# INVESTIGATION OF THE EFFECTS OF ACID DEPOSITION UPON CALIFORNIA CROPS

Final Report

Prepared for the

California Air Resources Board

Contract No. A5-087-32

January 8, 1986 - July 7, 1987

David M. Olszyk
Principal Investigator

Robert C. Musselman
Co-Principal Investigator

Andrzej Bytnerowicz
Co-Principal Investigator

Brent K. Takemoto
Postgraduate Research Associate

December 1987

Statewide Air Pollution Research Laboratory
University of California
Riverside, California 92521

OLZ-87:acidep-fr

## TABLE OF CONTENTS

## TABLE OF CONTENTS

Page

# ABSTRACT

The Statewide Air Pollution Research Center has a continuing mission to investigate the effects of air pollutants on agricultural crops, native vegetation and forests, and to determine the amount of loss being caused by these pollutants. To further this mission we conducted the comprehensive study: "Investigation of the Effects of Acid Deposition upon California Crops." The study evaluated the relationship between doses of acidic fog at pH 1.8 to 5.5 and responses of important winter crops of the San Joaquin Valley (alfalfa, broccoli, carrot, onion, potato, and wheat), and fog at pH 1.7 to 7.2 on spring South Coast crops (alfalfa, celery, green pepper, strawberry, and tomato). The study also evaluated the interaction between acidic fog and ambient oxidants (primarily $O_3$) on the South Coast crop species.

The spring fog and/or oxidant exposures were conducted in open-top field chambers maintained by the ARB at the University of California, Riverside, California. Ancillary exposures were conducted without chambers using air exclusion ducts in order to aid in interpreting the open-top field chamber results. The winter fog exposures were conducted under temporary covers which were removed after each fog episode.

Plant response measurements emphasized physiological parameters which will provide data with respect to the metabolic basis for acidic fog and acidic fog/oxidant effects. The measures of leaf response included net photosynthesis, stomatal conductance, transpiration, element content, buffering capacity, and chlorophyll concentration. Plant growth and yield measurements were made at the end of exposures.

For the spring study, fog at pH 1.68, 2.69 or 7.24 were applied twice weekly to potted plants grown in open-top field chamber or air exclusion plots for eleven weeks. Injury symptoms (i.e., necrosis) developed on leaves and fruits of all species exposed to pH 1.68 fog, but did not occur in plants exposed to pH 2.69 or 7.24 fog, or in plants that were not fogged. Season-long exposure to pH 1.68 fog significantly reduced fruit yield in strawberry, tomato, and green pepper by 30 to 58%, and biomass yield in alfalfa by 11% relative to yields measured in crops exposed to pH 7.24 fog. In contrast, biomass yield in celery was not altered by pH 1.68 fog. Ambient levels of gaseous pollutants reduced yields in tomato, green pepper, alfalfa, and celery. Overall, the combined effects of severe acidic fog (pH 1.68) and ambient gaseous pollutants were additive with respect to growth and yield responses in the five crops.

In general, the effects of the acidic fog treatments were less severe in the air exclusion than in the open-top chamber plots. The reduced effects were likely due to dilution of applied fog in ambient dew which occurred on leaves of plants grown in air exclusion systems and outside plots, but not in open-top chambers. Reduced replication in air exclusion chambers also likely played a role in lessened ability to detect statistically significant differences between treatments compared to open-top chambers.

For the winter study, fogs at pH 1.76, 2.23, 2.72, 3.22, and 5.48 were applied twice weekly to potted plants grown in ambient air for eleven weeks. Injury symptoms developed on leaves of all species exposed to pH 1.76 fog, and occasionally at pH 2.23 and 2.72. Season-long exposure to pH 2.23 fog affected leaf and shoot dry weight in broccoli, and pH 1.76 fog affected fresh and dry weights of all species, even though the reductions compared to the no fog or pH 5.5 condition were only statistically significant for broccoli. Whole season leaf transpiration, stomatal conductance, and net photosynthesis rates were reduced at pH 1.76 compared to pH 5.48 or no fog treatments for broccoli, but not potato.

Therefore, repeated application of only highly acidic fogs of pH 1.7-1.8 were generally phytotoxic. Species differed widely in their sensitivity to acidic fog in terms of yield and physiology, with green pepper and broccoli found to be the most sensitive in the spring and fall foggings, respectively. There was no evidence for any acidic fog-smog (ozone) interaction on these crops.

# ACKNOWLEDGMENTS

The authors wish to thank the following research staff of the Statewide Air Pollution Research Center for their efforts in this project: Drs. Patrick McCool and Patrick Temple for advice; Mr. Gerrit Kats, Mr. Philip Dawson, Ms. Joanne Wolf, Mr. Adam Johnson, Mr. Charles Parada, and Ms. Wendy Hutton for technical assistance; and Ms. Chris LaClaire and Ms. Barbara Crocker for aid in preparing this report. Special thanks go to Drs. Bill Walker and Homero Cabrera, Project Managers for the Air Resources Board, for their advice and encouragement.

# DISCLAIMER

## LIST OF FIGURES

# LIST OF TABLES

## LIST OF TABLES
## (continued)

## LIST OF TABLES
(continued)

## LIST OF TABLES
## (concluded)

# SUMMARY AND CONCLUSIONS

Acid precipitation is a major environmental issue in many areas of the United States as researchers, industry officials, governmental regulators and the public attempt to understand the causes and effects of acidic rain, snow or fog; and begin to formulate proper control procedures for acid precursors before they are emitted into the atmosphere.

There has been considerable research in recent years on the effects of acidic rain on crops and trees. The general consensus among researchers is that acidic rain must be at or below pH 4.0 to injure vegetation. Recent evidence suggests that acidic fog and not rain may be of prime interest in California. Hoffman and associates at the California Institute of Technology have measured fog pH's ranging from 2.2 to 4.0 with more acidic pH's associated with smog and haze events. In a few episodes, acidities below pH 2.0 have been found. The nitrate to sulfate anion ratios has been found to range from 2.5:1 to 1:1 in acidic fog compared to a predominance of sulfate in eastern United States acidic rain measurements. Apparently the polluted atmosphere of some sections of southern California provides acidic condensation nuclei for fog.

Acidic fog potentially is more injurious to vegetation than acidic rain because: (a) fog often persists for several hours at a time vs. generally shorter times of rain; (b) fog events are often more frequent than rain events, especially in southern California coastal areas; (c) fog normally occurs early in the morning when plant stomata are generally open and plants metabolically active whereas rain episodes are random; and (d) the greater acidity of fog than rain. There have been no systematic studies of the effects of ambient or artificial acidic fog on vegetation; the most applicable literature instead is based on laboratory acidic mist investigations. In general the mist itself, without added acidity, resulted in leaching of $K^+$ (potassium), $Ca^{2+}$ (calcium), amino acids and other constituents from leaves, with the extent of leaching increasing as the mist became more acidic. At low pH's, acidic mist also produced necrotic lesions on leaves.

California has important agricultural and forest resources in areas of the state affected by fog. Significant acreages of many valuable crops are grown in coastal areas including broccoli (1982 total value of $177 million), celery ($85 million), lettuce ($469 million), tomato ($148 million) and strawberry ($294 million) (California Department of Agriculture 1982). In addition, many important crops are grown in the San Joaquin Valley which is also subjected to fog. These include alfalfa and many other crops. Losses could currently be occurring with these crops or could increase if fog acidity increases.

The Los Angeles-South Coast Air Basin area is affected by photochemical oxidant air pollutants in addition to acidic fog. Oxidant levels often reach 0.2 ppm (measured as $O_3$) or greater on days that begin with a dense fog. Both crops and native vegetation are affected by the oxidants with yields of some crops such as alfalfa decreased by over 30% compared to yields in filtered air. Limited research with ambient $O_3$ and acidic rain suggested that acidic precipitation can alter plant response to $O_3$ by accentuating an $O_3$ induced decrease in yield or by altering the vegetative/reproductive mass relationship.

## Project Objectives

The primary objective of this project was to identify the metabolic basis for sensitivity of plant species to acidic fog. Plants were examined for growth, yield and physiological differences in response to a range of acidic strengths in the acidic fog treatments. A secondary objective was to identify if there was any possible interactive effect of acidic fog and ambient oxidants on the aforementioned measures of plant response.

The study evaluated the relationship between doses of acidic fog at pH 1.8 to 5.5 and responses of important winter crops of the San Joaquin Valley (alfalfa, broccoli, carrot, onion, potato, and wheat), and fog at pH 1.7 to 7.2 on spring South Coast crops (alfalfa, celery, green pepper, strawberry, and tomato). The study also evaluated the interaction between acidic fog and ambient oxidants (primarily $O_3$) for the South Coast crop species.

The spring fog and/or oxidant exposures were conducted in open-top field chambers maintained by the ARB at the University of California, Riverside. Ancillary exposures were conducted without chambers using air exclusion ducts in order to aid in interpreting the open-top field chamber results. The fall fog exposures were conducted under temporary covers which were removed after each fog episode.

Plant response measurements emphasized physiological parameters which provided data with respect to the metabolic basis for acidic fog and acidic fog-oxidant effects. The measures of leaf response included net photosynthesis, stomatal conductance, transpiration, element content, buffering capacity, and chlorophyll concentration. Plant growth and yield measurements were made at the end of exposures.

For the spring study, fog at pH 1.68, 2.69 or 7.24 were applied twice weekly to potted plants grown in open-top field chamber or air exclusion plots for eleven weeks. Injury symptoms (i.e., necrosis) developed on leaves and fruits of all species exposed to pH 1.68 fog, but did not occur in plants exposed to pH 2.69 or 7.24 fog, or in plants that were not fogged. Season-long exposure to pH 1.68 fog significantly reduced fruit yield in strawberry, tomato, and green pepper by 30 to 58%, and biomass yield in alfalfa by 11% relative to yields measured in crops exposed to pH 7.24 fog. In contrast, biomass yield in celery was not altered by pH 1.68 fog. Ambient levels of gaseous pollutants reduced yields in tomato, pepper, alfalfa, and celery. Overall, the combined effects of highly acidic fogs (pH 1.68) and ambient gaseous pollutants were additive with respect to growth and yield responses in the five crops.

In general, the effects of the acidic fog treatments were less severe in the air exclusion than in the open-top chamber plots. The reduced effects were likely due to the dilution of the applied fog in ambient dew which was present on leaves of plants growing in air exclusion systems and outside plots, but not in open-top chambers.

For the winter study, fogs at pH 1.76, 2.23, 2.72, 3.22, and 5.48 were applied twice weekly to potted plants grown in ambient air for eleven weeks. Injury symptoms developed on leaves of all species exposed to pH 1.76 fog, and occasionally on plants exposed to pH 2.23 and 2.72 fog. Season-long exposure to pH 2.23 fog affected leaf and shoot dry weight in broccoli, and pH 1.76 affected fresh and dry weights of all species, even though the reductions compared to the no fog or pH 5.48 condition were only statistically significant for broccoli. Leaf whole-season transpiration, stomatal conductance, and net photosynthesis rates were reduced at pH 1.76 compared to pH 5.48 or no fog treatments for broccoli, but not potato.

Therefore, repeated application of only highly acidic fogs of pH 1.7-1.8 were generally phytotoxic. Species differed widely in their sensitivity to acidic fog in terms of yield and physiology, with green pepper and broccoli found to be the most sensitive in the spring and winter foggings, respectively. There was no evidence for any acidic fog-smog (ozone) interaction on these crops.

Conclusions. Conclusions based on the Spring/South Coast phase of the acidic fog study were as follows:

1. There were no general significant interactive effects between acidic fog and ambient oxidants insofar as altering crop growth, yield, or physiological responses. Both ambient oxidants and pH 1.68 fog were detrimental to crops, but the effects were additive and not synergistic (greater than additive) or antagonistic (less than additive).

2. The application of fog stimulated crop growth as evidenced by the comparison of plant responses to pH 7.24 fog vs. no fog treatments.

3. The pH 2.69 treatment caused slight visible injury to only one crop (i.e. alfalfa), but had no other negative impact on plant responses.

4. The five species examined in the Spring Fog Study differed in sensitivity to acidic fog treatment; alfalfa, tomato, and green pepper were found to be sensitive; celery intermediate; and strawberry tolerant. The fog-tolerance of strawberry may in part be due to a reduced capacity for moisture retention on leaves following a fog episode, compared to the other species.

5. The pH 1.68 and ambient oxidant treatments appeared to have a greater impact on plants exposed in open-top field chamber than in air exclusion system plots. The difference may in part be due to the occurrence of ambient dew on leaves of plants grown in air exclusion system plots but not in open-top chambers, prior to fog exposure. However, reduced replication in air exclusion systems also likely

reduced the potential to detect statistically significant differences between treatments.

6. Plant growth was substantially greater in open-top field chambers than in outside plots. Plant growth in air exclusion systems was slightly greater than in outside plots.

7. The performance of the California Institute of Technology fog collector was satisfactory insofar as sampling suspended fog in the open-top chamber and air exclusion system plots. The pH and ion composition of the suspended fog samples were essentially the same as fog nozzle drip collections.

8. Ambient dew formation was not observed on leaves of plants grown in open-top field chambers, whereas dew formed on plants in air exclusion system and outside plots.

Conclusions based on the Winter/San Joaquin Valley study were as follows:

9. Broccoli was the most sensitive species to acidic fog, exhibiting reductions in biomass production at pH 1.76 and 2.23, and physiological activity at pH 1.76.

10. In all species, acidic fog at pH 1.76 caused visible injury to leaves and produced a trend toward reduced biomass production.

11. Decreased rates of net photosynthesis, stomatal conductance, and transpiration were observed in plants exposed to pH 1.76 fog, and appeared to be associated with reduced biomass production in broccoli, and possibly potato.

12. Dilution of fog by dew on leaf surfaces may at least be partially responsible for differences in tolerance between crop species to acidic fog. For example, the waxy surfaces of broccoli leaves apparently discouraged dew accumulation, which may have reduced the dilution of applied fog on this species compared to potato. Thus, more concentrated hydrogen ion on broccoli leaf surfaces may have contributed to the greater affects of acidic fog to this species.

# RECOMMENDATIONS

1. Additional research may not be required on crop plants at the present time, if the primary objective solely is to examine dose-response effects. Crop plants are not likely to be affected by acidic fog in the field, except with repeated exposures to highly acidic fog (pH < 2.0).

2. Future acidic fog studies should focus on perennial plants where leaves are retained for longer periods of time. This would allow for a greater total load of acidic inputs to be applied. Herbaceous plants have greater utility in mechanistic studies where rapid growth is of prime importance.

3. Focus on a narrower range of fog acidity (i.e. 1.8 to 2.8), which is more representative of naturally-occurring fog chemistries and is more likely to cause alterations in plant responses.

4. If feasible, fog studies should be conducted in temporary outside enclosures, rather than in open-top field chambers. The results from the spring study indicated that open-top field chambers do not allow for normal dew formation, which may profoundly effect plant responses to the deposition of fog. Furthermore, plant growth responses are different in open-top chambers (than in outside plots), which can also affect responses to fog. The utility of temporary covers used solely to contain fog during fog event was found to be effective for field use in the spring study. By this methodology, the covers can be removed to provide ambient growing conditions at all other times during the study period.

5. The chemical composition of suspended fog collected by a high volume sampler closely matches the composition of nozzle drip. Thus, collections of nozzle drip are reliable indicators of the chemistry of suspended fog.

6. Subsequent fog and ambient oxidant interaction studies should include sequential acidic fog and oxidant stresses during the appropriate seasons of the year, rather simultaneous stress application. There was no evidence of interactive effects between acidic fog and oxidant exposures, and any interaction would have been difficult to determine due to the severity of oxidant and fog impacts in the late spring. Moreover, sequential applications of stresses may produce interactive injury effects if acidic fog applications in spring predispose plants to injury from subsequent summer oxidant exposures.

# INTRODUCTION

Acid precipitation is a major environmental issue in many areas of the United States as researchers, industry officials, governmental regulators, and the public attempt to understand the causes and effects of acidic rain, snow or fog; and begin to formulate proper control procedures for acid precursors before they are emitted into the atmosphere.

There has been considerable research in recent years on the effects of acidic rain on crops and trees. The general consensus among researchers is that acidic rain must be at or below pH 4.0 to injure vegetation (Lindhurst et al., 1982). Applications of acid rain at pH levels of 4.0 or lower have reduced crop productivity in greenhouse (Irving, 1985) and field experiments (Evans et al., 1985). In general, the deleterious effects of acid rain are largely attributable to the direct deposition of $H^+$ to plant surfaces (Evans, 1984), and the subsequent acidification of the cytosol and cell surface structures can in turn lead to the formation of necrotic lesions on leaves. Most acidic wet deposition research efforts have been directed toward examining the chemical, physical and phytotoxic effects of acid rain (Evans, 1984), recent studies have found that the hydrological and chemical inputs from smaller particle-sized wet depositions (i.e. fog, cloudwater or mist) may also have important impacts on vegetation (Lovett et al., 1982). However, owing to the physical and chemical properties of fog, considerable uncertainty exists as to whether acidic fogs are phytotoxic, or if fogs can cause effects similar to those induced by acid rain.

Recent evidence suggests that acidic fog and not rain may be of prime interest in California, (Heileman, 1973; Roberts, 1982). Hoffman and associates at the California Institute of Technology, (Waldman et al., 1982; Munger et al., 1983) and Brewer et al. (1983), have measured fog pH's ranging from 2.2 to 4.0 with more acidic pH's associated with smog and haze events. In a few episodes, acidities of below pH 2.0 have been found (Jacob et al., 1985b). The nitrate to sulfate anion ratios ranged from 2.5:1 to 1:1 in acidic fog compared to a predominance of sulfate in eastern United States acidic rain measurements. Apparently, the polluted atmosphere of some sections of southern California provides acidic condensation nuclei for fog (Appel et al., 1982; Waldman et al., 1982).

Furthermore, it has been known for over 35 years that acidic fogs in southern California can be injurious to commercial crops. Ambient fog of pH less than 3.0 was reported to cause visible injury (necrotic spots) to field crops of spinach, endive, alfalfa, and beets in the early 1950's (Thomas, 1952).

Acidic fog potentially is more injurious to vegetation than acidic rain because: (a) fog often persists for several hours at a time vs. generally shorter times of rain; (b) fog events are often more frequent than rain events, especially in southern California coastal areas; and (c) the greater acidity of fog than rain. There have been no systematic studies of the effects of ambient or artificial acidic fog on vegetation; the most applicable literature instead is based on laboratory acidic mist investigations. In general the mist itself, without added acidity, resulted in leaching of $K^+$ (potassium), $Ca^{2+}$ (calcium), amino acids and other constituents from leaves, with the extent of leaching increasing as the mist became more acidic (Wood and Bormann, 1975; Scherbatskoy and Klein, 1983). At low pH's, acidic mist also produced necrotic lesions on leaves (Wood and Bormann, 1975; Scherbatskoy and Klein, 1983).

Recent research at the Statewide Air Pollution Research Center (SAPRC) of the University of California has shown that lettuce is injured by simulated acidic fog of pH 2.5 or lower (Granett and Musselman, 1984). Additional research has shown that radish, spinach, celery, bean, tomato, strawberry, azalea, alfalfa, and tree seedlings can also be injured by acidic fogs at about pH 2.0 in controlled experiments. At the SAPRC, acidic fog research has been conducted under the direction of Drs. Patrick Temple or Robert Musselman, funded by the United States Department of Agriculture Competitive Grants Program. The purpose of these studies was to determine if agricultural crops and trees were sensitive to acidic fog, and if exposure to fog results in reduced productivity or decreased plant quality.

The studies conducted by Dr. Patrick Temple were in two parts: (1) greenhouse studies to determine injury responses in Giant Sequoia and Jeffrey pine tree seedlings from combinations of acidic fog and ozone ($O_3$), and (2) field studies to determine yield losses to alfalfa exposed to combinations of acidic fog and $O_3$ (Temple et al., 1987). In the tree studies, acidic fogs of pH 2.0, 2.7, 3.4 and 4.1 were applied for three hours a day in the early morning, three days a week. The fog treatments were then followed by $O_3$ treatments of 0, 0.1 or 0.2 ppm for four hours. The alfalfa studies were conducted in open-top field chambers at Shafter, California (Temple et al. 1987). The acidic fog treatments were the same as for the tree studies, whereas the $O_3$ treatments were filtered air, ambient $O_3$, ambient $O_3$ x 1.3, ambient x 1.7, and ambient x 2.0. Acidic fog exposures were for two hours a day, three days a week, and with continuous $O_3$ treatments.

The studies of Dr. Robert Musselman included: (1) screening crop species in the greenhouse for sensitivity to acidic fog, (2) determining the effect of acidic fog on crops in field studies at the University of California's South Coast Field Station, and (3) examining the effects of different fog solution chemistries on plant response. The greenhouse screening studies were conducted using pH's of 1.6, 2.6, 3.6, 4.6 and 5.6 for two hours, once per week for several weeks. The field studies used the same acidic fog treatments, but were conducted beneath polyethylene-covered frames that were placed over plants only during fogging episodes. The fog composition studies used an acidity of pH 2.6, but with nitrate to sulfate ratios of 2:1, 1:1, 0:1, 1:0 and 1:2.

Overall, both Dr. Temple's and Dr. Musselman's studies have shown that plants exhibit visible necrotic symptoms from acidic fogs of about pH 2.5. Crop yields were reduced at very low pH's of approximately 2.0 and below. The acidic fog x $O_3$ studies have shown responses to fog or $O_3$, but data demonstrating any significant interactions between the two stresses is not yet available.

In general, most acidic deposition studies have been designed to only examine gross injury or yield effects, and have not been designed to evaluate underlying physiological responses. In the majority of the studies, important parameters such as net photosynthesis, stomatal conductance, or leaf element content have not been measured. Dr. Temple's alfalfa study incorporated measurements of net photosynthesis, stomatal conductance, and tissue buffering capacity. However, these measurements were made only for one crop.

California has important agricultural and forest resources in areas of the state affected by fog. Significant acreages of many valuable crops are grown in coastal areas including broccoli (1982 total value of $177 million), celery ($85 million), lettuce ($469 million), tomato ($148 million) and strawberry ($294 million) (California Department of Agriculture 1982). In addition, many important crops are grown in the San Joaquin Valley which is also subject to prolonged fog events, including alfalfa among others. Yield losses could currently be occurring in these crops, or could increase if fog acidity increases.

The Los Angeles-South Coast Air Basin area is affected by photochemical oxidant air pollutants in addition to acidic fog. Oxidant levels often reach 0.2 ppm (measured as $O_3$) or greater on days that begin with a dense fog. Both crops and native vegetation are affected by the oxidants with yields of some crops such as alfalfa decreased by over 30% compared to yields in filtered air (Thompson et al. 1976). Limited research with ambient $O_3$ and acidic rain suggested that acidic precipitation could alter plant response to $O_3$ by accentuating an $O_3$-induced decrease in yield or by altering the vegetative/reproductive mass relationship (Troiano et al., 1983).

## Project Objectives

The primary objective of this project was to identify the metabolic basis for sensitivity of plant species to acidic fog. Plants were examined for growth, yield and physiological, differences in response to a range of acidic strengths in the acidic fog treatments. A secondary objective was to identify if there was any interactive effect of acidic fog and ambient ozone on plant response to these pollutants. These objectives were evaluated using fog solutions and exposure facilities representative of ambient conditions.

