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Growth and Yield Response of Commercial Bearing-age 'Casselman' Plum Trees to Various Ozone Partial Pressures

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ABSTRACT

Nursery stock of plum (*Prunus salicina* Lindel., cv. Casselman) was planted 1 Apr. 1988 in an experimental orchard at the Univ. of California Kearney Agricultural Center near Fresno, CA. Trees in this study were enclosed in open-top fumigation chambers on 1 May 1989, and exposed to three atmospheric ozone partial pressures (charcoal filtered air, ambient air, and ambient air + ozone) during the 1989 through 1992 growing seasons (typically 1 Apr.–1 Nov.). A nonchamber treatment plot was used to assess chamber effects on tree performance. This study details the results of the exposures during the initial commercial bearing period (1991 through 1993) in this orchard. The mean 12-h (0800–2000 h Pacific Daylight Time [PDT]) ozone partial pressures during the experimental periods in the charcoal filtered, ambient, ambient + ozone, and nonchamber treatments averaged 0.031, 0.048, 0.091, and 0.056 μPa Pa^{-1} in 1991 and 1992, respectively. Fruit number per tree decreased as atmospheric ozone partial pressure increased from the charcoal filtered to ambient + ozone treatment, significantly affecting yield. Yield of plum trees averaged 23.6, 19.8, 13.7, and 17.9 kg tree^{-1} in 1991 and 1992 in the charcoal filtered, ambient, ambient + ozone, and nonchamber treatments, respectively. Only one out of the five original treatment plots was exposed to ozone treatments during the 1993 growing season. Yield of plum trees in this single replicate in 1993 was reduced by increased atmospheric ozone partial pressure. Yield of plum trees in the four remaining unexposed treatment plots in 1993 was 16.7, 17.9, and 16.0 kg tree^{-1} in the previous charcoal filtered, ambient, and ambient + ozone treatments, respectively. The similarity in yield of the post-chamber treatments indicates that a change in air quality in the current growing season can affect yield of Casselman plum trees.

THE planting of an orchard is a long-term investment, usually taking 3 or more years to bear a commercial crop with continued economic production for another 15 to 30 yr (LaRue and Johnson, 1989). During the commercial bearing period, the grower's objective is to optimize growth of each individual plant organ (shoot, branch, foliage, root, fruit, and bud) to ensure good plant health and sustained yields of a marketable crop over many years. Any environmental stress that interferes with the availability of mineral nutrients and/or carbohydrates to the plant can alter plant growth and yield during the commercial bearing period.

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More than two million metric tons of fruit and nut crops are produced in the San Joaquin Valley of California annually. However, this fruit production region is characterized by ambient ozone partial pressures that consistently exceed U.S. Environmental Protection Agency standards of 0.12 μPa Pa^{-1} at various times during the growing season (Cabrera et al., 1988). Ozone-induced reductions in photosynthesis previously have been related to reductions in crop growth and yield (Reich and Amundson, 1985; Lehnherr et al., 1988; Takemoto et al., 1988). Yield reductions in 'Valencia' orange trees have been documented in ozone partial pressures of 0.040 and 0.075 μPa Pa^{-1} compared to 0.020 μPa Pa^{-1} (Olszyk et al., 1990). Ozone-induced yield reductions in other annual and perennial crops have been reported (Brewer and Ashcroft, 1983; Adaros et al., 1990; Mebrahtu et al., 1991).

