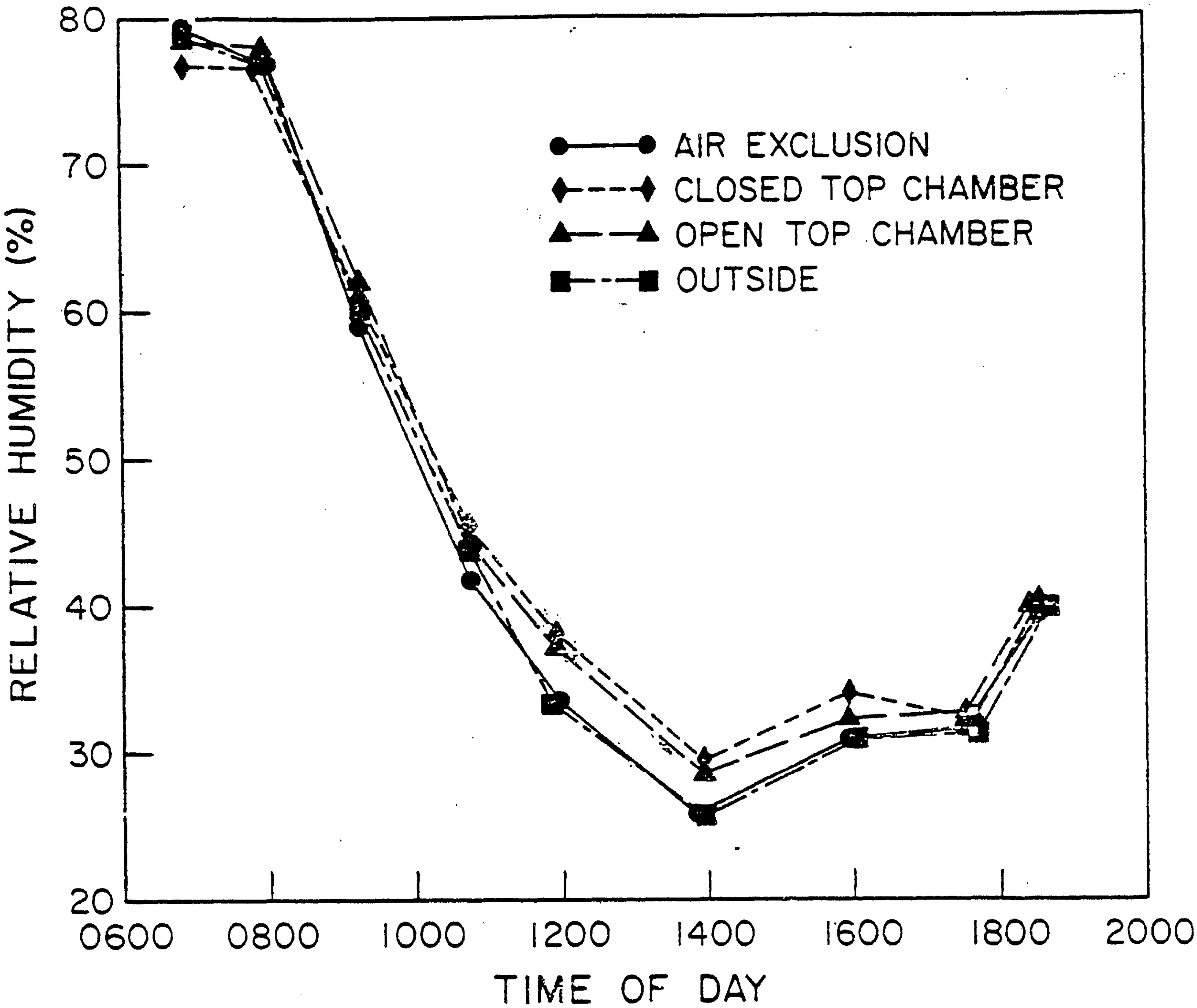


Figure 3-5. Diurnal relative humidity on 8/2/84. Each value is the mean of two plots.

DEW FORMATION

Dew did not form as readily within air exclusion systems or open top chambers as in outside plots on any date (Table 3-7). Nearly all outside plants had substantial dew accumulation that was 257% greater than in air exclusion systems and 488% greater than in chambers. Air exclusion systems had significantly greater dew formation than chambers even though the air speed was greater than in chambers. Thus, still air at the plant canopy level was not the only factor encouraging water condensation; the conductance of heat from plant leaves to a clear night sky also plays a major role in dew formation.

Table 3-7

DEW ON ALFALFA AND WHEAT LEAVES WITH DIFFERENT EXPOSURE SYSTEMS[a]

		Dew					
		Air Exclusion[b]			Open Top Chamber		
Species	Date	Nonfiltered		Outside	Nonfiltered		Outside
		($g\ m^{-2}$)					
Alfalfa	10/5/83	26.7	*	51.4	15.1	*	55.6
	10/11/83	25.3	*	89.6	11.0	*	92.9
	10/18/83	26.2	*	60.2	15.9	*	56.5
		(0-5 scale)[c]					
Wheat	1/16/84	0	*	3	0	*	3
	1/18/84	0	*	3	0	*	2
	1/20/84	0	*	5[d]	0	*	5[d]

[a]Values are means of eight observations, four from each of two plots for alfalfa; and four observations, one from each of four plots for wheat. Pairs of nonfiltered and outside values separated by a "*" are significantly different at $p<0.05$. For alfalfa all nonfiltered air exclusion systems are significantly different from nonfiltered chambers at $p<0.05$.

[b]High flow rate for alfalfa air exclusion systems.

[c]Dew rated at 0-5 scale where 0 = no dew on any plant and 5 = entire leaf surfaces of all plants covered with dew.

[d]Dew had solidified to frost.

The role of air flow on dew formation was more clearly elucidated using the oxidant linear gradient system at the 4th harvest (Table 3-8). Plots receiving high air flow had less dew formation than either medium or low flow plots. Filtering of duct air had no effect on dew.

Table 3-8

DEW ON ALFALFA LEAVES WITH DIFFERENT AIR FLOW RATES[a]

		Dew ($g\ m^{-2}$)					
		Flow					
Date	Treatment	Low		Medium		High	
10/5/83	Nonfiltered	49.5	a	40.3	a	20.1	b
	Filtered	36.7		37.6		26.2	
10/11/83	Nonfiltered	51.1	a	35.7	a	13.3	b
	Filtered	41.0		42.2		25.3	
10/18/83	Nonfiltered	54.8	a	38.8	a	21.9	b
	Filtered	56.6		57.0		26.2	

[a]Values are means of eight observations (four from each of two plots). Means for a date for pooled nonfiltered and filtered data at different flow rates followed by different letters are significantly different at $p<0.05$. There were no significant differences between nonfiltered and nonfiltered treatments at any flow rate on any date.

Section 4

PLANT EXPOSURES WITH DIFFERENT SYSTEM CONFIGURATIONS

Plant growth and injury responses were the ultimate test of the effectiveness of the air exclusion system in providing controlled pollutant exposures for crop loss research. The plant responses were evaluated both to determine the effects of the air exclusion system itself on plant growth and to determine how the system may alter plant response to air pollutants. Alfalfa (*Medicago sativa* L.) was the test plant for experiments with exclusion of ambient oxidants (ozone); wheat (*Triticum aestivum* L.) and lettuce (*Lactuca sativa* L.) were test plants with sulfur dioxide.

OZONE EXCLUSION

The ozone exclusion experiments were primarily simple treatments of either charcoal filtered or nonfiltered air in air exclusion systems or chambers. For one experiment the air exclusion systems were divided into three sections to provide three levels of air filtration.

Methods

Alfalfa (cultivar Northrup King 512) was grown from crowns in 3.8 liter paper pulp pots using University of California Standard soil mix. The pots were buried to the rim in the soil between air exclusion ducts and for linear outside control plots in both years. Pots were buried in the soil within open and closed top chambers in 1984, and not buried but surrounded to the rim with wood shavings in open top chambers in 1983. The circular outside pots were treated the same as chamber pots in 1983. The different pot locations, buried versus raised but surrounded by wood shavings had no effect on plant response as the linear and circular control plots had the same growth and yield in 1983. The alfalfa was watered as required using irrigation water supplemented with a fertilizer solution (full-strength North Carolina phytotron nutrient solution) on a weekly basis. The plants received sprays of Orthene (0,S-dimethyl acetyl phosphoramidothioate) or Sevin (1-naphthyl methylcarbamate) to control insects as needed during both years.

All growth periods were from cutting to cutting except for the first harvest in June 1984, where all plants had two weeks of growth in ambient air followed by only two weeks in the different treatments. Growth dates and ozone concentrations for the different treatments and harvests are shown in Table 2-7; and air temperatures are shown in Table 3-5.

Plants were harvested when flowering was at approximately 1/10-1/3 of full bloom. Parameters measured at each harvest are shown in Table 4-1. All weight data is per plant. Air drying was for 7-14 days in a nonventilated chamber. Height is for the tallest stem per plant. Data for numbers of empty nodes, flowers, nodes and percent empty nodes is for one stem per plant. There were three rows per plot with seven to 10 plants per row for a total of 21 to 30 plants, except for the closed top chambers in 1984 which had six plants in each of two rows and seven plants in a third row for a total of 19 plants. There were two plots for each treatment in each experiment.

Alfalfa was usually rated for chronic leaf injury attributable to oxidants (ozone), i.e., leaf chlorosis and necrosis. Nine ratings were made per plot, at each end and middle of each row. The rating was on a 0-4 scale with 0 = no injury and 4 = 100% leaves injured. Plants were rated just before harvest. No ratings were made during the first harvest in either 1983 or 1984.

Stomatal conductance was measured for all harvests in 1983 on 7/27, 8/22, 9/7 and 10/6, and for one harvest in 1984 on 8/1. There were one to three observations per row, for a total of three to nine per plot. Measurements were made with a Lambda Instruments Corporation LI-COR® LI-1600 steady-state porometer. Diurnal variation in stomatal conductance was measured during the fourth harvest on 10/19/84.

Net photosynthesis was measured during midday on 10/18/83 and in the morning and afternoon on 8/1/84. There were two observations per plot in 1983 and three per plot in 1984. Measurements were made with a ^{14}C-^{3}H dual isotope porometer (2). The ^{3}H data was not used for analysis. Net photosynthesis was calculated according to the following for formuli:

Table 4-1

RESULTS FROM ANALYSIS OF VARIANCE STATISTICAL ANALYSIS OF ALFALFA DATA

Factors[a]	Total Fresh Wt.	Total Dry Wt.	Dry Wt. Stems	Dry Wt. Leaves	Height	No. Nodes	No. Empty Nodes	% Empty Nodes	No. Flowers	Leaf Injury
					1983 First Harvest (July)					
T	ns	ns	ns	ns	ns	ns	***[b]	**	-	-
S	ns	ns	ns	ns	**	ns	ns	ns	-	-
TxS	ns	ns	ns	ns	ns	ns	*	ns	-	-
					1983 Second Harvest (August)					
T	**	*	*	**	*	ns	***	***	ns	***
S	*	ns	ns	*	**	ns	ns	ns	ns	***
TxS	ns	ns	ns	ns	ns	ns	ns	ns	ns	**
					1983 Third Harvest (September)					
T	**	***	**	**	**	*	***	***	ns	***
S	*	***	ns	ns	*	ns	ns	ns	ns	***
TxS	ns	ns	ns	ns	ns	ns	*	ns	*	***
					1983 Fourth Harvest (October)					
T	ns	ns	ns	ns	ns	-	-	-	-	***
S	**	**	**	ns	**	-	-	-	-	ns
TxS	ns	ns	ns	ns	ns	-	-	-	-	ns
					1984 First Harvest (June)					
T	ns	ns	-	-	ns	-	-	-	-	-
S	ns	ns	-	-	ns	-	-	-	-	-
TxS	ns	ns	-	-	ns	-	-	-	-	-
					1984 Second Harvest (July)					
T	ns	ns	-	-	ns	ns	***	*	-	***
S	*[c]	*[c]	-	-	*[c]	ns	*[d]	ns	-	ns
TxS	ns	ns	-	-	ns	ns	ns	ns	-	ns
					1984 Third Harvest (August)					
T	*	**	-	-	ns	ns	*	***	-	***
S	*[c]	**[c]	-	-	**[c]	*[e]	ns	ns	-	ns
TxS	ns	ns	-	-	ns	ns	ns	ns	-	ns

[a]T = treatments: filtered vs nonfiltered air; S = system: air exclusion vs open top chamber in 1983 and also vs closed top chamber in 1984.

(continued)

Table 4-1 (continued)

[b]***, ** and * = statistically significant at $p<0.005$, 0.01 and 0.05, respectively.

[c]System effect between air exclusion systems or open top chambers and closed top chambers.

[d]System effect between air exclusion systems and closed top chambers.

[e]System effect between air exclusion systems and open or closed top chambers.

1. ^{14}C uptake = DPM ^{14}C/(leaf area x sample time)
2. ^{14}C tank constant = DPM ^{14}C/sample volume
3. CO_2 conductance = ^{14}C uptake/^{14}C tank constant
4. Net photosynthesis = CO_2 conductance x atmospheric CO_2 (340 ppm or 1.39×10^{-2} mol m^{-3}) x $\frac{P_{exp}}{P_o}$ x $\frac{T_o}{T_{exp}}$, where $T_o = 298^oK$ and P_o = 101.33 kPa.

Statistical analysis procedures were adapted from Steel and Torrie (30) and Snedecor and Cochran (31). At each harvest the initial analysis was with a one-way analysis of variance considering data from air exclusion systems and chambers separately. Each analysis considered filtered, nonfiltered and outside control treatments as one factor and rows as blocks.