# II. METHODS

## A. Fog Exposure System

The fog application system consisted of three components: (1) the canister pressure system; (2) the fog solution canister; and (3) the fog dispensing unit. The canister pressure system consisted of a gaseous $N_2$ source and the plumbing needed to deliver $N_2$ to the fog solution canisters. The latter was constructed primarily of 1.27 cm diameter PVC pipe, and will hereafter be referred to as the 'main system pressure line(s). Connections to the fog canisters were made off the main system pressure lines with variable lengths of teflon tubing (0.64 cm diameter). The tubing was secured to the main system pressure line and to the top of the fog canister by a stainless steel connector or elbow (0.64 cm fractional tube to 0.64 cm NPT thread), respectively.

Fog solution to be applied to the crops, was held in cylindrical PVC canisters (Musselman et al., 1985). The 1.0 m tall fog canisters were constructed of 0.15 m diameter PVC pipe sealed at both ends with slip fitted end caps. Each fog solution canister had the capacity to hold up to 18.6 L of fog solution. Three openings were made in the top end cap to (a) allow gaseous $N_2$ from the main system pressure lines to enter and pressurize the fog solution canister, (b) fill the canister with fog solution, and (c) deliver the fog solution from the canister to the fog dispensing unit. During fog application episodes, the fog solution filling hole was sealed with a threaded plug made of PVC. Fog solution was withdrawn from the canister through a siphon tube (0.81 cm diameter PVC pipe), and delivery to the fog dispensing unit was controlled by a stainless steel plug valve (Series P4T, Nupro Co., Willoughby, OH). Teflon tubing was used to connect the canister to the fog dispensing unit.

The fog dispensing unit consisted of four fog nozzles mounted in a framework constructed of 1.27 cm PVC pipe. The framework allowed the nozzles to be positioned approximately 0.35 m from the center of the chamber at a height 1.2 m above the ground. The framework was constructed in the pattern of a cross to optimize fog dispersal throughout the chamber. The dispensing units were mounted on 1.0 m risers in the center of the plot. Fog particles were produced when the fog solution was forced through the orifice of a nozzle (Bete PJ-6, Bete Fog Nozzle, Inc., Green-field, MA in the spring, and Mee Nozzle, Mee Industries, El Monte, CA. in the winter) and impacted against the surface of a J-shaped pin positioned directly over the nozzle orifice. The fog was applied at a rate of approximately 0.5 mm $h^{-1}$.

## B. Spring South Coast Fog-Oxidant Study

### 1. Fog Treatments and Measurements

This study examined plant response to interactions of predawn acidic fog and afternoon oxidant (ozone) episodes. This acidic fog x oxidant exposure pattern was representative of conditions that can occur in the South Coast Air Basin. In this area, fogs often occur during the early morning, especially in coastal areas of Orange and Los Angeles counties. Fogs also occur in inland valleys and in the foothills of the mountains. The fogs occur in the Spring months and persist into June, especially near the coast. The fogs also occur during late fall and winter months. During the months of April, May and June photochemical oxidant levels begin to rise as the incident light radiation level and air temperature increase. The photochemical oxidant levels often remain high into October and November. According to Waldman et al. (1982), periods of fog and photochemical smog can coexist, and low fog acidities can be associated with smog and dense haze events. In the present experiment, conditions were representative of late Spring, where an early morning fog event is followed by ambient oxidants in the late morning and afternoon.

The study was carried out in two concurrent experiments (Figure 1). The open-top chamber experiment had two types of air treatments: charcoal-filtered (CF) and nonfiltered, i.e. ambient (NF). Four acidic fog treatments occurred with each air treatment: no fog, and fogs with target pH's of 1.6, 2.6 and 5.6. Thus the eight chamber treatments were CF-no fog, CF-1.6, CF-2.6, CF-5.6, NF-no fog, NF-1.6, NF-2.6, and NF-5.6. Each treatment was replicated three times. These treatments could be replicated only partially in air exclusion systems due to lack of space. Thus, the air exclusion system treatments were considered to be a separate but related experiment and no direct statistical comparison could be made chambers. The CF-no fog, CF-1.6, CF-05.6, NF-no fog, NF-1.6 and NF-5.6 treatments also occurred in the air exclusion systems with two replicated of each treatment. There were three circular outside plots in order to determine exposures system effects on plant response. All three plots

TREATMENTS

0 = Outside plots, open

CF = Charcoal filtered air

NF = Nonfiltered (ambient) air

NO = No fog

1.6 = Added fog at pH 1.6

2.6 = Added fog at pH 2.6

5.6 = Added fog at pH 5.6

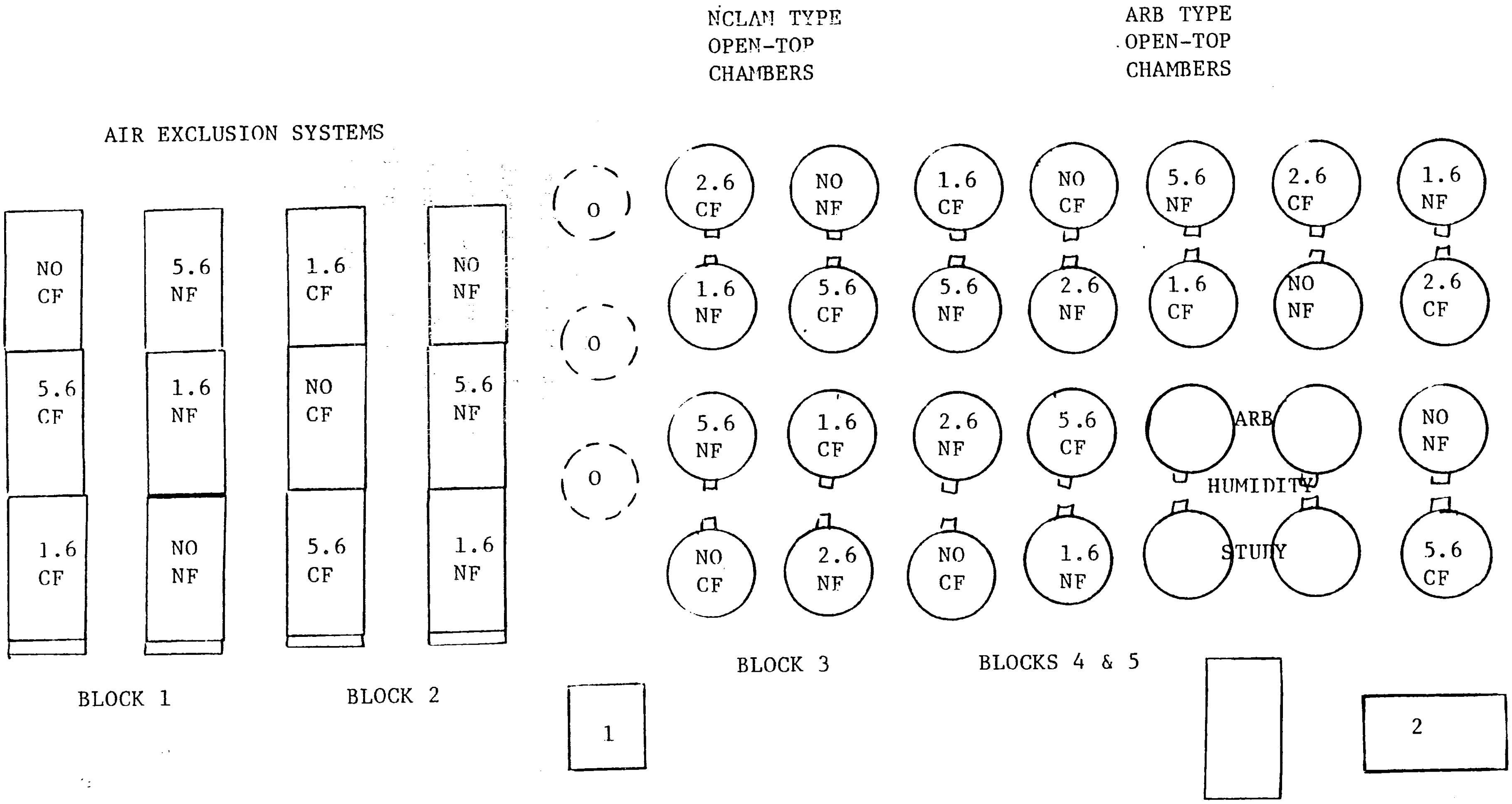

Figure 1. Plot diagram for spring (South Coast) fog study. Blocks 1 and 2 were for air exclusion systems; 3, 4 and 5 for open-top chambers. Buildings 1 and 2 house air monitoring systems for air exclusion systems and outside plots, and open-top chambers, respectively.

were used to determine open-top chamber effects, and two plots were used to air exclusion system effects; with all comparisons made vs. NF-no fog treatments for each system.

All fogging systems, chambers, air exclusion systems, and fog enclosures for air exclusion systems were maintained in good working condition during the study. Plastic was repaired both in chambers and air exclusion systems as needed. Several blowers malfunctioned during the course of the study, but were repaired immediately to prevent chamber overheating.

The target fogging solution used for the Spring exposures had a background chemical composition representative of South Coast Air Basin fogs (Table 1). Nitrate was the predominant anion, at a ratio of 2.5:1 to sulfate. The concentrations of all ions was substantially higher than for the Winter - San Joaquin Valley fog. The South Coast Fog represented an average of fogs from numerous sites in the basin as described by Waldman et al. 1982 and Munger et al. 1983 (four sites), Appel et al. 1982 (one site), and Brewer et al. 1983 (16 sites with a mobile unit).

The calculated ion concentrations in the solutions used in the spring study varied slightly from the target composition for specific ions based on literature (Table 1). This was unavoidable since readily soluble salts which contained both the cations and anions, had to be used to make the solutions. For example, $NH_4^+$ had to be added at a concentration approximately 60% higher, $Ca^{2+}$ 30% higher $Mg^{2+}$ 50% lower, and $Cl^-$ 33% higher in the actual solutions than target solutions in order to obtain the appropriate concentrations of the accompanying ions in the salts. Table 2 indicates the prepared solution concentrations of the major cations and anions at the different pH's. The trace metal ions were at the concentrations shown in Table 1 for all solutions.

Routine maintenance of the fog application system was conducted twice weekly on the morning prior to each fog event. A 'pre-test' of the system involved filling the fog solution canisters with 8 L of water and dispensing fog with the blowers operating. The former served to rinse the canisters and dispensing units of solution remaining from the previous fog event, thereby preventing potential problems due to salt accumulation. The latter allowed for establishing if any of the fog nozzles had become clogged due to salt or debris blocking the nozzle orifice. By dispensing

Table 1. Target Composition of Acidic Fog Solution and Elemental Loading for a Composite South Coast Air Basin Fog[a]

| Chemical | µeq $l^{-1}$ | meq $m^{-2}$[b] | Chemical | µeq $l^{-1}$ | meq $m^{-2}$[b] |
|---|---|---|---|---|---|
| $Na^+$ | 1286 | 14.69 | $NO_3^-$ | 4824 | 55.07 |
| $K^+$ | 166 | 1.89 | $SO_4^-$ | 2268 | 25.89 |
| $NH_4^+$ | 2957 | 33.76 |  | µ $gl^{-1}$ | mg $M^{2+}$ |
| $Ca^{2+}$ | 1042 | 45.66 | Fe | 1313 | 14.99 |
| $Mg^{2+}$ | 503 | 31.19 | Mn | 277 | 3.17 |
| $H^+$ | 1000 | 11.42 | Pb | 2008 | 22.93 |
| $Cl^-$ | 305 | 3.48 | Cu | 456 | 5.20 |
|  |  |  | Ni | 103 | 1.18 |

[a] Fog solution at pH 3.0. Solution was brought up to desired pH by adding or subtracting nitric acid ($HNO_3$) and sulfuric acid ($H_2SO_4$) in an appropriate 2.5:1 ratio. The solution represents fog sampled at over 10 sites throughout the South Coast Air Basin (Brewer et al. 1983, Munger et al. 1983, Waldman et al. 1982).

[b] Total elemental loading, according to the formula; meq $m^{-2}$ (or mg $l^{-1}$) = µeq $l^{-1}$ (or µg $l^{-1}$) x $10^{-3}$ meq µeq$^{-1}$ x 5.261 x $10^{-4}$ l $s^{-1}$ x 2 hours x 3600 s $h^{-1}$ 7.297 $m^{-2}$ surface area x 22 foggings (2 in each of 14 weeks) for circular ARB chamber.

fog with the blowers on, a minimal amount of the canister and dispensing unit rinse water was deposited to plant surfaces. Upon completion of the fog application system 'pre-test', preparations for the following morning's fog event were performed (i.e., filling the canisters with 10 L of fog solution, and sealing the solution filling holes).

On the morning of a fog event, chamber and air exclusion plots to which fog was to be applied, were enclosed with plastic. This entailed sealing the tops of the open-top chamber plots with plastic-covered hoops or placing a sheet of plastic over a rectangular frame which delimited the size of the air exclusion system plots (2.44 m wide x 3.05 m length x 1.83 m height). After all 26 fog plots were enclosed, the fog solution canisters were pressurized to 690 kPa (100 psi), and fog application was initiated by opening the plug valve on each canister. Fog episodes were started at 0500 h PST and lasted for approximately 2 h. After the last canister was empty, the plastic coverings were removed, 30 to 45 min before the blowers began operating.

Table 2. Calculated and Measured Ion Concentrations of Fog Solutions and Fog Samples Collected as Nozzle Drip and Suspended fog in the Spring Fog Study ($\mu$eq $l^{-1}$)[a]

| pH | Solution | Nozzle | Collector | Solution | Nozzle | Collector |
|---|---|---|---|---|---|---|
| | | $H^+$ | | | $Na^+$ | |
| 1.6 | 25119 | 27575 (6470) | 27559 (13882) | 1274 | 1972 (700) | 1729 (248) |
| 2.6 | 2512 | 2780 (565) | 2691 (683) | 1274 | 1661 (298) | 1754 (344) |
| 5.6 | 3 | 0.1 (0.01) | 0.1 (0.2)[b] | 1274 | 1401 (127) | 1859 (233) |
| | | $K^+$ | | | $NH_4^+$ | |
| 1.6 | 165 | 179 (61) | 178 (72) | 4739 | 4360 (1189) | 5202 (460) |
| 2.6 | 165 | 191 (44) | 196 (36) | 4739 | 4814 (181) | 5244 (949) |
| 5.6 | 165 | 143 (55) | 165 (30) | 4739 | 4621 (222) | 6369 (852) |
| | | $Ca^{2+}$ | | | $Mg^{2+}$ | |
| 1.6 | 1312 | 1004 (218) | 1081 (80) | 244 | 205 (33) | 245 (17) |
| 2.6 | 1312 | 1046 (62) | 1040 (152) | 244 | 217 (32) | 201 (72) |
| 5.6 | 1312 | 922 (57) | 1151 (198) | 244 | 232 (53) | 299 (54) |
| | | $F^-$[c] | | | $Cl^-$ | |
| 1.6 | 301 | 51 (101) | 73 (147) | 417 | 2401 (1666) | 2740 (1540) |
| 2.6 | 301 | 63 (126) | 46 (91) | 417 | 4189 (2576) | 4119 (2356) |
| 5.6 | 301 | 61 (121) | 86 (172) | 417 | 4587 (2773) | 3938 (2327) |
| | | $NO_3^-$ | | | $SO_4^{2-}$ | |
| 1.6 | 21903 | 25282 (11952) | 24684 (10058) | 12376 | 11871 (7359) | 13235 (5362) |
| 2.6 | 6694 | 6978 (545) | 7062 (796) | 3396 | 3573 (263) | 3660 (718) |
| 5.6 | 4790 | 4304 (2991) | 5338 (729) | 2270 | 2124 (321) | 3765 (1021) |

[a] Mean with standard deviation in parentheses. Values represent the mean concentration for nozzle and fog collector samples from four replicate sampling dates.

[b] Three samples.

[c] $F^-$ was present only in one sample from both nozzle and collector.

Fogging events occurred twice weekly, on Tuesday and Friday from approximately 0500 to 0700 h PST. The events were changed from Monday and Thursday as originally proposed to allow for checks of the fogging system the afternoon prior to each fogging. On Monday and Thursday afternoons test water from a water softener associated with the ARB humidity study was placed in the fog canisters. The fogging systems were then pressurized using this water to flush the system and to check for malfunctions in any nozzles. Distilled water could not be used for this check due to the large amount (>190 L) required to test all the systems simultaneously. Tap water could not be used because of chemical additives such as chlorine.

The use of the softened water apparently did not result in any significant deposition of background salts on leaves as the fog system tests occurred with the chamber and air exclusion system blowers on. Most of the test fog was blown up and away from the plants. It is possible that residual ions from the softened water may have contributed to the measured pH of approximately 7.2 in the low acidity "control" plots compared to the pH 5.6 of the fog solution at the time of mixing. Moreover, the PVC delivery system may also have contributed to some of the pH rise.

Filter paper discs were used to measure fog deposition to the floor of the chambers as an estimate of the rate of fog deposition to plant surfaces. Whatman #1 paper was used with 0.07 m diameter discs placed in petri dishes at different locations in the chambers.

Fog water samples were collected at three sites in the chambers to determine if the chemistry of the fog solution changed from the canister to the leaf surface. Samples of fog water were taken as nozzle drip, suspended fog collected with a high volume sampler supplied by Dr. Mike Hoffman of the California Institute of Technology (Jacob et al., 1985a), and as fog on leaves via leaf washes. A complete set of samples were taken on four dates (16 May, 23 May, 03 June, 13 June) including nozzle drip, suspended fog, and leaf washes from green pepper and strawberry. The pH of the fog samples was determined at U.C. Riverside, and then sent to Dr. Hoffman's Laboratory for cation (i.e. $K^+$, $Ca^{2+}$, $Na^+$, $NH^+$, $MG^{2+}$), and anion (i.e. $F^-$, $Cl^-$, $NO_3^-$, $SO_4^{2-}$) analyses.

The amount of moisture on leaves following fogging episodes was determined by excising leaves and placing them in preweighed, sealed plastic bags containing filter paper. The bags were then re-weighed after the leaf was removed to determine the amount of water (and possibly other materials) remaining on the filter paper. The planar surface area of the leaves was determined with a LI-COR® LI 3000 leaf area meter, and used to calculate leaf water and mineral concentrations on an area basis.

Leaf washes were made using approximately 0.1 L of distilled water per leaf. Leaves were cut from plants and transferred to clean beakers which were then filled with the water. The leaves were agitated in the water for about 15 s and them removed. The leaves were saved for planar area measurements. The solutions were placed in polyethylene (Nalgene®) bottles and measured for pH as soon as possible. Samples were then frozen at about 4±C for storage and then thawed prior to ionic analysis via a Dionex® system at the California Institute of Technology.

### 2. Oxidant Treatments and Measurements

Eight additional open-top field chambers were installed at the ARB site to bring the total number of chambers to twenty-four. Prior to use, the chambers were cleaned and prepared for the oxidant exposures. The filters were changed so as to provide for 12 charcoal-filtered and 12 nonfiltered plots. All chambers had particulate filters. The arrangement of the plot is given in Figure 1.

Four air exclusion systems (Thompson and Olszyk 1985) were refurbished for use in the present study. Each system had four 15 m long x 0.32 m wide (inflated) ducts with holes positioned to blow air over three rows of plants. These systems were previously found to be as effective as open-top chambers in providing oxidant exposures to plants. Two air exclusion systems blew filtered air over the plant canopy and two systems blew nonfiltered air over the canopy. All systems had particulate filters. The four systems duplicated part of the treatments the chambers (Figure 1).

Both the chambers and air exclusion systems were in operation between the hours of 0800 to 2000 h PST, and shut off between 2000 to 0800 h PST (which included the period of fogging).

Previous studies investigating the effects of air pollutants on winter crops indicated that lettuce and wheat can grow over three times as fast in open-top chambers than in outside plots (Thompson, 1985). Furthermore, the responses of wheat to sulfur dioxide exposures in chambers differed from the response plants exposed in chamberless air exclusion systems (Thompson and Olszyk, 1985). These workers found a statistically significant decrease in seed yield when the plants were exposed to 0.07 or 0.15 $\mu l\ l^{-1}$ sulfur dioxide in open-top chambers, but found no decrease or possibly an increase in yield when the plants were exposed to sulfur dioxide exposure in air exclusion systems.

The physiological basis for the difference in pollutant sensitivity in chambers versus air exclusion systems, or chambers versus outside plots was not determined. However, the chambers had slightly warmer air and soil temperatures which may have stimulated plant growth rates. In the sulfur dioxide study, the chambers were in continuous operation which produced warmer conditions during both the day and night. The partial replication of the fog acidity dose-response study in air exclusion systems as well as chambers provided a means of "calibrating" the chamber dose-response results.

Ambient $O_3$ levels were monitored continuously with a Dasibi® $O_3$ analyzer (Model 1003-AH, Dasibi Environmental Corp., Glendale, CA). Monthly calibrations were performed using a transfer standard maintained by the California Air Resources Board.

### 3. Environmental Measurements

General environmental conditions during the spring acidic fog study were determined based on ambient measurements made at the ARB Citrus project site, approximately 100 m Southeast of the fog study site. Light (quantum) intensity was measured with an LI 190SB sensor and air temperature with thermocouples. Both sensors provided electronic signals which were processed by a Cyborg® ISAAC interface and Apple IIe computer system. The data were expressed as 12 h (0800-2000 PDT) means averaged on a Saturday-Friday weekly basis. The data encompassed study dates between 3/29 and 7/4/87.

### 4. Plant Culture

Seed of Lycopersicon esculentum Mill. 'UC-82' (tomato) and Capsicum annuum L. 'California Wonder #300' (pepper), cuttings of Medicago sativa L. 'Moapa' (alfalfa), cold-stored rooted crowns of Fragaria x ananassa Duch. 'Chandler' (strawberry) and four-week old seedlings of Apium graveolens L. 'Bishop' (celery) were potted in a soil-sand mixture (University of California-Riverside standard soil mix #2) in 3.8 L pulp pots. Planting dates were staggered from November 1985 (i.e. strawberry) to March 1986 (i.e. celery) in order to have the plants in an early to mid-vegetative growth stage by April 1986. All crops were grown in a greenhouse for three to eight weeks, after which they were moved outdoors to an area adjacent to the field site. The plants were allowed to acclimate (to ambient outdoor conditions) for four to twelve weeks prior to being randomly assigned to one of the experimental plots (five plants per plot). During the course of the study, the plants were fertilized weekly with full-strength North Carolina State University Phytotron nutrient solution, and otherwise supplied with tap water as needed. Plants were sprayed as required with Plictran 50W (Tricyclohexylhydroxystannane, Dow Chemical Co., Midland, MI) to control mites and Orthene (O,S-dimethyl acetophosphoramidothioate, Chevron Chemical Co., San Francisco, CA) for aphid control.

The potted plants were grown in modified National Crop Loss Assessment Network (NCLAN) open-top field chambers and air exclusion system plots (Heagle et al. 1973; Olszyk et al. 1986). In both types of plots, blowers were used to dispense either charcoal-filtered (CF) or nonfiltered (NF) air from 0800 to 1800 h PST daily. The chamber blowers were turned off at night to allow normal dew formation. The plants were placed within plastic liners buried in the soil to a depth of 22 cm to insulate the pots from high ambient air temperatures, and to allow the soil in the pots to fluctuate with the ambient diurnal soil temperature cycle.