Two studies have demonstrated that net photosynthesis and trunk circumference of various fruit and nut tree species and cultivars of the same species decreased with increasing ozone partial pressure (Retzlaff et al., 1991, 1992a). However, these studies were conducted on nursery stock trees (bud grafted the previous year) that had been transplanted directly into open-top chambers. Retzlaff et al. (1992b) reported that increased ozone partial pressures decreased yield of Casselman plum trees in the first bearing year. However, the effects of ozone air pollution on crop production in a plum orchard following the establishment period are unknown. Based upon our previous investigations, we hypothesized that productivity of Casselman plum would be reduced following long-term exposure to ambient atmospheric ozone partial pressure and that future reductions in yield may be cumulative. A long-term study examining the effects of ozone on growth and productivity of plum trees grown in the San Joaquin Valley of California was established in 1988. This report describes the effects of different ozone partial pressures during the fourth through sixth years of tree growth, the first three commercial bearing years in this orchard. In addition, we determined possible carry-over effects of the previous years' ozone environment on the current season's yield.

MATERIALS AND METHODS

Plant Materials and Ozone Treatments

Nursery stock of plum on Citation (*Prunus* hybrid) rootstock was planted 1 Apr. 1988 in an experimental orchard at the Univ. of California Kearney Agricultural Center near

Abbreviations: CF, charcoal filtered; AA, ambient air; AO, ambient air + ozone; NC, nonchamber; PC, post chamber.

Fresno, CA (36°36′ N, 119°30′ W). Tree and row spacing was 1.83 and 4.27 m, respectively. Trees were trained to an open-vase shape with other cultural practices being similar to those used for the commercial production of plums. Trees were irrigated at a rate of approximately 200 L tree^{-1} wk^{-1} via low-volume fan jet sprinklers throughout each growing season. Trees were fertilized with 454 g N tree^{-1} (ammonium nitrate) in the 1991 growing season.

Open-top chamber frames used in this study were constructed from extruded aluminum tube-lock welded to 4 cm thinwall tubing. The chamber dimensions were 3 by 7 by 3 (W by L by H) m on a 3 by 7 m rectangular base of 5 by 30 cm redwood boards. Chamber frames were initially put around the trees on 4 Nov. 1988. Each chamber contained four plum trees. The chamber air delivery system consisted of a blower located at one end of each chamber with four 23 cm diam. plastic tube (Arizona Bag and Plastic Co., Phoenix, AZ)[1] air ducts running from one end of the chamber to the other along the 7 m chamber length. Two of the air ducts ran along the sides of the chamber at a height of 1.5 m above the chamber floor. Air from these two ducts was directed towards the middle and top of the tree canopies within the chamber. An additional pair of air ducts was located directly beneath the trees and this air was directed upwards into the lower canopy. Air from all the ducts passed into the chamber atmosphere through 8.5 cm diamond shaped holes cut every 30 cm in the delivery tubes. This air delivery system provided approximately 133 m^3 min^{-1} air to each chamber, enough to change the air volume in the chambers approximately two times per minute. Clear 12 mil PVC (Goss Products Inc., Corona, CA) walls were first put on the chambers 1–8 May 1989 and chamber blowers were turned on at that time. Chamber blowers were operated 24 h per day during the growing season.

Ozone treatments imposed in this study were charcoal filtered air (CF), ambient air (AA), and ambient air + ozone (AO). The target ozone partial pressure for the AO treatment was two times the AA treatment partial pressure. Treatments were randomly assigned to a chamber. In addition, there was a nonchamber treatment plot (NC). Ozone concentrations in all the treatment plots were monitored using a computer controlled monitoring system described previously (Retzlaff et al., 1991). A Dasibi Model 1003 AH Ozone Analyzer was used to measure ozone. Calibration occurred weekly and involved cleaning and frequency count checks. Each Spring and Fall all ozone analyzers were checked and corrected for drift against an ozone analyzer provided by the State of California Air Resources Board. Ozone treatments reported here were initiated on 1 and 8 Apr. 1991 and 1992, respectively, and continued until 31 Oct. 1991 and 1 Nov. 1992. It is important to note that these plum trees were exposed to the same ozone treatments during the 1989 and 1990 growing seasons. Trees were exposed to ambient air during the remainder of the year.