This analysis indicated whether air exclusion systems or chamber results were significantly different from corresponding outside areas. A second analysis compared circular versus linear outside plots. In all cases there was no difference in growth between the two types of controls. A final analysis used a two-way analysis of variance to compare plant response with the different systems. The two factors were treatment (filtered and nonfiltered) and system (air exclusion and chambers) with rows again as blocks. The levels of significance for treatment system and treatment x system effects using the third analysis are shown in Table 4-1.

Single Level Exclusion

Single level exclusion studies were carried out for four harvests of alfalfa in 1983 using the experimental designs shown in Figure 2-4 and 2-8, and three harvests in 1984 using the experimental design shown in Figure 2-5. During 1983 both linear and circular outside control plots were used for comparison to air exclusion and open top chambers, respectively. Plant response was the same in both types of controls, thus, in 1984, only linear control plots were used for comparison to air exclusion, open and closed top chambers.

The air exclusion systems were as effective as chambers in determining the effect of ambient ozone on the alfalfa plants. The type of effects, however, were different in air exclusion systems versus chambers depending on ambient ozone concentration and time during the growing season. The alfalfa responses due to ozone could be greater or less in air exclusion systems than chambers depending on exposure conditions. Alfalfa growth in air exclusion systems or chambers also could be greater or less than outside control plots. Table 4-1 shows the general results from statistical analysis for all alfalfa response parameters over the seven 1983 and 1984 harvests. Treatment (filtered versus nonfiltered), system (air exclusion versus chambers), and treatment x system interactions all were found. These results will be discussed separately for 1983 and 1984 as alfalfa growth was apparently different in these years.

1983 Response. Alfalfa growth and yield were greater in filtered versus nonfiltered treatments during the first three harvests of 1983, with greater plant effects due to ozone measured in open top chambers than in air exclusion systems. The yield reductions increased progressively over the first three harvests (Figure 4-1). The percentage reductions in dry weight for air exclusion systems versus open top chambers, respectively, were 11.7 and 17.4% for harvest 1; 16.3 and 27.5% for harvest 2; and 29.0 and 37.4% for harvest 3. The dry weight effects were statistically significant between treatments at the second harvest and between systems as well as treatments at the third harvest.

Over all three harvests the nonfiltered air exclusion system plants had similar dry weights vs outside control plants while nonfiltered open top chamber plants had lower weights than outside control plants. Thus, it was possible that plants were more sensitive to ambient oxidants in the open top chambers than outside, or that there was added depression of alfalfa growth solely due to the open top chambers. A chamber-induced yield reduction was more likely as yields also were consistently lower in nonfiltered chambers than in outside plots.

The air exclusion system, open top chamber, and outside treatment data for the first three harvests of 1983 fit a single linear relationship between ozone

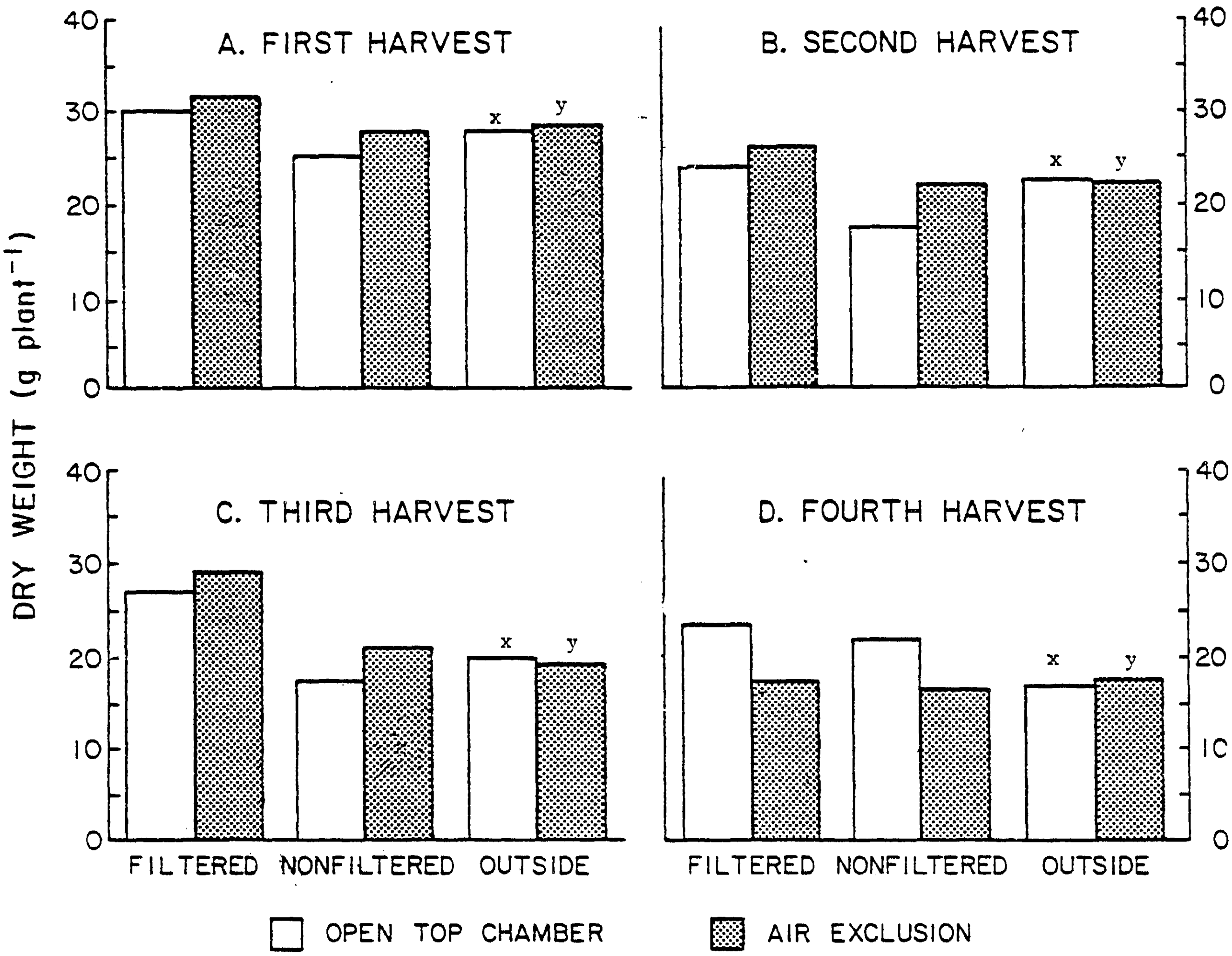


Figure 4-1. Alfalfa dry weight at four harvests during 1983. Outside plots x and y correspond to circular (for open top chambers) and linear (for air exclusion) plots, respectively. There were statistically significant differences at $p<0.05$ for second harvest, filtered versus nonfiltered air exclusion systems or open top chambers; third harvest, filtered versus nonfiltered air exclusion systems or open top chambers, and nonfiltered open top chambers versus outside plots; and fourth harvest nonfiltered open top chambers versus outside plots.

concentration and alfalfa dry weight (Figure 4-2). The data points for open top chambers had lower dry weights than for air exclusion systems or outside areas. However, inclusion of data from all systems gives a picture of plant response to ozone with different exposure conditions. Further verification of this analysis was shown by the similarity between the 36% yield loss predicted with 196 $\mu g\ m^{-3}$ ozone versus 49 $\mu g\ m^{-3}$ in Figure 4-2 and the 38% yield loss reported earlier with similar ozone concentrations (32).

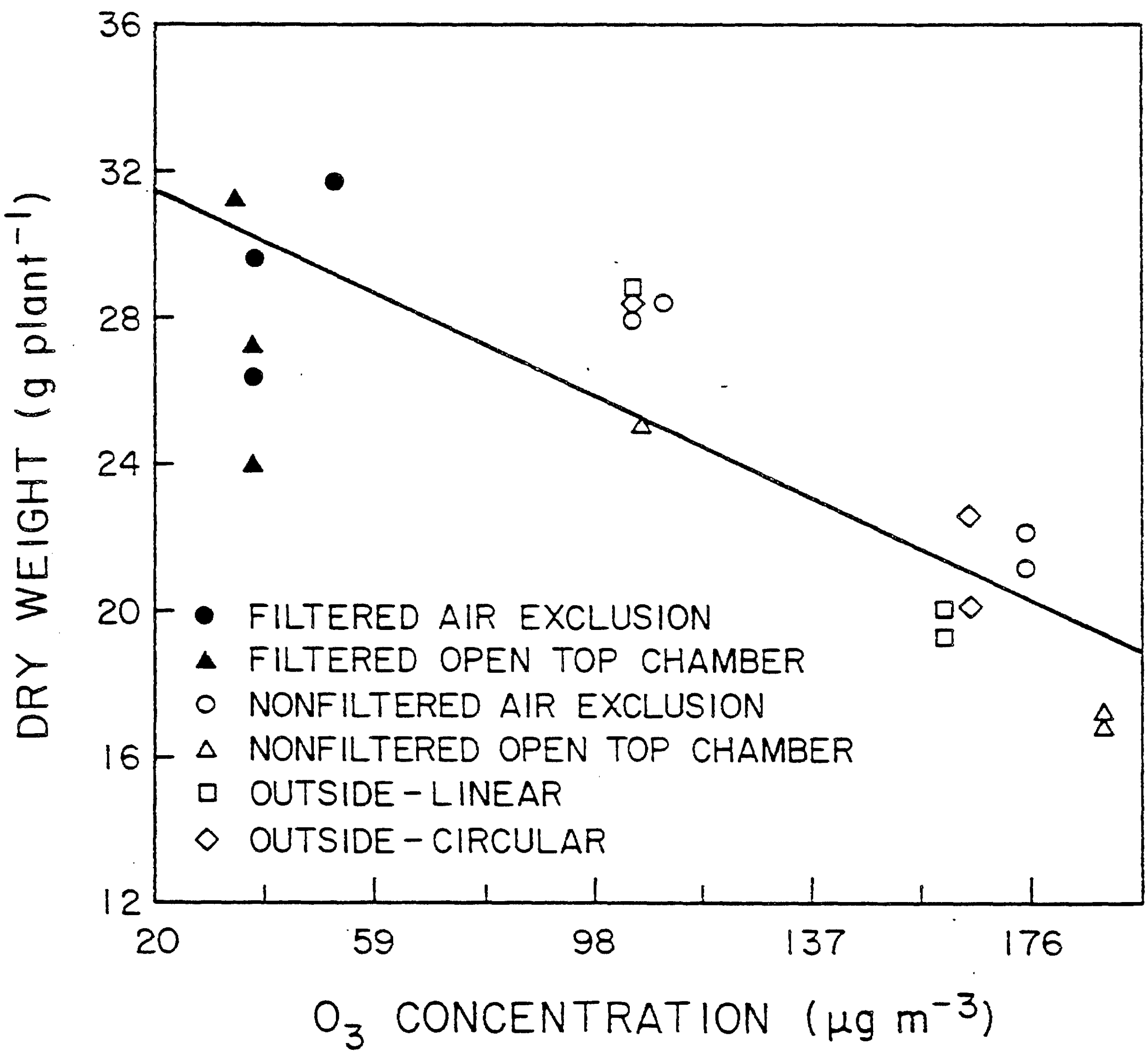


Figure 4-2. Linear regression analysis for alfalfa dry weight at first three harvests during 1983. Regression equation from linear regression analysis is: dry weight (g $plant^{-1}$) = 32.89-(O_3 concentration in $\mu g\ m^{-3}$ x 0.0714), for 18 observations and r = 0.87.

Other measurements indicated plant responses similar to dry weight differences with filtered versus nonfiltered treatments and the different systems. Total fresh weight, dry weight of stems, dry weight of leaves, height, number of nodes, number of empty nodes, and percentage empty nodes were all lower with nonfiltered than filtered air with both systems (Table 4-2). Total fresh weight, dry weight of leaves and especially height were consistently reduced in open top chambers versus air exclusion systems. For all parameters, alfalfa response with nonfiltered air exclusion systems was similar to response in outside plots, whereas plant growth and reduced height increased in nonfiltered open top chambers versus outside plots. This was especially evident for height which averaged 10, 3 and 10% higher in nonfiltered open top chambers versus outside control plots at the first, second and third harvests, respectively. Leaf injury was greater with nonfiltered open top chambers than nonfiltered air exclusion at the systems second and third harvests (Table 4-2). Injury with nonfiltered open top chambers also was greater than with outside plots at the first harvest. Injury with nonfiltered air exclusion systems was the same as outside areas at both harvests. Injury was much lower with filtered versus nonfiltered treatments at both harvests.

At the fourth harvests alfalfa growth and yield was the same with filtered and nonfiltered treatments (Figure 4-1, Table 4-2). This likely was related to the much lower ambient ozone concentrations compared to the first three harvests. Leaf injury was reduced with filtered versus nonfiltered treatments with the greatest injury occurring in nonfiltered open top chambers. There was, however, a significant overall increase in plant growth with open top chambers versus air exclusion systems or outside areas. Total dry weight and height were 25% and 41%, respectively, greater in open top chambers than outside areas. This increased growth likely was associated with the warmer temperatures in the chambers versus air exclusion systems on the outside.

Stomatal response was similar for air exclusion systems and open top chambers across most harvests. At the first harvest ambient oxidants apparently induced stomatal closure in both air exclusion systems and open top chambers (Table 4-3). However, the filtered versus nonfiltered treatments were significantly different only for open top chambers. For the second through fourth harvests, stomatal conductance was similar across filtered and nonfiltered chambers and with both air exclusion systems and chambers. The system factor was not statistically significant at any harvest.