### 5. Growth, Yield, and Injury Measurements

Foliar injury was visibly rated on a 0-4 scale on May 19, 1986 using a 0-4 scale where 0 = little or no injury, 1 = 5 to 25% leaf area injured, 2 = 25-50% of area injured, 3 = 50-75% of area injured, and 4 = 75-100% of area injured. Ratings were made on five plants per plot.

For the fruit crops (tomato, strawberry, and green pepper), ripe fruits were harvested at 7 to 10 day intervals, and fruit fresh weight and number were measured. Total fruit fresh weight was tabulated as the sum of all the interval harvests. For alfalfa, the plants were cut at 3 to 4 week intervals when the plants exhibited 'one-tenth bloom'. The combined dry weight of leaves and stems was measured at each interval harvest, and the sum of the harvest dry weights was the total season yield.

Whole-plant harvests were initiated three days after the final fog event. In the fruit crops, fruits (>2.0 cm diameter) were harvested, counted, and weighed before destructive sampling of the leaves and stems. The plants then were cut at ground-level and weighed immediately for the determination of whole-plant fresh weight. In strawberry and green pepper, the leaves were then removed, and the plant re-weighed to determine the stem fresh weight. Leaf fresh weight was calculated as the difference between the fresh weight of the whole-plant and the stem. In randomly selected strawberry and green pepper plants, (three from each fog chemistry x air quality treatment group), leaf area was measured for developing leaf area to dry weight regression equations used to estimate whole-plant leaf area. Leaf and stem samples were air-dried in greenhouses to constant weight (approximately five to ten days) for dry weight determinations.

### 6. Physiological Measurements

Physiological measurements were made to: a) assess plants responses which may be important insofar as the metabolic basis for any observed growth or yield effects, b) assess any differences in metabolism which could account for growth or yield differences between outside and chamber plants, and c) identify physiological parameters that may be sensitive indicators of plant stress under field conditions.

Net photosynthesis. Net photosynthesis was measured using a portable field photosynthesis system (Lambda Instruments Model 6000). The instruments produced instantaneous readings of net photosynthesis, stomatal conductance, transpiration, irradiance, leaf temperature, and air temperature. All values were stored in a computer and than transferred to a mainframe computer for processing and statistical analysis. Two strawberry and green pepper plants, representing an acidic fog-resistant and sensitive species, respectively, were measured in each of two plots per treatment group in the twice weekly readings. Measurements were started in the late morning through the early afternoon after the leaves had dried from the pre-dawn fogging treatment.

Stomatal conductance and transpiration. Stomatal conductance and transpiration also were measured by the portable photosynthesis meter. Two plants of each species were measured per plot.

Chlorophyll Concentration. Leaf chlorophyll concentration was assayed and the ethanol extraction method (Lichtenthaler and Wellburn 1983), and extract absorbances measured using a Beckman DB spectrophotometer.

Elemental analysis. Elemental analyses were made utilizing dried leaf tissue collected at the end of the experiment. Leaf samples were taken from the five plants in each plot, of all five plant species. Element concentration were determined by x-ray fluorescence (PIXIE) techniques (Crocker Nuclear Laboratory, University of California, Davis).

Foliar concentrations of Na, Mg, Al, Si, P, S, Cl, K, Ca, Ti, Mn, Fe, Ni, Cu, Bn and Br were determined.

The plant samples have been analyzed but considerable work still needs to be done to determine concentrations and to carry out statistical analysis on the data. This work will not be done as unless answers can be obtained to questions that have arisen considering the reliability of PIXIE analysis, especially for cations. This is beyond the scope of this project. Previous work with alfalfa samples indicated that cation concentrations were different with PIXIE analysis than the standard atomic absorption analysis accepted by most laboratories. Results will not be reported if they be inaccurate. However, lack of elemental concentration data does not alter any of the conclusions or recommendations of this report as there were no unusual responses that could only ba addressed based on elemental analysis.

Tissue buffering capacity. Tissue buffering capacity was determined by titrating solutions made with fresh leaf samples. The titration was with a strong base (0.017 NaOH) according to the general procedures described by Craker and Bernstein (1984), and Pylypec and Redmann (1984). Samples were taken from two green pepper and strawberry plants per plot, on two occasions during the experiment.

## 7. Statistical Analysis

Significance of treatment effects was tested by analysis of variance (ANOVA) for each species separately (Steel and Torrie 1960). Fog chemistry and air quality were the main treatment variables, and [fog chemistry x air quality] was the first order interaction variable. Within each plot, individual plants were considered as the subunits for statistical analysis. Results from open-top chambers and air exclusion systems were analyzed separately.

For the plants exposed to fog in open-top field chambers, the experimental design was a completely randomized split-plot with three replications. Fog chemistry and air quality were the main plot factors and crop species was the subplot factor. Each replicate block consisted of eight plots in which plant responses to all combinations of four fog chemistry (no fog application, or pH 7.24, 2.69 or 1.68 simulated fog) and two air quality regimes (CF and NF air) were tested. For plants exposed to fog in air exclusion plots, the same experimental design was used except the pH

2.69 simulated fog treatment was omitted (reducing the number of plots per block to six), and the number of replicate blocks was reduced to two.

## C. Winter San Joaquin Valley Fog Study

### 1. Fog Treatments and Measurements

The fog solution for the winter exposures were mixed to provide a background ion composition as shown in Table 3. The fog solution at pH 4.2 was acidified with a nitric and sulfuric acid mixture in an approximate 1:1.4 molar ratio as found in the southern San Joaquin Valley. At pH of 1.76, the H+ loading was projected to be approximately 364.7 meq m$^{-2}$ whereas at pH of 5.48, the H+ loading would be approximately 0.037 meq m$^{-2}$. The fog constituents represent the average concentrations for acidic fog based on published data for Bakersfield (Jacob et al. 1984).

Table 3. Target Composition of Acidic Fog Solution and Elemental Loading for a San Joaquin Valley Fog[a]

| Chemical | μeq l$^{-1}$ | meq m$^{-2}$[b] | Chemical | μeq l$^{-1}$ | meq m$^{-2}$[b] |
|---|---|---|---|---|---|
| $NA^+$ | 19.5 | 0.21 | $NO_3$- | 850 | 9.39 |
| $K^+$ | 9.3 | 0.11 | $SO_4^{2-}$ | 1160 | 12.82 |
| $NH_4$+ | 1440.0 | 15.92 | | | |
| $Cu^{2+}$ | 47.0 | 0.52 | | μg l$^{-1}$ | mg m$^{-2}$ |
| $Mg^{2+}$ | 6.3 | 0.07 | Fe | 400 | 4.42 |
| $H^+$ | 60.0 | 0.66 | Mn | 14 | 0.15 |
| $Cl^-$ | 47.0 | 0.52 | Pb | 330 | 3.65 |
| | | | Cu | 34 | 0.37 |
| | | | NI | 61 | 0.68 |

---

[a] Fog solution at pH 4.22. Solution was brought to the desired pH by adding nitric acid ($HNO_3$) and sulfuric acid ($H_2SO_4$) in an approximate 1.0:1.4 ratio (Jacob et al. 1984).

[b] Total elemental loading, according to the formula: meq m$^{-2}$ (or mg l$^{-1}$) = μeq l$^{-1}$ (or μg l$^{-1}$) x 10$^{-3}$ meq μeq x 5.261 x 10$^{-4}$ l s$^{-1}$ x 2 hours x 3600 sh$^{-1}$ x 7.4 m$^{-2}$ surface area x 21 foggings (1 or 2 in each of 11 weeks).

Fog collections were made on three dates, 16 November, 01 December, and 04 December 1986. Collections included samples of nozzle drip, suspended fog, and leaf washes as previously described. Leaf washes were performed on broccoli and potato, and the filter paper collections also included measurements on alfalfa.

The calculated ion concentrations for the actual solutions used for the study (Table 4), were very close to the target concentrations (Table 3). The concentrations of all ions except $NO_3^-$ and $SO_4^=$ were much lower than for the spring South Coast study, probably due to the less industrialized nature of the San Joaquin Valley as compared to the South Coast area.

The pH levels of 1.76 2.23, 2.72, 3.22 and 5.48 were chosen to represent a range of acidities used in previous USDA-SAPRC studies. Several pH's at the low end of the scale (i.e. 1.76, 2.23, 2.72) were chosen in order to provide more data on plant response in the pH range where injury effects have been previously reported (pH 1.6-2.6). The pH 5.48 treatment is included as a control to determine the effects of fog application on plants, where fog pH is representative of a solution acidified by the dissolution of $CO_2$ into water. This is a standard control pH used in many acidic precipitation studies. The fog solutions were periodically checked for pH, nitrate, sulfate, and cation concentrations. Deionized water was used to prepare the fog solutions.

The plots receiving fog were sealed to contain the fog during the 0600 to 0800 h PST twice weekly exposures. The enclosures consisted of rectangular frames constructed of a polyvinyl chloride (PVC) pipe, over which a sheet of vinyl was placed to cover the top and sides of the enclosure. The dimensions of the fog plot enclosures were 1.8 m x 2.4 m x 3.1 m (height x width x length) encompassing a volume of 13.4 $m^3$. The ground surface area was 7.4 $m^2$. The vinyl film was placed over the plots manually just before the fog exposures were initiated at 0600 h PST. The fogging dispensing units were situated at a height approximately 1.0 m above the ground, in the center of the plot. A diagram of the plots for the winter fog study is shown in Figure 2. Each pH, no fog or outside plot occurred in each of the three treatment blocks during the study period between 03 November 1986, and 15 January 15 (ambient air in Riverside typically contains low levels of gaseous pollutants during the

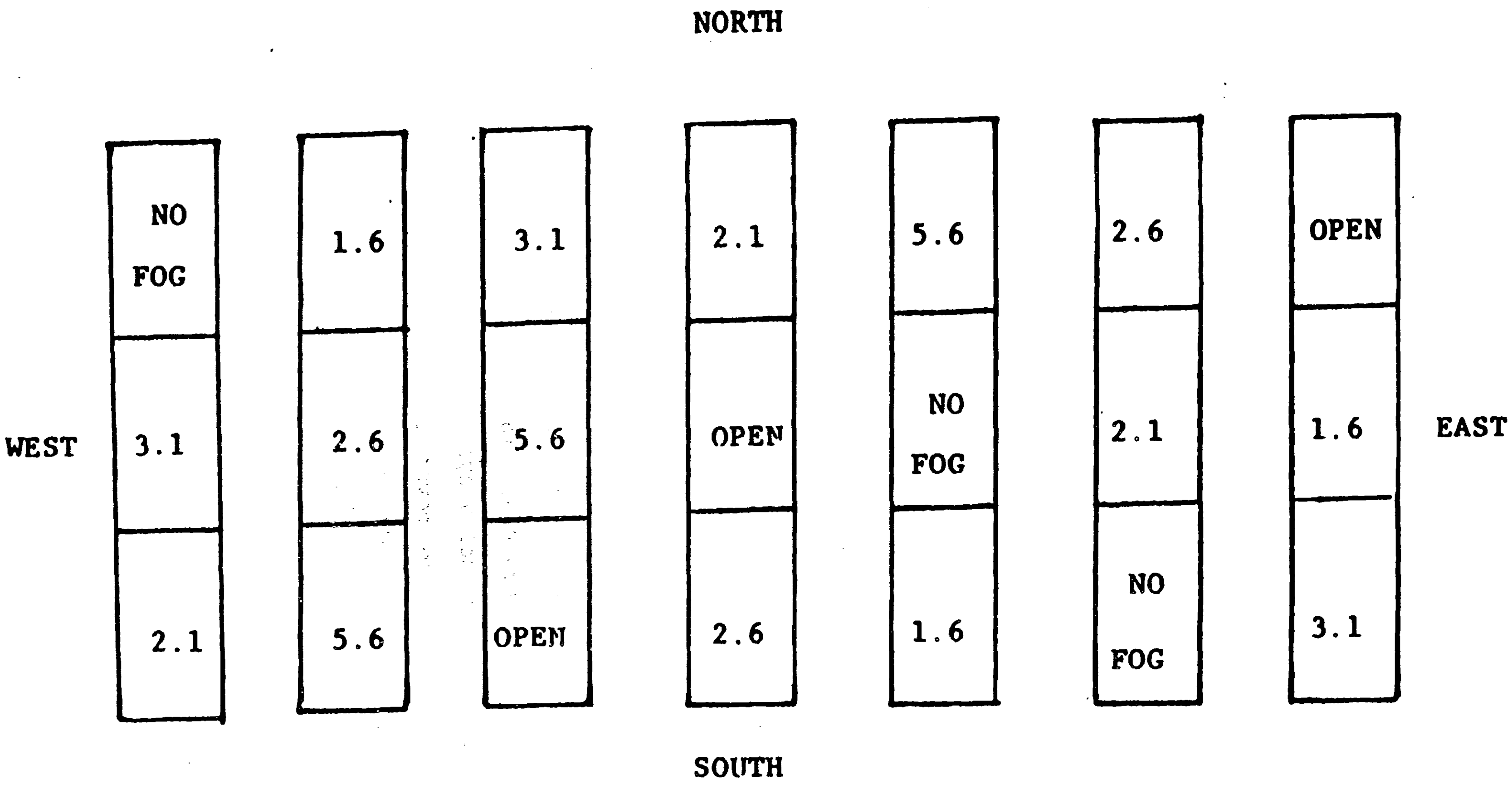

Figure 2. Plot diagram for the winter (San Joaquin Valley) fog study. Open plots do not have fog enclosures, no fog plots have the enclosures, but do not have fog. The plots are in three west to east blocks.

Table 4. Calculated and Measured Ion Concentrations of Fog Solutions and Fog Samples Collected as Nozzle Drip and Suspended Fog in the Winter Fog Study ($\mu eq\ l^{-1}$)[a]

| pH | Solution | Nozzle | Collector | Solution | Nozzle | Collector |
|---|---|---|---|---|---|---|
| | | $H^+$ | | | $Na^+$ | |
| 1.6 | 25119 | 11820 (5436) | 12900 (1082) | 20 | 40 (16) | 54 (20) |
| 2.1 | 7943 | 3127 (1859) | 3670 (1035) | 20 | 33 (2) | 75 (45) |
| 2.6 | 2512 | #211 (424) | 1152 (286) | 20 | 36 (1) | 53 (13) |
| 3.1 | 794 | 482 (74) | 339 (129) | 20 | 38 (6) | 54 (17) |
| 5.6 | 3 | 12 (5) | 5 (4) | 20 | 38 (6) | 59 (12) |
| | | $K^+$ | | | $NH_4^+$ | |
| 1.6 | 9 | 12 (5) | 19 (6) | 1440 | 1569 (117) | 1818 (101) |
| 2.1 | 9 | 12 (6) | 26 (13) | 1440 | 1500 (32) | 1835 (61) |
| 2.6 | 9 | 10 (2) | 17 (4) | 1440 | 1310 (234) | 1742 (363) |
| 3.1 | 9 | 12 (6) | 19 (7) | 1440 | 1503 (224) | 1791 (120) |
| 5.6 | 9 | 13 (8) | 17 (4) | 1440 | 1326 (10) | 1724 (156) |
| | | $Ca^{2+}$ | | | $Mg^{2+}$ | |
| 1.6 | 47 | 48 (12) | 90 (12) | 6 | 5 (3) | 15 (7) |
| 2.1 | 47 | 39 (1) | 138 (95) | 6 | 7 (1) | 24 (13) |
| 2.6 | 47 | 34 (19) | 86 (7) | 6 | 8 (1) | 17 (5) |
| 3.1 | 47 | 47 (9) | 104 (22) | 6 | 7 (2) | 19 (3) |
| 5.6 | 47 | 44 (8) | 77 (5) | 6 | 8 (3) | 15 (3) |
| | | $Cl^-$ | | | $NO_3^-$ | |
| 1.6 | 47 | 220 (138) | 213 (150) | 10393 | 10649 (1067) | 10238 (885) |
| 2.1 | 47 | 147 (150) | 214 (85) | 3957 | 3538 (361) | 3522 (429) |
| 2.6 | 47 | 94 (69) | 140 (151) | 1294 | 1229 (297) | 1259 (421) |
| 3.1 | 47 | 84 (59) | 263 (205) | 672 | 626 (152) | 713 (154) |
| 5.6 | 47 | 144 (171) | 94 (5) | 406 | 391 (113) | 596 (175) |
| | | $SO_4^{2-}$ | | | | |
| 1.6 | 29932 | 27240 (2417) | 26172 (2630) | | | |
| 2.1 | 11391 | 8959 (1066) | 8868 (869) | | | |
| 2.6 | 3718 | 3030 (10) | 3310 (390) | | | |
| 3.1 | 1928 | 1561 (235) | 1949 (605) | | | |
| 5.6 | 1161 | 919 (124) | 1266 (161) | | | |

---

[a] Mean with standard deviation in parentheses for three replicate sampling dates for nozzle and fog collector samples.

winter and early spring). Acidic fog treatments were applied between 0600 and 0800 h PST, twice per week on Mondays and Thursdays. Trial runs to check for malfunctioning nozzles were made periodically. The checks before each fog episode for the spring study indicated that repeated system checks were not necessary. All parts of the fogging system were refurbished prior to winter fog study. New nozzles were installed for all fog dispensing systems. Distilled water was used for occasional system pressure checks.

### 2. Air Pollution Measurements

All plants were grown in outside/ambient air. During this time of year (November to January), ambient concentrations of gaseous pollutants are normally low. Nevertheless, ambient concentrations of ozone, sulfur dioxide, nitrogen oxides, and peroxyacetyl nitrate (PAN) were measured at the field sites within close proximity to the winter fog study site. Ozone was measured with a Dasibi Model 1003 AH analyzer, sulfur dioxide with a Teco Model 43 analyzer, nitrogen oxides with a Beckman 952A analyzer, and PAN with a gas chromatograph.

### 3. Environmental Measurements

Environmental measurements were the same as for the winter fog study, but with the addition of dewpoint, (General Eastern chilled mirror analyzer). Air temperature and dewpoint data were used to calculate relative humidity. Data on relative humidity was collected from 01 November 1986 to 16 January 1987.

### 4. Plant Culture

Plants of *Daucus carota* L. 'Imperator' (carrot), *Brassica oleracea* L. 'Empire' (broccoli), *Solanum tuberosum* L. 'White Rose' (potato), *Allium sativa* 'Southport White Globe' (onion), *Triticum aestivum* L. 'Yecora roja' (wheat), and *Medicago sativa* L. 'Moapa' (alfalfa) were used in this study. These species are grown in areas of the San Joaquin Valley that are affected by winter fogs. They also have been used in other acidic fog studies, and have been shown to be sensitive to pH's in the range of 2.0 to 3.0. Carrot, broccoli, wheat, and onion plants were grown from seed. Alfalfa plants were clonal material, propagated from cuttings of field-grown plants. Potato plants were grown from seed pieces.

Alfalfa, potato, onion, and broccoli plants were placed in the fog plots by 29 October 1986. Carrot and wheat plants were added later due to slow seedling development or space limitations, respectively. In each test plot, there were five pots of each species. However, in some cases plant development was severely altered by insects or pests, reducing the total number of replicate plants in a given fog treatment group. All plants were grown in 3.8 L pulp pots placed in the ground within plastic liners. The plants were irrigated with North Carolina State University Phytotron nutrient solution or tap water as needed. Plants received insecticide treatments as required for pest control.

### 5. Growth, Yield and Injury Measurements

Plants were rated for visible injury on a 0-10 rating scale basis with 0 = no injury, and 1-9 = increments of 10-90% leaf area injured. Five plants in each of three plots were rated. Measurements focussed on broccoli because it appeared to be most sensitive to acidic fog from the beginning of the study. Growth and yield were determined as fresh and dry weights. Wherever applicable, separate weights were taken for different parts of the plants. A summary of weights taken is as follows: (1) onions--shoot (including bulb) and root fresh weight; (2) carrots--taproot and shoot fresh weight; (3) alfalfa--shoot fresh and dry weight; (4) wheat--shoot fresh and dry weight; (5) potato--tuber and shoot fresh weight, and stem and leaf dry weight; (6) broccoli--influorescence, stem, and leaf fresh weight, and stem, leaf, and root dry weight.

### 6. Physiological Measurements

Foliar net photosynthetic, stomatal conductance, transpiration, and elemental concentration measurements were made as described for the spring study. The gas exchange measurements (photosynthesis, conductance, and transpiration) focussed on broccoli and potato which appeared to be sensitive and resistant, respectively, to acid fog at the start of the study. Buffering capacity measurements were not made, as the spring study apparently showed no effects due to acidic fog, even in plants exposed to pH 1.68 fog.

### 7. Statistical Analysis

One-way analysis of variance was used to compare the five fog pH and the no fog treatments. Plant responses in the no fog and outside plots were similar, and further analyses to clarify differences due to enclosing the plants twice per week were not performed.

# III. RESULTS AND DISCUSSION

## A. Spring South Coast Fog-Oxidant Study

### 1. Fog Chemistry

Fog treatments were initiated on 11 April 1986, and treatments were continued (two per week) for the next 11 weeks. Nozzle drip samples were collected during each fog event for pH determination (Table 5). Over the course of the season, fog pH values for each fog treatment varied on an event basis, with the pH 5.6 fog exhibiting the greatest range. Unlike the pH 2.6 and 1.6 fog solutions where nitric and sulfuric acid was added to lower the pH, acids were not added to the pH 5.6 fog solution. Solutions with a low dissolved salt content at pH levels near neutrality (i.e. 7.0) are more sensitive to inputs of $H^+$ or $OH^-$, than highly acidic solutions (i.e. pH 2.6 and 1.6 fog solutions). However, in the present study, it was found that water remaining in the canister from fog system performance checks contributed to the observed changes in pH from the time of canister filling to the time of fog application. This was particularly evident for the pH 5.6 solution, since the same inputs of $OH^-$ will not cause large changes in pH in fog solutions that have $H^+$ concentrations 1,000 to 10,000 times greater (i.e. pH 2.6 and 1.6). For all remaining tables the treatments will be referred to by the actual mean pH's of 1.68, 2.69, and 7.24, respectively, and no longer as 1.6, 2.6, and 5.6.

The results from the pH determinations for the four complete set of samples are shown in Table 6. The nozzle drip pH's are similar to those measured for all 22 fogs. The fog collector pH's are the same as for nozzle drip, indicating that the acidity of the suspended fog was the same as the liquid prior to emission from the nozzles. The leaf water pH's indicate that the leaf surfaces of both green pepper and strawberry were considerably more acidic following pH 1.6 and 2.6 fog treatments as compared to the pH of the distilled water used to wash the leaves (i.e. 5.82 ± 0.06).

The concentrations of ions in nozzle drip or fog collector samples were similar to those in the original solution (Table 2). The concentration of $H^+$ was lower in the nozzle drip and fog collector samples, while the concentrations of $Na^+$ and $Cl^-$ were higher (both likely due to contamination from the water softener water used for testing).

