THE EFFECTS OF OZONE ON PHOTOSYNTHESIS, VEGETATIVE GROWTH AND DEVELOPMENT OF WOODY PERENNIALS IN THE SAN JOAQUIN VALLEY OF CALIFORNIA

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University of California
Davis, CA 95616
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Dr. L. E. Williams
Associate Professor
Department of Viticulture and Enology

Dr. T. M. DeJong
Associate Professor
Department of Pomology

Dr. W. A. Retzlaff
Post-doctoral Research Associate
Department of Viticulture and Enology

ABSTRACT

Nursery stock of nine fruit and nut tree species were planted in open-top chambers on 1 April 1988 at the University of California's Kearney Agricultural Center located in the San Joaquin Valley. The trees were then exposed to three levels of atmospheric ozone partial pressures (charcoal filtered air, ambient air, or ambient air + ozone) from 1 August to 17 November 1988. The mean 12-h (0800-2000 h) ozone partial pressure measured in open-top chambers of the charcoal filtered treatment averaged 0.030 $\mu Pa\ Pa^{-1}$ (0.030 ppm) ozone during the experimental period. Mean ozone partial pressures measured in the ambient chambers were 0.051 $\mu Pa\ Pa^{-1}$ (0.051 ppm) and those in the ambient + ozone treatment 0.117 $\mu Pa\ Pa^{-1}$ (0.117 ppm) over the same time period. The relationship between leaf net CO_2 assimilation rate and 12-h mean ozone partial pressure decreased linearly with increasing ozone partial pressure for the almond, plum, apricot, prune, pear, and apple cultivars. Stomatal conductances (g_s) of apricot, prune, apple, almond, and plum also decreased linearly with increasing ozone partial pressure. Cross-sectional area relative growth rates (RGRs) of almond, plum, apricot, pear, and apple declined linearly with increasing ozone partial pressure. Net CO_2 assimilation rate, stomatal conductance, and trunk growth of cherry, peach, and nectarine were unaffected by the ozone treatments. The results indicate that decreases in leaf gas exchange were probable contributors to decreases in young tree growth of the susceptible species/cultivars. However, several commercial fruit tree species/cultivars were identified as being relatively tolerant to ozone based upon measurements taken in this study.

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SUMMARY AND CONCLUSIONS

Chronic exposure to low partial pressures of ozone has been shown to have a negative effect on growth and photosynthesis of deciduous tree species. However, there has been no comprehensive study assessing the effects of ozone pollution on photosynthesis and growth of fruit and nut tree species. The objectives of the present study were to determine the effects of ozone pollution on leaf net CO_2 assimilation and growth of nine fruit and nut tree species in the San Joaquin Valley of California.

1. Data from this study indicate that ambient and slightly greater than two times ambient ozone partial pressures reduced mean rates of leaf net CO_2 assimilation of the plum, apricot, almond, prune, and pear varieties grown in this study when compared to mean rates of leaf net CO_2 assimilation in charcoal filtered air. Further, photosynthesis decreased linearly with increasing ozone partial pressure indicating more potential problems if atmospheric ozone continues to increase.

2. Mean rates of leaf net CO_2 assimilation of the peach, nectarine, and cherry varieties grown in this study were unaffected by increasing atmospheric ozone partial pressures. The lack of effects of chronic ozone exposure on some species indicates that it may be possible to breed or select fruit and nut tree cultivars with increased resistance to ozone.

3. Ozone partial pressures greater than 0.051 $\mu Pa\ Pa^{-1}$ (0.051 ppm) resulted in decreased cross-sectional area growth of plum, apricot, almond, apple, and pear. Decreases in trunk growth in the present study are apparently related to the decreases in leaf net CO_2 assimilation in these trees. Lack of a trunk growth response by the peach, nectarine, cherry, and prune varieties in the present study can be correlated with ozone's lack of effect on photosynthesis.

4. Ozone partial pressures greater than 0.051 $\mu Pa\ Pa^{-1}$ (0.051 ppm) decreased stored reserves (root starch) of peach, plum, apricot, and almond trees in this study. Decreased stored reserves could contribute to less new growth next year and an overall decline in tree growth in future years.

RECOMMENDATIONS

1. Photosynthesis and growth of fruit and nut trees was reduced in ambient and two times ambient ozone partial pressures in the present study. As a consequence, ozone pollution should be reduced from current levels to permit maximum fruit and nut production in the San Joaquin Valley of California.

2. Since there was a lack of effect of chronic ozone exposure on some species used in the present study, investigations into the mechanism of this response should be conducted. Further, development of fruit and nut tree cultivars with increased resistance to ozone pollution should be investigated.

INTRODUCTION

Chronic exposure to low partial pressures of ozone has a negative impact on growth of coniferous and deciduous tree species (Houston 1974, Reich and Amundson 1985, Steiner and Davis 1979, Townsend 1974, Pye 1988). Some of the reduction in growth of trees is apparently due to the inhibitory effect of ozone on the process of photosynthesis (Reich 1983, Reich and Amundson 1985). Air pollution (ozone) decreases the rate of leaf photosynthesis whether the plants are exposed to low pollution levels for an extended time (Reich 1983, Reich and Amundson 1985, Roper and Williams 1989) or to acute levels of the pollutant for a short time (Hill and Littlefield 1969, Roper and Williams 1989). Chronic exposure to low partial pressure of ozone may accelerate leaf aging and this may partially explain the decline in leaf photosynthetic capacity (Reich 1983).

The effect of ozone on the growth of woody perennials generally has been limited to studies involving small potted forest tree species (Reich and Amundson 1985, Steiner and Davis 1979, Taylor et al. 1986, Pye 1988). The results have indicated that ambient ozone partial pressure can reduce dry matter production and growth. In addition, yields of field-grown *Vitis vinifera* have been reduced by ambient levels of ozone when compared to charcoal filtered air (Brewer and Ashcroft 1983). The response of potted trees and field-grown grapevines in open-top chambers to low partial pressures of ozone indicate that the growth of fruit and nut trees may be reduced by chronic exposure to ambient ozone levels. There has been no comprehensive study assessing the effects of ozone pollution on growth and photosynthesis of fruit and nut tree species. The objectives of this study were to determine the effects of ozone pollution on leaf net CO_2 assimilation and growth of nine fruit and nut tree species in the San Joaquin Valley of California. This fruit production region is characterized by ambient ozone partial pressures that consistently exceed U. S. Environmental Protection Agency standards.

MATERIALS AND METHODS

Plant Materials and Ozone Treatments

Nursery stock of peach (*Prunus persica*, cv. 'O' Henry), nectarine (*P. persica*, cv. Fantasia), plum (*P. salicina*, cv. Casselman), apricot (*P. armeniaca*, cv. Tilton), almond (*P. dulcis*, cv. Nonpareil), prune (*P. domestica*, cv. Improved French), cherry (*P. avium*, cv. Bing), Oriental Pear (*Pyrus serotina*, cv. 20th Century), and apple (*Malus pumula*, cv. Granny Smith) were planted 1 April 1988 in 12 permanent open-top chambers at the University of California Kearney Agricultural Center near Fresno, CA. One tree of each species was planted per chamber.

Cultural practices for these trees were the same as those used commercially to establish young orchards. Trees were flood irrigated approximately once a week throughout the growing season. Just prior to ozone exposure, trees were fertilized with 45 g/tree of ammonium nitrate.

Open-top chambers used in this study were igloo shaped with a 3.7 x 3.7 m square base and a circular 3.1 m diameter open-top 2.7 m above the chamber floor. Chamber frames were constructed of metal conduit with the walls consisting of 12 mil polyvinyl plastic. Air ducts within the chambers were two 20 cm and two 15 cm diameter PVC pipes that extended along the chamber floor from one side wall to the other (3.7 m long) equidistant from one another. Holes (5 x 13 cm) were cut in the PVC pipe 31 cm apart to permit air flow upwards into the chambers.

Plastic walls were put on the chambers 20-24 July 1988 and blowers were turned on at that time. Blowers provided approximately 67.1 m^3 min^{-1} air, enough air to change the air volume in the chambers 2 times min^{-1}. Chamber blowers were operated 24 hours per day.

Ozone treatments were initiated on 1 August and continued until 17 November 1988. After 17 November, chamber tops were removed. Trees overwintered and were then allowed to flush the following spring (1989). Trees were removed from the chambers 1 April 1989.