Air for AA was blown directly into the chamber. Air for CF was first drawn through activated charcoal filters before delivery into the chambers. Ozone for AO chambers was generated from ambient air with a Griffin (Lodi, NJ) Model GTC-2A Ozone Generator and delivered via Teflon tubing to the delivery air stream of these chambers. The ozone generator was computer automated to increase or decrease the ozone output from 0800 to 2000 h Pacific Daylight Time (PDT) depending on the ambient atmospheric ozone partial pressure, so that the ozone partial pressure in the AO treatment chambers would be equal to twice that measured in the AA chambers.

Final ozone partial pressure data analysis was conducted utilizing the means procedure (Proc Means) of the Statistical Analysis System (SAS Institute, 1985). Ozone 12-h means (0800–2000 h PDT) were calculated for each treatment. These ozone partial pressures were used to assess the effects of ozone air pollution on tree growth, development, and yield.

Oxides of N were measured in the treatment/chambers on a 24-h basis with a Thermo Electron Corporation (Hillsborough, NC) Model 14B Chemiluminescent NO–NO_2–NO_X Gas Analyzer to determine whether the Griffin ozone generation system was releasing additional oxides of N into the AO treatment chambers. No differences in the partial pressure of oxides of N were found among treatments during the 1989 or 1990 growing seasons (data not shown).

Growth Measurements

Circumference of each tree trunk was measured at monthly intervals from 1 May through 1 December in 1991, 1992, and 1993. Painted bands on the trees 18 cm above the soil-line were used as reference points to minimize measurement errors. The increase in trunk cross-sectional area from 1 May to 1 December was calculated from the circumference measurements. Data were analyzed on a per tree basis. Trees also were visually inspected on a routine basis for foliar symptoms of chronic ozone injury.

Leaf-fall was measured by collecting the leaves from the ground below the trees in the chamber treatments (CF, AA, and AO) at various times throughout the growing season. All leaves on the ground below the trees were collected and any remaining foliage on the trees was stripped off to determine final foliage biomass at the end of the season. Data were analyzed on a per plot (chamber) basis.

Trees in the study were dormant pruned on 14, 24, and 28 Jan. 1992, 1993, and 1994, respectively. Fresh prunings were weighed and then placed in a forced air oven at 70°C until there was no further weight change and final dry weight determined. Pruning weights were analyzed on a per tree basis.

Fruit Yield

Differences in fruiting potential among trees in the four treatments was determined by counting all flowers on two trees in each plot just prior to full bloom (16, 11, and 19 Feb. 1991, 1992, 1993, respectively). After fruit set, any fruit that fell from the trees was picked up, counted, and added to total fruit number after harvest. At fruit maturity, fruit from individual trees in each treatment was picked. Harvest dates were 21 Aug. 1991, 5 Aug. 1992, and 5 Aug. 1993.

Statistical Analysis

The main experimental design was a randomized complete block with three ozone (CF, AA, and AO) treatments and five replications. The experiment was replicated/blocked five times to account for chamber location in the field and possible soil differences among chambers except in 1993. The last year of the study, data were collected on the four individual trees in each treatment of replication three. 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). Data collected on individual dates and/or only once during the study were analyzed by two-way ANOVA. In all analyses, linear contrasts with the 12-h mean ozone levels were used for a priori comparisons among treatment means

[1]The mention of commercial products, their source, or their use in connection reported herein is not to be construed as either an actual or implied endorsement of said products.

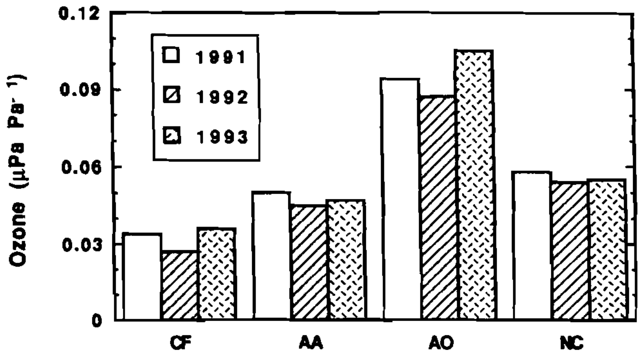

Fig. 1. Treatment 12-h (0800–2000 PDT) mean ozone partial pressures for the experimental periods in 1991, 1992, and 1993.