Table 5. The pH of Fog Nozzle Drip Samples in the Spring Fog Study[a]

| | | pH of Fog Solution | | |
|---|---|---|---|---|
| Date | Fog # | 5.6 | 2.6 | 1.6 |
| 11 April | 1 | 7.61 | 2.80 | 1.80 |
| 15 | 2 | 7.09 | 2.60 | 1.69 |
| 18 | 3 | 7.22 | 2.68 | 1.72 |
| 22 | 4 | 7.18 | 2.67 | 1.67 |
| 25 | 5 | 7.12 | 2.65 | 1.71 |
| 29 | 6 | 7.14 | 3.16 | 1.76 |
| 02 May | 7 | 7.20 | 2.76 | 1.80 |
| 06 | 8 | 7.55 | 3.05 | 1.78 |
| 09 | 9 | 7.24 | 2.49 | 1.90 |
| 13 | 10 | 7.25 | 2.59 | 1.35 |
| 16 | 11 | 6.79 | 2.52 | 1.36 |
| 20 | 12 | 6.78 | 2.50 | 1.28 |
| 23 | 13 | 7.15 | 2.45 | 1.78 |
| 27 | 14 | 7.16 | 2.79 | 1.74 |
| 30 | 15 | 7.26 | 2.69 | 1.82 |
| 03 June | 16 | 7.38 | 2.61 | 1.76 |
| 06 | 17 | 7.43 | 2.72 | 1.68 |
| 10 | 18 | 7.44 | 2.57 | 1.64 |
| 13 | 19 | 7.52 | 2.64 | 1.67 |
| 17 | 20 | 7.64 | 2.78 | 1.79 |
| 20 | 21 | 7.47 | 2.79 | 1.70 |
| 24 | 22 | 6.60 | 2.64 | 1.61 |
| Mean | | 7.24<br>(0.27)[a] | 2.69<br>(0.17)[a] | 1.68<br>(0.16)[a] |

[a] Values in parentheses are one standard deviation.

Table 6. pH of Fog at Nozzle Drip, Fog Collector, and Strawberry and Green Pepper Leaf Wash Samples in the Spring Fog Study[a]

| Treatment | Nozzle | Fog Collector | Strawberry | Pepper |
|---|---|---|---|---|
| 1.68 | 1.57 (0.09) | 1.60 (0.19) | 2.10 (0.77) | 1.41 (0.29) |
| 2.69 | 2.56 (0.09) | 2.58 (0.11) | 3.25 (0.66) | 3.48 (0.57) |
| 7.24 | 7.27 (0.75) | 6.95 (0.50)[b] | 10.08 (1.23) | 8.88 (3.33) |
| No fog | - | - | 10.74 (0.79) | 7.70 (3.26) |

[a] Mean with standard deviation in parentheses for four sampling dates. The pH's for strawberry and pepper were calculated based on the amount of water on leaf surfaces as measured with filter paper.

[b] Three sampling dates.

The pH of leaf wash samples depended largely upon the acidity of the water on the leaves, and the amount of leaf area wetted. Therefore, to determine the amount of $H^+$ on the leaf surface, the contribution of H+ due to the wash water was subtracted prior to calculating ion concentrations on an leaf area basis. Table 7 lists the concentrations of $H^+$ or $OH^-$ (negative $H^+$ values) as well as other major cations and anions on strawberry and green pepper leaves, averaged over the four complete sampling dates. There was no large difference in the amount of $H^+$ per unit surface area between the more acidic fog resistant species, (strawberry), and the more sensitive species, (green pepper).

Filter paper discs also were used to measure the rate of fog deposition in the fog plots. The capture of fog water by filter paper discs accounted for 29% of the total volume of fog dispensed during an event (data not shown). The remaining 71% of the fogwater was deposited to the chamber walls or dripped from the nozzles. The total depositions of $H^+$, $NO_3^-$ and $SO_4^{2-}$ to the soil surface on a single-event and whole-season basis were calculated incorporating a 29% capture efficiency (Table 8). Deposition rates to leaves based solely on these data are likely to underestimate actual rates of fog water capture by plants since evaporation, impaction and plant morphological parameters are not considered. The highest deposition rates were measured for discs placed 0 to 86 cm from the center of the chamber. Rates dropped slightly at a distance 86 to 122 cm from the center of the chamber, and was reduced by approximately 50% of the maximum deposition rate in the area closest to the chamber wall. Fog water evaporation rates from filter paper discs ranged from 10 to 30 mg $cm^{-2}$ $h^{-1}$.

Table 7. Ion Concentrations on Strawberry and Green Pepper Leaf Surfaces During the Spring Fog Study (μeq $m^{-2}$)[a]

| pH | Strawberry | Pepper | Strawberry | Pepper | Strawberry | Pepper |
|---|---|---|---|---|---|---|
| | $H^+$ | | $Na^+$ | | $K^+$ | |
| 1.68 | 1335 (1131) | 4029 (2371) | 369 (134) | 514 (269) | 284 (308) | 928 (1607) |
| 2.69 | 63 (61) | 133 (211) | 210 (151) | 328 (165) | 140 (213) | 700 (1294) |
| 7.24 | -18 (13) | -36 (36) | 263 (116) | 616 (154) | 209 (201) | 418 (629) |
| No fog | -31 (21) | -28 (37) | 210 (90) | 117 (80) | 389 (501) | 405 (522) |
| | $NH_4^+$ | | $Ca^{2+}$ | | $Mg^{2+}$ | |
| 1.68 | 625 (134) | 716 (408) | 462 (328) | 793 (569) | 172 (24) | 408 (91) |
| 2.69 | 400 (150) | 692 (253) | 223 (236) | 479 (351) | 79 (65) | 150 (85) |
| 7.24 | 619 (205) | 967 (514) | 319 (250) | 797 (260) | 113 (35) | 327 (76) |
| No fog | 48 (63) | 9 (16) | 622 (606) | 766 (527) | 184 (116) | 267 (30) |
| | $Cl^-$ | | $NO_3^-$ | | $SO_4^{2-}$ | |
| 1.68 | 4 (8) | 758 (1516) | 2975 (622) | 2837 (1546) | 1558 (357) | 2196 (905) |
| 2.69 | 0 | 691 (1381) | 567 (300) | 1042 (540) | 444 (454) | 890 (426) |
| 7.24 | 172 (307) | 308 (616) | 600 (68) | 1176 (574) | 450 (239) | 1514 (992) |
| No fog | 258 (302) | 359 (504) | 124 (144) | 36 (41) | 602 (522) | 731 (313) |

---

[a] Mean with standard deviation in parentheses for single leaves on each of four dates. Any calculated concentration of less than 0 was counted as 0.

[b] One sample.

Table 9 lists the amount of moisture collected on leaves based on data collected on one to six different days over the course of the spring fog study. The moisture data indicates that the species that exhibited the most injury following the first fog event, and which displayed more injury over the course of the study, also collected more moisture per unit leaf surface area during a fog event (i.e. tomato, green pepper, and alfalfa leaves tended to have more moisture than strawberry or celery leaves). During the first fog, it was apparent after a visual inspection of all the plots that the outside and air exclusion system plants had dew on their leaf surfaces, while the open-top chamber plants were relatively dry. This was quantified by leaf moisture collections, as both outside and no fog air exclusion system plants had more moisture overall than the no fog chamber plants (Table 9). Moreover in strawberry, the amount of moisture on outside or no fog air exclusion system plant leaves was approximately the same as for plants receiving fog in open-top chambers.

The air exclusion system plants that received fog had a similar amounts of moisture as plants fogged in open-top chambers. However, this amount of water may represent a maximum wetting capacity for leaf surfaces, due both to the formation of natural dew, as well as deposition of fog. Assuming that the concentration of $H+$ in dew is low, its presence may act to dilute fog water collected on the surface of leaves in air exclusion system plots to a greater extent than in open-top chambers. This dilution effect may likely be a major factor in the reduction of injury to plants from acidic fog in the air exclusion systems than in open-top field chambers.

At least part of the "moisture" collected from no fog chamber leaves may have actually been particulate matter released from leaf surfaces to the filter paper discs after the leaves were removed for surface area determinations.

### 2. Oxidant Measurements

Air Quality treatments (i.e., NF and CF air) were initiated on 31 March 1986, continued for 88 days, and terminated on 26 June 1986. Air monitoring (i.e., $O_3$) was performed from 15 April 15 to 22 June 1986. During this period (74 days), data was not collected on eight days due to mechanical problems. In the two week period prior to on-site monitoring, ambient $O_3$ and $SO_2$ concentrations were measured continuously at a site

Table 8. Calculated Total $H^+$, $NO_3^-$, and $SO_4^{2-}$ Deposited (Per Unit Soil Surface Area) on a Single-Event and Whole-Season Basis[a]

| | Deposition (μeq $m^{-2}$) | | |
|---|---|---|---|
| Fog pH | $H^+$ | $NO_3^-$ | $SO_4^{2-}$ |
| I. Single-Event | | | |
| 7.24 | 0.0023 | 190 | 100 |
| 2.69 | 8.1 | 270 | 140 |
| 1.68 | 830.0 | 870 | 500 |
| II. Whole-Season | | | |
| 7.24 | 0.5 | 41800 | 19900 |
| 2.69 | 17800.0 | 58600 | 29800 |
| 1.68 | 183000.0 | 191000 | 108200 |

[a] Deposition to plant surfaces based on a 29% water capture efficiency.

Table 9. Moisture Collected from Leaves in the Spring Fog Study[a]

| | "Moisture" on Leaves (g $m^{-2}$) | | | | |
|---|---|---|---|---|---|
| | | Chamber[c] | | Air Exclusion[d] | |
| Species | Outside[b] | No Fog | Fog[e] | No Fog | Fog[e] |
| Alfalfa | 70 (25) | 43 (19) | 143 ( 60) | --- | --- |
| Celery | 50 (0.1) | 35 ( 9) | 94 ( 38) | 38 ( 5) | 68 ( 14) |
| Pepper | 56 (16) | 33 ( 8) | 128 ( 81) | 56 (19) | 142 (130) |
| Tomato | 55 (12) | 50 ( 8) | 216 (104) | 70 (35) | 168 (106) |
| Strawberry | 97 (12) | 24 ( 5) | 83 ( 18) | 63 (27) | 107 ( 63) |

[a] For one leaf surface with standard deviation in parentheses.

[b] For n = 2, two samples on one date; except for n =4 for peppers, two samples on each of two dates.

[c] For n = 12, two samples on each of six dates.

[d] For n = 8, two samples on each of four dates.

[e] Fog from pH 7.24 chamber or air exclusion system.

0.125 km south of the field site. During this 14 day period, the 12-h average concentrations for $O_3$ and $SO_2$ were 0.034 and 0.001 $\mu l\ L^{-1}$ (ppm), respectively. Moreover, the National Ambient Air Quality Standard (NAAQS) for $O_3$ (1-h average $O_3$ concentration of 0.120 $\mu l\ L^{-1}$) was not exceeded (maximum 1-h average of 0.116 $\mu l\ L^{-1}$). Over the course of the 74 day study period, the seasonal 12-h average $SO_2$ concentration was 0.005 $\mu l\ L^{-1}$ with a maximum 1-h average of 0.016 $\mu l\ L^{-1}$.

The whole-season 12-h average $O_3$ concentrations for the open-top chamber plots, air exclusion plots, and ambient air monitoring sample points are listed in Table 10. Relative to ambient levels, seasonal 12-h (0800 to 2000) average $O_3$ concentrations were reduced 14 to 17%, and 58 to 75% in NF and CF plots, respectively. With respect to differences in air quality between the two gaseous pollutant exposure systems, NF air exposures differed only insofar as the number of hours above the NAAQS. However, air exclusion CF plots were found to have a 12-h average $O_3$ concentration, 1.7 times higher than in open-top chamber CF plots.

There were days with a number of high peak ozone values during the exposure period. There were 68 hours above the Federal Standard of 0.12 $\mu l\ l^{-1}$, and peak one-hour values above 0.2 $\mu l\ l^{-1}$. Peak values were slightly lower in chambers and air exclusion systems than in outside plots. Peak values were especially reduced in the CF chambers and air exclusion systems.

### 3. Environmental Measurements

Environmental conditions during the spring of 1986 are listed in Table 11. In general, the conditions were warm, sunny, and dry during the day typical conditions during this time of year at Riverside. Environmental conditions would have been slightly different in chambers. Based on previous studies, air temperatures would be expected to be 1 to 2°C higher, and light intensities slightly lower in the open-top chambers compared to outside plots (Thompson and Olszyk, 1985).

### 4. Fog Effects

#### a. Growth, Yield, and Injury

Applications of pH 1.68 fog induced the development of gray-green lesions on leaves within 6 h after the first fog treatment. After 24 h, necrotic spots (light-brown) were evident at intervenal regions in green pepper, tomato, and alfalfa, or along the margins of strawberry and

Table 10. Ozone Concentrations ($\mu l^{-1}$) Monitored During the Period from 15 April to 22 June 1986.[a]

| Sample Point Location | Seasonal 12-h Avg.[a] | Maximum 1-h | 2nd Max. 1-h | Avg. Daily 1-h Max. | # hr above N.A.A.Q.S. |
|---|---|---|---|---|---|
| I. Open-Top Chamber Plots | | | | | |
| CF | 0.019 (0.011) | 0.090 | 0.085 | 0.032 (0.012) | 0 |
| NF | 0.066 (0.030) | 0.219 | 0.210 | 0.102 (0.032) | 53 |
| II. Air Exclusion Plots | | | | | |
| CF | 0.032 (0.016) | 0.100 | 0.095 | 0.045 (0.023) | 0 |
| NF | 0.064 (0.028) | 0.195 | 0.185 | 0.099 (0.030) | 42 |
| III. Outside | | | | | |
| Ambient | 0.077 (0.034) | 0.232 | 0.223 | 0.114 (0.033) | 68 |

[a] Daily exposure period from 0800 to 2000 h PST. Values in parentheses are one S.D. NAAQS = National Ambient Air Quality Standard; 1-h Average $O_3$ concentration of 0.120 $\mu l\ L^{-1}$. CF = charcoal filtered and NF = nonfiltered.

celery leaves. Petals from the flowers of all three fruit crops exhibited necrosis after pH 1.68 fog treatment, but fog injury to fruits was more common in pepper and tomato than in strawberry. In comparison, pH 2.69 or 7.24 fog treatments did not cause necrosis in any of the crops examined.

Results of an injury rating of plants conducted midway through the spring fog study are shown in Table 12. Using this coarse rating scale to assess injury, the only clear response was an increase in general necrosis and chlorosis with pH 1.68 fog compared to the other treatments. Tomato appeared to have the highest injury rating in either charcoal-filtered or nonfiltered air, however, the standard deviations for each species are so large that no species difference could definitely be determined. These injury results were not analyzed statistically as the large standard deviations and scale of the rating system would have made it difficult to interpret any effects except at pH 1.68.

Table 11. Environmental Conditions During the Spring Fog Study[a]

| Dates | Air Temperature (°C) | Light Intensity ($\mu$mol $m^{-2}$ $s^{-1}$) |
|---|---|---|
| 3/29-4/3/86 | 19.4 | 793 |
| 4/2-4/8 | 23.3 | 1141 |
| 4/19-4/25 | 23.5 | 1071 |
| 4/26-5/2 | 24.6 | 1071 |
| 5/3-5/9 | 20.7 | 1144 |
| 5/10-5/16 | 21.4 | 975 |
| 5/17-5/23 | 26.6 | 1000 |
| 5/24-5/30 | 27.6 | 1015 |
| 5/31-6/6 | 23.6 | 868 |
| 6/7-6/13 | 26.5 | 975 |
| 6/14-6/20 | 28.0 | 1013 |
| 6/21-6/27 | 28.8 | 979 |
| 6/28-7/4 | 30.6 | 955 |

[a] Average between 0800 and 2000 h PST for each week, between Saturday and Friday. Measured at ARB citrus site. No data for 4/4-4/11 due to instrument malfunctions.

A large amount of growth and yield data were collected in this study. The results of statistical analysis of these data are shown separately for open-top chambers and air exclusion systems in Tables 13-15, and 16-18, respectively. These data describe the general fog chemistry or air quality effects. Individual treatment data for strawberry are shown in Table 19, tomato in Table 20, green pepper in Table 21, and celery and alfalfa in Table 22.

In strawberry, tomato and green pepper, fruit fresh weight tended to be reduced by pH 1.68 fog with the results statistically significant for open-top chambers (Table 13), but not air exclusion systems (Table 16). In general, fog and air quality treatment effects were not statistically significant for any species or parameter for air exclusion plants, even

Table 12. Effects of Fog Chemistry and Ambient Air Quality on Leaf Injury (0-4 scale)[a] in the Spring Fog Study[a]

| AQ | Fog | Strawberry | Tomato | Pepper | Alfalfa | Celery |
|---|---|---|---|---|---|---|
| I. Chambers | | | | | | |
| CF | NO | 0.1 (0.3) | 0.3 (0.5) | 0.7 (0.5) | 0.7 (0.6) | 0.7 (0.5) |
| CF | 7.24 | 0.1 (0.3) | 0.1 (0.3) | 0.2 (0.6) | 0.7 (0.5) | 0.1 (0.3) |
| CF | 2.69 | 0.2 (0.4) | 0.3 (0.5) | 0.5 (0.9) | 0.7 (0.5) | 0.9 (0.5) |
| CF | 1.68 | 1.4 (0.6) | 1.7 (1.0) | 1.0 (0) | 1.1 (0.3) | 1.2 (0.8) |
| NF | NO | 0.1 (0.4) | 0.7 (0.9) | 0.7 (0.5) | 0.9 (0.4) | 0.6 (0.5) |
| NF | 7.24 | 0 (0) | 0.3 (0.5) | 0.7 (0.5) | 0.9 (0.4) | 0.9 (0.3) |
| NF | 2.69 | 0.5 (0.5) | 0.1 (0.3) | 0.6 (0.5) | 0.8 (0.4) | 0.5 (0.5) |
| NF | 1.68 | 1.4 (0.5) | 1.9 (0.7) | 1.1 (0.3) | 1.3 (0.5) | 1.0 (0) |
| II. Air Exclusion System | | | | | | |
| CF | NO | 0.2 (0.4) | 0.5 (0.5) | 0.3 (0.5) | --- | 0.6 (0.5) |
| CF | 7.24 | 0.2 (0.4) | 0 (0) | 0.1 (0.3) | --- | 0.2 (0.4) |
| CF | 1.68. | 1.1 (0.3) | 1.0 (0) | 0.8 (0.4) | --- | 1.0 (0) |
| NF | NO | 0.1 (0.3) | 0 (0) | 0 (0) | --- | 0 (0) |
| NF | 7.24 | 0.3 (0.5) | 0 (0) | 0.4 (0.5) | --- | 0 (0) |
| NF | 1.68 | 1.5 (0.5) | 1.0 (0.7) | 0.8 (0.4) | --- | 1.1 (0.3) |
| III. Outside | | | | | | |
| NF | NO | 0.1 (0.4) | 0 (0) | 0.1 (0.3) | 0.5 (0.5) | 0.8 (0.4) |

---

[a] Values are means with standard deviation in parentheses for 15 or 10 plants, five from each of three or two replicate plots for open-top chambers and outside plots or air exclusion systems, respectively. Abbreviations: AQ = Air Quality, CF = Charcoal-filtered air, NF = Non filtered air, Fog = Fog pH, NO = No fog application.

though the percent reductions in responses were similar with pH 1.68 fog or nonfiltered air in both air exclusion systems and chambers. This lack of statistical significance was likely due to only 2 blocks with air exclusion systems vs. 3 fog chambers, and the greater block effect on plant response in the air exclusion systems. In open-top chambers fruit fresh weight was not significantly different among the no fog, (Table 13), pH 7.24 and pH 2.69 fog treatments in strawberry and tomato, but pepper plants that were not fogged exhibited fruit weights comparable to pH 1.68 fog-treated plants. In all three crops, significant reductions in fruit number due to pH 1.68 fog were also observed.

In strawberry and alfalfa, whole-plant dry weight was reduced significantly by pH 1.68 fog relative to values measured in the other fog treatment groups in open-top chambers (Table 14), but not in air exclusion systems. (Table 17). Tomato and pepper plant weights were also found to be lowered by pH 1.68 fog, however plant weights were also reduced in plants that were not fogged (Table 14). In contrast, celery plant weights were not lowered by pH 1.68 fog, but were only reduced by the no fog treatment (Table 14).

In strawberry and pepper, aboveground assimilate partitioning responses were also examined. For both crops, in open-top chambers pH 1.68 fog caused significant reductions in both stem and leaf dry weights (Tables 15, 19, 21). In strawberry, the percentage of the whole-plant dry weight allocated to leaves was reduced 8 to 12% by pH 1.68 fog relative to responses observed in the other fog treatment groups (Table 15). In pepper, the percentage of the whole-plant dry weight partitioned to leaves was consistently in the range of 39 to 41%. Fog at pH 1.68 significantly reduced calculated leaf area in strawberry, whereas in pepper, leaf area was significantly decreased only in plants that were not fogged. In strawberry, fruit fresh weight and numbers were significantly reduced by both pH 1.68 fog and ambient air exposures. In tomato, pH 1.68 fog reduced fruit fresh weight and number, while exposure to ambient air reduced only the number of fruit.. In pepper, pH 1.68 fog reduced fruit weight and number, but ambient air treatment only reduced fruit weight.

In air exclusion systems, the only statistically significant differences on crop stem and leaf growth parameters were for strawberry leaf dry weight (LDW) (Table 18). Acidic fog at pH 1.68 reduced LDW compared to pH 7.24 or no fog treatments, and LDW was actually higher for the nonfiltered than charcoal-filtered treatment.

### b. Physiology

The results of the statistical analysis for the open-top field chamber and air exclusion system data are shown in Tables 23-24 and 25-26, respectively. These data describe the general fog chemistry or air quality effects. Individual treatment data for green pepper are shown in Table 27, and strawberry in Table 28. Negative trends in plant response to acidic fog treatment are indicated from the data.

In green pepper photosynthesis, (Pn) and stomatal conductance to water vapor (Cs) responses were significantly inhibited by pH 1.68 fog as compared to responses by 7.24 plants in open-top chambers (Table 23) but not air

Table 13. Statistical Analysis of the Effects of Fog Chemistry and Ambient Air Quality on Crop Fruit Fresh Weight and Number Grown in Open-Top Field Chambers (g plant$^{-1}$)$^{a}$

| | Strawberry | | Tomato | | Pepper | |
|---|---|---|---|---|---|---|
| | F.W. | # | F.W. | # | F.W. | # |
| I. Fog Chemistry | | | | | | |
| No Fog | 865 y | 66 y | 1418 y | 38 yz | 231 y | 4.6 z |
| pH 7.24 | 954 y | 70 y | 1549 y | 42 y | 308 x | 6.1 y |
| pH 2.69 | 830 y | 68 y | 1489 y | 45 y | 324 x | 6.2 y |
| pH 1.68 | 669 z | 57 z | 974 z | 32 z | 130 z | 3.8 z |
| L.S.D.$^{a}$ | 123 | 9.2 | 260 | 7.9 | 45 | 1.2 |
| II. Air Quality | | | | | | |
| CF | 754 z | 60 z | 1416 | 42 y | 265 y | 5.2 |
| NF | 904 y | 71 y | 1299 | 36 z | 232 z | 5.1 |
| L.S.D. | 115 | 6.5 | -- | 5.6 | 32 | -- |
| III. ANOVA Effect | | | | | | |
| Block | ** | ** | * | NS | NS | NS |
| Fog (F) | * | *** | ** | *** | *** | * |
| Air (A) | ** | NS | NS | * | * | NS |
| F x A | NS | NS | NS | NS | NS | NS |
| C.V. (%) | 29.0 | 27.5 | 37.4 | 39.5 | 35.3 | 46.9 |

---

[a] L.S.D. - least significant difference; samples sizes of n = 30 and n = 60 were analyzed in the assessment of fog chemistry or air quality effects, respectively. Abbreviations: F.W. = Fresh weight; # = Number of fruits.