Ozone treatments imposed in this study were charcoal filtered air (C), ambient air (A), and ambient air + ozone (T). Treatments were randomly assigned to a chamber and there were 4 replications containing 1 chamber of each treatment. Ozone partial pressures in the chambers were measured with a Dasibi Model 1003 AH Ozone Analyzer. Calibration occurred weekly and involved cleaning and frequency count checks. An Apple IIe microcomputer interfaced with Cyborg's Integrated System for Automated Acquisition and Control (Model 91A) permitted sequential sampling of chamber ozone partial pressure hourly from 0800 to 1900 h (Pacific Daylight Time, PDT) daily. Chambers were connected to the monitoring system via teflon tubing and solenoid valves. Inlets for air samples were suspended 1 meter above the soil in the center of each chamber. Air from each chamber was passed through the monitoring system for 2 minutes prior to measuring ozone levels to permit residue purging from common sampling lines and the ozone monitor. After each measurement, chamber number, ozone level, hour, and date were stored on floppy disk and printed on paper for backup.

Ozone for the ambient air + ozone (T) treatment chambers was generated from ambient air with an OREC Model 03B-AR/0 Ozone Generator and delivered via teflon tubing to the delivery air stream of these chambers. The ozone generator was computer automated to operate at full potential from 0800 to 1900 h. This resulted in ozone concentrations approximately 2 times ambient.

At the end of the ozone treatment period (17 November), ozone data stored on floppy disks were transmitted to a PRIME minicomputer. Final ozone partial pressure data analysis was conducted utilizing SAS. Ozone 12-h means (0800-2000 h PDT) and number of hours greater than 0.10 $\mu Pa\ Pa^{-1}$ (0.10 ppm) and 0.20 $\mu Pa\ Pa^{-1}$ (0.20 ppm) were calculated for each treatment. These ozone partial pressures were used to assess the effects of ozone pollution on tree growth and development.

Lastly, gas concentrations can be expressed in several ways: volume or mass or number of moles of gas per unit of volume or as partial pressure or mole fraction. S. I. units of volume concentrations are m^3 or cm^3 m^{-3} as opposed to the more frequently used (volume) parts per million. The proportion of gas in a mixture also can be described by its pressure (the unit used to express pressure is the pascal [Pa]). Dalton's law of partial pressure states that in a mixture of gases each gas has the same pressure as if occupying the volume alone and the total pressure is the sum of the partial pressures of all gases in the volume. Partial pressure and mole fraction of a gas are numerically equal. Many instruments for measuring gases (such as an ozone analyzer) indicate concentration as vpm (ppm) and this is directly proportional to the gas' mole fraction. Therefore, to conform with S. I. units, ozone was expressed as a partial pressure in this report. An ozone partial pressure of 0.25 μPa Pa^{-1} is roughly equivalent to 0.25 ppm or 0.25 μl l^{-1} in air.

Gas Exchange

Approximately three weeks after treatment initiation, measurements of leaf net CO_2 assimilation and stomatal conductance (g_s) were made on a single species each day on a rotating basis. This process was repeated at 16-day intervals and at the end of the study each species had been measured 4 times. On each date for a particular species measurements were made on 4 leaves from each tree in every treatment/chamber (16 leaves/treatment, 48 leaves per sample day). Fully expanded leaves that were in direct sunlight were selected for measurement. These leaves were from similar canopy levels near the point where the shoots were tagged for length measurements. Measurements were made between 1030 and 1130 h.

All measurements were made utilizing an Analytical Development Corporation (Hoddesdon, England) Portable Infrared CO_2 Analyzer (Model LCA-2), Air Supply Unit with Mass Flowmeter (Model ASUM), Data Processor for the LCA-2 (Model DL-2), and broad leaf Parkinson Leaf Chamber. The IRGA was used in the differential mode. Air for the leaf chamber was taken from the internal duct system of the open-top chamber in which the tree was growing. Data were recorded on the data processor until all measurements on that particular date had been taken. Data was then transferred to the minicomputer for later analysis.

Growth Measurements

From 1 August 1988 (treatment initiation) and at 2 month intervals through 1 December 1988 circumference of each tree trunk was measured. Painted bands on the trees just above the soil-line were used as reference points in order to minimize measurement errors. The increase in trunk cross-sectional area from 1 August to 1 December 1988 was calculated from the circumference data using the equation:

$$\text{Cross-sectional area} = (\text{circumference}^2)/4*\text{Pi}$$

Cross-sectional area was used because small increases in circumference result in geometric increases in cross-sectional area. Cross-sectional area relative growth rate (RGR) was calculated for the entire exposure period (1 August to 1 December 1988) to quantify the effects of changing atmospheric ozone partial pressures on the mean rate of increase of cross-sectional area per unit of cross-sectional area present.

Four growing shoots per tree were selected on all species to follow shoot growth, leaf number, and lateral branching response characteristics. Four shoots of peach, apricot, cherry, nectarine, apple, pear, and almond were tagged on 1 August above the last fully expanded leaf, so that any increases in shoot length, leaf number, and lateral branches above this point could be determined. Shoots on plum and prune were tagged and then summer pruned to prevent them from extending above the chamber top. The lateral shoot that emerged immediately below the pruning cut was used for shoot measurements.

In all nine species, the shoot length, leaf number, and lateral branch determinations were made on 16 August, 1 and 21 September 1988, and 10 January and 1 April 1989. Since there were no leaves on the trees on 10 January, counts of node numbers per shoot were made instead of leaf number. Trees were visually inspected for foliar symptoms of chronic ozone injury when measurements were taken.

On 1 April 1989, all trees were removed from the ozone chambers in this study. Foliage that had emerged following the overwinter period was stripped from each tree and total foliage dry weight was determined. Trees were cut off at the ground-line and total dry weights of the trunk and branches were determined. A backhoe was used to scoop up the main portion of each trees root system in order to get a representative root sample for carbohydrate analysis. A sample of each tree's foliage, branches, and trunk also was prepared for carbohydrate analysis.

Carbohydrate Analysis

Soluble carbohydrates were analyzed by high pressure liquid chromatography (HPLC) with methods adapted from McBee and Maness (1982). Plant materials were dried at 78 °C in a forced air oven. Samples were ground to pass a 40 mesh screen in a rotary mill. Subsamples (100 mg) of ground tissue were extracted for 1 h in 5 ml 80% ethanol at 54 °C. Solids were then removed with a Swinnex filter. The pH of the filtrate was adjusted to 7 with 0.1 N KOH and 400 mg ion exchange resin was added and the samples shaken for 1 h. The ion exchange resin was removed by filtration and the samples were taken to dryness at 54 °C. The samples were resuspended in 3 ml water and injected into a Beckman Model 330 isocratic HPLC. Soluble sugars (fructose, glucose and sucrose) were separated with an Altex μ-spherogel column and detected with an Altex Model 156 refractive index detector. Peaks were integrated with a Hewlett-Packard 3390A reporting integrator.

The solids remaining from the initial filtration were resuspended in water and autoclaved for 30 min to solubilize the starch. The pH was adjusted to 5 with 0.2 N phosphoric acid and 23 units amyloglucosidase (Sigma) were added. Samples were incubated for 2 h at 54 °C after which the pH was adjusted to 7 and 400 mg ion exchange resin was added. After shaking for 30 min the samples were filtered and taken to dryness at 54 °C. Determination of the insoluble fraction was as described previously for the soluble portion.

Species selected for carbohydrate analysis included almond, plum, and apricot, all species that exhibited decreases in leaf net CO_2 assimilation with increasing ozone partial pressures, and peach and nectarine which had no changes in leaf net CO_2 assimilation with increasing ozone partial pressures.

Statistical Analysis

The experimental design was a randomized complete block with 3 treatments and 4 replications. The experiment was replicated/blocked four times to account for chamber location in the field and possible soil differences among chambers. Data for measurements that were repeated throughout the study were analyzed using a repeated measures analysis of variance with two grouping factors (replication and treatment) and one within factor (time) (Table A-3). Data collected only once during the study were analyzed by a standard ANOVA. In all analyses, Tukey's method was used for post hoc comparisons among treatment means ($\alpha<0.05$). Relationships between affected species growth and photosynthesis and corresponding ozone treatment levels were determined using regression analysis. Trends of interest in the data were presented as percent change from the C treatment to the A and T treatments even when there was no significant difference detected between treatment means.

Long-term Plum Experiment

Appendix B contains a status report describing the 1988 activities to establish the orchard setup for the long-term plum experiment.

RESULTS

Ozone Treatments

Hourly ozone partial pressures were averaged from 1 August to 17 November 1988 (Figure 1). The 12-hour mean ozone partial pressures (0800 to 2000 h PDT) of the charcoal filtered treatment were 60% of the ambient treatment, while the high ozone treatment was greater than twice that of ambient (Table 1). The number of hours each treatment ozone concentration was above 0.10 and 0.20 $\mu Pa\ Pa^{-1}$ (0.10 and 0.20 ppm) also indicated large treatment differences (Table 1).