($a < 0.05$). In addition, two-way ANOVA was used to compare the responses of trees in AA chambers with those of the NC plots.

1993 Experiment

Trees from one replication (previous replication three) were enclosed in open-top fumigation chambers and exposed to the three ozone treatments (as described above) starting on 30 Apr. 1993. Ozone treatments were discontinued on 23 Aug. 1993 following fruit harvest because of lack of funding to continue the experiment. For the same reason, the remaining treatment plots (redesignated as the post-chamber [PC] treatment; previous replications 1, 2, 4, and 5) were not enclosed or exposed to different ozone concentrations during the 1993 growing season. Similar statistical analyses, as stated previously, were used in 1993 for the PC treatments.

RESULTS

Ozone Treatments

In 1991, seasonal 12-h mean ozone partial pressures in CF were 68% of those in AA, whereas those in AO were 188% of those in AA (Fig. 1). In 1992, seasonal 12-h mean ozone partial pressures in CF were 60% of those in AA, whereas those in AO were 193% of those in AA. In 1993, seasonal 12-h mean ozone partial pressures in CF were 77% of those in AA, whereas those in AO were 223% of those in AA. Ozone partial pressures in AA were 86, 83, and 85% of those in NC in 1991, 1992, and 1993, respectively. Ozone partial pressures in the PC treatments (0.052 μPa Pa^{-1}, 1993 only) were 95% of those in the NC treatment plots.

Table 1. Probabilities of statistically significant ozone treatment effects for trunk cross-sectional area growth (Fig. 2), dormant pruning weights (Fig. 3), leaf weight remaining on the tree (Fig. 4), and total leaf dry weight (Fig. 5) of 'Casselman' plum exposed to different seasonal ozone partial pressures in 1991, 1992, and 1993.

	Trunk cross-sectional area growth	Dormant pruning weight	Leaf weight remaining on tree	Total leaf dry weight
1991				
Linear	NS†	NS	*	NS
AA vs. NC	*‡	*	–§	–
1992				
Linear	*	NS	*	NS
AA vs. NC	NS	NS	–	–
1993				
Linear	NS	NS	*	NS
AA vs. NC	NS	NS	–	–

† A significant linear treatment effect (*) indicates that each mean from the CF, AA, and AO treatments is different at the 5% level. NS indicates not significant.
‡ A significant treatment effect (*) indicates that each mean from the AA and NC treatments is different at the 5% level. NS indicates not significant.
§ Foliage was not collected on the ground below the NC trees, so no comparison with the AA treatment could be made.

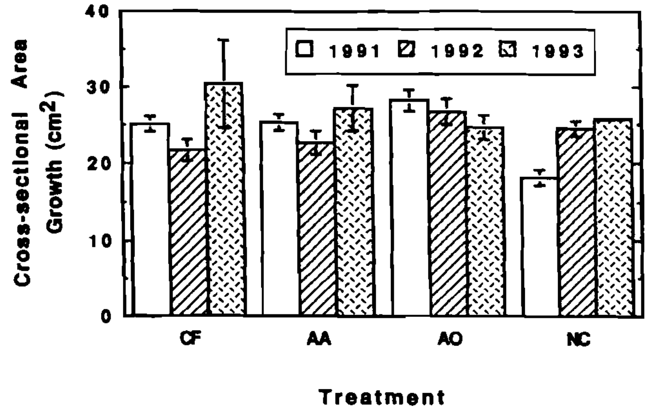

Fig. 2. Trunk cross-sectional area growth, during the exposure period, of Casselman plum trees exposed to different seasonal ozone partial pressures in 1991, 1992, and 1993. Vertical bars represent ± 1 SE and are shown when they are larger than the data symbol. There was a significant linear treatment effect only in 1992 (also see Table 1). n = 20 individual trees in 1991 and 1992; n = 4 individual trees in 1993.