Table 4-2

RESULTS FROM ALFALFA OXIDANT EXCLUSION STUDIES IN 1983[a]

	Air Exclusion					Open Top Chamber				
Harvest	Filtered		Nonfiltered		Linear Outside	Filtered		Nonfiltered		Circular Outside
					Total Fresh Weight (g)					
1	136	ns	131	ns	125	125	ns	101	ns	135
2	124	*	100	ns	84	105	*	78	*	103
3	137	*	96	ns	90	108	*	84	ns	100
4	76	ns	72	ns	81	109	ns	101	*	75
					Height (m)					
1	0.57	ns	0.58	ns	0.58	0.72	ns	0.68	*	0.62
2	0.60	ns	0.57	ns	0.55	0.68	*	0.62	ns	0.60
3	0.59	*	0.52	ns	0.53	0.67	ns	0.64	ns	0.58
4	0.45	ns	0.47	ns	0.48	0.65	ns	0.65	*	0.46
					Stem Dry Weight (g)					
1	15.6	ns	14.5	ns	14.2	16.1	ns	12.8	ns	14.5
2	13.3	ns	10.8	ns	9.2	12.3	*	8.3	ns	11.1
3	14.3	ns	11.9	ns	8.9	14.2	*	8.5	ns	10.0
4	6.2	ns	6.0	ns	7.2	10.8	ns	10.1	ns	6.3
					Leaf Dry Weight (g)					
1	16.1	ns	13.5	ns	14.5	14.3	ns	12.3	ns	14.0
2	13.1	ns	11.3	ns	11.0	11.7	*	9.1	*	11.6
3	15.3	*	9.3	ns	10.4	13.1	*	8.5	*	10.0
4[b]	11.5	ns	11.0	ns	11.1	13.3	ns	12.4	*	11.2
					Number of Nodes per Stem					
1	29.5	ns	31.2	ns	30.4	29.8	ns	30.8	ns	30.7
2	29.5	ns	29.7	ns	27.8	28.9	ns	29.7	ns	29.9
3	31.5	ns	32.9	ns	30.9	32.4	ns	34.8	ns	32.7
					Number of Empty Nodes					
1	5.8	ns	15.1	ns	14.4	2.1	*	18.4	ns	16.0
2	3.0	*	11.3	ns	11.8	2.0	*	12.6	ns	13.1
3	3.0	*	21.0	ns	21.4	1.0	*	22.6	ns	22.2
					% Empty Nodes					
1	35.4	*	46.2	ns	44.8	32.0	*	49.2	ns	46.6
2	32.5	*	41.0	ns	39.6	42.3	*	30.8	ns	43.0
3	34.5	*	53.9	ns	52.3	33.3	*	57.3	ns	55.0

(continued)

Table 4-2 (continued)

RESULTS FROM ALFALFA OXIDANT EXCLUSION STUDIES IN 1983[a]

	Air Exclusion					Open Top Chamber				
Harvest	Filtered		Nonfiltered		Linear Outside	Filtered		Nonfiltered		Circular Outside
					Number of Flowers per Stem					
2	6.2	ns	6.8	ns	6.2	5.6	ns	3.6	*	5.7
3	4.4	ns	5.3	ns	3.0	5.0	ns	2.9	ns	3.1
					Leaf Injury (0-4 Scale)[c]					
2	0.1	*	1.9	ns	1.8	0.1	*	2.6	*	1.9
3	0.2	*	1.8	ns	2.1	0.1	*	2.8	ns	2.7
4	0.8	*	1.6	ns	1.3	0.9	*	2.1	*	1.2

[a]Values are means per plant for 60 and 40 observations per treatment, for harvests 1 to 3 and 4, respectively, with 30 or 20 pots from each of two replicate plots. Pairs of filtered vs nonfiltered, or nonfiltered vs outside values separated by a "*" are significantly different at $p<0.05$.

[b]Values obtained by subtraction of mean treatment stem dry weight from total dry weight.

[c]Values are means per plant for 18 observations per treatment, nine from each of two replicates.

Stomata closed in chambers at the first harvest, as shown by the significant difference in stomatal conductance between nonfiltered open top chambers and outside control areas (Table 4-3). A similar response occurred at the fourth harvest, however, in this case stomatal conductance was lower in ambient versus outside plots for air exclusion systems as well as open top chambers.

Stomatal response over the day was similar in air exclusion systems and open top chambers (Table 4-4). Stomatal conductance tended to be higher in filtered than nonfiltered treatments. The filtered versus nonfiltered difference was statistically significant at 1015, for both systems; plus 0845, 1445 and 1600 for open top chambers. Conductance was similar in nonfiltered air exclusion systems or chambers and outside plots all day, except for open top chambers at 0845.

Table 4-3

ALFALFA STOMATAL CONDUCTANCE FROM OXIDANT EXCLUSION STUDIES IN 1983[a]

	Stomatal Conductance ($cm\ s^{-1}$)									
	Air Exclusion					Open Top Chamber				
Harvest	Filtered		Nonfiltered		Linear Outside	Filtered		Nonfiltered		Circular Outside
1	1.57	ns	1.38	ns	1.35	1.53	*	1.11	*	1.39[b]
2 am	1.29	ns	1.27	ns	1.45	1.41	ns	1.11	ns	1.24
2 pm	0.59	ns	0.46	ns	0.56	0.63	ns	0.58	ns	0.38
3	0.74	ns	0.77	ns	0.75	0.74	ns	0.75	ns	0.83
4	0.90	ns	0.89	*	1.22	0.71	ns	0.78	*	1.03

[a]Values are means of six (harvest 2 pm), 12 (2 am and 4) or 18 (1,3) observations with three, six, or nine plants, respectively, from each of two replicate plots. Pairs of filtered vs nonfiltered or nonfiltered vs outside values separated by "*" are significantly different at $p<0.05$.

[b]Mean of nine observations from one plot.

Table 4-4

DIURNAL VARIATION IN STOMATAL CONDUCTANCE FOR ALFALFA DURING THIRD HARVEST, 1983[a]

	Air Exclusion			Open Top Chamber		
Time	Filtered	Nonfiltered	Linear Outside	Filtered	Nonfiltered	Circular Outside
0745	0.82	0.73	0.81	0.88	0.87	0.89
0845	1.18 a	0.94 ab	1.08 a	1.20 a	0.64 b	0.89 a
1015	1.39 a	0.91 b	1.25 ab	1.54 a	0.97 b	1.31 ab
1100	1.21	1.02	1.23	1.36	0.81	0.88
1355	1.07	0.91	0.77	1.10	0.61	1.10
1445	0.98 b	0.83 b	0.86 b	1.58 a	0.82 b	1.05 b
1600	0.98 ab	0.69 b	0.67 b	1.27 a	0.61 b	0.74 b
1645	1.12	0.71	0.86	1.20	0.83	0.86
1730	0.82	0.60	0.67	1.19	0.83	0.68

[a]Values are means of four observations, two from each of two plots. Values in a row for air exclusion or open top chamber treatments followed by different letters are significantly different at $p<0.05$.

Net photosynthesis at the fourth harvest (10/18/83) was slightly higher in air exclusion systems than in chambers, however, the difference was not statistically significant (Table 4-5). There were no differences in net photosynthesis between filtered and nonfiltered plots, or nonfiltered and outside plots.

1984 Response. Alfalfa growth and yield was lower overall in 1984 than in 1983, presumably because the potted plants were losing vigor due to confinement of the roots. The pattern of plant response to filtered versus nonfiltered air and with the different systems was different from 1983. Total dry weight was reduced by ambient oxidants only at the third harvest (Figure 4-3), with only the filtered versus nonfiltered treatments for the air exclusion systems being statistically significant. Lack of effects at the first harvest apparently was due to the shorter exposure period compared to other harvests. The large reduction in yield in nonfiltered versus filtered treatments at the third harvest was more likely a result of the cumulative exposures over the summer than the particular ozone exposure at that harvest. The average ozone concentration in fact was over 25%

Table 4-5

ALFALFA NET PHOTOSYNTHESIS FROM OXIDANT EXCLUSION STUDIES IN 1983 AND 1984[a]

		Net Photosynthesis ($\mu mol\ m^{-2}\ s^{-1}$)								
		Air Exclusion			Open Top Chamber			Closed Top Chamber		
Date	Outside[b]	Filtered		Non-Filtered	Filtered		Non-Filtered	Filtered		Non-Filtered
10/18/83	9.63 [c]	13.06	ns	11.68	9.25	ns	8.65	-		-
8/1/84 am	14.25	12.36	ns	9.77	13.42	ns	12.52	16.21	ns	12.91
8/1/84 pm	6.88	8.95	ns	8.63	18.39	*	9.63	20.15	*	11.67

[a]Values are means of four (10/18/83) or six (8/1/84) observations, with two or three plants from each of two replicate plots. Pairs of filtered vs. nonfiltered values separated by a "*" are significantly different at $p<0.05$.

[b]No outside vs nonfiltered treatments are significantly different except for 8/1/84 am where outside plots are significantly different from nonfiltered air exclusion systems at $p<0.05$.

[c]Average of linear outside (11.51 $\mu mol\ m^{-2}\ s^{-1}$) and circular outside (7.74 $\mu mol\ m^{-2}\ s^{-1}$) plots.

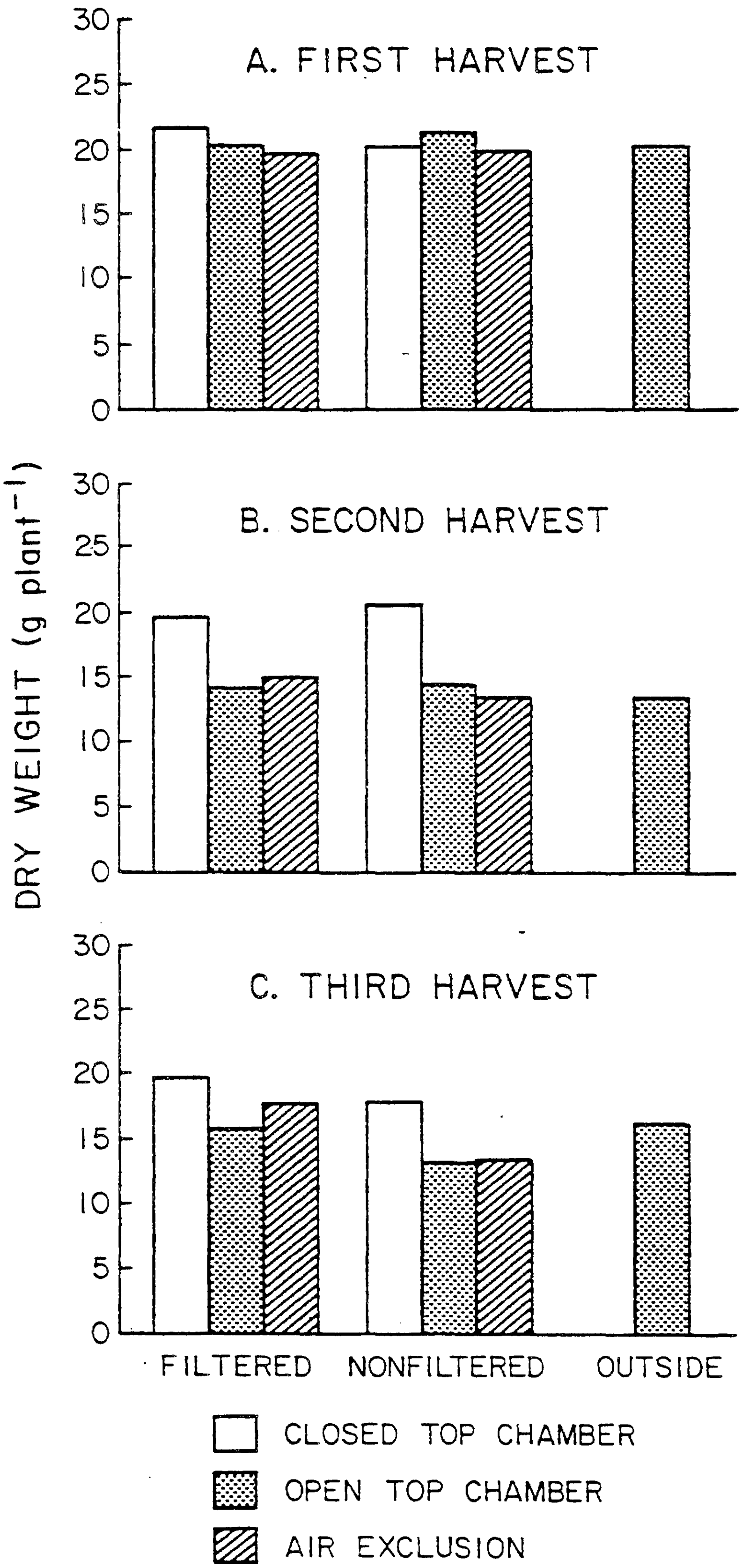


Figure 4-3. Alfalfa dry weight at three harvests during 1984. There were statistically significant differences at $p<0.05$ for first harvest, nonfiltered closed top chambers versus outside plots; and third harvest, filtered versus nonfiltered air exclusion systems.

lower during the third growth period than the preceding two periods (Table 2-7). The percentage changes in dry weight for air exclusion systems versus open and closed top chambers, respectively, were 0 and a 14.3% increase for harvest 1; 13.3% decrease and 0 for harvest 2; and 24.3 and 15.9% decrease for harvest 3. This greater apparent effect of ambient oxidants in air exclusion systems versus open top chambers was the opposite of the response found in 1983. In the closed top chambers dry weight was not reduced by ambient oxidants at any harvest.

Over all three harvests the ambient air exclusion plants had similar dry weights vs outside control plants (Figure 4-3). Nonfiltered open and closed top plants had higher dry weights than outside plants at the first two harvests. At the third harvest, nonfiltered open top chamber plants also had similar dry weights as outside plants except for the significantly higher dry weight in nonfiltered closed top chambers than outside plots at the first harvest. Plants grown in the closed top chambers with both filtered and nonfiltered air had over 25% greater dry weight compared to either air exclusion system, open top chamber or outside plants at harvests 2 and 3. The environmental conditions in the closed top chambers apparently increased crop growth, possibly by reducing the evaporative stress to plants because of the reduced light intensity compared to open top chambers or outside plots.