Gas Exchange

Differences in leaf assimilation rate between trees growing in the C and A chambers and those growing in the T chambers for the plum, apricot, prune, almond, and pear varieties grown in this study began to appear approximately thirty days following treatment initiation (Table A-1). Differences in assimilation rate for these species continued until the end of the study period. Peach, cherry, nectarine, and apple trees showed little or no assimilation rate response to increasing atmospheric ozone partial pressures over the entire study period.

Leaf assimilation rate, averaged across the four measurement dates, for plum, apricot, prune, almond, and pear trees grown in the A chambers was slightly reduced (2-18%) compared with those in the C chambers (Table 2). There were larger reductions (> 37%) in leaf assimilation rates of these 5 affected species and apple grown in the T chambers compared with those from the C chambers. Furthermore, the relationship between seasonal mean CO_2 assimilation rate and mean ozone partial pressure for almond, plum, apricot, prune, pear, and apple trees decreased linearly with increasing ozone partial pressure in the present study (Figure 2a,b). However, assimilation rates of peach, nectarine, and cherry showed only a small response to increasing ozone partial pressure (Table 2, Figure 2c). Regression equations describing the relationships between leaf net CO_2 assimilation and increasing ozone partial pressures (Figure 2a,b,c) are presented in Table 11.

Plum, almond, and apple stomatal conductance (g_s) from the trees in the T chambers was less than that of the C and A chambers on several measurement dates (Table A-2). There were no differences over time in g_s with increasing atmospheric ozone partial pressures for the peach, apricot, cherry, prune, nectarine, and pear varieties grown in this study.

Stomatal conductances of plum and almond in the T chambers, averaged across the four dates, were reduced by more than 50% compared with trees grown in the C chambers (Table 3). Stomatal conductances of apricot, prune, and apple in the T chambers were only reduced 40% compared with trees grown in the C chambers. However, seasonal mean g_s of apricot, prune, and apple as well as from almond and plum declined linearly with increasing ozone partial pressure (Figure 3a,b). Stomatal conductances of peach, nectarine, cherry, and pear showed little or no response to increasing ozone partial pressure (Figure 3b,c). Regression equations describing the relationships between stomatal conductance and increasing ozone partial pressures (Figure 3a,b,c) are presented in Table 12.

Tree Growth

The mean cross-sectional area growth of plum, apricot, almond, pear, and apple in the T chambers was at least 30% less than the trees grown in the C chambers (Table 4). There was less or no reduction in cross-sectional area growth of the same species in the A chambers compared with the trees in the C chambers. Peach, cherry, prune, and nectarine trees in the T or A chambers had slight or no reductions in cross-sectional area growth compared with the trees from the C chambers.

Cross-sectional area relative growth rates (RGRs) from 1 August to 1 December followed the same patterns as cross-sectional areas (Table 5). However, plum, apricot, almond, pear, and apple trees in T chambers all had at least a 25 % reduction in the cross-sectional area relative growth rate compared with trees from the C chambers. The reduction in cross-sectional area relative growth rate of A chamber trees compared to trees from the C chambers was less than 25%. Peach, cherry, prune, and nectarine trees in the T or A chambers had slight or no reductions in cross-sectional area relative growth rates compared to trees from the C chambers.

Cross-sectional area RGR for almond, plum, apricot, pear, and apple decreased linearly with increasing 12-h mean ozone partial pressure (Figure 4a,b). Peach, nectarine, cherry, and prune cross-sectional area RGRs showed little or no response to ozone partial pressures (Figure 4b,c). Regression equations describing the relationships between cross-sectional area RGRs and increasing ozone partial pressures (Figure 4a,b,c) are presented in Table 13.

In general, trunk dry weights of plum, apricot, almond, and pear were reduced by at least 15% in the T chambers compared to trees grown in the C chambers (Table 6). There was less or no reduction in dry weight of the same species in the A chambers compared with trees from the C chambers. Dry weights of peach, cherry, prune, nectarine, and apple trees in T or A chambers were slightly reduced or equal to dry weights of trees grown in the C chambers.

Increased ozone in the chamber atmosphere generally had no effects on branch or leaf growth in the present study (Tables 7 & 8). Shoot length, leaf/node number, and lateral branching characteristics of all nine species were unaffected by increasing ozone concentration in this study. Shoot growth, as measured in this study, was highly variable and there were no significant response trends.

Carbohydrate Analysis

Almond trunk starch concentration was reduced for trees grown in the T chambers when compared to those grown in the C or A chambers (Table 9). All other species examined exhibited no reductions in trunk starch concentration with increasing atmospheric ozone partial pressure. Further, peach, plum, apricot, and almond root starch concentrations of trees in the T chambers were reduced compared to trees in the C or A chambers (Table 10). Nectarine exhibited no reductions in root starch concentration with increasing atmospheric ozone partial pressures. There were no reductions in trunk or root soluble sugars (glucose, sucrose, fructose) of any species in the present study.

Foliar Injury

Visual injury was observed on several species in the high ozone chambers approximately 3 weeks following treatment initiation. No visible injury symptoms were observed on any of the tree species in the C or A treatment/chambers throughout the study. At first, visible injury in the T chambers consisted of chlorotic spots and yellow flecking on the leaf surfaces of older foliage. This foliage had developed on the trees in the ambient environment prior to treatment initiation. As time progressed, these chlorotic areas became larger and turned brown due to tissue necrosis. Visual symptoms also began to appear on foliage that had emerged in the T atmosphere. Symptoms were most noticeable on the almond trees and to a lesser extent on the plum, apricot, prune, and pear trees. No visual injury symptoms appeared on the peach, cherry, nectarine, or apple varieties grown in this study.

Soon after visible injury became evident in the T chambers, the lower leaves abscised. By the time the ozone monitoring period was completed (17 November 1988), almond, apricot, and pear had lost approximately 50% of their older foliage (visual estimate). The plum and prune trees had lost some of their foliage (< 25% by visual estimate) while the peach, cherry, nectarine, and apple trees had lost virtually no leaves.

DISCUSSION

Mean CO_2 assimilation rates of plum, apricot, almond, prune, and pear were reduced by ambient and 2 times ambient ozone partial pressures when compared to charcoal filtered air. Reductions in these species rates of photosynthesis ranged from 2-18% in the ambient (A) atmosphere to > 41% in the enriched (T) atmosphere when compared to clean (C) air. The reductions in net CO_2 assimilation due to ambient ozone partial pressures exhibited by the trees in this study are similar to those reported by Reich and Amundson (1985) and Roper and Williams (1989). Data from 25 experiments on seedlings of 43 tree species also indicate that ozone can reduce photosynthesis at ambient concentrations common in many areas (Pye 1988). In the above cited studies, as well as in the present study, ozone partial pressures near or slightly above ambient partial pressure resulted in decreases in net CO_2 assimilation after 1 month or more following fumigation initiation, reflecting a cumulative response mechanism.

Not all species in the present study had depressed rates of photosynthesis with increasing ozone partial pressures. Peach, nectarine, and cherry were unaffected by increased ozone in the chamber atmosphere. Differential species responses to increasing atmospheric ozone partial pressures have been shown previously. White pine net photosynthesis decreased 15-20% in 0.14 μPa Pa^{-1} (0.14 ppm) ozone when compared with that measured in 0.02 μPa Pa^{-1} (0.02 ppm) (Reich et al. 1987). However in another study, there were no changes in the rate of photosynthesis of red spruce seedlings grown for 3 months in different ozone partial pressures (Laurence et al. 1989).

The reductions in net CO_2 assimilation for six of the species (plum, apricot, almond, apple, prune, and pear) with increasing ozone partial pressure were linearly related to ozone partial pressure. Reich and Amundson (1985) also found that long term exposure to ozone resulted in linear reductions in photosynthesis. The linear response of net CO_2 assimilation to ozone partial pressure should simplify modeling the effects of air pollution on carbon assimilation by trees. With the exception of cross-sectional area and cross-sectional area RGR, typical above ground growth measures from the present study failed to detect a deleterious response to ozone. In previous studies, it has been found that above ground growth is usually less affected than below ground growth by increased atmospheric ozone partial pressures (Pye 1988). If the photosynthetic response to ozone is cumulative during the exposure period, which has been reported previously and is illustrated in this study, then differences in growth responses would be expected to increase with longer periods of exposure (Pye 1988).

Cross-sectional area RGRs declined linearly in plum, apricot, almond, apple, and pear. Adams et al. (1988) found significant differences in above ground volume (D^2H) of loblolly pine seedlings exposed to elevated ozone levels. In their study as well as in the present study, differences appeared 1 month after fumigation began and continued until the end of the studies. Slight increases in peach and nectarine cross-sectional area RGRs are probably due to the small sample size (1 tree/chamber) and the large variability between individual trees. However, reduced competition from other greatly affected species in the chambers could also contribute to this small increase in growth.