Tree Vegetative Growth

Three-Year Ozone Study

Trunk growth of Casselman plum was increased by increased atmospheric ozone partial pressures in 1992 (Table 1, Fig. 2). Trunk growth of NC trees was less than that of AA trees in 1991, but was the same in 1992 and 1993. Dormant pruning weights across all three exposure years were similar among all treatments (Table 1, Fig. 3).

Post-Chamber Study

Trunk growth of PC trees (1993 only) was the same regardless of the previous ozone treatment (data not

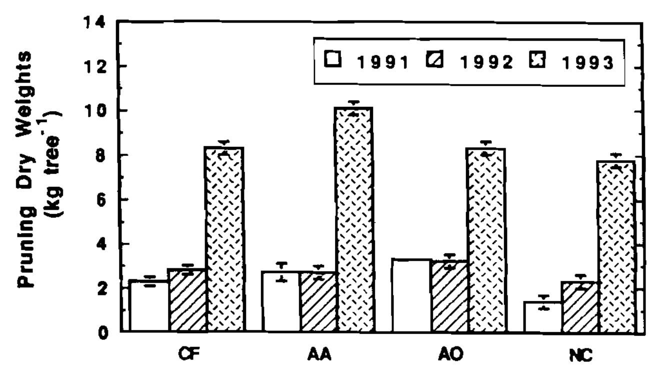

Fig. 3. Dormant pruning weights of Casselman plum trees exposed to different ozone partial pressures in 1991, 1992, and 1993. There were no significant differences found among treatments. Other information as found in Fig. 2. n = 20 individual trees in 1991 and 1992; n = 4 individual trees in 1993.

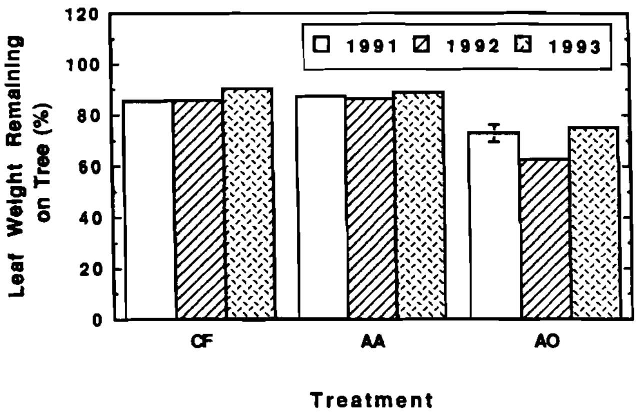

Fig. 4. Percentage of total leaf dry weight remaining at the end of growing season on Casselman plum trees exposed to different ozone partial pressures in 1991, 1992, and 1993. There were significant linear treatment effects each year of the study. Other information as found in Fig. 2. Data were collected on a chamber basis; $n = 5$ in 1991 and 1992; $n = 1$ in 1993.

given). Pruning weights of PC trees (1993 only) were the same regardless of the previous ozone treatment (data not given).

Foliar Injury

Visual injury, in the form of chlorotic spots and yellow flecking on the leaf surface of older foliage, was observed on Casselman plum trees in the AO treatment approximately 2 mo following treatment initiation in each of the three growing seasons. As the growing season progressed, foliar ozone injury increased and some leaf abscission of injured foliage occurred. By 10 November in all three growing seasons, >85% of the total foliage remained on the CF and AA trees while < 73% of the total foliage remained on the AO trees (Table 1, Fig. 4). Following an application of a foliar fertilizer (36% Zn sulfate; 16.8 kg ha^{-1}) on 7 November, 6 November, and 26 October (in 1991, 1992, and 1993, respectively) most of the remaining foliage on trees in all the treatments abscised. Final cumulative foliage dry weight was similar across all 3 yr in all the chamber treatments (Table 1, Fig. 5).