Changes in alfalfa total fresh weight, height, number of nodes, empty nodes and percent empty nodes, all followed the same pattern as total dry weight (Table 4-6). Plant growth was reduced in nonfiltered versus filtered systems at the second and third harvests, but only the difference for total fresh weight was statistically significant. Plant growth in ambient air exclusion systems was more similar to that in outside chambers than ambient open top or closed chambers. Overall growth was greater in the closed top chambers than with the other systems.

Ambient oxidants were affecting the alfalfa plants at both the second and third harvests as indicated by both visible leaf injury and percent empty nodes (Table 4-6).

Stomatal response differed in the three exposure systems. In the morning there was an overall higher stomatal conductance in filtered versus nonfiltered treatments, however, only the difference in closed top chambers was statistically significant (Table 4-7). Nonfiltered open top and closed top chambers had lower and higher stomatal conductances, respectively, than outside plots. In the

Table 4-6

RESULTS FROM ALFALFA OXIDANT EXCLUSION STUDIES IN 1984[a]

		Air Exclusion			Open Top Chamber			Closed Top Chamber		
Harvest	Outside[b]	Filtered		Non-filtered	Filtered		Non-filtered	Filtered		Non-filtered
				Total Fresh Weight (g)						
1	81.3	79.7	ns	77.7	84.1	ns	88.1	86.8	ns	92.6
2	48.3	54.1	ns	47.4	49.0	ns	53.8	77.0	ns	82.3
3	59.4	69.3	*	52.6	61.5	ns	51.3	81.1	ns	72.3
				Height (m)						
1	0.45 o,c	0.50	ns	0.52	0.55	ns	0.56	0.60	ns	0.59
2	0.45	0.46	ns	0.44	0.49	ns	0.48	0.54	ns	0.57
3	0.45 c	0.50	ns	0.44	0.52	ns	0.49	0.54	ns	0.57
				Number of Nodes per Stem						
2	25.3 c	25.4	ns	25.9	26.4	ns	25.2	25.4	ns	28.1
3	25.0 o,c	28.0	ns	25.0	27.4	ns	27.4	28.2	ns	28.2
				Number of Empty Nodes per Stem						
2	11.4	1.2	*	9.4	2.0	*	10.8	1.9	*	14.3
3	7.4	0.9	ns	4.5	1.2	*	6.0	1.3	ns	9.8
				% Empty Nodes						
2	44.8	4.8	*	35.4	7.4	*	41.8	7.3	*	50.0
3	29.5	3.2	*	17.5	4.6	*	21.7	4.5	*	35.5
				Leaf Injury (0-4 Scale)						
2	1.7	0.5	*	1.5	0.6	*	1.9	0.3	*	2.2
3	1.2	0.4	ns	0.6	0.4	ns	0.7	0.3	*	1.0

[a]Values are means for 42-48 observations per treatment for all parameters except leaf injury which had 18 observations. There were 21-24 or nine observations from each of two replicate plots. Pairs of filtered vs nonfiltered values separated by a "*" are significantly different at $p<0.05$.

[b]Outside plot values followed by "o" and "c" are significantly different from nonfiltered open top chambers (o) and closed top chambers (c), respectively, at $p<0.05$. There were no significant differences between outside values and nonfiltered air exclusion systems.

Table 4-7

STOMATAL CONDUCTANCE FROM OXIDANT EXCLUSION STUDIES IN 1984[a]

Harvest Time	Outside[b]		Air Exclusion: Filtered		Air Exclusion: Non-filtered	Open Top Chamber: Filtered		Open Top Chamber: Non-filtered	Closed Top Chamber: Filtered		Closed Top Chamber: Non-filtered
	Stomatal Conductance (cm s^{-1})										
3 am	1.22	o,c	1.29	ns	0.94	1.15	ns	0.82	1.37	*	1.00
3 pm	0.78	c	1.15	*	0.64	1.09	ns	0.88	1.56	ns	1.52

[a]Values are means of six observations per treatment from each of two replicate plots.

[b]Outside plot values followed by "o" and "c" are significantly different from nonfiltered open top chambers (o) and closed top chambers (c), respectively, at $p<0.05$. There are no significant differences between outside values and nonfiltered air exclusion systems.

afternoon there was a significantly higher stomatal conductance in filtered versus nonfiltered air exclusion systems, but not open or closed chambers. Ambient closed top chambers again had a higher conductance than outside plots.

Net photosynthesis was similar in air exclusion systems and open or closed top chambers for morning measurements during the third harvest (Table 4-5). Nonfiltered air exclusion systems had a lower rate of photosynthesis than outside plots at this time even though it was not statistically significant, whereas nonfiltered open or closed top chambers had rates similar to outside areas. During the afternoon on the same day open and closed top chambers had higher photosynthesis rates than air exclusion systems, and had higher rates in filtered than nonfiltered chambers.

Linear Gradient

The linear gradient exposure was successful in producing three different levels of oxidant exposure with a single air exclusion system using low, medium, and high air speed rates shown in Table 3-2. However, no growth effects from oxidant were found at any level because all ozone concentrations were relatively low

(Table 2-12). The weather in Riverside during late September and early October 1983, was unusually cool, cloudy and rainy; all conditions which discourage ozone formation. Overall alfalfa yields were also lower than for the first three harvests of 1983, possibly due to the cooler temperatures. There was a small amount of leaf injury to the plants which was greater in nonfiltered than filtered plots at all three air flow rates. There was no difference in leaf injury between air flow rates within either the filtered or nonfiltered treatments.

The linear gradient system indicated that air flow by itself from the ducts can have a significant effect on plant growth. Total dry weight was reduced by 13% in the high flow section of the ducts compared to medium or low flows (Table 4-8). This reduction occurred both for filtered and nonfiltered plots. Alfalfa height, total fresh weight and other dry weight also were reduced with the high compared to low flows. The decreased plant growth at the high flow may have been associated with seismomorphic responses (20) or greater plant transpiration at the high air flow possibly resulting in water stress.

Stomatal conductance was not affected by either air flow or filtering ambient oxidants (Table 4-9). Net photosynthesis was greater with high air flow rates than medium or low flows, and was not affected by filtering the air.

SULFUR DIOXIDE ADDITION

The sulfur dioxide gradient experiment was designed to assess: (1) the sulfur dioxide-plant growth response relationship with air exclusion systems versus open top chambers, (2) the response of plants to winter ambient pollutants with the two types of systems, and (3) the overall effects of air exclusion systems versus open top chambers on plant growth during the winter.

Methods

Lettuce (cultivar Empire) and wheat (cultivar Yecora Rojo) were grown from seed. Lettuce seed pelleted in Endrin® insecticide was planted on 11/29/83 in trays placed in a charcoal-filtered chamber. The seeds were planted in a commercial firbark-redwood shavings-peat-sand media (Supersoil®) and were treated with a pelleted fertilizer (Osmocote®). The seedlings were transplanted into the ground in the plots on 12/19-21/83.

Lettuce plants were placed in three rows in one-half of each chamber or circular open control plots, with seedlings placed 0.13 m apart within rows and 0.25 m

Table 4-8

ALFALFA RESPONSES TO OXIDANT EXPOSURES WITH LINEAR GRADIENT AIR EXCLUSION SYSTEM[a]

Treatment	Total Dry Weight (g)	Height (m)	Leaf Injury[b]	Total Fresh Weight (g)	Stem Dry Weight (g)
Low flow-filtered	20.1	0.51	1.1	89.1	7.8
	y[c]	y	z	y	y
Low flow-nonfiltered	19.1	0.51	1.5	85.0	7.4
Medium flow-filtered	20.7	0.49	1.0	92.9	8.1
	y	yz	z	y	y
Medium flow-nonfiltered	19.8	0.49	1.4	85.6	7.3
High flow-filtered	17.7	0.45	0.8	76.4	6.2
	z	z	z	z	z
High flow-nonfiltered	17.0	0.47	1.6	71.7	6.0

[a]Data is average per plant with 21 replicates per plot and two plots per treatment. Data for total fresh weight and stem dry weight is not reported here, but followed the same pattern as total dry weight and height.

[b]Leaf injury on 0 to 4 scale with 0 = no injury and 4 = 100% injury. Data is average of nine replicates per plot and two plots per treatment. The filtered versus nonfiltered treatments are significantly different for each flow rate.

[c]Pairs of values followed by different letters are significantly different at $p<0.05$ using Duncan's Multiple Range Test.

Table 4-9

ALFALFA STOMATAL CONDUCTANCE AND NET PHOTOSYNTHESIS WITH LINEAR GRADIENT AIR EXCLUSION SYSTEM[a]

	Stomatal Conductance ($cm\ s^{-1}$)		Net Photosynthesis ($\mu mol\ m^{-2}\ s^{-1}$)	
Air Flow	Filtered	Nonfiltered	Filtered	Nonfiltered
Low	1.02	1.17	6.82	8.01
Medium	0.91	1.05	6.30	8.08
High	0.90	0.90	13.06	11.68

[a]Values are means of 12 (conductance) and four (photosynthesis) observations, six and two from each of two replicate plots, respectively. There were no significant differences between any treatments for stomatal conductance. For net photosynthesis, the pooled data for filtered and nonfiltered treatments is significantly different from low and medium versus high flow values at $p<0.05$.

apart between rows. Lettuce was planted in three rows between the ducts of the air exclusion systems and in linear open control plots, with seedlings placed 0.25 m apart. There was a total of approximately 40 seedlings planted in each chamber or circular open plot (4 inner row, 18 middle row, 18 outer row), and 24 seedlings in each air exclusion system or linear open plot (8 in each of 3 rows).

Wheat was planted directly into the soil on 12/15-16/83. Seeds were placed in seven concentric half-circle rows in chambers and circular open plots. Two seeds were planted together with 0.05 m between pairs of seeds and 0.18 m between rows. Wheat was planted in two rows between ducts of the air exclusion systems and linear open plots. Seeds were planted 0.025 apart with 0.18 m between the two rows. Thus, there were approximately 1600 wheat seeds per chamber or circular open plot and 750 seeds per air exclusion or linear open plot. Wheat was thinned to one plant every 0.025 m several weeks after planting.

Plants were watered as needed via a drip irrigation system using irrigation water supplemented with a fertilizer solution (full strength North Carolina State

University Phytotron solution) weekly. The plant received sprays of Orthene® and Sevin® as needed to control insects.

There were a total of 12 treatments in the study each replicated four times as shown in Figure 2-9. Exposures were initiated on 1/18/84 and continued until final harvest of wheat on 5/15-16/84. All exposures were continuous except when sulfur dioxide was turned off during brief periods of heavy rain or with high wind speeds early during the year. Target versus actual concentrations of sulfur dioxide obtained with the exposures are shown in Table 2-16. Sulfur dioxide concentrations were similar with the two systems.

Ozone concentrations averaged 82 and 43 $\mu g\ m^{-3}$, respectively, in nonfiltered and filtered air exclusion systems, and 92 and 37 $\mu g\ m^{-3}$, respectively, in nonfiltered and filtered chambers over the entire exposure period (Table 2-18). Ozone averaged 92 $\mu g\ m^{-3}$ in outside plots.

Sulfur dioxide concentrations were uniform over the entire experiment except for a brief high concentration exposure in the air exclusion systems when the sulfur dioxide control system malfunctioned. For one day sulfur dioxide reached over 2620 $\mu g\ m^{-3}$ in the high concentration air exclusion plots and proportionally less in the medium and low concentration plots. Acute injury was seen on lettuce and wheat plants within two days at the high concentration of sulfur dioxide. Only a trace of injury was seen on the medium, and none on the low sulfur dioxide concentration plots. An estimate of the percentage injury was made for each plot was made. The plants recovered rapidly from this accidental exposure.

The chambers and air exclusion systems were turned on at the time of lettuce planting at which time the ambient air or filtered treatments were initiated. Sulfur dioxide was added to the proper filtered chambers beginning 1/18/84. A first harvest of lettuce was made on 2/1-2/84 after approximately 14 days of exposure. A first harvest of wheat was made on 2/9-10/84 after 22 days of exposure. A final harvest of lettuce was made on 3/13-19/84 after 47 days of exposure. A final harvest of wheat was made on 5/15-16/84 after 118 days of exposure.

During the early part of the exposures growth of lettuce and wheat was monitored by nondestructive methods. Lettuce planar area was determined for four plants per plot by placing a transparent acetate sheet imprinted with a grid over the plant and then counting the grid intersections directly over leaf tissue (22).

Measurements were initiated in the chamber and for circular outside plots 12/30/83, three weeks before beginning the sulfur dioxide exposures. Planar area measurements were initiated later at 1/13/84 for the air exclusion systems and linear outside areas as little lettuce growth occurred early in January in these plots. Measurements were continued through 2/3/84, after which time the plants were too large to determine planar area.

Wheat height was measured for four plants per plot beginning 1/20/84 and continuing for eight weeks until 3/23/84. The tallest point on the plant was measured whether it was the top of the areas or the tip of an upright flag leaf. The extent of heading of four wheat plants per plot was determined weekly between 3/2 and 3/23/84 at which time all plants had headed.

For the first harvest every other lettuce plant was removed from the middle row in chambers and circular outside areas, and all three rows in air exclusion systems and linear outside areas. This resulted in 8-10 plants from open-top chambers and 12-15 plants from air exclusion systems. Lettuce plants were cut off at soil level and total fresh weight measured immediately. Leaf area was measured for four plants selected randomly from the harvested plants. Two plants per plot were reserved for total sulfur analysis and the rest dried at 32^{o}C in forced air driers to obtain dry weights. The plants were inspected for air pollutant injury, but no symptoms representative of sulfur dioxide or ozone injury were found on any plants.