Decreases in trunk growth in the present study are apparently related to the decreases in photosynthesis of these trees. Lack of a shoot and trunk growth response by the peach, nectarine, cherry, and prune varieties in the present study is apparently correlated with a lack of an ozone effect on photosynthetic responses. Red spruce, which showed no photosynthetic response to increasing atmospheric ozone, also had no changes in growth (Taylor et al. 1986, Laurence et al. 1989).

Significant decreases in root starch concentration were found in peach, plum, apricot, and almond trees grown in the high ozone atmospheres of the present study. Root starch concentration of pitch pine seedlings also was found to decrease with increasing ozone partial pressure (Scherzer and McClenahan 1989). Decreases in CO_2 assimilation of the plum, apricot and almond in the present study are apparently contributing to changes in the carbohydrate partitioning of these trees. However, decreases in peach root starch concentration cannot be directly attributed to decreases in CO_2 assimilation. Since CO_2 assimilation in peach was not reduced by high atmospheric ozone, normal reserves were apparently diverted away from storage for maintenance of other organs. Low levels of ozone (0.05-0.10 μPa Pa^{-1}) (0.05-0.10 ppm) have been reported to change the partitioning of carbohydrates in perennial plants such that shoots are favored over roots (Cooley and Manning 1987, Chappelka et al 1988). Further, at higher ozone levels (> 0.10 μPa Pa^{-1}) (> 0.10 ppm) when photosynthesis is reduced, the amount of carbohydrate partitioned to all sinks decreases, resulting in growth reductions.

The small areas of chlorosis and yellow flecking on the leaf surfaces of older foliage of the almond, plum, apricot, prune, and pear varieties grown in the T chambers in the present study are similar to those reported for other tree species. Typically, this visible ozone injury is often limited to small single groups of epidermal and palisade cells resulting in flecks and stipples (Prinz 1988). Pitch pine seedlings exhibited light chlorotic mottle on their oldest needles following 5 weeks in 0.3 μPa Pa^{-1} (0.3 ppm) ozone (Scherzer and McClenahen 1989). Chronic ozone partial pressures as low as 0.08 μPa Pa^{-1} (0.08 ppm) resulted in chlorosis or yellow flecking of leaves of birch seedlings (Keane and Manning 1988). Chappelka et al. (1988) observed visual symptoms on green and white ash seedlings grown at 0.10 μPa Pa^{-1} (0.10 ppm) for 6 weeks. Symptoms were characterized by stippling on the adaxial leaf surfaces which turned into tannish-brown necrotic lesions. These symptoms began appearing on the older ash leaves 3 weeks following fumigation initiation. In the present study, a similar time lapse occurred prior to observation of visual foliar symptoms indicating a cumulative response mechanism in the foliage.

Foliage that exhibited ozone damage on the almond, plum, apricot, prune, and pear all exhibited accelerated rates of leaf drop in the high (T) ozone atmospheres. Foliar leaf symptoms are often followed by leaf abscission and early or premature senescence (Prinz 1988). No indications of premature leaf drop were observed from the same species in the C or A chambers. Leaf drop of the almond, plum, apricot, prune, and pear foliage was observed approximately 4 weeks after treatment initiation in the T chambers. Again, this seems to indicate a threshold or cumulative response mechanism. Keller (1988) found that the life span of leaves from sensitive American aspen clones was reduced by increasing atmospheric ozone partial pressure. The ozone-sensitive clones exhibited leaf drop according to the length and partial pressure of the ozone exposure. At low partial pressures (0.027 μPa Pa^{-1} or ppm), leaf drop began occurring approximately 44 days following initiation of fumigation . At higher partial pressures (> 0.051 μPa Pa^{-1} or ppm), leaf drop began as early as 14 days following initiation of fumigation.

As indicated in the previous discussion, large differences exist within these nine fruit and nut tree species in their response to increasing atmospheric ozone partial pressures. Within the Prunus genus, almond, plum, and apricot all have decreased rates of net CO_2 assimilation and growth when exposed to increased atmospheric ozone. However, peach, nectarine, and cherry were unaffected. This indicates a differential species response within this genus. Most previous research has involved only one or two species per study with rare comparisons of differential ozone response within a single genus.

Pye (1988) cites multiple studies involving tree species exposed to increased atmospheric ozone partial pressures. Within a group of eleven individual studies involving the Pinus genus, all 4 species studied showed decreased rates of photosynthesis when trees exposed to high ozone partial pressures were compared to trees exposed to charcoal filtered air. Chappelka et al. (1988) reported a differential response in visible injury, shoot elongation, and shifts in biomass allocation as a result of increased atmospheric ozone in green ash (Fraxinus pennsylvanica Marsh.) and white ash (F. americana L.). However, even though there were differential responses, both ash species had negative responses to increased atmospheric ozone partial pressures. The present study is one of the first to indicate differential species responses, no response in some species and negative in others, within a single genus to increasing atmospheric ozone partial pressures.

In the present study, increasing ozone partial pressures to twice ambient for a 3 month period resulted in significant decreases in net CO_2 assimilation rate and reduced growth in plum, almond, apricot, apple and pear trees. These reductions appeared one month after treatment initiation and continued until the end of the study period, indicating a possible cumulative response mechanism. Exposing the same tree species to ambient partial pressures of ozone resulted in smaller reductions in net CO_2 assimilation and growth. However, as indicated by Reich and Amundson (1985), a 1 to 2 percent annual reduction in growth would result in much larger reductions over one or two decades. Therefore, the effect of small reductions in growth may be compounded over time in long-lived orchards. The maximum productive age of fruit orchards may be as great as 20 years, while for orchards of nut crops, such as almonds, it can be greater than 30 years. Thus, there is a distinct possibility that future ambient partial pressures of ozone will have a significant negative effect on fruit and nut tree growth, development, and productivity. However, the lack of effects of chronic ozone exposure on some species indicates that it may be possible to breed and select fruit and nut tree cultivars with increased resistance to ozone pollution.

LITERATURE CITED

Adams, M. B., J. M. Kelly and N. T. Edwards. 1988. Growth of *Pinus taeda* L. seedlings varies with family and ozone exposure. Water, Air and Soil Pollution 38:137-150.

Brewer, R. F. and R. Ashcroft. 1983. The effects of ambient air pollution on Thompson Seedless grapes. Final Report on Air Resources Board Contract A1-132-33. The effect of present and potential air pollution on important San Joaquin Valley crops: Grapes. 15 p.

Chappelka, A. H., B. I. Chevone, and T. T. Burk. 1988. Growth response of green and white ash seedlings to ozone, sulfur dioxide, and simulated acid rain. For. Sci. 34:1016-1029.

Cooley, D. R. and W. J. Manning. 1987. The impact of ozone on assimilate partitioning in plants: A review. Environ. Pollut. 47:95-113.

Hill, A. C. and N. Littlefield. 1969. Ozone. Effect on apparent photosynthesis, rate of transpiration, and stomatal closure in plants. Environ. Sci. Tech. 3:52-56.

Houston, D. B. 1974. Response of selected *Pinus strobus* L. to fumigations with sulfur dioxide and ozone. Can. J. For. Res. 4:65-68.

Keane, K. D., and W. J. Manning. 1988. Effects of ozone and simulated acid rain on birch seedling growth and formation of ectomycorrhizae. Environ. Pollut. 52:55-65.

Keller, T. 1988. Growth and premature leaf fall in American aspen as bioindicators for ozone. Environ. Pollut. 52:183-192.

Laurence, J. A., R. J. Kohut, and R. G. Amundsen. 1989. Response of red spruce seedlings exposed to ozone and simulated acidic precipitation in the field. Arch. Environ. Contam. Toxicol. 18:285-290.

McBee, G. G. and N. O. Maness. 1983. Determination of sucrose, glucose and fructose in plant tissue by high performance liquid chromatography. J. Chromatogr. 264:474-478.

Prinz, B. 1988. Ozone effects on vegetation. Tropospheric Ozone:161-184.

Pye, J. M. 1988. Impact of ozone on the growth and yield of trees: A review. J. Environ. Qual. 17(3):347-360.

Reich, P. B. 1983. Effects of low concentrations of ozone on net photosynthesis, dark respiration, and chlorophyll contents in aging hybrid poplar leaves. Plant Physiol. 73:291-296.

Reich, P. B. and R. G. Amundson. 1985. Ambient levels of ozone reduce net photosynthesis in tree and crop species. Science 230:566-570.

Reich, P. B., A. W. Schoettle, H. F. Stroo, J. Troiano, and R. G. Amundson. 1987. Effects of ozone and acid rain on white pine (Pinus strobus) seedlings grown in five soils. I. Net photosynthesis and growth. Can J. Bot. 65:977-987.