Table 13. Statistical Analysis of the Effects of Fog Chemistry and Ambient Air Quality on Crop Fruit Fresh Weight and Number Grown in Open-Top Field Chambers (g plant$^{-1}$)$^{a}$

| | Strawberry | | Tomato | | Pepper | |
|---|---|---|---|---|---|---|
| | F.W. | # | F.W. | # | F.W. | # |
| I. Fog Chemistry | | | | | | |
| No Fog | 865 y | 66 y | 1418 y | 38 yz | 231 y | 4.6 z |
| pH 7.24 | 954 y | 70 y | 1549 y | 42 y | 308 x | 6.1 y |
| pH 2.69 | 830 y | 68 y | 1489 y | 45 y | 324 x | 6.2 y |
| pH 1.68 | 669 z | 57 z | 974 z | 32 z | 130 z | 3.8 z |
| L.S.D.[a] | 123 | 9.2 | 260 | 7.9 | 45 | 1.2 |
| II. Air Quality | | | | | | |
| CF | 754 z | 60 z | 1416 | 42 y | 265 y | 5.2 |
| NF | 904 y | 71 y | 1299 | 36 z | 232 z | 5.1 |
| L.S.D. | 115 | 6.5 | -- | 5.6 | 32 | -- |
| III. ANOVA Effect | | | | | | |
| Block | ** | ** | * | NS | NS | NS |
| Fog (F) | * | *** | ** | *** | *** | * |
| Air (A) | ** | NS | NS | * | * | NS |
| F x A | NS | NS | NS | NS | NS | NS |
| C.V. (%) | 29.0 | 27.5 | 37.4 | 39.5 | 35.3 | 46.9 |

[a] L.S.D. - least significant difference; samples sizes of n = 30 and n = 60 were analyzed in the assessment of fog chemistry or air quality effects, respectively. Abbreviations: F.W. = Fresh weight; # = Number of fruits.

Table 14. Statistical Analysis of the Effects of Fog Chemistry and Ambient Air Quality on Crop Plant Dry Weight Grown in Open-Top Field Chambers (g plant$^{-1}$)[a]

| | Strawberry | Tomato | Pepper | Alfalfa | Celery |
|---|---|---|---|---|---|
| I. Fog Chemistry | | | | | |
| No Fog | 78.0y | 64.4yz | 13.8z | 153.2y | 135.5z |
| pH 7.24 | 79.3y | 65.3yz | 17.5y | 154.9y | 154.0y |
| pH 2.69 | 73.2y | 74.9y | 18.5y | 160.3y | 148.1y |
| pH 1.68 | 57.5z | 55.5z | 13.3z | 138.4z | 158.0y |
| L.S.D.[a] | 3.4 | 12.1 | 2.3 | 13.9 | 12.5 |
| II. Air Quality | | | | | |
| CF | 70.0 | 75.6y | 17.6y | 170.3y | 156.7y |
| NF | 72.7 | 54.4z | 14.0z | 133.1z | 141.2z |
| L.S.D. | 2.7 | 8.5 | 1.6 | 9.8 | 8.8 |
| III. ANOVA Effect | | | | | |
| Block | NS | * | NS | * | NS |
| Fog (F) | *** | * | *** | * | ** |
| Air (A) | NS | *** | * | *** | *** |
| F x A | NS | NS | NS | NS | NS |
| C.V. (%) | 26.4 | 36.3 | 28.8 | 17.9 | 16.4 |

---

[a] L.S.D. = least significant difference; sample sizes of n = 30 and n = 60 were analyzed in the assessment of fog chemistry or air quality effects, respectively.

Table 16. Statistical Analysis of the Effects of Fog Chemistry and Ambient Air Quality on Crop Fruit Fresh Weight and Number Grown in Air Exclusion Systems (g plant)$^{-1}$ [a]

| | Strawberry | | Tomato | | Pepper | |
|---|---|---|---|---|---|---|
| | F.W. | # | F.W. | # | F.W. | # |
| I. Fog Chemistry | | | | | | |
| No Fog | 823 | 65 | 1254 | 41 | 274 | 7 |
| pH 7.24 | 752 | 64 | 1291 | 45 | 358 | 10 |
| pH 1.68 | 664 | 58 | 1015 | 38 | 175 | 6 |
| L.S.D. | -- | -- | -- | -- | -- | -- |
| II. Air Quality | | | | | | |
| CF | 773 | 65 | 1240 | 39 | 304 | 8 |
| NF | 719 | 60 | 1133 | 43 | 234 | 7 |
| L.S.D. | -- | -- | -- | -- | -- | -- |
| III. ANOVA Effect | | | | | | |
| Block | * | * | NS | * | NS | NS |
| Fog (F) | NS | NS | NS | NS | NS | NS |
| Air (A) | NS | NS | NS | NS | NS | NS |
| F x A | NS | NS | NS | NS | NS | NS |
| C.V. (%) | 31.1 | 37.8 | 25.8 | 31.9 | 38.7 | 44.3 |

[a] L.S.D. = least significant difference; sample sizes of n = 20 and n = 30 was analyzed in the assessment of fog chemistry or air quality effects, respectively. Abbreviations: F.W. = Fresh weight; # = Number of fruits.

Table 17. Statistical Analysis of the Effects of Fog Chemistry and Ambient Air Quality on Crop Plant Dry Weight Grown in Air Exclusion Systems (g $plant^{-1}$)[a]

| | Strawberry | Tomato | Pepper | Celery |
|---|---|---|---|---|
| <u>I. Fog Chemistry</u> | | | | |
| No Fog | 76.1 | 57.3 | 20.1 | 154.0 |
| pH 7.24 | 78.1 | 64.9 | 21.2 | 163.9 |
| pH 1.68 | 64.4 | 53.1 | 18.7 | 157.4 |
| L.S.D. | -- | -- | -- | -- |
| <u>II. Air Quality</u> | | | | |
| CF | 73.0 | 58.5 | 20.9 | 160.9 |
| NF | 72.8 | 58.4 | 19.0 | 155.9 |
| L.S.D. | -- | -- | -- | -- |
| <u>III. ANOVA Effect</u> | | | | |
| Block | * | NS | * | NS |
| Fog (F) | NS | NS | NS | NS |
| Air (A) | NS | NS | NS | NS |
| F x A | NS | NS | NS | NS |
| C.V. (%) | 30.4 | 31.9 | 21.1 | 13.5 |

---

[a] L.S.D. = least significant difference; sample sizes of n = 20 and n = 30 were analyzed in the assessment of fog chemistry or air quality affects, respectively.

Table 18. Statistical Analysis of the Effects of Fog Chemistry and Ambient Air Quality on Crop Stem and Leaf Growth Parameters in Air Exclusion Systems (g plant)$^{-1a}$

| | Strawberry | | | Pepper | | |
|---|---|---|---|---|---|---|
| | SDW | LDW | LA | SDW | LDW | LA |
| **I. Fog Chemistry** | | | | | | |
| No Fog | 35.9 | 40.2y | 3959 | 11.5 | 8.6 | 1090 |
| pH 7.24 | 38.4 | 39.7y | 4489 | 11.9 | 9.3 | 1133 |
| pH 1.68 | 36.0 | 28.4z | 2882 | 10.1 | 8.5 | 1433 |
| L.S.D. | -- | 1.6 | -- | -- | -- | -- |
| **II. Air Quality** | | | | | | |
| CF | 38.2 | 34.8z | 3622 | 11.5 | 9.4 | 1268 |
| NF | 35.3 | 37.5y | 3930 | 10.9 | 8.2 | 1169 |
| L.S.D. | -- | 1.3 | -- | -- | -- | -- |
| **III. ANOVA Effect** | | | | | | |
| Block | * | NS | NS | * | NS | * |
| Fog (F) | NS | * | NS | NS | NS | NS |
| Air (A) | NS | * | NS | NS | NS | NS |
| F x A | NS | NS | NS | NS | NS | NS |
| C.V. (%) | 30.6 | 34.3 | 37.9 | 24.2 | 25.0 | 26.0 |

[a] L.S.D. = least significant differenc; sample sizes of n = 20 and n = 30 were analyzed in the assessment of fog chemistry or air quality effects, respectively. Abbreviations: SDW = stem dry weight (g); LDW = leaf dry weight (g) and LA = leaf area (cm$^2$) on an individual plant basis.

Table 19. Effects of Fog Chemistry and Ambient Air Quality on Strawberry Growth and Fruit Yield-Individual Treatment Means[a]

| AQ | Fog | Fruit Fr. Wt. | Leaf Area | Plant Dry Wt. | Leaf Dry Wt. |
|---|---|---|---|---|---|
| I. Chambers | | | | | |
| CF | NO | 751 (102) | 4089 ( 397) | 81 ( 5) | 40 ( 4) |
| CF | 7.24 | 827 (292) | 4174 ( 771) | 75 ( 5) | 38 ( 6) |
| CF | 2.69 | 800 (114) | 4132 (1740) | 71 (13) | 35 ( 4) |
| CF | 1.68 | 614 (176) | 2047 ( 430) | 52 ( 5) | 22 ( 3) |
| NF | NO | 979 (158) | 3962 ( 28) | 75 ( 4) | 36 ( 2) |
| NF | 7.24 | 1077 (119) | 5130 ( 782) | 83 ( 9) | 45 ( 5) |
| NF | 2.69 | 812 (136) | 4345 ( 777) | 76 ( 5) | 38 ( 4) |
| NF | 1.68 | 745 ( 58) | 2604 ( 738) | 58 (14) | 24 ( 7) |
| II. Air Exclusion System | | | | | |
| CF | NO | 821 ( 12) | 4003 ( 300) | 78 (15) | 39 ( 4) |
| CF | 7.24 | 818 (164) | 4424 ( 130) | 80 ( 9) | 40 ( 1) |
| CF | 1.68 | 669 ( 33) | 2442 ( 824) | 62 ( 2) | 26 ( 6) |
| NF | NO | 816 (213) | 4569 ( 628) | 75 (13) | 42 ( 5) |
| NF | 7.24 | 686 (249) | 4552 (1026) | 76 (20) | 40 (10) |
| NF | 1.68 | 648 ( 32) | 3325 ( 463) | 67 ( 2) | 31 ( 3) |
| III. Outside | | | | | |
| NF | NO | 760 (133) | 3755 ( 761) | 66 (12) | 34 ( 5) |

[a] Weight measurements given in g and leaf area in $cm^2$ per plant. Values in parentheses are one standard deviation. Sample sizes for the chamber and outside plots (n = 15), differs from air exclusion system plots (n = 10). Abbreviations: CF = Charcoal-filtered air, NF = Nonfiltered air, Fog = Fog pH, NO = No fog application.

Table 19. Effects of Fog Chemistry and Ambient Air Quality on Strawberry Growth and Fruit Yield-Individual Treatment Means[a]

| AQ | Fog | Fruit Fr. Wt. | Leaf Area | Plant Dry Wt. | Leaf Dry Wt. |
|---|---|---|---|---|---|
| I. Chambers | | | | | |
| CF | NO | 751 (102) | 4089 ( 397) | 81 ( 5) | 40 ( 4) |
| CF | 7.24 | 827 (292) | 4174 ( 771) | 75 ( 5) | 38 ( 6) |
| CF | 2.69 | 800 (114) | 4132 (1740) | 71 (13) | 35 ( 4) |
| CF | 1.68 | 614 (176) | 2047 ( 430) | 52 ( 5) | 22 ( 3) |
| NF | NO | 979 (158) | 3962 ( 28) | 75 ( 4) | 36 ( 2) |
| NF | 7.24 | 1077 (119) | 5130 ( 782) | 83 ( 9) | 45 ( 5) |
| NF | 2.69 | 812 (136) | 4345 ( 777) | 76 ( 5) | 38 ( 4) |
| NF | 1.68 | 745 ( 58) | 2604 ( 738) | 58 (14) | 24 ( 7) |
| II. Air Exclusion System | | | | | |
| CF | NO | 821 ( 12) | 4003 ( 300) | 78 (15) | 39 ( 4) |
| CF | 7.24 | 818 (164) | 4424 ( 130) | 80 ( 9) | 40 ( 1) |
| CF | 1.68 | 669 ( 33) | 2442 ( 824) | 62 ( 2) | 26 ( 6) |
| NF | NO | 816 (213) | 4569 ( 628) | 75 (13) | 42 ( 5) |
| NF | 7.24 | 686 (249) | 4552 (1026) | 76 (20) | 40 (10) |
| NF | 1.68 | 648 ( 32) | 3325 ( 463) | 67 ( 2) | 31 ( 3) |
| III. Outside | | | | | |
| NF | NO | 760 (133) | 3755 ( 761) | 66 (12) | 34 ( 5) |

[a] Weight measurements given in g and leaf area in $cm^2$ per plant. Values in parentheses are one standard deviation. Sample sizes for the chamber and outside plots (n = 15), differs from air exclusion system plots (n = 10). Abbreviations: CF = Charcoal-filtered air, NF = Nonfiltered air, Fog = Fog pH, NO = No fog application.

Table 21. Effects of Fog Chemistry and Ambient Air Quality on Green Pepper Growth and Fruit Yield - Individual Treatment Means[a]

| AQ | Fog | Fruit Fr. Wt. | Leaf Area | Plant Dry Wt. | Leaf Dry Wt. |
|---|---|---|---|---|---|
| I. Chambers | | | | | |
| CF | NO | 238 (62) | 681 (100) | 14.3 (2.2) | 5.8 (0.8) |
| CF | 7.24 | 333 (56) | 1168 (151) | 21.0 (1.5) | 8.8 (1.1) |
| CF | 2.69 | 344 (19) | 912 (190) | 19.9 (2.4) | 8.6 (2.2) |
| CF | 1.68 | 142 (75) | 1138 (309) | 15.1 (1.8) | 6.3 (1.8) |
| NF | NO | 223 (31) | 715 ( 15) | 13.4 (1.1) | 5.0 (0.1) |
| NF | 7.24 | 283 (39) | 653 (162) | 14.1 (3.2) | 5.2 (1.4) |
| NF | 2.69 | 304 (82) | 900 (250) | 17.2 (3.2) | 6.4 (1.6) |
| NF | 1.68 | 117 ( 9) | 778 ( 55) | 11.4 (0.9) | 4.6 (0.1) |
| II. Air Exclusion System | | | | | |
| CF | NO | 336 (29) | 1010 (148) | 21.2 (3.3) | 9.2 (1.5) |
| CF | 7.24 | 390 (96) | 1260 ( 35) | 21.7 (1.4) | 9.8 (0.1) |
| CF | 1.68 | 186 (45) | 1559 ( 47) | 19.8 (0.4) | 9.4 (0.4) |
| NF | NO | 212 ( 6) | 1169 (276) | 19.0 (4.4) | 8.1 (1.9) |
| NF | 7.24 | 327 (37) | 1033 (192) | 21.9 (3.2) | 8.8 (1.3) |
| NF | 1.68 | 164 (45) | 1305 ( 31) | 17.5 (0.3) | 7.7 (0.5) |
| III. Outside | | | | | |
| NF | NO | 194 (69) | 966 (159) | 15.2 (1.6) | 6.9 (1.2) |

[a] Units: Fruit fresh weight, plant dry weight, leaf dry weight in (g); leaf area in ($cm^2$). Values in parentheses are one standard deviation. Sample sizes for the chamber and outside plots (n = 15), differs from air exclusion system plots (n = 10). Abbreviations: AQ = Air quality, CF = Charcoal-filtered air, NF = Nonfiltered air, Fog = Fog pH, NO = No fog application.

Table 21. Effects of Fog Chemistry and Ambient Air Quality on Green Pepper Growth and Fruit Yield - Individual Treatment Means[a]

| AQ | Fog | Fruit Fr. Wt. | Leaf Area | Plant Dry Wt. | Leaf Dry Wt. |
|---|---|---|---|---|---|
| I. Chambers | | | | | |
| CF | NO | 238 (62) | 681 (100) | 14.3 (2.2) | 5.8 (0.8) |
| CF | 7.24 | 333 (56) | 1168 (151) | 21.0 (1.5) | 8.8 (1.1) |
| CF | 2.69 | 344 (19) | 912 (190) | 19.9 (2.4) | 8.6 (2.2) |
| CF | 1.68 | 142 (75) | 1138 (309) | 15.1 (1.8) | 6.3 (1.8) |
| NF | NO | 223 (31) | 715 ( 15) | 13.4 (1.1) | 5.0 (0.1) |
| NF | 7.24 | 283 (39) | 653 (162) | 14.1 (3.2) | 5.2 (1.4) |
| NF | 2.69 | 304 (82) | 900 (250) | 17.2 (3.2) | 6.4 (1.6) |
| NF | 1.68 | 117 ( 9) | 778 ( 55) | 11.4 (0.9) | 4.6 (0.1) |
| II. Air Exclusion System | | | | | |
| CF | NO | 336 (29) | 1010 (148) | 21.2 (3.3) | 9.2 (1.5) |
| CF | 7.24 | 390 (96) | 1260 ( 35) | 21.7 (1.4) | 9.8 (0.1) |
| CF | 1.68 | 186 (45) | 1559 ( 47) | 19.8 (0.4) | 9.4 (0.4) |
| NF | NO | 212 ( 6) | 1169 (276) | 19.0 (4.4) | 8.1 (1.9) |
| NF | 7.24 | 327 (37) | 1033 (192) | 21.9 (3.2) | 8.8 (1.3) |
| NF | 1.68 | 164 (45) | 1305 ( 31) | 17.5 (0.3) | 7.7 (0.5) |
| III. Outside | | | | | |
| NF | NO | 194 (69) | 966 (159) | 15.2 (1.6) | 6.9 (1.2) |

[a] Units: Fruit fresh weight, plant dry weight, leaf dry weight in (g); leaf area in ($cm^2$). Values in parentheses are one standard deviation. Sample sizes for the chamber and outside plots (n = 15), differs from air exclusion system plots (n = 10). Abbreviations: AQ = Air quality, CF = Charcoal-filtered air, NF = Nonfiltered air, Fog = Fog pH, NO = No fog application.

exclusion systems (Table 25). The highest values of Pn and Cs were observed in plants treated with pH 7.24 fog, and the lowest values for plants treated with pH 1.68 fog under either air quality regime (Table 27). Higher transpiration ratios were consistently displayed by plants subjected to pH 1.68 fog than for plants receiving any other fog treatment (i.e. pH 7.24, 2.68 or no fog).

Strawberry physiological process rates were also higher in pH 7.24 and 2.69 fog-exposed plants than for strawberry grown under no fog and pH 1.68 fog regimes in open-top chambers (Table 24), but not in air exclusion systems (Table 26).

The alteration of plant physiological responses by acid fog appears to involve specific effects on stomatal function in these two crops. Since Ts was not significantly affected by acidic fog (Tables 23, 24, 25 26) the regulatory function of stomata insofar as controlling rates of leaf water vapor emission, may be impaired in plants that exhibit leaf injury due to fog exposure.

Buffering capacity was not reduced by acidic fog at either of two measuring periods (Tables 29 and 30). There was no evidence of any trend toward decreased buffering capacity in the pH 1.68 treated plants. However, there was evidence to suggest that strawberry had an inherently higher buffering capacity than pepper which may have contributed to its greater resistance to acidic fog injury. Nevertheless, due to the large standard deviations between measurements, it was difficult to determine any statistically significant results.

Leaf pigment concentrations were found to be sensitive indicators of physiological stress from acidic fog, but the effects differed among species and between open-top chambers and air exclusion systems (Tables 31-36). Chlorophyll content was altered by pH 1.68 fog in three crops, with tomato, and alfalfa exhibiting decreases (15 to 30%) and pepper displaying an increase in concentration in open-top chambers (Table 31). However, fog at pH 1.68 had no significant effect on chlorophyll levels in stawberry or celery. The application of fog may stimulate an increase in leaf chlorophyll levels since pigment levels were usually higher in plants exposed to pH 7.24 fog than no fog plants. Fog at pH 2.69 significantly altered alfalfa chlorophyll responses (reduced 17%), but had no effect on the other species examined.

Leaf carotenoid responses to acidic fog were similar in magnitude of change, and species-specificity to leaf chlorophyll responses in open-top chamber-grown plants (Table 32). In plants grown in air exclusion systems, alterations in chlorophyll or carotenoid responses were far less sizeable (i.e. increases or decreased of 5% or less; Tables 33, 34). Overall, the effect of acidic fog application on crop leaf pigments was not pigment-specific, but rather appeared to cause the break down of all pigments examined.

5. Air Quality Effects

a. Growth, Yield, and Injury

Air quality effects in this study were attributed to ozone, the main component of photochemical smog. Visible injury characteristic of ozone exposures (i.e. chlorosis) was observed on alfalfa, however, the presence of ozone injury did not produce any sizeable difference in the amount of leaf injury due to fog (Table 12).

Ozone had detrimental effects on the yield and growth responses of most of the species examined. Green pepper fruit fresh weight and tomato fruit number were reduced in NF air, relative to values in CF open-top chambers (Table 13). Strawberry fresh fruit weight and number actually were higher for NF compared to CF plants. No explanation for this was found in this study. However, it is possible that the combined ozone and extra temeprature stress in the chambers may have enhanced fruiting. In any event the chambers played some role as there was no difference in yield for NF vs. CF air exclusion systems (Table 16). Total plant aboveground dry weight was reduced in NF vs. CF open-top chambers in tomato, green pepper, alfalfa, and celery (Table 14). The ozone-sensitivity of green pepper growth responses was made even clearer upon examination of stem and leaf dry weight responses (Table 15). In contrast, strawberry was the most resistant crop to $O_3$, displaying no significant effects of NF air on stem or leaf dry weight, and a significant increase in leaf area. Again, differences between charcoal-filtered and nonfiltered treatments were generally not statistically significant in air exclusion systems (Tables 16-18).

Table 23. Statistical Analysis of the Effects of Fog Chemistry and Ambient Air Quality on Pepper Physiological Responses in Open-Top Field Chambers[a]

|  | Ts | Cs | Pn | Ts/Pn |
|---|---|---|---|---|
| I. Fog Chemistry |  |  |  |  |
| No Fog | 130.4 | 0.95 yz | 0.55 yz | 268 yz |
| pH 7.24 | 143.9 | 1.19 x | 0.65 x | 236 z |
| pH 2.69 | 139.4 | 1.09 xy | 0.60 xy | 252 yz |
| pH 1.68 | 124.1 | 0.79 z | 0.48 z | 292 y |
| L.S.D. | -- | 0.20 | 0.07 | 41 |
| II. Air Quality |  |  |  |  |
| CF | 147.6 y | 1.22 y | 0.63 y | 254 |
| NF | 121.3 z | 0.79 z | 0.51 z | 270 |
| L.S.D. | 15.6 | 0.14 | 0.05 | -- |
| III. ANOVA Effect |  |  |  |  |
| Fog (F) | NS | *** | *** | * |
| Air (A) | *** | *** | *** | NS |
| F x A | NS | NS | NS | NS |
| C.V. (%) | 38.0 | 60.3 | 39.6 | 47.5 |

---

[a] L.S.D. = least significant difference; sample sizes of n = 72 and n = 144 were analyzed in the assessment of fog chemistry or air quality effects, respectively. Abbreviations: Ts = Transpiration (mg $H_2O$ $m^{-2}s^{-1}$); Cs = Stomatal conductance to water vapor (cm $s^{-}$ ); Pn = Net Photosynthesis (mg $CO_2$ $m^{-2}$ $s^{-1}$); Ts/Pn = Transpiration Ratio (mg $H_2O$/mg $CO_2$).