At the final harvest all remaining lettuce plants were used from the inner and middle rows in open top chambers or circular outside areas, or from all three rows of air exclusion systems or the linear outside areas. Plants in the outer row of open top chambers were discarded as guard row plants whose growth was affected by the adjacent chamber wall. This resulted in 12 to 14 plants from both open top chambers and air exclusion systems. Total plant and head fresh weights were determined immediately. Measurements were made of plant and head diameters. A rating of leaf tip burn was made per plant and plants were again rated for air pollutant injury. As at the first harvest, no air pollutant injury was found. Four plants per plot were saved for dry weight determinations.

For the first wheat harvest four subsamples of at least eight plants each were taken randomly from among all rows of each plot. The fresh weight of six plants from each subsample was determined immediately and saved for dry weight and total sulfur determinations. Two plants were removed from each subsample and measured for number of tillers and leaf area and all leaves were rated for air pollutant injury on a 0 (no injury) to 10 (100% injury) scale. The leaves from two plants from each plot were saved for chlorophyll concentration according to the absolute ethanol extraction procedure of Knudson et al. (17).

At the final harvest subsamples of 10 plants each were taken on 5/15-16/84 and air dried for approximately one month. The air exclusion systems and linear outside plots yielded two to three subsamples per row for a total of six to nine subsamples per plot. There was considerably more wheat in the open top chambers than air exclusion systems, thus subsamples were taken only from the middle rows in chambers. Two to five subsamples were taken from each of four rows for a total of approximately 11 subsamples per plot. After drying, subsamples were measured for total dry weight, number of ears, ear weight, seed weight and 100 seed weight.

No rating was made for air pollution injury at the final wheat harvest, as plants had sun dried and turned brown. However, a rating of wheat (0-10 scale) was made on 4/4/84 to evaluate injury to plants during the important grain filling period. Four plants per plot were selected at random and all leaves on the plant were rated for injury. There were approximately four to six leaves per plant, however, the flag leaf nearest the developing head is the most important to produce photosynthate for grain filling. Stomatal conductance was measured with the LI-1600 steady state porometer. Two plants per plot were measured for each species. Transpiration and photosynthesis were measured with the ^{3}H and ^{14}C dual isotope porometer on the same plants as the LI-1600 measurements. Lettuce was measured on 2/7/84 and wheat on 3/12/84.

Buffering capacity (a measure of sulfur dioxide induced acidity) was measured for one frozen wheat sample per plot according to the procedure of Scholz and Reck (27). Samples were from the first harvest.

Ratings of relative dew formation and guttation were made on wheat plants for all plots on three early winter dates, 1/16, 1/18 and 1/20/84. Each plot was visually rated on a scale with 0 = no dew or guttation water and 5 = all leaves covered with dew or a large drop of guttation water on the tips of all wheat leaves.

Wheat

General results from statistical analysis of wheat data are summarized in Table 4-10. Across both air exclusion systems and open top chambers, sulfur dioxide had a significant effect on number of tillers and leaf injury at the first harvest, and dry weight, 100 seed weight and number of ears at the final harvest. Ozone had a significant effect on 100 seed weight and number of ears at the final harvests. However, the extent of these pollutant effects varied when examined separately for air exclusion systems or open top chambers. There were significant system effects for air exclusion systems verus open top chambers for a number of parameters at both harvests. These effects generally consisted of greater growth in open top chambers than in air exclusion systems. There also were significant treatment x system interactions for a number of parameters.

Table 4-10

RESULTS FROM ANALYSIS OF VARIANCE FOR WHEAT DATA

Harvest	Factors[a]	Fresh Wt	Dry Wt	Ear Wt	Seed Wt	100 Seed Wt	No. Tillers	No. Ears	Leaf Area	Height	Leaf Injury
First	T_1-SO_2	ns[b]	ns	-	-	-	*	-	ns	ns	***
	T_2-O_3	ns	ns	-	-	-	ns	-	ns	ns	ns
	S_1-SO_2	ns	ns	-	-	-	***	-	**	***	ns
	S_2-O_3	ns	ns	-	-	-	ns	-	**	***	ns
	T_1 x S_1	*	ns	-	-	-	*	-	ns	ns	ns
	T_2 x S_2	*	*	-	-	-	ns	-	ns	ns	ns
Final	T_1-SO_2	-	*	ns	ns	***	-	**	-	-	-
	T_2-O_3	-	ns	ns	ns	**	-	*	-	-	-
	S_1-SO_2	-	**	*	ns	ns	-	***	-	-	-
	S_2-O_3	-	ns	ns	ns	***	-	*	-	-	-
	T_1 x S_1	-	*	*	ns	***	-	ns	-	-	-
	T_2 x S_2	-	ns	ns	ns	ns	-	ns	-	-	-

[a] T = treatments: T_1-SO_2 for 0, 79, 183 and 393 $\mu g\ m^{-3}$ sulfur dioxide, T_2-O_3 for filtered versus nonfiltered air; S = system: S_1-SO_2 for air exclusion systems versus open top chamber across sulfur dioxide exposures, S_2-O_3 for air exclusion systems versus open top chambers across filtered and nonfiltered exposures.

[b] ***, ** and * = statistically significant at $p<0.005$, 0.01 and 0.05, respectively.

First Harvest. Wheat seedlings emerged on approximately 12/22/83 in chambers and a few days later in air exclusion systems and outside plots. The earlier germination in open top chambers was likely due to warmer temperatures than in air exclusion systems or outside plots. The soil also stayed more moist in open top chambers, presumably due to lack of convective drying of soil by wind.

Enhanced growth of wheat in chambers was maintained over time as indicated by the greater plant height compared to air exclusion systems or outside areas (Table 4-11). Plant height was greater in air exclusion systems than outside areas. However, there was only an average 19% greater height for air exclusion systems versus outside plots compared to a 35% greater height for open top chambers versus outside plots over the 10 weeks of measurement.

At the first harvest there were scattered treatment effects on wheat due to exposure system, sulfur dioxide, and ambient oxidants (Table 4-12). Air exclusion plants had lower leaf areas, were shorter, and had more tillers than open top chamber plants. Dry weight, fresh weight, and leaf injury were similar with both systems. Plant growth was greater in both air exclusion systems and open top chambers than in outside plots.

Sulfur dioxide had an apparent stimulatory effect on growth in air exclusion systems at 79 $\mu g\ m^{-3}$, increasing fresh and dry weights. In contrast, height and leaf area were reduced in open top chambers, but only at 183 $\mu g\ m^{-3}$ sulfur dioxide. Exposure to 183 and 393 $\mu g\ m^{-3}$ sulfur dioxide definitely caused leaf chlorosis in both air exclusion systems and open top chambers.

Similar leaf injury occurred in air exclusion systems and chambers despite the fact that air exclusion plants had received the accidental brief acute injury exposure 12 days earlier. The leaf injury followed relatively cool and short days and was not seen later during the exposures indicating that the winter environmental conditions may have increased the sensitivity of plants to sulfur dioxide as reported by Bell et al. (3) and Davies (5).

The chlorophyll measurements, however, did not reinforce the visual observations of injury as there were no differences in chlorophyll concentration between sulfur dioxide concentrations in either air exclusion systems or open top chambers (Table 4-12). There was a trend toward a higher chlorophyll content in both ambient air exclusion systems and chambers than in outside plots, but the

Table 4-11

WHEAT HEIGHT WITH SULFUR DIOXIDE AND OXIDANT EXPOSURES[a]

			Height (m)			
			Sulfur Dioxide ($\mu g\ m^{-3}$)			
Week[b]	Outside	Nonfiltered	0	79	183	393
		Air Exclusion Systems				
5	0.15	0.17	0.17	0.17	0.17	0.16
6	0.17	0.21	0.21	0.20	0.21	0.22
7	0.25	0.27	0.25	0.29	0.21	0.27
8	0.29	0.32	0.35	0.36	0.34	0.34
9	0.30	0.37	0.36	0.39	0.40	0.39
10	0.38	0.44	0.47	0.51	0.51	0.50
11	0.47	0.51	0.50	0.53	0.54	0.55
12	0.51	0.54	0.59	0.64	0.61	0.60
13	0.53	0.62	0.63	0.71	0.68	0.66
14	0.58	0.61	0.66	0.72	0.70	0.69
		Open Top Chambers				
5	0.14	0.20	0.20	0.20	0.21	0.23
6	0.17	0.24	0.25	0.22	0.24	0.27
7	0.24	0.28	0.29	0.31	0.31	0.33
8	0.29	0.37	0.39	0.39	0.35	0.39
9	0.31	0.44	0.45	0.46	0.46	0.43
10	0.36	0.53	0.52	0.52	0.53	0.53
11	0.49	0.63	0.62	0.61	0.62	0.62
12	0.55	0.69	0.66	0.67	0.68	0.69
13	0.61	0.80	0.75	0.79	0.78	0.78
14	0.63	0.79	0.77	0.78	0.79	0.78

[a]Values are means based on 16 observations, four from each of four plots.

[b]Beginning on 1/20/84, five weeks after planting.

Table 4-12

WHEAT RESPONSE TO SULFUR DIOXIDE AND OXIDANT EXPOSURES AT FIRST HARVEST[a]

Response	Outside		Nonfiltered		Sulfur Dioxide ($\mu g\ m^{-3}$)			
					0	79	183	393
			Air Exclusion Systems					
Dry weight (g)	3.7	*	4.2	*	3.4 a	4.8 b	4.1 ab	3.8 a
Fresh weight (g)	20.1	*	23.7	*	17.2 a	28.1 b	21.1 a	20.6 a
Height (m)	0.29	*	0.31	*	0.34	0.35	0.35	0.34
Leaf area (cm^2)	26.4	*	33.3	ns	34.5	37.6	34.5	32.1
Tillers (#)	3.6	ns	3.1	*	1.9 a	4.0 c	2.8 b	3.0 b
Chlorophyll (mg g dr wt^{-1})	7.19	ns	7.97	ns	9.47	10.63	8.12	9.11
Leaf Injury (0-10 scale)	0.5	ns	0.4	ns	0.5 a	0.5 b	2.2 c	2.7 d
			Open Top Chambers					
Dry weight (g)	3.0	ns	3.5	ns	4.0	4.0	3.4	3.8
Fresh weight (g)	17.5	ns	20.4	ns	21.6	20.5	19.3	23.0
Height (m)	0.29	*	0.36	*	0.38 b	0.39 b	0.36 a	0.39 b
Leaf area (cm^2)	26.8	*	41.9	ns	42.6 b	42.6 b	36.6 a	45.2 b
Tillers (#)	3.5	*	2.1	ns	2.0	1.9	1.5	1.9
Chlorophyll (mg g dry wt^{-1})	6.45	ns	8.45	ns	8.67	7.04	9.31	9.60
Leaf Injury (0-10 scale)	0.4	ns	0.5	ns	0.2 a	0.6 a	2.5 b	3.5 c

[a]Values are means per plant of 32 observations (eight from each of four plots) for height, leaf area, tillers and leaf injury; and eight observations for chlorophyll concentration (two from each of four plots). For dry and fresh weights are means for six plants per observation (four from each of four plots). Pairs of outside versus nonfiltered or nonfiltered versus 0 means separated by a "*" are significantly different at $p<0.05$ level. Means for sulfur dioxide concentrations followed by different letters are significantly different at $p<0.05$ level.

differences were not statistically significant. There was no difference in chlorophyll content between filtered and nonfiltered chambers with either system.

There was greater plant growth in nonfiltered compared to filtered air exclusion systems. This effect likely was due to soil factors. The nonfiltered end of the air exclusion systems had previously contained a path that ran perpendicular to the lettuce and wheat rows across all four replicate systems. Even though the field had been disked for uniformity, water still tended to puddle this area of the field. Wheat germination was lower and lettuce transplanting was less successful in the zero sulfur dioxide portion compared to the rest of the air exclusion systems. As the season progressed, plants were less uniform in the nonfiltered air exclusion systems than in other plots. Growth was not greater in nonfiltered than filtered chambers, further indicating that the soil and not a component of the ambient air was related to the air exclusion system differences.

There was a lower buffering capacity in open top chamber wheat plants exposed to sulfur dioxide than in control wheat plants. Buffering capacity was 1.67 ± 0.03, 1.87 ± 0.003, 1.90 ± 0.03 and 2.29 ± 0.06 mℓ N/60 HCl g^{-1} fresh weight pH $unit^{-1}$ with the 393, 183, 79 and 0 $\mu g\ m^{-3}$ sulfur dioxide treatments, respectively. With four observations per treatment (1 from each of four chambers) and a SE of 0.13 the control treatment was significantly different from the three sulfur dioxide treatments. This further indicated that sulfur dioxide was affecting the overall ionic composition of plants, even though these perturbations had no effect on plant growth. No buffering capacity measurements were made for air exclusion plants.

There clearly was less guttation at the tips of wheat leaves in air exclusion systems and open top chambers than in outside plots (Table 4-13). Furthermore, guttation was less in air exclusion systems than chambers, and lowest in the 0 sulfur dioxide portion of the air exclusion system than in the high sulfur dioxide portion. Apparently air speed over the plants was the determining factor in guttation, with the most guttation in the still air outside plots and a decrease in guttation as air flow over the plants increased. The reduced leaf guttation for plants in the zero compared to sulfur dioxide treated portions of the air exclusion systems indicated that these portions of the ducts had a greater air speed blowing over the plant canopy. This increased stress also may

Table 4-13

GUTTATION ON WHEAT LEAVES WITH DIFFERENT EXPOSURE SYSTEMS[a]

		Leaf Guttation (0-5.0 scale)[b]											
						Sulfur Dioxide ($\mu g\ m^{-3}$)							
Date	System	Outside		Nonfiltered		0		79		183		393	
1/16/84	Air exclusion	3.8	*	1.3	*	0.3		1.0		1.5		2.0	
	Open top chamber	5.0	*	2.3	ns	2.8		2.5		2.0		1.8	
1/18/84	Air exclusion	3.8	*	0.5	ns	0	a	1.0	ab	1.8	bc	2.5	c
	Open top chamber	5.0	*	1.5	ns	1.5		1.8		1.5		2.5	
1/20/84	Air exclusion	4.3	*	0.3	ns	0	a	0.5	ab	1.3	bc	2.0	c
	Open top chamber	5.0	*	2.8	ns	2.0	ab	1.5	a	2.5	b	2.8	b

[a]Values are means of four observations (one from each of four plots). Pairs of outside versus nonfiltered, or nonfiltered versus 0 sulfur dioxide values separated by a "*" are significantly different at $p<0.05$. Values for sulfur dioxide concentrations in the same row followed by different letters are significantly different at $p<0.05$.