Roper, T. R. and L. E. Williams. 1989. The effects of ambient and acute partial pressures of ozone on leaf net CO_2 assimilation of field-grown Vitis vinifera L. Plant Physiol. 91:1501-1506.

Scherzer, A. M. and J. R. McClenahen. 1989. Effects of ozone or sulfur dioxide on pitch pine seedlings. J. Environ. Qual. 18:57-61.

Steiner, K. C. and D. D. Davis. 1979. Variation among Fraxinus families in foliar response to ozone. Can. J. For. Res. 9:106-109.

Taylor, G. E., R. J. Norby, S. B. McLaughlin, A. H. Johnson, and R. S. Turner. 1986. Carbon dioxide assimilation and growth of red spruce (Picea rubens Sarg.) seedlings in response to ozone, precipitation chemistry, and soil type. Oecologia 70:163-171.

Townsend, A.M. 1974. Sorption of ozone by nine shade tree species. J. Amer. Soc. Hort. Sci. 99(3):206-208.

Table 1. Treatment 12-hour (0800-2000 h PDT) mean ozone partial pressures and the number of hours greater than 0.1 and 0.2 $\mu Pa\ Pa^{-1}$ (0.1 and 0.2 ppm) for the experimental period from 1 August to 17 November 1988.

Treatment[a]	12-h Mean	# Hours > 0.1	# Hours > 0.2
	$\mu Pa\ Pa^{-1}$ (ppm)		
C	0.030	0	0
A	0.051	33	0
T	0.117	761	127

[a)] C, A, and T refer to the charcoal filtered, ambient, and ambient + ozone treatments, respectively.

Table 2. Mean rate of leaf photosynthesis of nine fruit and nut tree species exposed to increased atmospheric ozone. The percent reduction of photosynthesis compared rates of those exposed to increased ozone to those exposed to charcoal filtered air.

	Net Photosynthesis[a]			% Change	
Tree Type	C	A	T	C TO A	C TO T
	---------(μmol m^{-2} sec^{-1}) -------				
Peach	14.08 a (0.61)	13.00 a (0.63)	13.36 a (0.64)	- 8	- 5
Plum	13.87 a (0.54)	12.75 a (0.64)	7.37 b (0.39)	- 9	- 47
Apricot	12.71 a (0.67)	11.69 a (0.55)	6.77 b (0.66)	- 8	- 47
Almond	23.10 a (0.82)	22.70 a (1.14)	11.60 b (1.16)	- 2	- 50
Cherry	11.20 a (0.84)	11.67 a (0.45)	10.29 a (0.64)	4	- 8
Prune	16.14 a (0.64)	13.17 ab (0.53)	9.47 b (0.69)	- 18	- 41
Nectarine	16.97 a (0.68)	16.25 a (0.68)	16.16 a (0.71)	- 4	- 5
Pear	12.87 a (0.61)	10.86 a (0.69)	5.49 b (0.51)	- 16	- 57
Apple	14.37 a (0.56)	14.42 a (0.54)	9.12 a (1.30)	0.3	- 37

a) These values represent the means of the four measurement dates for each treatment and tree type. Means followed by a different letter within a row are significantly different at the 5% level. Values in parenthesis represent one standard error. n=16.

Table 3. Mean stomatal conductance of nine fruit and nut tree species exposed to increased atmospheric ozone.[a]

	Stomatal Conductance			% Change	
Tree Type	C	A	T	C to A	C to T
	---- (mmol $m^{-2}sec^{-1}$) ------				
Peach	0.53 a (0.03)	0.43 a (0.02)	0.46 a (0.03)	- 19	- 13
Plum	0.48 a (0.03)	0.45 a (0.03)	0.23 b (0.01)	- 6	- 52
Apricot	0.40 a (0.03)	0.37 a (0.02)	0.24 a (0.02)	- 8	- 40
Almond	1.33 a (0.14)	1.33 a (0.17)	0.65 b (0.06)	0	- 51
Cherry	0.38 a (0.05)	0.40 a (0.02)	0.36 a (0.03)	5	- 5
Prune	0.58 a (0.07)	0.43 a (0.02)	0.33 a (0.03)	- 26	- 43
Nectarine	0.53 a (0.02)	0.50 a (0.03)	0.48 a (0.03)	- 6	- 9
Pear	0.47 a (0.04)	0.38 a (0.04)	0.41 a (0.02)	- 19	- 13
Apple	0.61 a (0.05)	0.58 a (0.05)	0.34 a (0.05)	- 5	- 44

a) Other information as found in Table 2. n=16.

Table 4. Cross-sectional area growth of nine fruit and nut tree species exposed to increased atmospheric ozone.

	Cross Sectional Area Growth[a]			% Change	
Tree Type	C	A	T	C to A	C to T
	------- (cm^2) --------				
Peach	14.30 (0.59)	11.49 (1.48)	13.63 (1.83)	- 20	- 5
Plum	5.53 (0.94)	3.79 (0.77)	2.72 (0.43)	- 32	- 51
Apricot	4.29 (1.40)	6.20 (0.99)	1.73 (0.16)	45	- 60
Almond	8.04 (0.70)	7.49 (1.34)	5.48 (0.44)	- 7	- 32
Cherry	9.17 (1.63)	7.47 (2.37)	7.50 (1.35)	- 19	- 18
Prune	7.70 (1.23)	5.46 (0.85)	8.16 (2.33)	- 29	6
Nectarine	8.60 (2.00)	11.03 (0.80)	11.67 (1.58)	28	36
Pear	2.31 (0.21)	2.42 (0.92)	0.69 (0.20)	5	- 70
Apple	3.06 (0.51)	2.73 (0.34)	2.06 (0.82)	- 11	- 33

a) Cross-sectional area = (circumference * circumference)/4 * Pi. These values represent the increase in cross-sectional area between 1 August and 1 December 1988. There were no significant differences among treatments. Other information as found in Table 2. n=4.

Table 5. Cross-sectional area relative growth rate of nine fruit and nut tree species exposed to increased atmospheric ozone.

Tree Type	Cross-Sectional Area RGR[a] C	A	T	% Change C to A	C to T
	----- (cm^2 cm^{-2} day^{-1})		------		
Peach	0.0090 (0.0004)	0.0082 (0.0003)	0.0095 (0.0003)	- 9	6
Plum	0.0049 (0.0006)	0.0040 (0.0007)	0.0028 (0.0003)	- 18	- 43
Apricot	0.0051 (0.0011)	0.0064 (0.0007)	0.0024 (0.0002)	25	- 53
Almond	0.0067 (0.0006)	0.0063 (0.0006)	0.0048 (0.0004)	- 6	- 28
Cherry	0.0045 (0.0006)	0.0036 (0.0010)	0.0034 (0.0005)	- 20	- 24
Prune	0.0067 (0.0009)	0.0050 (0.0005)	0.0064 (0.0100)	- 25	- 4
Nectarine	0.0083 (0.0008)	0.0088 (0.0006)	0.0095 (0.0006)	6	14
Pear	0.0037 (0.0003)	0.0034 (0.0009)	0.0015 (0.0005)	- 8	- 59
Apple	0.0039 (0.0004)	0.0031 (0.0003)	0.0026 (0.0009)	- 21	- 33

[a)]These values represent the cross-sectional area RGRs between 1 August and 1 December 1988. There were no significant differences among ozone treatments for any tree species. Other information as found in Table 2. n=4.

Table 6. Total trunk dry weight of nine fruit and nut tree species exposed to increased atmospheric ozone.

Tree Type	Dry Weight[a] C	Dry Weight[a] A	Dry Weight[a] T	% Change C to A	% Change C to T
	($g\ tree^{-1}$)				
Peach	730 a (39)	709 a (118)	743 a (68)	- 3	2
Plum	497 a (30)	477 a (34)	414 a (35)	- 4	- 17
Apricot	459 ab (64)	493 a (54)	293 b (19)	7	- 36
Almond	824 a (88)	810 a (79)	655 a (36)	- 2	- 21
Cherry	877 a (48)	761 a (81)	820 a (40)	- 13	- 6
Prune	424 a (31)	425 a (25)	394 a (30)	0.2	- 7
Nectarine	509 a (61)	659 a (118)	726 a (164)	29	43
Pear	267 a (47)	339 a (79)	156 a (10)	27	- 42
Apple	394 a (80)	481 a (43)	445 a (49)	22	13

[a] Means followed by a different letter within a row are significantly different at the 5% level. Other information as found in Table 2. n=4.

Table 7. Total branch dry weight of nine fruit and nut tree species exposed to increased atmospheric ozone.