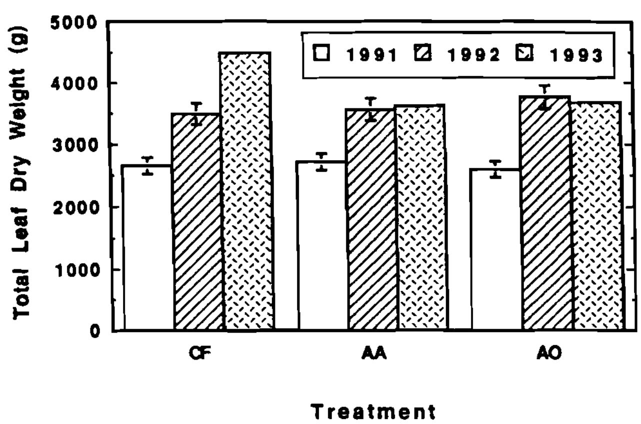

Fig. 5. Total leaf dry weight of Casselman plum trees exposed to different ozone partial pressures in 1991, 1992, and 1993. There were no significant differences among treatments. Other information as found in Fig. 2. Data were collected on a chamber basis; $n = 5$ in 1991 and 1992; $n = 1$ in 1993.

Fruit Yield

Three-Year Ozone Study

Fruit yield per tree and per hectare was reduced in the AA and AO compared to the CF treatment in all three exposure years (Table 2). Differences in yield among ozone treatments were primarily related to differences in total number of fruit per tree rather than average fruit size (Table 2). In 1992 average fruit size of the AO treatment was greater than the other treatments. There was a linear reduction in yield with an increase in mean ozone partial pressure each growing season (Fig. 6).

The cause of the differences in number of fruit harvested per tree varied among years. In 1991 the mean number of flowers per tree was similar among treatments but the percent fruit set was significantly reduced in the AO treatment trees (Table 3). In 1992, the trees exposed to higher ozone treatments had significantly fewer flowers at bloom but percent fruit set and percent fruit drop were unaffected. In 1993, initial flower numbers appeared lower in the high ozone treatments but the differences were not statistically significant. In that same year, percent fruit set appeared unaffected by ozone treatment, but percent fruit drop during the growing season was substantially increased.

The yield of trees outside the chamber (NC) was similar to the trees exposed to ambient ozone within the chambers in 1991 and 1992 but greater in 1993 (Table 2). The yield differences in 1993 were due to greater fruit numbers per tree and not fruit size; the greater fruit numbers per tree were primarily related to de-

Table 2. Fruit production and yield data of 'Casselman' plum trees exposed to different atmospheric ozone partial pressures in 1991, 1992, and 1993.

Ozone treatment	Total no. of fruit/tree at harvest†	Average fruit weight, g	Yield, kg/tree†	Yield, kg/ha
1991				
CF	227 (16)‡	87 (1.7)	19.8 (1.5)	25 291 (1 992)
AA	191 (14)	84 (1.7)	15.9 (1.3)	20 390 (1 609)
AO	79 (11)	82 (2.4)	6.8 (1.0)	8 715 (1 259)
P > F	*§	NS	*	*
NC	212 (23)	75 (1.3)	15.8 (1.7)	20 160 (2 157)
P > F	NS¶	*	NS	NS
1992				
CF	348 (29)	80 (2.1)	27.4 (2.1)	35 008 (2 684)
AA	306 (26)	80 (2.4)	23.7 (1.7)	30 290 (2 213)
AO	242 (26)	86 (1.7)	20.5 (2.1)	26 241 (2 737)
P > F	*	*	*	*
NC	262 (22)	78 (1.8)	19.9 (1.5)	25 490 (1 935)
P > F	NS	NS	NS	NS
1993				
CF	217 (4)	88 (2.7)	19.1 (0.8)	24 409 (1 001)
AA	166 (13)	88 (1.7)	14.5 (1.3)	18 598 (1 638)
AO	103 (44)	84 (2.2)	8.8 (3.9)	11 309 (5 017)
P > F	*	NS	*	*
NC	243 (17)	83 (0.3)	20.1 (1.4)	25 760 (1 841)
P > F	*	*	*	*