[b]Guttation rated on 0 to 5 scale where 0 = no beads of water at tips of any wheat plants in the plot and 5 = beads of water at tips of all plants in plot.

have been responsible for the decreased plant growth for the nonfiltered plots compared to other air exclusion treatments.

Final Harvest. Wheat plants continued to grow rapidly between 2/10/84 and harvest on 5/15-16/84. Air exclusion plants were consistently taller than outside plants, but shorter than chamber plants (Table 4-11, weeks 7-14). Full heading of wheat plants was advanced by one and two weeks, respectively, in the air exclusion systems (3/16/84) and chambers (3/9/84) versus the outside plots. Porometer measurements on 3/12/84 indicated that stomatal conductance was similar in wheat plants grown in air exclusion systems and outside plots (Table 4-14). Plants growing in chambers had higher conductances than in air exclusion systems.

Net photosynthesis in wheat was unaffected by either sulfur dioxide or ambient oxidants (Table 4-15). There was a reduction in photosynthesis with the nonfiltered air exclusion versus outside plots. Results with the open top

Table 4-14

STOMATAL CONDUCTANCE FOR WHEAT AND LETTUCE EXPOSED TO SULFUR DIOXIDE AND AMBIENT OXIDANTS

System	Stomatal Conductance ($cm\ s^{-1}$) Outside	Nonfiltered	Sulfur Dioxide ($\mu g\ m^{-3}$) 0	79	183	393
Wheat[a]						
Air exclusion	0.22	0.17	0.18	0.22	0.20	0.19
Open top chamber	0.21	0.27	0.31	0.35	0.30	0.27
Lettuce[b]						
Air exclusion	0.30	0.22	0.23	0.30	0.22	0.34
Open top chamber	0.36	0.23	0.25	0.24	0.27	0.23

[a]For wheat (n=8) there were no significant differences between sulfur dioxide concentrations, between filtered and nonfiltered treatments, or between outside and nonfiltered treatments in either air exclusion systems or chambers. There was a significant increase in conductance in chambers versus air exclusion systems across sulfur dioxide concentrations, or across filtered versus nonfiltered treatments at $p<0.05$.

[b]For lettuce (n=8) there were no significant differences between sulfur dioxide concentrations between filtered and nonfiltered treatments, and between systems across sulfur dioxide concentrations and 0.02 across filtered versus nonfiltered treatments), and between nonfiltered air exclusion systems and outside plots. There was a significant difference between nonfiltered chambers and outside plots at $p<0.05$.

chambers paralleled results with air exclusion systems; however, the data from these two exposure systems could not be compared due to a change in porometer sensitivity between air exclusion and open top chamber measurements.

During the time of grain filling, the leaves of wheat plants gradually became chlorotic and then necrotic as senescence progressed. The injury was most severe on lower leaves and least severe on flag leaves which lie just below the wheat heads. These flag leaves contribute most of the photosynthate transported to the developing grains. There were no differences in leaf injury attributable to either sulfur dioxide or ambient oxidants with either system (Table 4-16). There

Table 4-15

NET PHOTOSYNTHESIS FOR WHEAT AND LETTUCE EXPOSED TO SULFUR DIOXIDE AND AMBIENT OXIDANTS[a]

	Net Photosynthesis ($\mu mol\ m^{-2}\ s^{-1}$)					
			Sulfur Dioxide ($\mu g\ m^{-3}$)			
System	Outside	Nonfiltered	0	79	183	393
		Wheat[b]				
Air exclusion	7.94	3.60	3.21	4.15	6.32	5.94
Open top chamber	0.88	0.77	2.44	1.23	2.01	1.57
		Lettuce				
Air exclusion	5.31	3.75	4.27	4.31	6.53	4.83
Open top chamber	7.35	6.32	4.75	4.95	6.67	6.84

[a]Values are means of eight observations (two from each of four plots). The only statistically significant different between any treatments is between outside plots and nonfiltered air exclusion systems for wheat.

[b]Wheat data from air exclusion systems is not compatible with open top chamber data due to change in instrument sensitivity between measurements for the two systems. This is evident from the large difference in net photosynthesis between outside air exclusion versus outside open top chamber plots.

was no difference in either whole plant or flag leaf injury between air exclusion systems and outside plots. However, there was much less injury to wheat plants in chambers than air exclusion chambers or outside plots either on a whole plant or flag leaf basis. The chamber environment apparently encouraged a delay in leaf senescence.

At the final harvest wheat growth and yield responses differed between air exclusion systems and open top chambers (Table 4-17). Plant dry weight, ear weight, total seed weight and number of ears were all increased with sulfur dioxide treatment in air exclusion systems, but not open top chambers. These weight increases in air exclusion systems were most evident at 79 $\mu g\ m^{-3}$ sulfur dioxide, and seemed to be countered by sulfur dioxide toxicity at 183 and 393 $\mu g\ m^{-3}$. Plant growth appeared to be depressed at zero sulfur dioxide in the air

Table 4-16

INJURY TO WHEAT LEAVES EXPOSED TO SULFUR DIOXIDE OR AMBIENT OXIDANTS[a]

	Leaf Injury (0-10 scale)					
			Sulfur Dioxide ($\mu g\ m^{-3}$)			
System	Outside	Nonfiltered	0	79	183	393
		Whole Plant				
Air exclusion	6.5	5.3	6.8	6.3	6.5	7.0
Open top chamber	5.9	4.8	4.7	5.3	5.9	6.4
		Flag Leaf				
Air exclusion	3.5	2.4	3.3	3.0	2.3	3.0
Open top chamber	3.3	0.9	0.9	0.9	0.9	1.5

[a]Values are means for 16 observations, four from each of four plots. There were significant differences between: systems across sulfur dioxide concentrations for both whole plants and flag leaves, system across nonfiltered and filtered treatments for both whole plant and flag leaves, and between outside plots and nonfiltered chambers for flag leaves. The other differences were not significant, i.e., outside plots versus nonfiltered air exclusion systems for whole plants and flag leaves, outside plots versus nonfiltered air exclusion systems and nonfiltered versus filtered plots for any system or leaves.

exclusion systems probably because of the soil and air speed conditions described earlier. This may amount for some of the apparent comparative increase in growth at 79 $\mu g\ m^{-3}$ sulfur dioxide. However, the plant response with sulfur dioxide also were greater than in the nonfiltered air exclusion systems, indicating that the growth stimulation may be real. One hundred seed weight was reduced with 393 $\mu g\ m^{-3}$ sulfur dioxide in air exclusion systems, and all sulfur dioxide concentrations in open top chambers (Table 4-17). Total seed weight was reduced with 183 and 393 $\mu g\ m^{-3}$ in open top chambers. Thus sulfur dioxide appeared to primarily increase wheat growth in air exclusion systems and decrease growth in open top chambers. In air exclusion systems there were apparently more, but smaller seeds per plant with sulfur dioxide exposures. Reduced individual seed weight was the primary cause for the decreased yield in open top chambers.

Table 4-17

WHEAT RESPONSE TO SULFUR DIOXIDE AND OXIDANT EXPOSURES AT FINAL HARVEST[a]

Response	Outside		Non-filtered		Sulfur Dioxide ($\mu g\ m^{-3}$) 0		79		183		393	
Air Exclusion Systems												
Dry weight (g)	12.2	ns	13.2	ns	11.0	a	19.6	c	14.9	b	16.3	b
Ear weight (g)	7.0	*	8.7	ns	7.7	a	13.2	c	10.3	b	11.1	b
Total seed weight (g)[b]	4.6	*	5.8	ns	5.7	a	9.6	c	7.6	b	8.0	b
100 Seed weight (g)	0.37	*	0.42	ns	0.45	b	0.42	ab	0.44	ab	0.40	a
Ears (#)	5.6	ns	5.4	*	4.2	a	6.2	b	4.8	ab	5.8	b
Open Top Chambers												
Dry weight (g)	11.3	*	13.8	ns	12.9		13.4		12.5		11.2	
Ear weight (g)	6.7	*	9.7	ns	9.6		9.8		9.1		7.5	
Total seed weight (g)[b]	4.7	*	7.2	ns	7.2	b	7.5	b	6.8	ab	5.3	a
100 seed weight (g)	0.37	*	0.45	*	0.49	c	0.45	b	0.43	b	0.35	a
Ears (#)	4.9	ns	4.1	ns	3.6		4.5		4.3		4.4	

[a]Values are means per plant based on 10 plants per observation. There were 24 to 36 and 44 observations (6 to 9 and 11 from each of four plots) for air exclusion systems and open top field chambers, respectively. Only the means for each plot were used for statistical analysis. Pairs of outside versus nonfiltered, or nonfiltered versus zero means separated by a "*" are significantly different at $p<0.05$. Means for sulfur dioxide concentrations followed by different letters are significantly different.

[b]Analyzed separately for air exclusion systems and open top chambers as response was in different directions.

Ambient oxidants had no effect on overall wheat growth or yield in either system (Table 4-17). The only statistically significant effects were in a decreased number of ears in filtered versus nonfiltered air exclusion systems, and an increased 100 seed weight in filtered versus nonfiltered chambers.

Both the air exclusion systems and open top chambers had a significant effect on wheat growth compared to outside plots (Table 4-17). The increased growth in exposure systems was evident for yield parameters, i.e., ear weight, total seed weight and 100 seed weight, but not vegetative growth parameters, i.e., total dry weight and number of ears. Overall plant growth was similar in both nonfiltered air exclusion systems and open top chambers.

Lettuce

Results from statistical analysis of lettuce data are shown in Table 4-18. Sulfur dioxide had no overall effect on growth at any harvest. Ozone had an effect on leaf area at the first harvest, and total fresh weight and plant diameter at the final harvest. There were significant system effects for all parameters at the first harvest, and head weight, total dry weight and head diameter at the final harvest. There were few treatment x system interactions.

First Harvest. Stomatal conductance for lettuce in air exclusion systems was similar to conductance in both open top chambers and outside plots (Table 4-14). Conductance tended to be lower in open top chambers than outside plots, with the difference statistically significant between nonfiltered chambers and outside plots. There were no differences in conductance for either sulfur dioxide or ambient oxidant treatments.

Net photosynthesis was similar across all treatments (Table 4-15). There were no differences in photosynthesis between air exclusion systems and open top chambers, among sulfur dioxide concentrations, filtered versus nonfiltered air, or systems versus outside plots.

Lettuce planar leaf area was similar in air exclusion systems and outside plots at weeks 3 and 4 after planting (Figure 4-4). During the following two weeks filtered air exclusion and outside plot leaf areas remained similar while areas with the other treatments in general increased. Planar leaf area was much greater in open top chambers than in outside plots (Figure 4-5). Leaf area was similar for all sulfur dioxide and the nonfiltered treatments in chambers. Leaf area was much less in air exclusion systems than open top chambers across all treatments.

At the first harvest there were no responses for lettuce attributable to sulfur dioxide with either air exclusion systems or open top chambers (Table 4-19). There was an increased fresh weight with 183 $\mu g\ m^{-3}$ in air exclusion systems that was not statistically significant. Ambient oxidants also had no detrimental

Table 4-18

RESULTS FROM ANALYSIS OF VARIANCE FOR LETTUCE DATA

Harvest	Factors[a]	Total Fresh Weight	Head Weight	Total Dry Weight	Leaf Area	Plant Diameter	Head Diameter
First	T_1-SO_2	ns[b]	-	ns	ns	-	-
	T_2-O_3	ns	-	ns	*	-	-
	S_1-SO_2	***	-	***	***	-	-
	S_2-O_3	**	-	*	***	-	-
	$T_1 \times SO_2$	ns	-	ns	**	-	-
	$T_2 \times O_3$	ns	-	ns	ns	-	-
Final	T_1-SO_2	ns	ns	ns	-	ns	ns
	T_2-O_3	*	ns	ns	-	*	ns
	S_1-SO_2	ns	**	***	-	ns	**
	S_2-O_3	ns	*	*	-	ns	*
	$T_1 \times SO_2$	ns	ns	*	-	ns	ns
	$T_2 \times O_3$	ns	ns	ns	-	ns	ns

[a]T = treatments: T_1-SO_2 for 0, 79, 183 and 393 $\mu g\ m^{-3}$ sulfur dioxide, T_2-O_3 for filtered versus nonfiltered air; S = system: S_1-SO_2 for air exclusion systems versus open top chambers within sulfur dioxide exposures, S_2-O_3 for air exclusion systems versus open top chambers within filtered versus nonfiltered exposures.

[b]***, ** and * = statistically significant at $p<0.005$, 0.01 and 0.05, respectively.