	Dry Weight[a]			% Change	
Tree Type	C	A	T	C to A	C to T
	($g\ tree^{-1}$)				
Peach	1132 (79)	996 (171)	1102 (175)	- 12	- 3
Plum	507 (69)	405 (97)	337 (63)	- 20	- 34
Apricot	465 (62)	610 (80)	377 (53)	31	- 19
Almond	827 (102)	980 (202)	897 (48)	19	8
Cherry	393 (31)	403 (70)	437 (68)	3	11
Prune	721 (84)	664 (74)	751 (34)	- 8	4
Nectarine	748 (199)	1039 (231)	1088 (334)	39	45
Pear	159 (24)	147 (38)	75 (13)	- 8	- 53
Apple	260 (43)	296 (55)	245 (70)	14	- 6

[a)] There were no significant differences among ozone treatments for any tree species. Other information as found in Table 2. n=4.

Table 8. Total leaf dry weight of nine fruit and nut tree species exposed to increased atmospheric ozone.

	----- Dry Weight %[a] ----			% Change	
Tree Type	C	A	T	C to A	C to T
	-------- ($g\ tree^{-1}$) ---------				
Peach	349 a (15)	311 a (61)	306 a (14)	- 11	- 12
Plum	174 a (7)	156 a (17)	146 a (6)	- 10	- 16
Apricot	155 a (22)	157 a (22)	106 a (15)	1	- 32
Almond	404 a (28)	425 a (101)	443 a (40)	5	10
Cherry	103 a (10)	98 a (7)	122 a (21)	- 5	18
Prune	97 a (11)	76 a (11)	82 a (9)	- 22	- 15
Nectarine	332 a (45)	450 a (45)	492 a (82)	36	48
Pear	105 ab (9)	121 a (13)	79 b (10)	15	- 25
Apple	62 a (10)	47 a (8)	65 a (24)	- 24	5

a) Means followed by a different letter within a row are significantly different at the 5% level. Other information as found in Table 2. n=4.

Table 9. Trunk starch concentration of five fruit and nut tree species exposed to increased atmospheric ozone.

	Starch Concentration[a]			Total Starch[ab]		
Tree Type	C	A	T	C	A	T
	----- (% of Dry Weight) ---			-------- (g $tree^{-1}$) -------		
Peach	11.1 a (0.3)	10.9 a (0.5)	10.6 a (0.6)	81.2 a (3.5)	76.0 a (11.1)	80.1 a (11.7)
Plum	8.4 a (0.1)	8.6 a (0.5)	7.9 a (0.2)	41.5 a (2.0)	40.7 a (1.2)	33.0 a (2.4)
Apricot	7.5 a (0.2)	7.5 a (0.1)	7.1 a (0.1)	34.5 ab (5.0)	36.7 a (3.5)	20.7 b (1.5)
Almond	9.8 b (0.6)	11.0 a (0.5)	8.8 c (0.5)	81.8 a (12.5)	88.6 a (8.7)	58.1 a (6.2)
Nectarine	9.9 a (0.5)	9.4 a (0.4)	8.8 a (0.5)	50.1 a (6.2)	60.6 a (10.1)	63.6 a (14.1)

a) Means followed by a different letter within a row are significantly different at the 5% level. Other information as found in Table 2. n=4.

b) Total Starch = Starch Concentration * Trunk Dry Weight (From Table 6).

Table 10. Root starch concentration of five fruit and nut tree species exposed to increased atmospheric ozone.

Tree Type	Starch Concentration[a] C	A	T
	(% of Dry Weight)		
Peach	25.0 a (0.7)	25.3 a (1.3)	18.9 b (1.8)
Plum	10.1 ab (0.7)	10.6 a (0.6)	7.8 b (0.1)
Apricot	9.5 a (0.7)	8.4 ab (0.3)	7.0 b (0.2)
Almond	18.9 a (1.5)	23.0 a (3.4)	10.8 b (0.6)
Nectarine	14.9 a (0.9)	14.7 a (1.4)	14.6 a (2.1)

a)Other information as found in Table 2. n=4.

Table 11. Regression equations describing the relationships between leaf net CO_2 assimilation and increasing ozone partial pressure represented in Figure 2 a,b,c.

Tree Type	Regression Equation	R^2
Almond	y = 28.4 - 140.8x	0.96
Plum	y = 16.5 - 77.2x	0.99
Apricot	y = 15.0 - 69.8x	0.99
Prune	y = 17.7 - 71.7x	0.95
Pear	y = 15.3 - 84.0x	0.99
Apple	y = 16.9 - 65.1x	0.94
Peach	y = 13.8 - 5.0x	0.17
Nectarine	y = 16.9 - 7.4x	0.57
Cherry	y = 0.40 - 0.32x	0.53

Table 12. Regression equations describing the relationships between stomatal conductance and increasing ozone partial pressure in Figure 3a,b,c.

Tree Type	Regression Equation	R^2
Almond	y = 1.70 - 8.4x	0.95
Plum	y = 0.58 - 3.0x	0.99
Apricot	y = 0.46 - 1.9x	0.99
Prune	y = 0.61 - 2.5x	0.85
Pear	y = 0.45 - 0.4x	0.17
Apple	y = 0.72 - 3.2x	0.98
Peach	y = 0.51 - 0.5x	0.20
Nectarine	y = 0.54 - 0.5x	0.85
Cherry	y = 0.40 - 0.3x	0.53

Table 13. Regression equations describing the relationships between cross-sectional area relative growth rate and increasing ozone partial pressure presented in Figure 4a,b,c.

Tree Type	Regression Equation	R^2
Almond	y = 7.4 - 22.1x	0.99
Plum	y = 5.3 - 22.3x	0.93
Apricot	y = 7.2 - 38.1x	0.72
Prune	y = 5.9 + 2.5x	0.02
Pear	y = 4.6 - 26.1x	0.99
Apple	y = 4.1 - 13.2x	0.83
Peach	y = 8.3 + 9.1x	0.40
Nectarine	y = 8.0 + 13.0x	0.96
Cherry	y = 4.5 - 10.3x	0.64

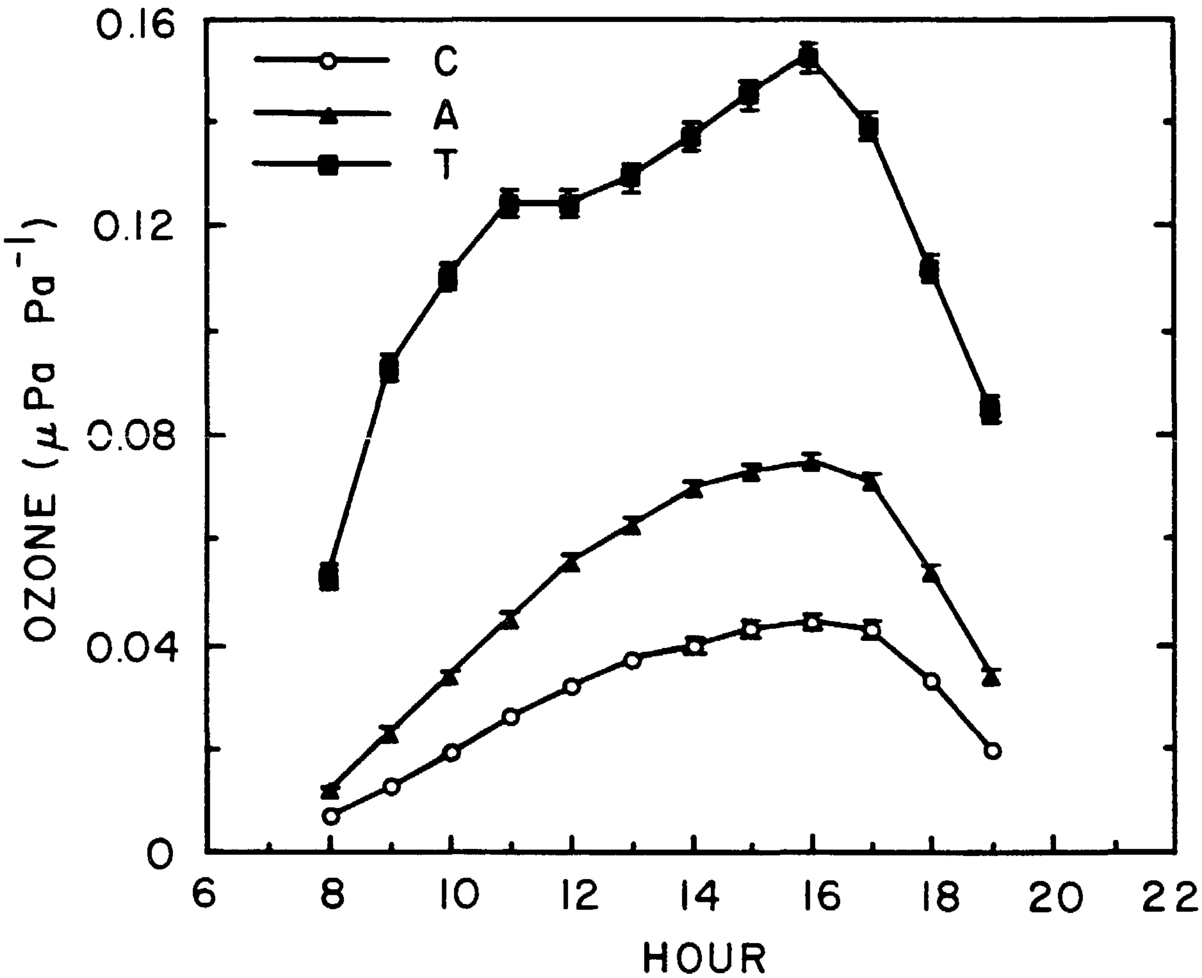

Figure 1. Average hourly ozone partial pressures from 1 August to 17 November 1988.