† $n = 20$ for total no. of fruit and yield per tree.
‡ Numbers in parenthesis represent ± 1 SE.
§ A significant treatment effect (*) indicates that each mean from the CF, AA, and AO treatments is different at the 5% level. NS indicates not significant.
¶ A significant treatment effect (*) indicates that each mean from the AA and NC treatments is different at the 5% level. NS indicates not significant.

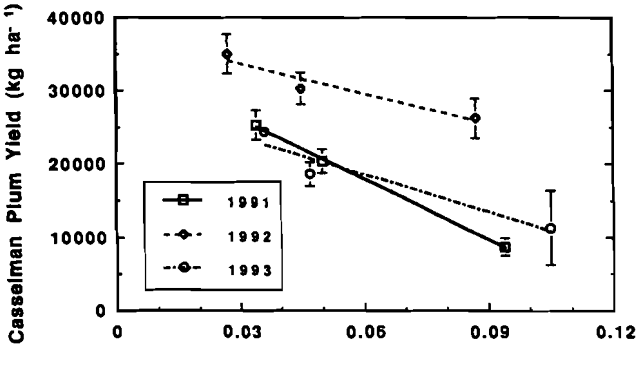

Fig. 6. Yield of Casselman plum trees exposed to different ozone partial pressures in 1991, 1992, and 1993. Other information as found in Fig. 2. Yield (1991) = $-273943(O_3) + 34386$, $r^2 = 0.99$; Yield (1992) = $-137307(O_3) + 37790$, $r^2 = 0.93$; Yield (1993) = $-168637(O_3) + 28673$, $r^2 = 0.91$. Each data point is the mean of 20 individual trees in 1991 and 1992 and four individual trees in 1993.

creased fruit drop in the NC trees compared to the AA trees (Table 3).

Post-Chamber Study

Yield and components of yield were the same for all PC treatment plots in 1993 regardless of the preceding year's ozone exposure regime (Table 4). The yield of the previous CF treatment trees was similar to the other treatments even though initial flower numbers and fruit set were higher because of higher percentages of fruit abscission.

DISCUSSION

Trunk growth of Casselman plum was not affected (1991 and 1993) or was increased (1992) by ozone partial pressures that were nearly twice the ambient level (Fig. 2). Previously, trunk growth of plum in a newly established orchard was found to decrease linearly with increasing ozone partial pressure (Retzlaff et al., 1991; Retzlaff et al., 1992b). The decrease in plum trunk growth in the previous reports was apparently related to the decrease in photosynthesis and loss of photosynthetic leaf area of these newly established plum trees in response to increased ozone partial pressures. As fruit trees progress from the orchard establishment period to commercial bearing-age, there is a shift in carbohydrate allocation from vegetative growth to fruit production. One hypothesis for the similarity (1991 and 1993) and increase (1992) in plum trunk growth in the AO treatment compared to the other treatments in this study is that there may be additional photosynthate available for trunk growth in the AO trees because of the reduced fruit load on these trees (Table 3, Fig. 6).