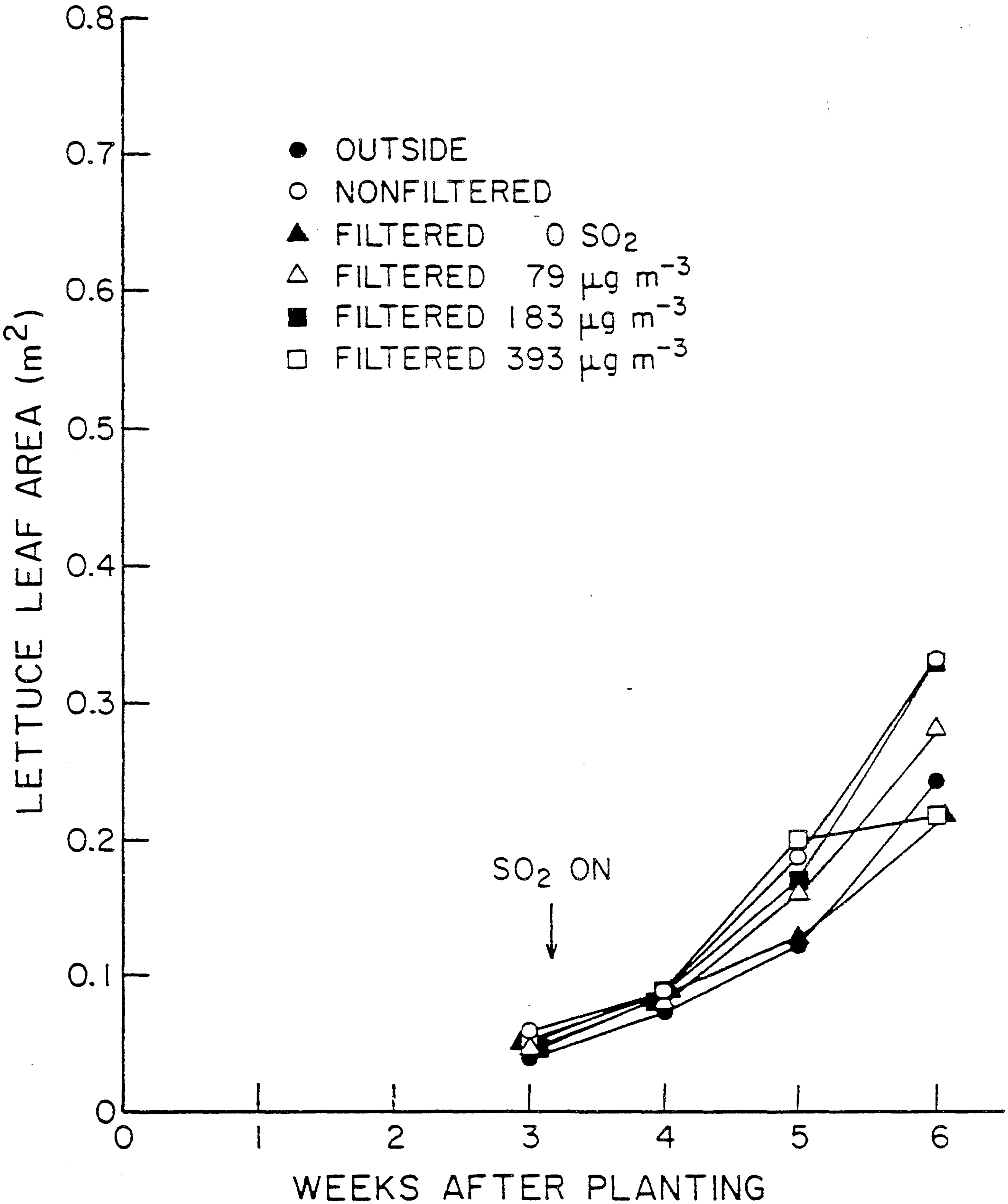


Figure 4-4. Lettuce planar area with sulfur dioxide and oxidant exposures in air exclusion systems. Each point represents the mean of 16 plants, four in each of four plots.

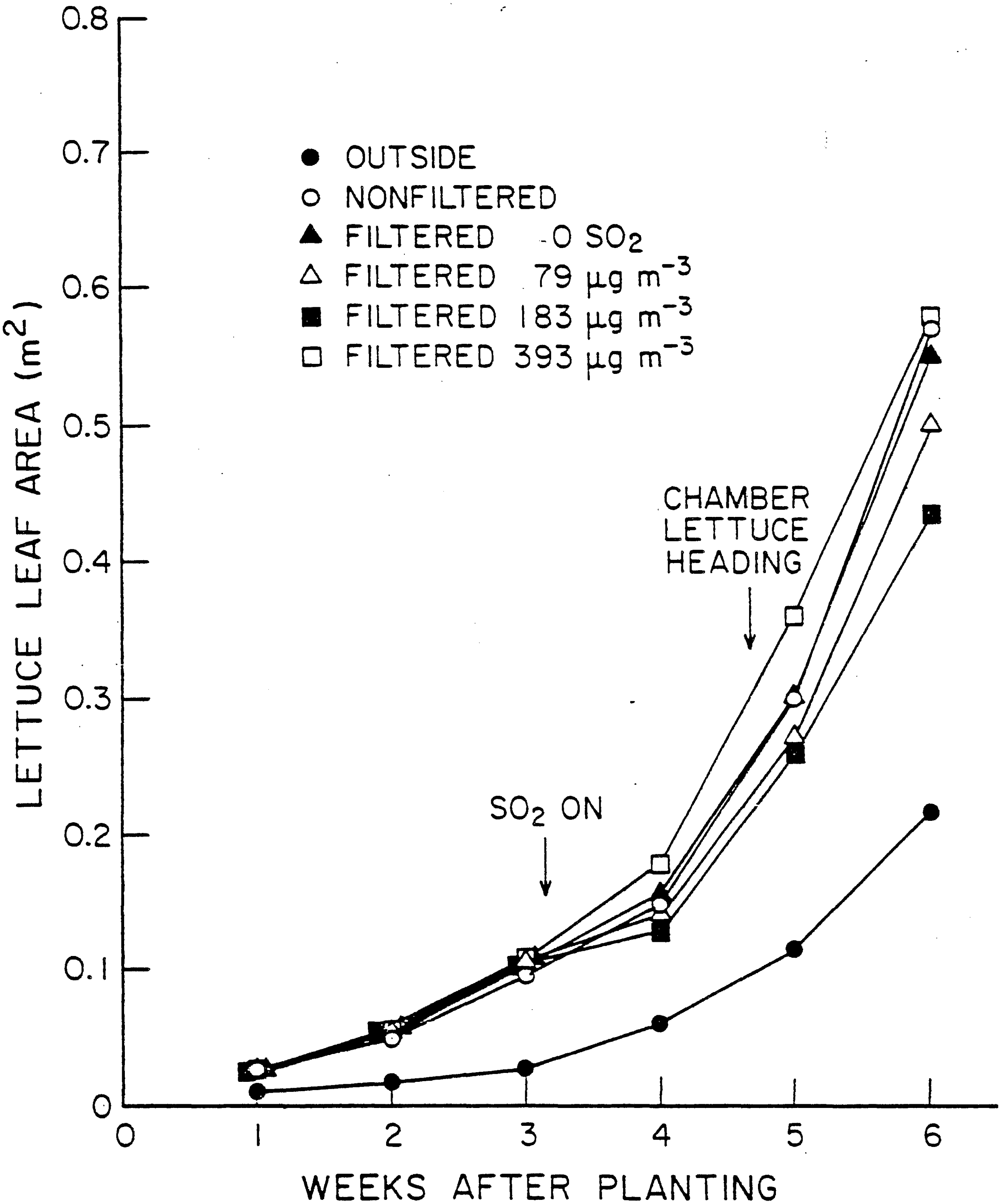


Figure 4-5. Lettuce planar area with sulfur dioxide and oxidant exposures in open top chambers. Each point represents the mean of 16 plants, four in each of four plots.

Table 4-19

LETTUCE RESPONSE TO SULFUR DIOXIDE AND AMBIENT OXIDANT EXPOSURES AT FIRST HARVEST[a]

Response	Outside		Non-filtered		Sulfur Dioxide ($\mu g\ m^{-3}$) 0	79	183	393
			Air Exclusion Systems					
Fresh weight (g)	27.3	*	38.8	ns	23.0	28.1	34.4	23.4
Dry weight (g)	1.7	ns	2.1	ns	1.4	1.5	1.8	1.5
Leaf area (m^2)	0.53	ns	0.65	ns	0.42	0.37	0.61	0.46
			Open Top Chambers					
Fresh weight (g)	20.2	ns	59.8	ns	53.0	62.6	48.7	63.1
Dry weight (g)	1.2	ns	2.6	ns	2.4	2.8	2.4	2.8
Leaf area (m^2)	0.29	*	0.97	ns	0.85	1.13	0.81	0.98

[a]Values are means of 32 to 60 observations, 8 to 15 from each of four plots per treatment. Only the means per plot were used for statistical analysis. Pairs of outside versus nonfiltered, or nonfiltered versus zero means separated by a "*" are significantly different at $p<0.05$. Means for sulfur dioxide concentrations followed by different letters are significantly different at $p<0.05$.

affect on lettuce growth. The overall significant oxidant on leaf area shown in Table 4-18, was not evident with t-tests between nonfiltered and filtered air exclusion systems or open top chambers.

Lettuce growth was greater in both air exclusion systems and open top chambers than outside plots (Table 4-19). However, growth was less in air exclusion systems than chambers.

Final Harvest. Sulfur dioxide had no effect on plant growth when both systems were considered together (Table 4-18). However, a separate statistical analysis indicated that in air exclusion systems total fresh weight, total dry weight and plant diameter were lower with 393 than 79 or 183 $\mu g\ m^{-3}$ sulfur dioxide (Table 4-20). This response could be due to a growth supression at 393 $\mu g\ m^{-3}$ sulfur dioxide as the weights were much lower than for nonfiltered air exclusion systems. However, a growth stimulation at 79 and 183 $\mu g\ m^{-3}$ is also possible as

Table 4-20

LETTUCE RESPONSE TO SULFUR DIOXIDE AND AMBIENT OXIDANT EXPOSURES AT FINAL HARVEST[a]

Response	Outside		Nonfiltered		Sulfur Dioxide ($\mu g\ m^{-3}$) 0		79		183		393	
Air Exclusion Systems												
Total fresh weight (g)[b]	630	ns	670	ns	545	a	720	b	700	ab	550	a
Head fresh weight (g)[b]	364	ns	432	ns	338	a	455	b	465	b	349	a
Total dry weight (g)	37.2	ns	33.8	ns	28.5		35.0		35.3		27.4	
Plant diameter (m)	0.35	ns	0.35	ns	0.32	a	0.35	bc	0.36	c	0.33	ab
Head diameter (m)	0.34	ns	0.34	ns	0.32		0.35		0.35		0.32	
Open-Top Chambers												
Total fresh weight (g)	578	ns	677	ns	586		639		626		628	
Head fresh weight (g)	313	*	509	ns	443		493		466		488	
Total dry weight (g)	32.2	*	26.6	ns	27.2		25.7		25.1		26.6	
Plant diameter (m)	0.35	ns	0.36	ns	0.34		0.34		0.33		0.34	
Head diameter (m)	0.33	ns	0.36	ns	0.36		0.36		0.36		0.36	

[a]Values are means of 48 to 64 observations, 12 to 14 from each of four plots per treatment. Only the means per plot were used for statistical analysis. Pairs of outside versus nonfiltered, or nonfiltered versus zero means separated by a "*" are significantly different at $p<0.05$. Means for sulfur dioxide concentrations for air exclusion systems followed by different letters are significantly different at $p<0.05$ using simple one-way analysis of variance between SO_2 levels.

weights were higher than nonfiltered systems. Unfortunately, the filtered zero sulfur dioxide air exclusion systems cannot be used for accurate treatment comparisons due to the confounding soil and air speed effects described earlier.

Ambient oxidants had no effect on lettuce growth in either air exclusion systems or open top chambers (Table 4-20). The total fresh weight and plant diameter effects shown in Table 4-18 were not evident when t-tests were made between nonfiltered and filtered air exclusion or open top chamber treatments.

By the final harvest there was little apparent affect of air exclusion systems on lettuce growth as shown by similar responses in nonfiltered and outside plots (Table 4-20). Lettuce growth also was similar in open top chambers and outside plots except for a higher head fresh weight but lower total dry weight in nonfiltered chambers versus outside plots. The outside lettuce plants apparently grew faster than either air exclusion or open top chambers plants between the first and final harvests and compensated for slower growth earlier during the year. Plants in air exclusion systems also apparently grew faster than open top chamber plants during the second half of the growing period.

Section 5

MOBILE SYSTEM DESIGN AND TESTING

Components of a versatile portable air exclusion system are shown in Figure 5-1. This system would have the capacity for addition of any desired pollutant (e.g., ozone, sulfur dioxide, nitrogen dioxide or hydrogen sulfide) to the air blown over the plants. Thus a single system could be used for a variety of pollutant combinations using different levels of ambient pollutant filtration versus levels of pollutant addition.

Information and experience acquired during the course of previous experiments led to the design of a more portable air pollution exclusion system. Blower modules were fabricated from 20 gauge galvanized sheet metal. The modules were 1.22 m long, 0.61 m deep and 0.41 m tall. A 0.61 x 0.61 x 0.25 m extension on the top was designed to accept a 0.61 x 0.61 x 0.20 m charcoal filter cannister with dust filters. Two centrifugal blowers (Dayton Model #4C054) were installed inside the box with the exhaust port of the housing feeding into short 0.32 m diameter galvanized ducts. The distance between the ducts was 0.40 m. The blowers were specified to deliver 0.463 m^3 s^{-1} of free air.