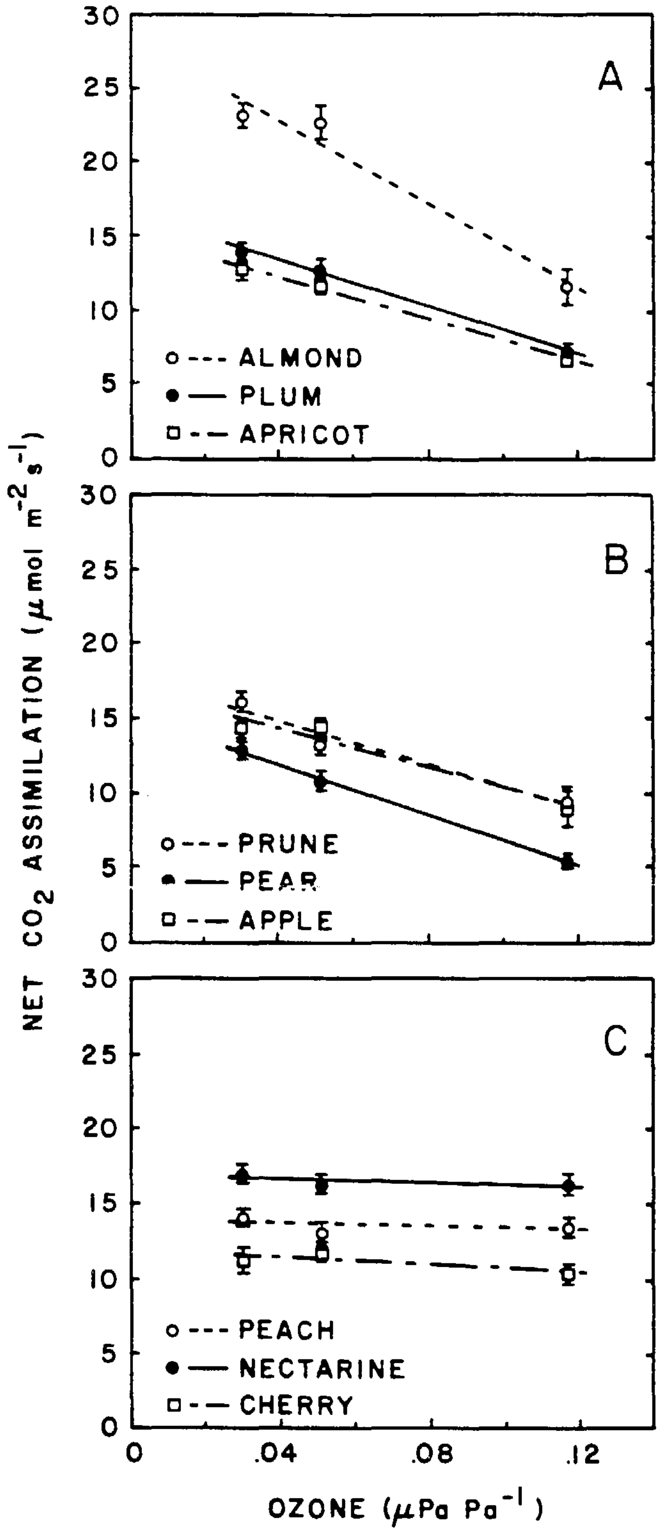

Figure 2. Relationship between leaf net CO_2 assimilation and increasing ozone partial pressure. Bars represent ± one standard error.

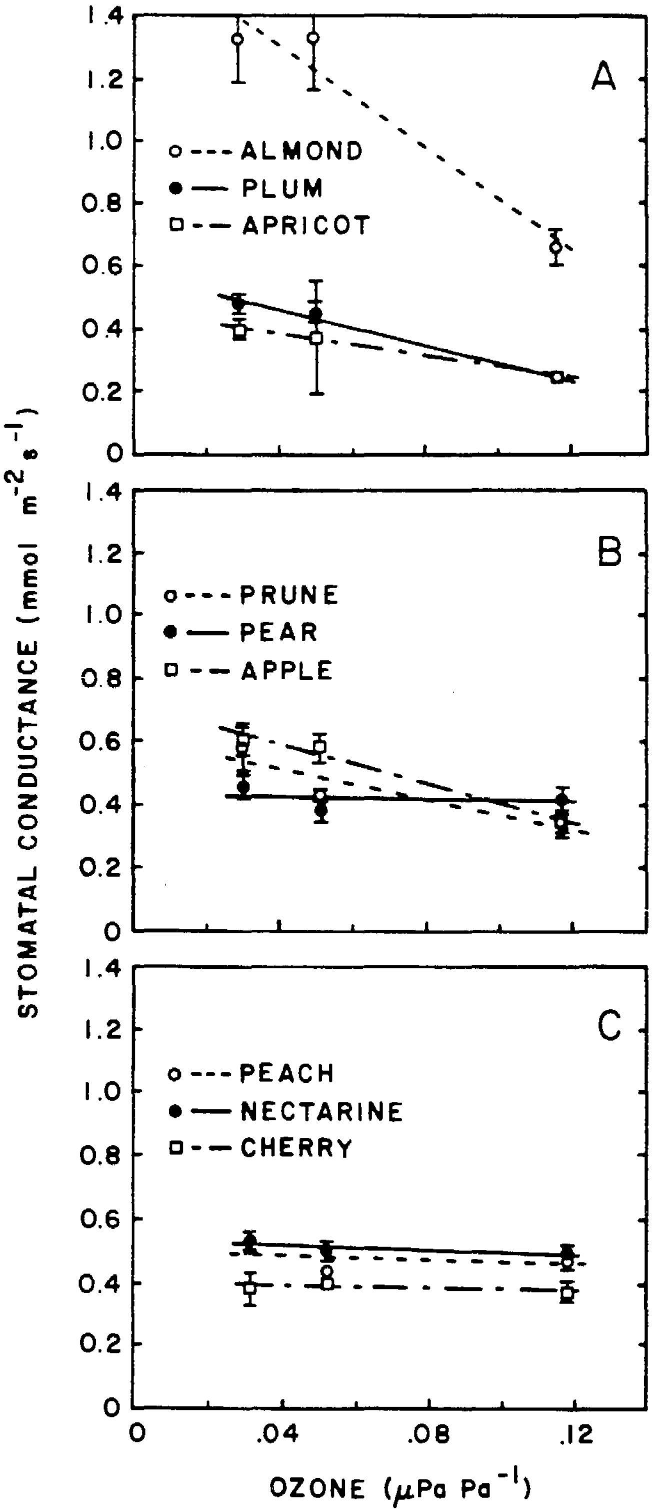

Figure 3. Relationship between stomatal conductance and increasing ozone partial pressure. Bars represent ± one standard error.