Table 23. Statistical Analysis of the Effects of Fog Chemistry and Ambient Air Quality on Pepper Physiological Responses in Open-Top Field Chambers[a]

| | Ts | Cs | Pn | Ts/Pn |
|---|---|---|---|---|
| I. Fog Chemistry | | | | |
| No Fog | 130.4 | 0.95 yz | 0.55 yz | 268 yz |
| pH 7.24 | 143.9 | 1.19 x | 0.65 x | 236 z |
| pH 2.69 | 139.4 | 1.09 xy | 0.60 xy | 252 yz |
| pH 1.68 | 124.1 | 0.79 z | 0.48 z | 292 y |
| L.S.D. | -- | 0.20 | 0.07 | 41 |
| II. Air Quality | | | | |
| CF | 147.6 y | 1.22 y | 0.63 y | 254 |
| NF | 121.3 z | 0.79 z | 0.51 z | 270 |
| L.S.D. | 15.6 | 0.14 | 0.05 | -- |
| III. ANOVA Effect | | | | |
| Fog (F) | NS | *** | *** | * |
| Air (A) | *** | *** | *** | NS |
| F x A | NS | NS | NS | NS |
| C.V. (%) | 38.0 | 60.3 | 39.6 | 47.5 |

---

[a] L.S.D. = least significant difference; sample sizes of n = 72 and n = 144 were analyzed in the assessment of fog chemistry or air quality effects, respectively. Abbreviations: Ts = Transpiration (mg $H_2O$ $m^{-2}s^{-1}$); Cs = Stomatal conductance to water vapor (cm $s^{-1}$); Pn = Net Photosynthesis (mg $CO_2$ $m^{-2}$ $s^{-1}$); Ts/Pn = Transpiration Ratio (mg $H_2O$/mg $CO_2$).

Table 25. Statistical Analysis of the Effect of Fog Chemistry and Ambient Air Quality on Pepper Physiological Responses in Air Exclusion Systems[a]

| | Ts | Cs | Pn | Tn/Pn |
|---|---|---|---|---|
| I. Fog Chemistry | | | | |
| No Fog | 148.0 | 1.15 | 0.89 | 165 |
| pH 7.24 | 138.2 | 1.12 | 0.73 | 192 |
| pH 1.68 | 117.8 | 0.84 | 0.62 | 200 |
| L.S.D. | -- | -- | -- | -- |
| II. Air Quality | | | | |
| CF | 124.0 | 0.98 | 0.70 | 184 |
| NF | 132.0 | 0.98 | 0.65 | 208 |
| L.S.D. | -- | -- | -- | -- |
| III. ANOVA Effect | | | | |
| Fog (F) | NS | NS | NS | NS |
| Air (A) | NS | NS | NS | NS |
| F x A | NS | NS | NS | NS |
| C.V. (%) | 27.8 | 41.1 | 30.9 | 21.2 |

---

[a] L.S.D. = least significant difference; n = 8 for the assessment of the effects of fog chemistry, and n = 12 for the assessment of the effects of air quality. Abbreviations: Ts = Transpiration (mg $H_2O$ $m^{-2}$ $s^{-1}$); Cs = Stomatal conductance to water vapor (cm $s^{-1}$); Pn = Net Photosynthesis (mg $CO_2$ $m^{-2}$ $s^{-1}$); Ts/Pn = Transpiration Ratio (mg $H_2O$/mg $CO_2$).

Table 26. Statistical Analysis of the Effect of Fog Chemistry and Ambient Air Quality on Strawberry Physiological Responses in Air Exclusion Systems[a]

| | Ts | Cs | Pn | Tn/Pn |
|---|---|---|---|---|
| I. Fog Chemistry | | | | |
| No Fog | 116.3 | 0.75 | 0.68 | 172 |
| pH 7.24 | 104.7 | 0.65 | 0.61 | 175 |
| pH 1.68 | 98.5 | 0.57 | 0.50 | 208 |
| L.S.D. | -- | -- | -- | -- |
| II. Air Quality | | | | |
| CF | 102.7 | 0.66 | 0.58 | 179 |
| NF | 100.4 | 0.56 | 0.53 | 204 |
| L.S.D. | -- | -- | -- | -- |
| III. ANOVA Effect | | | | |
| Fog (F) | NS | NS | NS | NS |
| Air (A) | NS | NS | NS | NS |
| F x A | NS | NS | NS | NS |
| C.V. (%) | 34.3 | 33.4 | 29.1 | 37.1 |

[a] L.S.D. = least significant difference; n = 8, for the assessment of the effects of fog chemistry, and n = 12 for the assessment of the effects of air quality. Abbreviations: Ts = Transpiration (mg $H_2O$ $m^{-2}$ $s^{-1}$); Cs = Stomatal conductance to water vapor (cm $s^{-1}$); Pn = Net Photosynthesis (mg $CO_2$ $m^{-2}$ $s^{-1}$); Ts/Pn = Transpiration Ratio (mg $H_2O$/mg $CO_2$).

Table 27. Effects of Fog Chemistry and Ambient Air Quality on Green Pepper Whole-season, Transpiration, Stomatal Conductance to Water Vapor, and Photosynthetic Rates - Individual Treatment Means[a]

| AQ | Fog | Ts | Cs | Pn | Ts/Pn |
|---|---|---|---|---|---|
| I. Chambers | | | | | |
| CF | NO | 135 (15) | 1.09 (.41) | 0.60 (.19) | 225 |
| CF | 7.0 | 158 (12) | 1.40 (.33) | 0.70 (.14) | 226 |
| CF | 2.6 | 158 (26) | 1.30 (.48) | 0.66 (.20) | 239 |
| CF | 1.6 | 137 (29) | 0.92 (.14) | 0.54 (.12) | 254 |
| NF | NO | 120 (20) | 0.76 (.13) | 0.50 (.17) | 240 |
| NF | 7.0 | 127 (14) | 0.84 (.14) | 0.57 (.16) | 223 |
| NF | 2.6 | 127 (35) | 0.83 (.22) | 0.53 (.17) | 240 |
| NF | 1.6 | 116 (24) | 0.69 (.11) | 0.45 (.12) | 258 |
| II. Air Exclusion System | | | | | |
| CF | NO | 150 (28) | 1.13 (.40) | 0.91 (.12) | 165 |
| CF | 7.0 | 128 (23) | 1.08 (.36) | 0.73 (.15) | 175 |
| CF | 1.6 | 120 (26) | 0.89 (.40) | 0.69 (.24) | 174 |
| NF | NO | 146 (41) | 1.16 (.65) | 0.88 (.13) | 166 |
| NF | 7.0 | 149 (51) | 1.16 (.43) | 0.73 (.24) | 204 |
| NF | 1.6 | 116 (36) | 0.79 (.42) | 0.56 (.20) | 207 |
| III. Outside | | | | | |
| NF | NO | 113 (23) | 1.45 (.64) | 0.81 (.19) | 140 |

[a] Values in parentheses are one standard deviation. Two plants were sampled from each of two plots, on 12 days, for a total of 48 observations. Abbreviations: AQ = Air Quality; CF = Charcoal-filtered air; NF = Nonfiltered air; Fog = Fog pH; NO = No fog application; Ts = Transpiration (mg $H_2O$ $m^{-2}$ $s^{-1}$); Cs = Stomatal conductance to water vapor (cm $s^{-1}$); Pn = Net Photosynthesis (mg $CO_2$ $m^{-2}$ $s^{-1}$). Ts/Pn = Transpiration Ratio (mg $H_2O$/mg $CO_2$).

Table 27. Effects of Fog Chemistry and Ambient Air Quality on Green Pepper Whole-season, Transpiration, Stomatal Conductance to Water Vapor, and Photosynthetic Rates - Individual Treatment Means[a]

| AQ | Fog | Ts | Cs | Pn | Ts/Pn |
|---|---|---|---|---|---|
| I. Chambers | | | | | |
| CF | NO | 135 (15) | 1.09 (.41) | 0.60 (.19) | 225 |
| CF | 7.0 | 158 (12) | 1.40 (.33) | 0.70 (.14) | 226 |
| CF | 2.6 | 158 (26) | 1.30 (.48) | 0.66 (.20) | 239 |
| CF | 1.6 | 137 (29) | 0.92 (.14) | 0.54 (.12) | 254 |
| NF | NO | 120 (20) | 0.76 (.13) | 0.50 (.17) | 240 |
| NF | 7.0 | 127 (14) | 0.84 (.14) | 0.57 (.16) | 223 |
| NF | 2.6 | 127 (35) | 0.83 (.22) | 0.53 (.17) | 240 |
| NF | 1.6 | 116 (24) | 0.69 (.11) | 0.45 (.12) | 258 |
| II. Air Exclusion System | | | | | |
| CF | NO | 150 (28) | 1.13 (.40) | 0.91 (.12) | 165 |
| CF | 7.0 | 128 (23) | 1.08 (.36) | 0.73 (.15) | 175 |
| CF | 1.6 | 120 (26) | 0.89 (.40) | 0.69 (.24) | 174 |
| NF | NO | 146 (41) | 1.16 (.65) | 0.88 (.13) | 166 |
| NF | 7.0 | 149 (51) | 1.16 (.43) | 0.73 (.24) | 204 |
| NF | 1.6 | 116 (36) | 0.79 (.42) | 0.56 (.20) | 207 |
| III. Outside | | | | | |
| NF | NO | 113 (23) | 1.45 (.64) | 0.81 (.19) | 140 |

[a] Values in parentheses are one standard deviation. Two plants were sampled from each of two plots, on 12 days, for a total of 48 observations. Abbreviations: AQ = Air Quality; CF = Charcoal-filtered air; NF = Nonfiltered air; Fog = Fog pH; NO = No fog application; Ts = Transpiration (mg $H_2O$ $m^{-2}$ $s^{-1}$); Cs = Stomatal conductance to water vapor (cm $s^{-1}$); Pn = Net Photosynthesis (mg $CO_2$ $m^{-2}$ $s^{-1}$). Ts/Pn = Transpiration Ratio (mg $H_2O$/mg $CO_2$).

Table 28. Effects of Fog Chemistry and Ambient Air Quality on Strawberry Whole-season Transpiration, Stomatal Conductance to Water Vapor, and Photosynthetic Rates - Individual Treatment Means[a]

| AQ | Fog | Ts | Cs | Pn | Ts/Pn |
|---|---|---|---|---|---|
| I. Chambers | | | | | |
| CF | NO | 121 (13) | 0.77 (.13) | 0.61 (.15) | 198 |
| CF | 7.0 | 117 (14) | 0.78 (.06) | 0.60 (.07) | 195 |
| CF | 2.6 | 114 (11) | 0.69 (.14) | 0.55 (.16) | 207 |
| CF | 1.6 | 117 (11) | 0.69 (.03) | 0.52 (.17) | 225 |
| NF | NO | 107 (16) | 0.61 (.10) | 0.53 (.08) | 202 |
| NF | 7.0 | 114 (15) | 0.67 (.18) | 0.59 (.13) | 193 |
| NF | 2.6 | 106 (15) | 0.61 (.13) | 0.54 (.13) | 196 |
| NF | 1.6 | 107 (10) | 0.57 (.07) | 0.50 (.06) | 214 |
| II. Air Exclusion System | | | | | |
| CF | NO | 121 (20) | 0.79 (.17) | 0.68 (.11) | 178 |
| CF | 7.0 | 95 (30) | 0.64 (.25) | 0.62 (.18) | 153 |
| CF | 1.6 | 111 (42) | 0.68 (.24) | 0.55 (.17) | 201 |
| NF | NO | 112 (15) | 0.71 (.06) | 0.68 (.01) | 164 |
| NF | 7.0 | 115 (37) | 0.67 (.17) | 0.60 (.10) | 192 |
| NF | 1.6 | 86 (29) | 0.46 (.14) | 0.46 (.19) | 187 |
| III. Outside | | | | | |
| NF | NO | 81 (14) | 0.80 (.24) | 0.74 (.15) | 109 |

[a] Parenthetical data are one standard deviation. Two plants were samples from each of two plots, on 12 days, for a total of 48 observations. Abbreviations: AQ = Air Quality; CF = Charcoal-filtered air; NF = Nonfiltered air; Fog = Fog pH; NO = No fog application; Ts = Transpiration (mg $H_2O$ $m^{-2}$ $s^{-1}$). Cs = Stomatal conductance to water vapor (cm $s^{-1}$); Pn = Net Photosynthesis (mg $CO_2$ $m^2$ $s^{-1}$); Ts/Pn = Transpiration Ratio (mg $H_2O$/mg $CO_2$).

Table 29. Buffering Capacity in Strawberry and Green Pepper Leaves After Eleven Fog Events in the Spring Fog Study[a]

| | | Strawberry | | Pepper | |
|---|---|---|---|---|---|
| AQ | Fog pH | Chamber | Air Exclusion | Chamber | Air Exclusion |
| Outside | -- | 0.41 (0.27) | -- | 0.13 (0.02) | -- |
| CF | No Fog | 0.19 (0.14) | 0.22 (0.14) | 0.20 (1.00) | 0.13 (0.05) |
| | 7.24 | 0.11 (0.05) | 0.19 (0.11) | 0.14 (0.09) | 0.11 (0.05) |
| | 2.69 | 0.23 (0.14) | -- | 0.11 (0.04) | -- |
| | 1.68 | 0.29 (0.20) | 0.15 (0.12) | 0.13 (0.05) | 0.18 (0.04) |
| NF | No Fog | 0.35 (0.18) | 0.33 (0.22) | 0.17 (0.06) | 0.13 (0.02) |
| | 7.24 | 0.19 (0.15) | 0.31 (0.25) | 0.12 (0.02) | 0.12 (0.04) |
| | 2.69 | 0.19 (0.11) | -- | 0.11 (0.05) | -- |
| | 1.68 | 0.32 (0.20) | 0.25 (0.32) | 0.14 (0.05) | 0.11 (0.02) |

---

[a] Mean with standard deviation in parentheses, for six plants per treatment group, two from each of three replicate plots. Buffering cpapcity is expressed as ml 0.17 N Hcl $q^{-1}$ fresh weight of leaves. Abbreviations: AQ = Air Quality, CF = Charcoal Filtered Air, NF = Non Filtered Air.

Table 30. Buffering Capacity in Strawberry and Green Pepper Leaves After Twenty-two Fog Events in the Spring Fog Study

| | | Strawberry | | Pepper | |
|---|---|---|---|---|---|
| AQ | Fog pH | Chamber | Air Exclusion | Chamber | Air Exclusion |
| Outside | - | 0.58 (0.39) | -- | 0.27 (0.07) | -- |
| CF | No Fog | 0.19 (0.08) | 0.20 (0.03) | 0.15 (0.06) | 0.17 (0.03) |
| | 7.24 | 0.22 (0.15) | 0.35 (0.32) | 0.12 (0.03) | 0.16 (0.05) |
| | 2.69 | 0.26 (0.14) | -- | 0.17 (0.07) | -- |
| | 1.68 | 0.29 (0.18) | 0.29 (0.18) | 0.10 (0.12) | 0.18 (0.03) |
| NF | No Fog | 0.33 (0.18) | 0.30 (0.21) | 0.23 (0.03) | 0.25 (0.09) |
| | 7.24 | 0.18 (0.08) | 0.24 (0.14) | 0.20 (0.10) | 0.24 (0.08) |
| | 2.69 | 0.30 (0.19) | -- | 0.17 (0.10) | -- |
| | 1.68 | 0.26 (0.13) | 0.23 (0.13) | 0.10 (0.07) | 0.20 (0.07) |

[a] Mean with standard deviation in parentheses for six plants per treatment group, two from each of three replicate plots. Buffering capacity is expressed as ml of 0.017 N HCl $q^{-1}$ fresh weight of leaves. Abbreviations: AQ = Air Quality, CF = Charcoal Filtered Air, NF = Non Filtered Air.

Table 32. Statistical Analysis of the Effects of Fog Chemistry and Ambient Air Quality on Total Leaf Carotenoid Content in Open-Top Field Chambers (mg g dry weight$^{-1}$).[a]

| | Strawberry | Tomato | Pepper | Alfalfa | Celery |
|---|---|---|---|---|---|
| I. Fog Chemistry | | | | | |
| No Fog | 0.97 | 1.10 | 1.32 z | 1.24 x | 1.49 |
| pH 7.24 | 0.93 | 1.19 | 1.36 z | 1.29 x | 1.71 |
| pH 2.69 | 0.94 | 1.25 | 1.43 yz | 1.06 y | 1.56 |
| pH 1.68 | 0.94 | 1.01 | 1.59 y | 0.78 z | 1.63 |
| L.S.D. | -- | -- | 0.18 | 0.49 | -- |
| II. Air Quality | | | | | |
| CF | 0.92 | 1.31 y | 1.38 | 1.15 y | 1.80 y |
| NF | 0.97 | 0.97 z | 1.47 | 1.03 z | 1.39 z |
| L.S.D. | -- | 0.13 | -- | 0.11 | 0.13 |
| III. ANOVA Effect | | | | | |
| Block | NS | NS | NS | * | * |
| Fog (F) | NS | NS | * | * | NS |
| Air (A) | NS | * | NS | * | * |
| F x A | NS | NS | NS | NS | * |
| C.V. (%) | 16.3 | 28.9 | 22.4 | 23.7 | 20.4 |

[a] L.S.D. = least significant difference; n = 24 for the assessment of the effects of fog chemistry, and n = 48 for the assessment of the effects of air quality. Abbreviations: CF = Charcoal-filtered air; NF = Nonfiltered air.

Table 33. Statistical Analysis of the Effects of Fog Chemistry and Ambient Air Quality on Total Leaf Chlorophyll Content in Air Exclusion Systems (mg g dry weight$^{-1}$)[a]

| | Strawberry | Tomato | Pepper | Celery |
|---|---|---|---|---|
| <u>I. Fog Chemistry</u> | | | | |
| No Fog | 3.41 | 5.98 | 5.08 | 4.59 z |
| pH 7.24 | 3.46 | 6.02 | 4.75 | 5.41 y |
| pH 1.68 | 3.60 | 6.28 | 4.76 | 5.44 y |
| L.S.D. | -- | -- | | 0.63 |
| <u>II. Air Quality</u> | | | | |
| CF | 3.17 z | 6.42 | 4.57 z | 5.50 y |
| NF | 3.81 y | 5.77 | 5.16 y | 4.79 z |
| L.S.D. | 0.33 | -- | 0.27 | 0.52 |
| <u>III. ANOVA Effect</u> | | | | |
| Block | NS | * | * | * |
| Fog (F) | NS | NS | NS | * |
| Air (A) | * | NS | * | ** |
| F x A | NS | NS | * | NS |
| C.V. (%) | 16.3 | 24.6 | 9.4 | 17.3 |

---

[a] L.S.D. = least significant difference; n = 24 for the assessment of the effects of fog chemistry, and n = 48 for the assessment of the effects of air quality. Abbreviations: CF = Charcoal-filtered air; NF = Nonfiltered air.

Table 34. Statistical Analysis of the Effects of Fog Chemistry and Ambient Air Quality on Total Leaf Carotenoid Content in Air Exclusion Systems (mg g dry weight$^{-1}$)[a]

| | Strawberry | Tomato | Pepper | Celery |
|---|---|---|---|---|
| I. Fog Chemistry | | | | |
| No Fog | 1.07 | 1.32 | 1.47 | 1.38 z |
| pH 7.24 | 1.07 | 1.23 | 1.39 | 1.57 y |
| pH 1.68 | 1.10 | 1.24 | 1.39 | 1.61 y |
| L.S.D. | -- | -- | -- | 0.19 |
| II. Air Quality | | | | |
| CF | 1.03 z | 1.29 | 1.34 z | 1.58 |
| NF | 1.13 y | 1.23 | 1.49 y | 1.47 |
| L.S.D. | -- | -- | 0.09 | -- |
| III. ANOVA Effect | | | | |
| Block | NS | NS | * | NS |
| Fog (F) | NS | NS | NS | * |
| Air (A) | * | NS | * | NS |
| F x A | NS | NS | * | NS |
| C.V. (%) | 13.5 | 26.7 | 10.4 | 17.1 |

[a] L.S.D. = least significant difference; n = 24 for the assessment of the effects of fog chemistry, and n = 48 for the assessment of the effects of air quality. Abbreviations: CF = Charcoal-filtered air; NF = Nonfiltered air.

Table 35. Effects of Fog Chemistry and Ambient Air Quality on Total Leaf Chlorophyll Content- Individual Treatment Means (mg g dry wt$^{-1}$).[a]

| AQ | Fog | Strawberry | Tomato | Pepper | Alfalfa | Celery |
|---|---|---|---|---|---|---|
| I. Chambers | | | | | | |
| CF | NO | 3.02 (0.25) | 5.68 (1.35) | 3.95 (0.72) | 7.69 (1.11) | 6.55 (1.29) |
| CF | 7.24 | 3.14 (0.84) | 7.55 (1.73) | 4.00 (0.63) | 8.16 (1.56) | 6.77 (1.37) |
| CF | 2.69 | 3.45 (0.60) | 7.13 (2.23) | 4.74 (0.95) | 6.01 (1.40) | 6.36 (1.37) |
| CF | 1.68 | 3.48 (0.37) | 5.31 (1.33) | 5.23 (0.96) | 5.44 (1.47) | 6.24 (1.32) |
| NF | NO | 3.75 (0.68) | 4.53 (1.09) | 4.24 (0.81) | 4.85 (0.87) | 3.69 (1.30) |
| NF | 7.24 | 3.34 (0.41) | 4.29 (0.94) | 4.86 (1.52) | 5.07 (1.27) | 4.80 (0.72) |
| NF | 2.69 | 3.36 (0.52) | 5.32 (1.44) | 4.70 (1.41) | 4.99 (1.04) | 4.39 (1.68) |
| NF | 1.68 | 3.43 (0.40) | 4.48 (0.97) | 5.46 (0.58) | 3.90 (1.23) | 5.17 (1.85) |
| II. Air Exclusion System | | | | | | |
| CF | NO | 3.02 (0.43) | 6.11 (0.73) | 5.08 (0.09) | --- | 5.32 (0.83) |
| CF | 7.24 | 3.14 (0.40) | 6.34 (1.17) | 4.00 (0.54) | --- | 5.59 (0.59) |
| CF | 1.68 | 3.36 (0.60) | 6.81 (1.12) | 4.62 (0.89) | --- | 5.59 (0.95) |
| NF | NO | 3.80 (0.67) | 5.86 (1.42) | 5.08 (0.09) | --- | 3.86 (1.35) |
| NF | 7.24 | 3.77 (0.59) | 5.70 (1.68) | 5.50 (0.45) | --- | 5.23 (0.47) |
| NF | 1.68 | 3.85 (0.79) | 5.75 (2.69) | 4.90 (0.22) | --- | 5.29 (1.52) |
| III. Outside | | | | | | |
| NF | NO | 3.08 (0.76) | 5.55 (0.68) | 4.48 (1.30) | 3.93 (0.76) | 5.12 (0.60) |

---

[a] Means with standard deviation in parentheses for 12 or 8 plants, four from each of three or two replicate plots for open-top chambers and air exclusion systems, respectively. Abbreviations: AQ = Air Quality; CF = Charcoal-Filtered air; NF = Nonfiltered air; Fog = Fog pH; NO = No fog application.