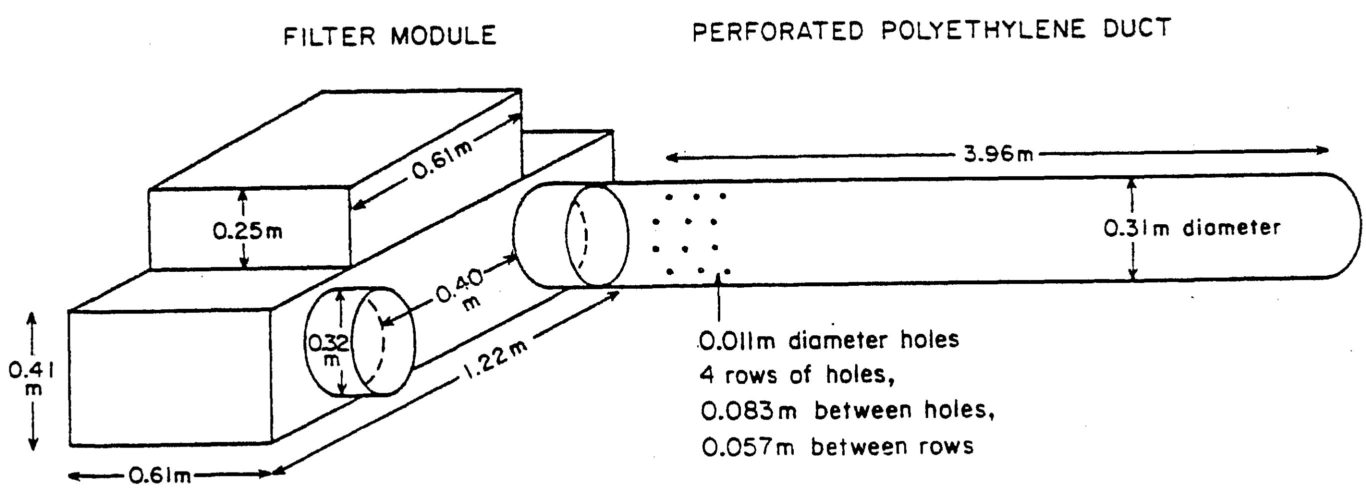


Figure 5-1. Diagram of simple mobile air exclusion system.

Two blower modules with two ducts each would form a four duct system in principle similar to the more fixed system used in previous experiments. The polyethylene ducts used were perforated with four rows of holes of 0.011 m diameter on each side of the ducts. Since each duct was inflated with its own blower, all ducts were perforated the same in order to have the same flow rate per unit length of duct throughout the system (Figure 5-1).

Using the simple design shown in Figure 5-1, air exclusion systems could be paired to provide enough exclusion space for three rows of 7-10 plants each assuming 0.31 m per pot. This would be about the same plant growing area as in a single open top chamber of the standard Heagle et al. design (8). However, all of the area could be used for experimental plants with the air exclusion system versus unavailability of the "guard row" area near the chamber walls. The cost of the two exclusion systems is approximately $1,000 versus $1,700 for a single chamber (Table 5-1). A fixed air exclusion system is the most cost-effective method for plant exposures if space for a number of treatments is desired. One fixed system can be used to expose as many plants as three chambers or three mobile systems.

The air exclusion system would be much more portable than the chamber, and, if desired, could be split to form two smaller systems of seven plants each.

The pollutant monitors, scanivalve and computer data acquisition/exposure control system shown in Figure 2-2 could handle up to 24 separate air exclusion systems and/or outside plots assuming one sampling tube per plot. The blower boxes for these air exclusion systems would be stacked in a truck for transport, which would also contain pre-die cut vinyl ducts and metal bars for stabilizing the inflated ducts.

An added air pollutant could be injected either into the blower box of single ducts or midway down the length of ducts to provide a "split plot." Adding the pollutant to the box directly would allow for the best mixing, whereas duct addition would require baffles in the vinyl duct to insure mixing as described in Section 2.

All control components could be housed in a single van equipped witha power source and auxiliary air conditioning and/or heating and adequate insulation.

Table 5-1

COST ESTIMATES AND PLANT CAPACITY FOR MOBILE AND
FIXED AIR EXCLUSION SYSTEMS VERSUS OPEN TOP FIELD CHAMBERS

	Air Exclusion System		Open Top Chamber	
Component	Mobile	Fixed[a]	ARB	NCLAN
Aluminum frames ($)	$ 29	$ 29	$ 177	$ 620
Blower box ($)	460	326	110	150
Vinyl ($)	40	40	600	290
Filter ($)	150	450	300	225
Fan ($)	250	747	334	334
Labor - Hours	0.5	8	32	8
Dollars	24	48	192	48
Total Costs	$953	$1640	$1713	$1667
Plant capacity - Rows	3	3	3	3
Row length (m)	2.5	7.5	2.5	2.5
Plants (#)	25	75	25	25

[a]The fixed system has a more powerful blower adequate to supply 7.5 m of ducting.

[b]At $6.01 per hour for laboratory helper level staff.

EXCLUSION TESTS

The flow rate of a system with the charcoal filter installed and two 4.6 m long ducts, was tested by measuring the dilution of carbon monoxide injected at the beginning of the ducts. The flow rates were 1.16 and 1.21 $m^3\ s^{-1}$, respectively indicating 0.079 $m^3\ s^{-1}$ per m of duct. The latter value compares well with the values for fixed systems. The static pressures inside the ducts ranged from 0.005 to 0.0055 m of water from beginning to end.

Oxidant exclusion was measured for the module system only during the third harvest. Over comparable 17 days the ozone concentration averged 33 $\mu g\ m^{-3}$ in the filtered mobile system versus 29 $\mu g\ m^{-3}$ in the filtered fixed system. Compared to the 145 $\mu g\ m^{-3}$ ozone in the outside plots, the extent of oxidant exclusion was similar in both systems at 77% for the mobile versus 80% for the fixed system.

PLANT RESPONSE

Alfalfa growth and yield response in mobile versus fixed air exclusion systems is shown in Table 5-2. These results, however, should be interpreted with caution as only one mobile system was available. Dry weight was reduced in filtered versus nonfiltered only in mobile systems at first harvest, and only in fixed systems at the third harvest. Fresh weight was decreased and percent empty nodes increased in filtered versus nonfiltered fixed, but not in mobile systems at the third harvest. Other responses were similar with the two systems. Thus, the mobile system was apparently as effective as the fixed system in controlling plant exposure to air pollutants.

Table 5-2

ALFALFA GROWTH AND YIELD WITH FIXED VERSUS MOBILE AIR EXCLUSION SYSTEMS[a]

	Fixed System			Mobile System			Fixed System			Mobile System		
Harvest	Filtered		Non-filtered	Filtered		Non-filtered	Filtered		Non-filtered	Filtered		Non-filtered
	Dry weight (g)						Nodes (#)					
1	19.7	ns	19.7	24.6	*	21.2	-		-	-		-
2	15.0	ns	13.1	14.3	ns	12.8	25.4	ns	25.9	26.3	ns	25.1
3	17.7	*	13.4	18.2	ns	20.1	28.0	ns	25.0	26.2	ns	26.9
	Fresh Weight (g)						Empty Nodes (#)					
1	79.7	ns	77.7	91.2	ns	81.4	-		-	-		-
2	54.1	ns	47.4	52.1	ns	41.8	1.2	*	9.4	1.9	*	8.6
3	64.3	*	52.6	73.7	ns	76.7	0.9	ns	4.5	1.3	ns	1.4
	Height (m)						% Empty Nodes					
1	0.50	ns	0.52	0.48	ns	0.47	-		-	-		-
2	0.46	ns	0.44	0.45	ns	0.40	4.8	*	35.4	6.9	*	33.9
3	0.50	ns	0.44	0.47	ns	0.52	3.2	*	17.5	5.0	ns	5.1

[a]Values are means for 42 and 21 observations per treatment for fixed and mobile air exclusion systems respectively. There were 21 observations from each of two replicate plots for fixed systems and only one plot for mobile systems. Pairs of filtered and values separated by a "*" are significantly different at $p<0.05$.

Section 6

CONCLUSIONS AND RECOMMENDATIONS

The air exclusion system provides an effective alternative to open top field chambers for controlled exposures of plants to air pollutants. Exposure characteristics: oxidant exclusion, sulfur dioxide addition, and environmental conditions were similar in air exclusion systems and open top chambers. Added advantages of the air exclusion systems which indicate its potential are:

- Simplicity of system design and construction.
- Ability to easily alter air flow over plants, air pollutant monitoring system and system configuration.
- Mobility.
- High air speed to insure high leaf boundary layer conductances.
- Essentially no difference in light intensity, relative humidity, and air, soil and leaf temperatures compared to outside plots in the summer and fall.
- Environmental conditions nearer to outside than for open top chambers during winter and early spring.
- Virtually no system effect when ducts deflated.
- Ability to control dew and fog deposition and guttation on leaves by altering air flow over the plant canopy.

Characteristics of the air exclusion system that need additional research and/or modification are:

- Degree of air exclusion above the ducts.
- Limitation for use with lower growing row crops.
- High air speed over plant canopy.
- Higher leaf, air and soil temperature than outside plots in winter that can result in enhanced plant growth.

Based on the above considerations the air exclusion system is recommended as a useful system for plant-air pollutant studies especially with low growing row crops, remote areas, and fall, winter or spring exposures. Additional testing is needed to adapt the air exclusion system to higher growing plants such as tree seedlings, to reduce the environmental modification in the winter. Testing also is needed to combine the air exclusion system with the small diameter tubing zonal air pollutant (ZAP) system for maximum flexibility in pollutant exposures in remote areas. Additional comparisons with open top chambers are recommended to evaluate the precision of the NCLAN and other crop loss estimates based on open top chamber research.

Section 7

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APPENDIX B

RAW OZONE DATA FOR OUTSIDE

PLOTS AND CHAMBERS

OZONE CONCENTRATION (pphm)

TIME	2/1/84			2/7/84			2/14/84			2/21/84		
	OUT.	AMB.	FIL.	OUT.	AMB.	FIL.	OUT.	AMB.	FIL.	OUT.	AMB.	FIL.
0800–0900	2.2	1.2	0.1	1.7	1.2	0.6	1.2	0.6	0.6	0.1	0.1	0.1
0900–1000	2.2	2.2	0.1	0.6	0.6	0.6	1.2	0.6	0.1	1.2	0.1	0.1
1000–1100	2.2	1.2	0.1	1.2	0.6	0.6	2.2	2.2	0.6	1.2	0.6	0.1
1100–1200	3.2	2.7	0.6	3.7	3.2	1.7	3.2	3.2	1.2	3.2	3.2	1.2
1200–1300	3.2	3.2	0.6	4.2	3.7	1.7	4.2	3.7	1.2	2.7	3.2	1.2
1300–1400	4.2	3.7	0.6	4.2	3.7	1.2	4.2	4.2	1.2	5.3	4.7	1.2
1400–1500	5.3	4.7	0.6	4.7	4.2	1.2	5.3	5.3	1.7	5.3	5.3	1.7
1500–1600	5.3	4.7	0.6	5.3	4.7	1.2	6.3	5.8	1.7	5.8	4.7	1.7
1600–1700	3.2	3.2	0.1	6.8	7.8	2.7	6.3	5.8	1.7	5.3	5.3	1.2
1700–1800	2.7	2.2	0.1	8.3	7.3	2.2	5.3	4.2	1.2	4.7	4.2	1.2
1800–1900	1.7	1.2	0.1	1.7	1.7	0.6	3.2	2.7	1.2	3.2	3.2	0.6
1900–2000	1.2	1.2	0.1	1.2	1.2	0.6	1.7	1.7	0.6	2.2	0.6	0.1

TIME	2/28/84		
0800–0900	0.6	0.1	0.1
0900–1000	0.6	0.1	0.1
1000–1100	1.2	1.2	0.1
1100–1200	2.2	3.2	0.6
1200–1300	5.3	3.2	1.2
1300–1400	4.2	3.7	0.6
1400–1500	4.2	4.2	1.2
1500–1600	5.3	4.2	1.2
1600–1700	5.3	4.2	1.2
1700–1800	5.3	5.3	1.7
1800–1900	6.3	5.3	1.2
1900–2000	4.2	3.7	0.6

TIME	3/7/84			3/12/84			3/23/84			3/29/84		
0800–1000	0.6	0.6	0.1	2.2	2.2	0.6	1.2	1.7	0.6	0.6	1.7	0.1
1000–1200	1.2	0.6	0.1	5.3	6.3	1.2	3.2	3.2	1.2	5.3	6.3	1.7
1200–1400	2.2	3.2	1.2	8.3	7.8	1.7	4.2	3.7	1.2	5.3	6.3	2.2
1400–1600	4.2	4.2	1.2	7.3	7.8	2.2	5.3	6.8	2.2	7.3	5.3	2.2
1600–1800	7.3	7.3	1.7	6.3	5.3	1.2	5.3	4.7	1.7	4.7	4.2	2.7
1800–2000	8.3	8.3	2.2	3.2	2.7	0.6	2.2	1.7	0.6	4.2	3.7	0.6

TIME	4/5/84			4/11/84			4/18/24			4/24/84		
0800–1000	1.2	2.2	0.1	1.2	1.2	0.1	3.2	3.2	0.6	3.2	3.2	1.2
1000–1200	2.2	2.7	1.2	4.2	4.7	1.2	3.7	4.2	0.6	5.3	5.3	1.7
1200–1400	4.2	4.2	1.2	6.3	7.3	1.7	5.3	5.3	1.2	8.3	8.3	2.2
1400–1600	5.3	5.3	1.2	7.3	7.3	1.7	6.3	6.3	1.2	5.3	5.3	1.7
1600–1800	3.7	3.2	1.2	9.4	9.4	2.2	4.2	4.2	1.2	4.2	4.2	1.2
1800–2000	3.2	2.7	0.1	8.3	6.8	1.2	4.2	3.7	0.6	3.2	3.2	1.7

TIME	5/3/84		
0800–1000	1.2	2.2	0.1
1000–1200	5.3	6.3	1.7
1200–1400	7.3	7.8	2.2
1400–1600	11.4	12.4	2.7
1600–1800	11.4	10.4	2.2
1800–2000	6.3	5.3	1.7

* OUT = Outside plot, AMB = Ambient air chamber, FIL = Filtered air chamber. The raw data was taken from stip charts, with one day per week, with one outside plot, one ambient chamber, and one filtered air chamber chosen as being representative for the exposures. Each sampling point was measured only once per every two hours after 3/7/84.