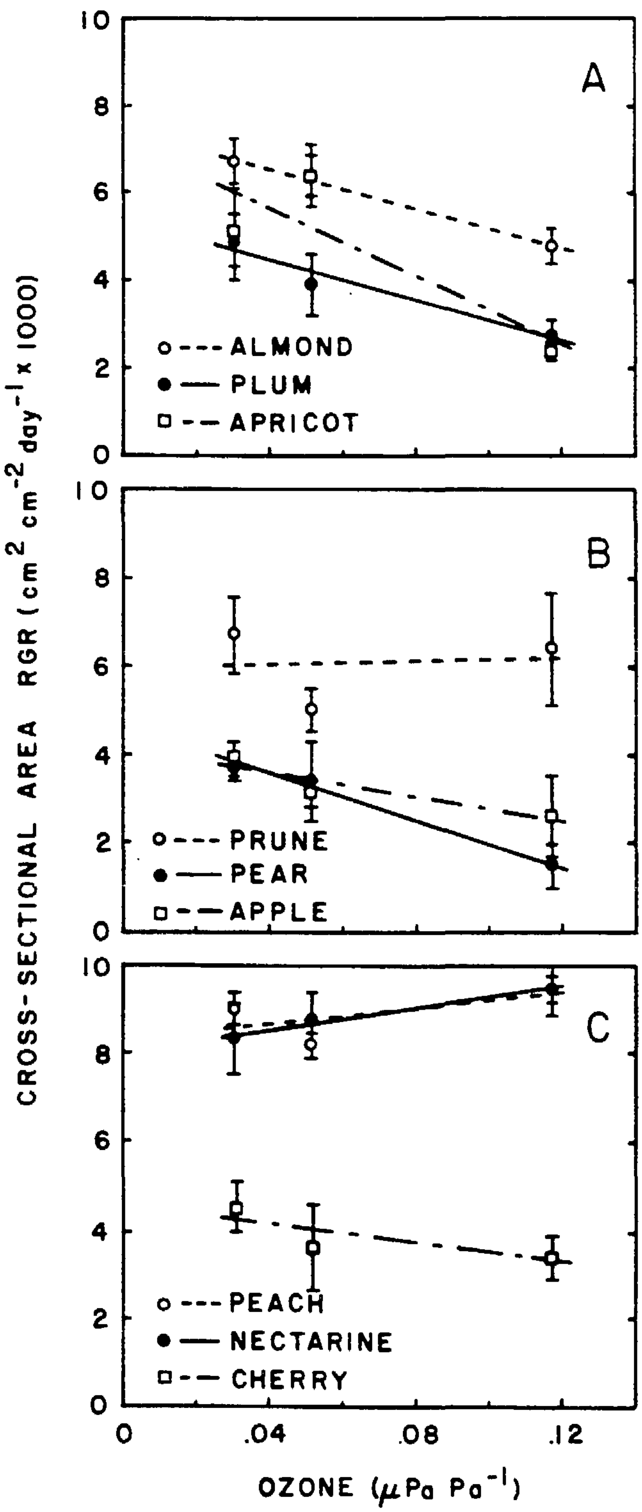

Figure 4. Relationship between cross-sectional area relative growth rate and increasing ozone partial pressure. Bars represent ± one standard error.

APPENDIX A

Table A-1. Leaf photosynthesis of nine fruit and nut tree species exposed to increased atmospheric ozone.

Tree Type	Treatment[a]	Date 1[bc]	Date 2	Date 3	Date 4
		----------------	μmol m^{-2} sec^{-1}	----------------	
	C	11.61 a	14.83 a	15.97 a	13.91 a
Peach	A	10.71 a	14.18 a	15.63 a	11.77 a
	T	10.66 a	15.21 a	15.36 a	12.23 a
	C	13.62 a	13.24 a	13.41 a	15.61 a
Plum	A	12.93 ab	12.04 a	12.57 a	13.48 a
	T	8.51 b	6.64 b	8.05 b	6.29 b
	C	12.33 a	13.57 a	13.90 a	11.03 a
Apricot	A	11.57 ab	13.58 a	12.31 a	9.32 ab
	T	7.12 b	8.66 a	5.74 b	5.54 b
	C	26.80 a	24.50 a	20.90 a	20.30 a
Almond	A	26.50 ab	24.90 a	19.70 a	19.70 a
	T	16.20 b	9.60 b	8.60 b	12.10 b
	C	9.40 a	12.58 a	13.42 a	9.41 a
Cherry	A	10.66 a	12.69 a	13.48 a	9.85 a
	T	10.14 a	11.68 a	11.48 a	7.85 a
	C	14.68 a	17.61 a	16.42 a	15.86 a
Prune	A	13.96 a	13.56 ab	11.32 a	13.84 a
	T	12.11 a	9.51 b	9.29 a	6.96 b
	C	20.40 a	17.12 a	15.56 a	14.59 a
Nectarine	A	18.79 a	18.01 a	15.09 a	13.13 a
	T	17.78 a	15.89 a	15.58 a	15.40 a
	C	12.39 a	14.54 a	11.71 a	12.83 a
Pear	A	10.57 a	11.47 a	10.99 a	10.40 a
	T	7.45 a	5.71 b	4.10 b	4.69 b
	C	17.33 a	14.10 a	13.70 a	12.34 a
Apple	A	14.96 a	13.76 a	15.30 a	13.64 a
	T	11.09 a	6.98 b	8.58 a	9.85 a

a) C, A, and T refer to the charcoal filtered, ambient, and ambient + ozone treatments respectively. n=16.

b) Intervals between dates were approximately 16-days.

c) Means followed by a different letter within a column and species are significantly different at the 5% level.

Table A-2. Stomatal conductances of nine fruit and nut tree species exposed to increased atmospheric ozone.[a]

Tree Type	Treatment	Date 1	Date 2	Date 3	Date 4
		------------- mmol m^{-2} sec^{-1}			-----------------
	C	0.51 a	0.42 a	0.49 a	0.71 a
Peach	A	0.44 a	0.40 a	0.41 a	0.49 a
	T	0.43 a	0.42 a	0.43 a	0.55 a
	C	0.43 a	0.45 a	0.45 a	0.58 a
Plum	A	0.42 a	0.43 a	0.41 a	0.52 ab
	T	0.24 a	0.20 a	0.22 b	0.25 b
	C	0.34 a	0.38 a	0.44 a	0.46 a
Apricot	A	0.34 a	0.41 a	0.33 a	0.39 a
	T	0.22 a	0.23 a	0.24 a	0.28 a
	C	2.00 a	1.20 a	1.00 a	1.10 b
Almond	A	1.80 ab	1.30 a	1.00 a	1.20 a
	T	0.90 b	0.50 a	0.60 a	0.60 b
	C	0.45 a	0.32 a	0.38 a	0.38 a
Cherry	A	0.43 a	0.36 a	0.38 a	0.44 a
	T	0.48 a	0.31 a	0.34 a	0.32 a
	C	0.44 a	0.56 a	0.80 a	0.50 a
Prune	A	0.42 a	0.36 a	0.51 a	0.41 ab
	T	0.35 a	0.26 a	0.46 a	0.26 b
	C	0.48 a	0.51 a	0.52 a	0.61 a
Nectarine	A	0.44 a	0.54 a	0.57 a	0.46 a
	T	0.42 a	0.44 a	0.57 a	0.50 a
	C	0.33 a	0.44 a	0.56 a	0.53 a
Pear	A	0.30 a	0.32 a	0.50 a	0.40 a
	T	0.36 a	0.37 a	0.49 a	0.42 a
	C	0.53 a	0.52 a	0.76 a	0.61 a
Apple	A	0.45 a	0.46 ab	0.72 a	0.69 a
	T	0.29 a	0.21 b	0.42 a	0.43 a

[a]) Other information as found in Table A-1.

Table A-3. Analysis of variance for a repeated measures analysis.

Source of Variation	Degrees of Freedom
Model	29
Replication	3
Treatment	2
Replication * Treatment	6
Date	3
Replication * Date	9
Treatment * Date	6
Error	18
Corrected Total	47

Appropriate F-tests:

For Replication; $F = \frac{\text{Replication}}{\text{Replication*Treatment}}$

For Treatment; $F = \frac{\text{Treatment}}{\text{Replication*Treatment}}$

APPENDIX B

1988 Status Report - Long Term Plum Experiment

Nursery material of Prunus salicina (cv. Casselman) on Citation rootstock were planted in February 1988 at the University of California Kearney Agricultural Center, near Fresno, California to assess the long-term effects of ambient ozone on fruit tree production. Tree and row spacing was set at 1.83 and 4.27 m, respectively. Trees were initially trained to an upright vase shape utilizing summer and dormant season pruning techniques. Other cultural practices in this orchard were similar to those used for the commercial production of plums. A low-volume fan jet irrigation system was installed to permit uninterrupted measurements and for safer working conditions around electrical equipment.

Initial project installation during 1988 included electrical wiring in the orchard for the chamber blower systems and at the control trailer location for the ozone monitoring system. Blower systems and chamber frames were set up around the measurement plots in September, so that the chambers could be covered with plastic soon after budbreak in 1989. A blower/ducting system was developed for the open-top chambers and tested to insure proper air movement/distribution in the chambers.

A small portable shed was built on the control site and a Griffon ozonator was installed inside. A computer control system was developed and tested to generate proper ozone output from the ozonator. This output system was then integrated into the ozone monitoring system, so that all chambers received correct ozone treatment levels. The ozone monitoring/control system was set up in the control trailer and was operated several days to test system accuracy and durability.