Table 35. Effects of Fog Chemistry and Ambient Air Quality on Total Leaf Chlorophyll Content- Individual Treatment Means (mg g dry wt$^{-1}$).[a]

| AQ | Fog | Strawberry | Tomato | Pepper | Alfalfa | Celery |
|---|---|---|---|---|---|---|
| I. Chambers | | | | | | |
| CF | NO | 3.02 (0.25) | 5.68 (1.35) | 3.95 (0.72) | 7.69 (1.11) | 6.55 (1.29) |
| CF | 7.24 | 3.14 (0.84) | 7.55 (1.73) | 4.00 (0.63) | 8.16 (1.56) | 6.77 (1.37) |
| CF | 2.69 | 3.45 (0.60) | 7.13 (2.23) | 4.74 (0.95) | 6.01 (1.40) | 6.36 (1.37) |
| CF | 1.68 | 3.48 (0.37) | 5.31 (1.33) | 5.23 (0.96) | 5.44 (1.47) | 6.24 (1.32) |
| NF | NO | 3.75 (0.68) | 4.53 (1.09) | 4.24 (0.81) | 4.85 (0.87) | 3.69 (1.30) |
| NF | 7.24 | 3.34 (0.41) | 4.29 (0.94) | 4.86 (1.52) | 5.07 (1.27) | 4.80 (0.72) |
| NF | 2.69 | 3.36 (0.52) | 5.32 (1.44) | 4.70 (1.41) | 4.99 (1.04) | 4.39 (1.68) |
| NF | 1.68 | 3.43 (0.40) | 4.48 (0.97) | 5.46 (0.58) | 3.90 (1.23) | 5.17 (1.85) |
| II. Air Exclusion System | | | | | | |
| CF | NO | 3.02 (0.43) | 6.11 (0.73) | 5.08 (0.09) | --- | 5.32 (0.83) |
| CF | 7.24 | 3.14 (0.40) | 6.34 (1.17) | 4.00 (0.54) | --- | 5.59 (0.59) |
| CF | 1.68 | 3.36 (0.60) | 6.81 (1.12) | 4.62 (0.89) | --- | 5.59 (0.95) |
| NF | NO | 3.80 (0.67) | 5.86 (1.42) | 5.08 (0.09) | --- | 3.86 (1.35) |
| NF | 7.24 | 3.77 (0.59) | 5.70 (1.68) | 5.50 (0.45) | --- | 5.23 (0.47) |
| NF | 1.68 | 3.85 (0.79) | 5.75 (2.69) | 4.90 (0.22) | --- | 5.29 (1.52) |
| III. Outside | | | | | | |
| NF | NO | 3.08 (0.76) | 5.55 (0.68) | 4.48 (1.30) | 3.93 (0.76) | 5.12 (0.60) |

---

[a] Means with standard deviation in parentheses for 12 or 8 plants, four from each of three or two replicate plots for open-top chambers and air exclusion systems, respectively. Abbreviations: AQ = Air Quality; CF = Charcoal-Filtered air; NF = Nonfiltered air; Fog = Fog pH; NO = No fog application.

### b. Physiology

Green pepper exhibited significant reductions in Ts, Cs, and Pn in NF vs. CF in open-top chambers (Table 23). Strawberry also displayed significant reductions in all three parameters, but the differences between NF and CF plant responses were not as sizeable as observed in green pepper (Table 24). No significant differences were observed in air exclusion systems (Tables 25, 26). Buffering capacity was approximately the same in NF vs. CF treatments in both open-top chamber and air exclusion system plants (Tables 29 and 30). Both leaf chlorophyll and carotenoid contents were reduced in NF vs. CF chambers in tomato, green pepper, alfalfa, and celery; but not for strawberry (Tables 31 and 32). The same trends were observed in air exclusion systems, except for leaf carotenoid responses in celery (Tables 33 and 34).

## 6. Exposure System Effects

### a. Growth, Yield, and Injury

It was difficult to determine differences in plant response between open-top chamber and air exclusion system plots as the results could not be compared statistically. Replicate blocks were partitioned differently in the two gaseous pollutant exposure systems, which did not allow for direct comparisons (i.e. statistical) to be made. A qualitative examination of the results indicated that tomato, pepper, and celery growth and yield responses tended to be the same for a given fog chemistry/air quality treatments group, irrespective of the pollutant exposure systems, but that the results were not statistically significant for air exclusion systems. In contrast, tomato's increased growth with celery and green pepper growth and yield expenses ozone occurred only in open-top chambers and not in air exclusion system plots (Tables 19-22). In general, plant growth was most similar between NF chamber and outside plots in strawberry, green pepper, and celery; higher in both chamber and air exclusion system plots than outside plots in tomato; and higher in chamber than outside plots in alfalfa.

### b. Physiology

Ts, Cs, and Pn rates tended to be lower in air exclusion systems than in chambers in strawberry, whereas the reverse was found in green pepper (Tables 27 and 28). In general, Ts rates were lower for both species in both systems than for comparable plants in outside plots. Cs and Pn rates for both species tended to be most similar in air exclusion systems and outside plots and higher than in open-top chambers. Leaf chlorophyll and carotenoid contents appeared to be similar in both open-top chamber and air exclusion systems, as well as in outside plots (Tables 35 and 36).

## 7. Interactions

### a. Growth, Yield, and Injury

There were essentially no statistically significant interactive effects of fog chemistry and air quality on any of the plant responses, in any gaseous pollutant exposure system. The only exception was in open-top chambers, where pepper leaf area was greater in the presence of acid fog than no fog, but primarily in nonfiltered treatments. This may have been due to a stimulation of pepper leaf growth associated with less water stress due to the presence of fog in early morning. The increased leaf growth may have been evident only in CF treatments as ozone had a significant detrimental effect on growth in NF treatments. The general lack of an acidic fog x oxidant interaction for all species was the same as recently reported for alfalfa by Temple et al. (1987).

### b. Physiology

There were no statistically significant interactions between fog chemistry and air quality for transpiration, stomatal conductance, or photosynthesis (Tables 23, 24, 25, 26). However, significant interactions were common between fog chemistry and air quality for chlorophyll and carotenoid contents. There was a significant interactive effect on chlorophyll content in strawberry, tomato, and alfalfa (Table 31); and on carotenoid content in celery (Table 32); in open-top chambers. In air exclusion systems, significant interactive effects were observed in green pepper chlorophyll and carotenoid responses (Tables 33 and 34). In open-top chambers, the nature of the interaction was that plants in CF treatments tended to have a higher chlorophyll or carotenoid contents than plants in NF air, especially in the no fog and lower acidity treatments (i.e. pH 7.24 or 2.69). In air exclusion systems, green pepper plants tended to have higher pigment contents in NF than CF treatments, especially with when treated with pH 1.68 fog.

## B. Winter San Joaquin Valley Fog Study

### 1. Fog Chemistry

The fog solutions were acidfied with an acid stock solution containing sulfuric and nitric acid in 1.4:1 soil ratio. The ion composition of nozzle drip and fog collector samples were shown in Table 4. Table 37 lists the measured pH values for the five fog treatments over the course of the winter fog study. The measured pH's were close to the target pH's. From now on the mean pH's of 5.48, 3.22, 2.72, 2.23, and 1.76 will be used in place of the target pH values of 5.6, 3.1, 2.6, 2.1, and 1.6, respectively. A complete set of fog samples (i.e. nozzle drip, suspended fog, leaf washes) were taken on three dates during the winter fog study.

The average pH's of the fog collector (i.e. suspended fog) samples are listed in Table 38. In general, pH's for the nozzle drip and fog collector samples are very close, except at pH 5.48 where the fog collector samples exhibited lower pH's. This was likely due to some residual contamination from the preceding set of measurements (i.e., residual pH 1.76 fog).

The leaf wash data in general indicated that acid neutralizing substances were present on leaf surfaces, which could buffer the acid inputs from fog deposited on leaves (Table 38). This is especially noticeable for the no fog and pH 5.48 treatments, where the pH of the 90 to 100 ml leaf wash samples were raised from pH 5.0 to 8.11 or higher. The leaf surface pH data were adjusted for leaf area and the amount of water on the leaf, to determine the hydrogen ion buffering capacities of the leaf surfaces. Currently, elemental analyses of the fog and leaf wash samples are being conducted, which could aid in identifying the chemical moities responsible for the buffering of acidic depositions to leaf surfaces.

In the no fog treatments, there was less moisture on broccoli than on potato or alfalfa leaves (Table 39). Apparently, broccoli leaves are not as effective in collecting dew, and may have had drier leaf surfaces than the other crops before the fog episodes began. Broccoli leaves collected after fog treatments had similar amounts of surface water as potato or alfalfa leaves (Table 39). While these data are scant, they do suggest that the greater sensitivity of broccoli to acidic fog may in part be due to a reduced capacity to dilute acidic depositions by dew on leaf sur-

Table 37. The pH of Fog Nozzle Drip Samples in the Winter Fog Study (3 November 1986 to 15 January 1987)[a]

| | | pH of Fog Solution | | | | |
|---|---|---|---|---|---|---|
| Date | Fog # | 5.6 | 3.1 | 2.6 | 2.1 | 1.6 |
| 03 Nov | 1 | 6.57 | 3.11 | 2.70 | 2.19 | 1.72 |
| 06 | 2 | 5.70 | 3.10 | 2.72 | 2.20 | 1.70 |
| 10 | 3 | 5.39 | 3.12 | 2.71 | 2.28 | 1.82 |
| 13 | 4 | 5.36 | 3.80 | 2.82 | 2.32 | 1.85 |
| 17 | 5 | 5.27 | 3.17 | 2.72 | 2.20 | 1.72 |
| 20 | 6 | 4.85 | 3.23 | 2.72 | 2.21 | 1.87 |
| 24 | 7 | 5.32 | 3.33 | 2.92 | 2.53 | 2.07 |
| 26 | 8 | 4.94 | 3.14 | 2.80 | 2.25 | 1.84 |
| 01 Dec | 9 | 5.68 | 3.64 | 3.14 | 2.59 | 1.90 |
| 04 | 10 | 5.36 | 3.28 | 2.81 | 2.30 | 1.79 |
| 08 | 11 | 5.88 | 3.25 | 2.54 | 2.25 | 1.77 |
| 11 | 12 | 5.28 | 3.54 | 3.11 | 2.55 | 2.05 |
| 15 | 13 | 5.43 | 3.08 | 2.67 | 2.16 | 1.68 |
| 18 | 14 | 5.95 | 3.02 | 2.63 | 2.12 | 1.62 |
| 22 | 15 | 6.07 | 3.07 | 2.52 | 2.00 | 1.55 |
| 24 | 16 | 6.47 | 3.20 | 2.63 | 2.09 | 1.66 |
| 29 | 17 | 6.41 | 3.19 | 2.57 | 2.07 | 1.74 |
| 05 Jan | 18 | 4.50 | 3.10 | 2.66 | 2.18 | 1.67 |
| 08 | 19 | 5.64 | 3.06 | 2.55 | 2.09 | 1.63 |
| 12 | 20 | 3.89 | 3.09 | 2.59 | 2.13 | 1.64 |
| 15 | 21 | 5.07 | 3.19 | 2.58 | 2.10 | 1.65 |
| Mean | | 5.48 | 3.22 | 2.72 | 2.23 | 1.76 |
| | | (0.65) | (0.20) | (0.17) | (0.16) | (0.14) |

---

[a] Values in parentheses are one standard deviation.

Table 38. pH of fog Nozzle drip, Fog Collector and Broccoli and Potato Leaf Wash Samples in the Winter Fog Study[a]

| Treatment | Nozzle | Fog Collector | Broccoli | Potato |
|---|---|---|---|---|
| 1.76 | 1.96 (0.23) | 1.89 (0.04) | 2.78 (0.03)[b] | 2.34 (0.70) |
| 2.23 | 2.43 (0.10) | 2.45 (0.12) | 3.12 (0.24) | 2.71 (0.69) |
| 2.72 | 2.93 (0.14) | 2.95 (0.10) | 3.10 (0.58) | 3.26 (0.42) |
| 3.22 | 3.32 (0.07) | 3.50 (0.19) | 6.04 (3.28) | 7.90 (3.71) |
| 5.48 | 4.96 (0.21) | 5.00 (0.71) | 8.11 (3.48) | 10.13 (0.32) |
| No fog | - | - | 9.76[c] | 10.85 (0.92) |

[a] Mean with standard deviation in parentheses for three sampling dates.
[b] Two sampling dates.
[c] One sampling date, no water or leaves for other sampling dates.

faces. In broccoli the waxy leaf surfaces would discourage dew accumulation whereas in potato the pubescent leaves likely would encourage dew accumulation.

The ion concentrations of broccoli and potato leaf wash samples are listed in Table 40. In general, the concentrations of all ions were similar on a surface area basis in both species.

## 2. Air Pollution Measurements

Air pollution levels were low during the winter fog study (Table 41). Twelve-hour daylight averages fo $O_3$ and $SO_2$ were 0.019 $\mu l\ l^{-1}$ and 0.001 $\mu l\ l^{-1}$, respectively over the 11 week exposure period (Table 41). Concentrations of PAN (12-h averages) were also very low, usually at levels less than 0.001 $\mu l\ l^{-1}$, and hourly maximum as high as 0.003 $\mu l\ l^{-1}$.

## 3. Environmental Measurements

Environmental conditions during the winter fog study are shown in Table 42. In comparison to the spring, air temperatures were cooler, light intensity was lower, and relative humidity was higher (Tables 11 and 42).

Table 39. Moisture on Leaves in the Winter Fog Study (g $m^{-2}$)[a]

| Treatment | Broccoli | Potato | Alfalfa |
|---|---|---|---|
| No Fog | 39.3 (38.6) | 112.6 (149.3) | 78.0 (85.3) |
| pH 5.48 Fog | 143.5 (76.6) | 143.0 (85.6) | 185.0 (100.7) |

[a] Mean of six measurements on a one-sided leaf area basis, two on each of three dates, with standard deviations in parentheses.

## 4. Fog Effects

### a. Growth, Yield, and Injury

Injury to broccoli plants was rated on a 0-10 scale from mid-November to mid-January (Table 43). Injury (i.e. necrosis) was observed in plants exposed to pH 2.23 and 1.76 fog, and in plants treated with pH 2.72 fog on 19 November 1986. The injury at pH 2.72 was the only occurrence of acidic fog injury in plants exposed to fogs above pH 2.3 in the winter fog study. Broccoli was clearly the most acidic fog-sensitive crop in the winter study, and possibly the most sensitive of all ten species tested in either season. The lack of an increase in injury with each successive fog event indicates that the plants continued to grow, even when exposed to pH 1.76 fog. Thus, the production of new leaf tissue was greater than the amount injury due to acidic fog exposure.

Most of the data have been compared statistically utilizing one-way analysis of variance, testing differences among the five fog and the no fog treatments, in which the data from all plots were pooled. The data from the outside plots (not covered at any time during the study) were not included in the analyses. Non-statistical comparisons indicated that the responses of the outside plants were similar to those of no fog treated plants. Data from the physiological measurements were also pooled over all dates to calculate a value for the average whole-season response. The physiological measurements focussed on potato and broccoli as these species exhibited leaf morphologies that could be easily measured, and because they both exhibited visible injury from acidic fog.

Table 40. Ion Concentrations on Broccoli and Potato Leaf Surfaces in the Winter Fog Study ($\mu$eq $m^{-2}$)[a]

| pH | Broccoli | Potato | Broccoli | Potato | Broccoli | Potato |
|---|---|---|---|---|---|---|
| | $H^+$ | | $Na^+$ | | $K^+$ | |
| 1.76 | 798 (834)* | 1928 (2892) | 213 (97) | 171 (108) | 484 (258) | 141 (122)* |
| 2.23 | 115 (58) | 654 (858) | 338 (337) | 518 (417) | 139 (53) | 200 (95) |
| 2.72 | 322 (484) | 112 (89) | 158 (23) | 195 (177) | 88 (87) | 47 (48)* |
| 3.22 | 24 (28) | -7 (45) | 225 (179) | 135 (51) | 122 (107)* | 127 (58) |
| 5.48 | -26 (22) | -23 (13) | 101 (51) | 66 (93)* | 234 (178) | 48 (72)* |
| No fog | -27 (20)* | -41 (36) | 91 (32) | 241 (368) | 60 (61)* | 55 (48) |
| | $NH_4^+$ | | $Ca^{2+}$ | | $Mg^{2+}$ | |
| 1.76 | 559 (548) | 296 (157) | 1575 (886) | 1265 (992) | 335 (122) | 237 (103) |
| 2.23 | 85 (20) | 314 (251) | 332 (159) | 707 (402) | 103 (81) | 173 (41) |
| 2.72 | 116 (22) | 289 (239) | 258 (121) | 483 (456) | 84 (52) | 120 (116) |
| 3.22 | 157 (28) | 165 (183) | 313 (109) | 695 (455) | 87 (52) | 155 (100) |
| 5.48 | 89 (30) | 119 (75) | 267 (62) | 296 (239) | 86 (59) | 60 (36) |
| No fog | 32 (3) | 57 (18) | 365 (81) | 446 (276) | 106 (92) | 132 (77) |
| | $Cl^-$* | | $NO_3^-$ | | $SO_4^=$ | |
| 1.76 | 285 (91) | 67 (80) | 2915 (3526) | 1265 (782) | 8270 (10257) | 5253 (3133) |
| 2.23 | 246 (76) | 345 (42) | 269 (164) | 670 (371) | 542 (315) | 1906 (1182) |
| 2.72 | 136 (62) | 73 (48) | 205 (119) | 359 (304) | 439 (299) | 934 (803) |
| 3.22 | 261 (156) | 114 (49) | 192 (82) | 284 (172) | 415 (212) | 709 (402) |
| 5.48 | 195 (80) | 104 (147) | 118 (57) | 113 (41) | 265 (203) | 317 (135) |
| No fog | 241 (30) | 85 (33) | 91 (83) | 146 (68) | 151 (98) | 351 (237) |

---

[a] Mean with standard deviation in parentheses for single leaves on each of three dates, except for two dates for $Cl^-$, and as marked by an asterisk.

Table 41. Gaseous Pollutant Concentrations Monitored During the Period from 01 November 1986 through 16 January 1987

| Dates | Ozone<br>µl l$^{-1}$ | SO$_2$[b]<br>µl l$^{-1}$ | PAN<br>µl l$^{-1}$ |
|---|---|---|---|
| 11/1-11/7/87 | 0.034 (0.022) | 0 (0.001) | 0.0009 (0.0009)[d] |
| 11/8-11/4 | 0.022 (0.015) | 0.001 (0.003) | 0.0003 (0.0005) |
| 11/15-11/21 | 0.017 (0.011) | 0 (0.001) | 0 (0) |
| 11/22-11/28 | 0.019 (0.012) | 0.001 (0.003) | No Data |
| 11/29/12/5 | 0.016 (0.016) | 0.001 (0.003) | No Data |
| 12/6-12/12 | 0.022 (0.017) | 0 (0) | No Data |
| 12/13-12/19 | 0.020 (0.016) | 0 (0.002) | 0.0007 (0.0008)[d] |
| 12/20-12/26 | 0.017 (0.010) | 0 (0.001) | 0.0001 (0.0002) |
| 12/27-1/2/87 | 0.017 (0.013) | 0.001 (0.002) | 0.0002 (0.0003) |
| 1/3-1/9 | 0.018 (0.012) | 0.002 (0.002) | 0.0001 (0.0002) |
| 1/10-1/16 | 0.017 (0.007) | 0.003 (0.002) | 0 (0) |
| Average[c] | 0.019 (0.005) | 0.001 (0.001) | 0.0004 (0.0004)[e] |

---

[a] Average between 0800 and 2000 h PST; Ozone and SO$_2$ measurements at ARB citrus site, and PAN at ARB humidity site. The value in parentheses is the average standard deviation for the two outside measuring points for ozone and SO$_2$, and for seven daily average sample measurements for PAN.

[b] An 0 indicates measurements below the recorded minimum level of detection (.005 µl l$^{-1}$).

[c] Average with standard deviation in parentheses of all weekly values.

[d] Three days of sampling.

[e] For seven weeks of data.

Table 42. Environmental Conditions During the Winter Fog Study[a]

| Dates | Air Temperature (°C) | Light Intensity ($\mu$mol $m^{-2}$ $s^{-1}$) | Relative Humidity (%) |
|---|---|---|---|
| 11/1-11/7/86 | 23.2 | 526 | 33 |
| 11/8-11/14 | 23.4 | 508 | 25 |
| 11/15-11/21 | 21.2 | 362 | 60 |
| 11/22-11/28 | 22.7 | 540 | 22 |
| 11/29-12/5 | 20.4 | 410 | 28 |
| 12/6-12/12 | 16.9 | 445 | 49 |
| 12/13-12/19 | 21.1 | 444 | 37 |
| 12/20-12/26 | 21.2 | 446 | 32 |
| 12/27-1/2/87 | 20.3 | 386 | 31 |
| 1/3-1/9 | 17.6 | 498 | 35 |
| 1/10-1/16 | 19.4 | 506 | 18 |

[a] Average between 0800 and 2000 h PST for each week of the Winter fog Study. Data collected at the ARB citrus site.

Table 43. Effects of Fog Chemistry on Broccoli Leaf Injury[a]

| Date | Cumulative | Fog Chemistry | | | | | |
|---|---|---|---|---|---|---|---|
| | # Fogs | No Fog | 5.48 | 3.22 | 2.72 | 2.23 | 1.76 |
| Nov. 19 | 5 | 0 | 0 | 0 | 0.8(2.1) | 5.2(3.7) | 19.6(7.1) |
| Nov. 26 | 8 | 0 | 0 | 0 | 0 | 5.0(2.6) | 22.3(4.8) |
| Dec. 05 | 10 | 0 | 0 | 0 | 0 | 6.6(3.7) | 27.0(7.3) |
| Dec. 12 | 12 | 0 | 0 | 0 | 0 | 5.2(2.1) | 25.2(7.5) |
| Dec. 17 | 13 | 0 | 0 | 0 | 0 | 7.0(3.1) | 29.9(8.0) |
| Jan. 07 | 18 | 0 | 0 | 0 | 0 | 5.2(0.9) | 27.3(4.5) |

[a] Mean with standard deviation in parenthesis. Values represent the average of 15 plants, five from each of three plots.

Table 44. Effects of Fog Chemistry on Onion Root and Shoot Fresh Weight[a]

| Treatment | Fresh Weight (g) Root | Fresh Weight (g) Shoot |
|---|---|---|
| No Fog | 10.7 (6.7) | 32.2 (14.0) |
| pH 5.48 | 10.9 (4.8) | 42.2 (17.5) |
| pH 3.22 | 9.8 (4.2) | 33.5 (15.4) |
| pH 2.72 | 8.4 (4.6) | 35.9 (16.0) |
| pH 2.73 | 8.8 (3.1) | 33.1 (11.5) |
| pH 1.76 | 7.8 (5.6) | 27.3 (11.4) |
| Outside | 9.4 (6.4) | 33.3 (17.9) |
| ANOVA | NS | NS |

[a] Listed means represent the average fresh weight of 15 individual plants with standard deviations in parentheses; plants exposed to fog in 21 events.

Onion showed a trend towards lowest shoot and fibrous root weights with the lowest fog pH of (1.76) (Table 44). The belowground onion bulb was included in the shoot weight. However, the results were not statistically significant primarily because of the large amount of variability between replicate plants.

Carrots also showed a trend towards lowest tap root and shoot weights at the lowest fog pH, but fog effects were not statistically significant (Table 45).

Alfalfa showed a trend towards lowest top fresh weight at the lowest pH, which was not statistically significant (Table 46). The plants received fog beginning 03 November 1986, however, the early growth was harvested on 16 December 1986 and discarded because of possible ambient ozone injury in late October. Thus the alfalfa harvested in late January were exposed to eight fog events.

The wheat seeds germinated slowly in the fall, and were large enough to begin fogging on 15 December 1986. They received a total of eight fogs through 15 January 1987. Wheat also showed a trend toward a reduction in aboveground fresh weight (Table 46).

Table 45. Effects of Fog Chemistry on Carrot Root and Shoot Fresh Weight[a]

| Treatment | Fresh Weight (g) | | | |
|---|---|---|---|---|
| | Whole-Plant | Root (R) | Shoot (S) | R:S Ratio |
| No Fog | 98.8 (30.5) | 66.6 (16.6) | 32.2 (19.4) | 2.39 (0.87) |
| pH 5.48 | 101.5 (31.5) | 67.3 (19.6) | 34.1 (15.2) | 2.17 (0.73) |
| pH 3.22 | 78.6 (52.5) | 52.5 (23.6) | 26.1 (10.9) | 2.06 (0.62) |
| pH 2.72 | 91.3 (36.0) | 57.6 (33.8) | 33.8 (15.8) | 1.89 (0.58) |
| pH 2.23 | 79.5 (28.1) | 53.4 (19.1) | 26.0 (10.7) | 2.10 (0.69) |
| pH 1.76 | 72.0 (38.1) | 47.0 (26.1) | 25.0 (14.1) | 1.98 (0.79) |
| Outside | 89.8 (31.3) | 62.2 (24.2) | 27.6 ( 9.5) | 2.30 (0.84) |
| ANOVA | NS | NS | NS | NS |

[a] Listed means represent the average fresh weight for 13 to 15 separate plants with standard deviations in parentheses. Each plant was exposed to 21 fog events.

Table 46. Effects of Fog Chemistry on Alfalfa and Wheat Aboveground Fresh Weight[a]

| Treatment | Fresh Weight (g) | |
|---|---|---|
| | Alfalfa | Wheat |
| No Fog | 93.5 (29.3) | 124.3 (27.9) |
| pH 5.48 | 107.2 (35.8) | 124.5 (25.0) |
| pH 3.22 | 96.1 (27.8) | 119.1 (30.7) |
| pH 2.72 | 94.4 (31.3) | 112.3 (33.4) |
| pH 2.23 | 91.3 (29.7) | 124.7 (14.5) |
| pH 1.76 | 79.3 (25.7) | 107.1 (29.2) |
| Outside | 94.0 (29.3) | 116.3 (24.2) |
| ANOVA | NS | NS |

[a] Listed means represent the average fresh weight of 15 individual plants with standard deviations in parentheses. The alfalfa plants were exposed to 21 fog events and wheat exposed to eight events.

Table 47. Effects of Fog Chemistry on Potato Root and Shoot Fresh Weight[a]

| | Fresh Weight (g) | | |
|---|---|---|---|
| Treatment | Root (R) | Shoot (S) | R:S Ratio |
| No Fog | 417 (147) | 243 (47) | 1.78 (0.40) |
| pH 5.48 | 440 (171) | 241 (57) | 1.79 (0.54) |
| pH 3.22 | 459 (176) | 246 (54) | 1.71 (0.50) |
| pH 2.72 | 414 (204) | 240 (59) | 1.66 (0.60) |
| pH 2.23 | 443 (140) | 245 (46) | 1.78 (0.43) |
| pH 1.76 | 405 (108) | 260 (43) | 1.56 (0.36) |
| Outside | 459 (147) | 259 (47) | 1.75 (0.40) |
| ANOVA | NS | NS | NS |

[a] Listed means represent the average fresh weight in 15 sample plants with standard deviations in parentheses. Plants were exposed to 11 fog events from 03 November 1986 to 08 December 1987.

Table 48. Effects of Fog Chemistry on Potato Shoot Dry Weight[a]

| | Dry Weight (g) | | |
|---|---|---|---|
| Treatment | Shoot | Leaves | Stem |
| No Fog | 27.0 (4.8) | 18.4 (4.1) | 8.6 (1.9) |
| pH 5.48 | 27.1 (4.8) | 18.8 (3.1) | 8.9 (2.6) |
| pH 3.22 | 28.0 (5.1) | 19.3 (3.5) | 8.6 (2.0) |
| pH 2.72 | 28.1 (9.1) | 18.5 (4.8) | 10.0 (5.3) |
| pH 2.23 | 28.2 (4.6) | 19.6 (3.5) | 8.6 (1.5) |
| pH 1.76 | 30.2 (4.6) | 21.2 (3.6) | 9.0 (1.4) |
| Outside | 29.1 (5.3) | 19.9 (3.3) | 9.2 (2.4) |
| ANOVA | NS | NS | NS |

[a] Listed means represent the average values of 14 or more plants per treatment group with standard deviations in parentheses. Plants exposed to fog received 11 exposures.

Table 49. Effects of Fog Chemistry on Measures of Broccoli Aboveground Biomass[a]

| | Fresh Weight (g) | | | |
|---|---|---|---|---|
| Treatment | Influorescence | Shoot | Stem | Leaves |
| No Fog | 167 (39)xy | 407 (26)x | 127 (10)x | 280 (22)x |
| pH 5.48 | 160 (42)xy | 393 (36)x | 115 (14)y | 278 (29)x |
| pH 3.22 | 147 (37)y | 412 (49)x | 121 (16)xy | 291 (38)x |
| pH 2.72 | 183 (34)x | 406 (30)x | 123 (15)xy | 283 (22)x |
| pH 2.23 | 156 (41)xy | 354 (22)y | 113 (10)y | 241 (19)y |
| pH 1.76 | 105 (29)z | 230 (29)z | 76 (15)z | 154 (19)z |
| Outside | 151 (32) | 392 (49) | 117 (16) | 275 (36) |
| ANOVA | * | * | * | * |

[a] Listed means represent the average values of 15 individual plants with standard deviations in parentheses. Plants were exposed to 19 fog events.

The potato plants received 11 fog events between 03 November and 08 December 1986, at which time the plants were harvested because the tubers were outgrowing the pots. There was no evidence for any significant decrease in potato shoot dry weight (Table 47), or in either the dry weight of leaf and stem portions (Table 48). Potato exhibited a trend toward decreased tuber (i.e root), but not decreased shoot fresh weights with increasing fog acidity (Table 47). The tuber/shoot ratio (i.e. R:S ratio) also appeared to decrease with increasing fog acidity, however, the differences in responses among treatment groups were not statistically significant.

Broccoli appeared to be the most sensitive species to acidic fog. This species exhibited the largest and only statistically significant differences in biomass production due to acidic fog exposure. Fresh weights of the influorescence, shoot, stem, and leaves were all reduced by pH 1.76 fog compared to pH 5.48 or no fog plants (Table 49). Fresh weights of shoots, stem, and leaves were also reduced by pH 2.23 fog. Dry weight of shoots, leaves, and stems were all reduced by pH 1.76 and 2.23 fogs (Table 50). There was also a trend toward reduced dry weight responses in plants exposed pH 2.72 fogs, though the differences compared to pH 5.48 and no fog plants were not statistically significant. Root dry

Table 50. Effects of Fog Chemistry on Measures of Broccoli Aboveground and Belowground Biomass[a]

| | Dry Weight (g) | | | |
|---|---|---|---|---|
| Treatment | Shoot | Leaf | Stem | Root |
| No Fog | 69.5 (11.0)wx | 45.6 (9.2)wx | 23.9 (3.3)w | 116 (37)y |
| pH 5.48 | 66.4 ( 6.9)wx | 45.9 (5.6)wx | 20.6 (3.3)xy | 117 (36)y |
| pH 3.22 | 72.3 (10.9)w | 49.4 (8.8)w | 22.9 (4.3)wx | 124 (39)y |
| pH 2.72 | 64.5 ( 7.8)x | 42.7 (5.5)x | 21.7 (4.4)wxy | 96 (32)yz |
| pH 2.23 | 54.3 ( 4.9)y | 35.1 (3.6)y | 19.2 (3.0)y | 118 (44)y |
| pH 1.76 | 32.4 ( 3.9)z | 22.0 (2.2)z | 10.4 (2.2)z | 73 (40)z |
| Outside | 67.8 (12.0) | 45.3 (8.2) | 22.5 (4.9) | 114 (50) |
| ANOVA | ** | ** | ** | ** |
| L.S.D. | 6.02 | 4.75 | 2.66 | 28.95 |

[a] Listed means represent the average dry weight of 14 or more plants with standard deviations in parentheses. Plants received fog in 19 events.

weights also were significantly lower in pH 1.76 plants compared to the other treatments groups.

b. Physiology

Potato leaf Ts, Cs, and Pn rates all were altered significantly by acidic fog treatment (Table 51). There appeared to be decreases in all three parameters at both pH 3.22 and 1.76, but not 2.72 and 2.23. Broccoli leaf Ts, Cs, and Pn rates all were significantly reduced by the pH 1.76 acidic fog treatment (Table 52).

## C. Synthesis

Mean fog pH levels of 1.68 to 7.24 were used in the present study to examine crop growth and yield responses to twice weekly applications of fog. The pH 7.24 (spring) and 5.48 (winter) fogs were used as control fog treatments to allow for assessing the effects of fog acidity on plant responses (i.e. compared to pH 1.68 fog treatment) separate from the effects of fog application (i.e. compared to 'no fog' treatment). The selection of a pH range from 1.68 to 3.22 was based on results from greenhouse studies (Granett and Musselman, 1984; Bytnerowicz et al., 1986), and

Table 51. Effects of Fog Chemistry on Physiological Responses in Potato[a]

| Treatment | Ts | Cs | Pn |
|---|---|---|---|
| No Fog | 98.5 (44.9)x | 0.56 (0.29)x | 0.69 (0.26)y |
| pH 5.48 | 89.6 (40.1)yx | 0.47 (0.22)xyz | 0.62 (0.21)yz |
| pH 3.22 | 72.0 (35.5)z | 0.39 (0.23)z | 0.59 (0.22)z |
| pH 2.72 | 96.3 (37.0)yx | 0.53 (0.21)xy | 0.70 (0.21)y |
| pH 2.23 | 86.8 (33.2)xyz | 0.47 (0.21)xyz | 0.64 (0.21)yz |
| pH 1.76 | 80.0 (38.0)yz | 0.44 (0.23)yz | 0.56 (0.26)z |
| Outside | 102.0 (51.0) | 0.55 (0.30) | 0.66 (0.21) |
| ANOVA | * | * | * |
| L.S.D. | 15.23 | 0.09 | 0.09 |

[a] Listed means represent the whole-season average of 51 sample measurements taken on the morning of nine fog events, with standard deviations in parentheses. Values followed by dissimilar letter designations indicate statistically significant differences at a level of $p<0.05$. Plants received a total of 11 fog applications. Abbreviations: Ts = Transpiration (mg $H_2O$ $m^{-2}$ $s^{-1}$); Cs = Stomatal conductance to water vapor (cm $s^{-1}$); Pn = Net Photosynthesis (mg $CO_2$ $m^{-2}$ $s^{-1}$)

the findings of Jacob et al. (1985), who collected and measured the most acidic natural fog sample (i.e. pH 1.69) at Corona del Mar.

In the present study, growth and yield responses in all eleven commercially-important crops were found to be adversely affected by twice weekly applications of pH 1.68 or 1.76 fog, relative to responses measured in crops exposed in the 'control' fog treatment groups. Moreover, there was a tendency for plants that were not fogged to exhibit lower fruit yield or whole-plant weights than plants exposed to pH 2.22 to 7.24 fog.

Acidic wet depositions (pH 4.0 or lower) previously were found to have deleterious effects on fruit and flower development in crops and trees (Evans, 1984). Mechanistically, for example, the reduction of soybean seed yield by acid rain was found to be due to decreased pod number per plant, caused by reduced rates of flower pollination, increased flower drop, or inadequate development of fruits (Evans et al., 1985). In the three fruit crops examined in the present study (strawberry, tomato, and green pepper), fruit yield (fresh weight and number) and whole-plant dry weight were consistently reduced by pH 1.68 fog relative to values found in plants exposed to pH 7.24 fog. Specifically, fog at pH 1.68

Table 52. Effects of Fog Chemistry on Physiological Responses in Broccoli[a]

| Treatment | Ts | Cs | Pn |
|---|---|---|---|
| No Fog | 115.5 (45.5)y | 0.88 (0.34)y | 0.98 (0.28)y |
| pH 5.48 | 109.0 (41.3)y | 0.83 (0.38)y | 0.95 (0.25)y |
| pH 3.22 | 107.2 (42.5)y | 0.80 (0.37)y | 0.97 (0.28)y |
| pH 2.72 | 109.0 (43.4)y | 0.83 (0.38)y | 0.98 (0.27)y |
| pH 2.23 | 104.1 (36.8)y | 0.78 (0.33)y | 0.91 (0.26)y |
| pH 1.76 | 88.4 (38.4)z | 0.66 (0.31)z | 0.67 (0.27)z |
| | | | |
| Outside | 109.9 (40.1) | 0.83 (0.33) | 0.95 (0.26) |
| ANOVA | * | * | * |
| L.S.D. | 12.27 | 0.10 | 0.08 |

[a] Listed means represent the whole-season average of 88 sample measurements taken on the morning of thirteen fog events, with standard deviations in parentheses. Plants received a total of 19 fog exposures. Means followed by dissimilar letter designations indicate statistically significant differences ($p<0.05$).

reduced fruit fresh weight by 30 to 58%, and whole-plant dry weight by 15 to 28%. In tomato and green pepper, percentage reductions in fruit fresh weight were approximately twice as great as those observed for whole-plant dry weight, suggesting that fruit production in these crops may be more sensitive than vegetative growth to $H^+$ depositions from fog. The observed fruit weight reductions in plants exposed to pH 1.68 fog were in part due to decreased fruit number.

In contrast, percentage reductions in strawberry fruit (30%) and whole-plant dry weight (28%) caused by pH 1.68 fog were of similar magnitude. Relative to yield responses in tomato and green pepper, the lack of an enhanced reduction in fruit weight (with respect to percentage decreases in whole-plant dry weight) may have been due to reduced depositions of $H^+$ to strawberry fruits directly. In comparison, green pepper and tomato fruits intercepted sizeable quantities of $H^+$ as necrotic lesions (on fruits) were common in plants exposed to pH 1.68 fog (visual observations).

In alfalfa and celery, biomass yield responses to acid fog seemed to be species-specific. Whole-plant dry weight in alfalfa was reduced by pH

1.68 fog, but celery plant weight was not adversely affected. Tolerance of celery to pH 1.68 fog may have in part been due to a compact growth habit, which effectively reduced the amount of plant surface area for fog interception. Moreover, the acidification of stem and leaf cells may also have been moderated by a highly developed cuticle (i.e. which reduced $H^+$ entry into cells). In alfalfa, the more open growth habit could encourage fog transport through and deposition to leaves and a likely thin leaf cuticle could have contributed to a lower acid fog tolerance. In view of these considerations, differences in fog sensitivity between these two crops may be principally a function of the amount of fog captured per unit mass of plant tissue.

Alterations in growth and yield responses due to acid fog or $O_3$ could be correlated to reduced rates of photosynthesis in strawberry and green pepper. In particular, transpiration ratios were markedly higher in plants exposed to pH 1.68 fog, suggesting that water use efficiency was disrupted. The mechanism of disruption on a whole-plant basis appears to differ for strawberry and green pepper in that leaf area was reduced by pH 1.68 fog in strawberry, and by $O_3$ in green pepper. Reduced fruit yields in both instances could in part be explained by the combination of lower leaf area and modest reductions in photosynthesis. Decreased assimilate partitioning to storage and/or belowground organs at the expense of maintaining vegetative structures may occur when plants are exposed to acid precipitation or $O_3$.

Comparison of percentage reductions in fruit yield vs. total plant dry weight support preliminary assessments that the sensitivity of reproductive structures to acid fog or $O_3$ is greater than for vegetative plant parts. For crops where yield depends on the growth of vegetative structures (i.e. celery), injury to stems and leaves may reduce the marketable yield, but not dry matter accumulation.

It is concluded that the highly acidic fogs (pH 1.8 or lower) that occasionally occur in the South Coast Air Basin or San Joaquin Valley of California can be phytotoxic, if plants are exposed to repeated applications of fog, over extended periods of time. Despite low rates of deposition (i.e. mm $h^{-1}$), inputs of $H^+$ from fog may exceed the acid buffering capacity of crops and disrupt normal plant growth and development. Moreover, the adverse effects of $H^+$ loading may have a greater impact on the development of reproductive structures. However, because these most highly acidic fogs are not common, the effects of current ambient acidic fogs on commercial crops may not be very great. More common acidic fogs of pH 2.0 and higher could affect crop quality only if visible symptoms affected the commercially important part of the plant, but not productivity.

Physiologically, it appears that acidic fog and smog can cause small alterations in fundamental plant growth processes (i.e. photosynthesis and transpiration) that may have a cumulative effect over the course of a growing season. While sizeable (i.e. statistically significant) alterations may not be detectable at any specific time of sampling, the sum of the small changes that occur over time (i.e. expressed as the whole-season average response) appear to be correlated with yield or whole-plant growth responses. In view of the relatively short growing cycle of crops, the insidious impacts of acidic fog or smog may not cause significant alterations in growth or yield due to the short duration of pollutant exposure. Longer-term exposures, such as those experienced by forest tree species may provide a more appropriate experimental design for accurately assessing the effects of these air pollutant stresses.

# IV. REFERENCES

Appel, B.R., E.M. Hoffer, Y. Tokiwa and E.L. Kothny. 1982. Measurement of sulfuric acid and particulate strong acidity in the Los Angeles Basin. Atmos. Environ. 16:589-593.

Brewer, R.L., R.J. Gordon, L.S. Shepard and E.C. Ellis. 1983. Chemistry of mist and fog from the Los Angeles urban area. Atmos. Environ. 17:2267-2270.

California Department of Food and Agriculture. 1982. California Agriculture.

Craker, L.E. and D. Bernstein. 1984. Buffering of acid rain by leaf tissue of selected crop plants. Environ. Pollut. 36:375-381.

Evans, L.S. 1984. Acidic precipitation effects on terrestrial vegetation. Ann. Rev. Phytopath. 22:397-420.

Granett, A.L. and R.C. Musselman. 1984. Simulated acidic fog injures lettuce. Atmos. Environ. 18:887-890.

Heileman, B. 1983. Acid fog. Environmental Science and Technology 17:117-120A.

Irving, P.M. 1985. Modeling the response of greenhouse-grown radish plants to acidic rain. Environ. Exp. Bot. 25:327-338.

Jacob, D.J., J.M. Waldman, M. Haghi, M.R. Hoffman and R.C. Flagan. 1985. Instrument to collect fogwater for chemical analysis. Rev. Sci. Inst. 56:1291-1293.

Jacob, D.J., J.M. Waldman, J.W. Munger and M.R. Hoffman. 1985. Chemical composition of fogwater collected along the California coast. Environ. Sci. Tech. 19: 730-740.

Lindhurst, R.A., J.P. Baker and A.M. Bartuska. 1982. Effects of acidic deposition: A brief review. pp. 82-113 in Atmospheric Deposition. A Specialty Conference. E.R. Frederick (ed.). APCA Publ. SP-49.

Lichtenthaler, H.K. and A.R. Wellburn. 1983. Determination of total carotenoids and chlorophylls a and b of leaf extracts in different solvents. Biochem. Soc. Trans. 603:591-592.

Lovett, G.M., W.A. Reiners, and R.K. Olson. 1982. Cloud droplet deposition in subalpine fir forests: hydrological and chemical inputs. Science 218:1303-1304.

Munger, J.W., D.J. Jacob, J.M. Waldman and M.R. Hoffman. 1983. Fogwater chemistry in an urban atmosphere. J. Geophys. Res. 88:5109-5121.

Musselman, R.C., J.L. Sterrett and A.L. Granett. 1985. A portable fogging apparatus for field or greenhouse use. HortScience 20:1127-1129.

Pylypec, B. and R.E. Redmann. 1984. Acid-buffering capacity of foliage from boreal forest species. Can. J. Bot. 62:2650-2653.

Roberts, L. 1982. California's fog is far more polluted than acid rain. BioScience 32:778-789.

Scherbatskoy, T. and R.M. Klein. 1983. Response of spruce and birch foliage to leaching by acidic mists. J. Environ. Qual. 12:189-195.

Steel, G.D and J.H. Torrie. 1960. Principles and Procedures of Statistics. 1st ed. New York: McGraw-Hill.

Temple, P.J., R.W. Lennox, A. Bytnerowicz and O.C. Taylor. 1987. Interactive effects of simulated acidic fog and ozone on field grown alfalfa. Environ. Exp. Bot., 27:409-417.

Thomas, M.D., R.H. Hendrick and G.R. Hill. 1952. Some impurities in the air and their effects on plants. In: Air Pollution, Proceedings of the U.S. Technical Conference on Air Pollution. (L.C. McCabe, ed.), McGraw-Hill, New York, pp. 40-47.

Thompson, C.R., G. Kats, E.L. Pippen and W.H. Isom. 1976. Effect of photochemical air pollution on two varieties of alfalfa. Environ. Sci. and Tech. 10:1237-1240.

Thompson, C.R. and D.M. Olszyk. 1985. A Field Air Exclusion System for Measuring Air Pollutant Effects on Crops. Electric Power research institute, Final Report for Project number NP1908-3, In Press.

Thompson, C.R. 1985. Final Report for the Project "Effects of Air Pollutants on California Winter Crops." Contract Number A3-057-33.

Troiano, J., L. Colavito, L. Heller, D.C. McCune, and J.S. Jacobson. 1983. Effects of acidity of simulated rain and its joint action with ambient ozone on measures of biomass and yield in soybean. Environ. and Exp. Bot. 23:113-119.

Waldman, J.M., J.W. Munger, D.J. Jacob, R.C. Flagan, J.J. Morgan and M.R. Hoffman. 1982. Chemical composition of acid fog. Science 218:677-680.

Wood, T. and F.H. Bormann. 1975. Increases in foliar leaching caused by acidification of an artificial mist. Ambio 4:169-171.