Other measures of vegetative growth were unaffected by increased ozone partial pressures. Dormant pruning weights (Fig. 3) were similar across ozone treatments each growing season, illustrating a lack of a vegetative growth response by Casselman plum to changes in atmospheric ozone partial pressure. Retzlaff et al. (1991, 1992b) reported that shoot length, leaf number, numbers of lateral branches, and dormant pruning weights of newly established Casselman plum trees also were unaffected by increased ozone partial pressure. Ozone apparently alters height growth differently than diameter for plum, as has been reported previously for other trees (Pye, 1988). In contrast, beech (*Fagus sylvatica* L.) exposed to ozone during the previous growing season had a reduced rate of shoot elongation during the first week after bud break and a reduced (17% less) amount of total seasonal growth that was the result of reduced

Table 3. Flower and fruit production parameters of 'Casselman' plum trees exposed to different atmospheric ozone partial pressures in 1991, 1992, and 1993.

Ozone treatment	Total no. flowers per tree	Total no. fruit set/tree†	Percentage set‡	Fruit abscised per tree	Percentage drop§
1991					
CF	6817 (594)	363 (48)	5.3 (0.3)	137 (25)	37 (2.4)
AA	6913 (741)	296 (32)	4.3 (0.2)	105 (13)	35 (0.7)
AO	5468 (500)	126 (20)	2.2 (0.2)	47 (7)	35 (2.4)
P > F	NS¶	*	*	*	NS
NC	6113 (388)	288 (31)	4.9 (0.7)	77 (9)	27 (0.3)
P > F	NS#	NS	NS	NS	NS
1992					
CF	9162 (739)	622 (90)	6.7 (0.7)	274 (58)	42 (4.4)
AA	6989 (892)	495 (74)	7.1 (0.7)	189 (30)	38 (1.0)
AO	5319 (777)	395 (61)	7.5 (0.4)	153 (23)	39 (2.5)
P > F	*	NS	NS	NS	NS
NC	6694 (773)	395 (46)	5.9 (0.5)	133 (13)	34 (2.0)
P > F	NS	NS	NS	NS	*
1993					
CF	9407 (345)	432 (4)	4.6 (0.1)	214	50 (0.4)
AA	7249 (1116)	332 (13)	4.6 (0.2)	167	50 (1.8)
AO	5930 (128)	342 (44)	5.8 (0.7)	239	73 (8.0)
P > F	NS	NS	NS	–	*
NC	9748 (1142)	366 (17)	3.8 (0.2)	123	34 (1.7)
P > F	NS	NS	*	–	*

† Total no. fruit set per tree = fruit no. at harvest (Table 2) + fruit abscised per tree.
‡ Percentage set = (total no. fruit set per tree/total no. flowers per tree) × 100.
§ Percentage drop = (fruit abscised per tree/total no. fruit set per tree) × 100.
¶ A significant treatment effect (*) indicates that each mean from the CF, AA, and AO treatments is different at the 5% level. NS indicates not significant.
# A significant treatment effect (*) indicates that each mean from the AA and NC treatments is different at the 5% level. NS indicates not significant.

internodal expansion (Pearson and Mansfield, 1994). The ozone response difference among studies could be that the majority of height growth in fruit trees occurs early in the growing season before the ozone treatments affect photosynthesis (Retzlaff et al., 1991, 1992b), whereas fruit tree diameter growth continues throughout the entire growing season (DeJong et al., 1987).

Foliar injury occurred on Casselman plum trees only in the AO plots in the present study and was similar to that reported previously for this plum cultivar and for other tree species (Chappelka et al., 1988; Keane and Manning, 1988; Retzlaff et al., 1991, 1992a, 1992b; Scherzer and McClenahen, 1989). In addition, premature leaf senescence of the injured foliage occurred (Fig. 4) during the exposure of these plum trees. Foliar ozone symptoms are often followed by leaf fall (Keller, 1988; Lehnherr et al., 1988; Prinz, 1988; Reich and Amundson, 1985; Retzlaff et al., 1992a,b). In the present study, the cumulative leaf dry weight produced on the plum trees was the same (Fig. 5) in all chamber treatments at the end of the growing season indicating that ozone-induced foliar injury did not affect leaf formation or development (i.e., there was no lammas shoot elongation following foliage senescence). Similarly, hybrid poplar (*Populus* × *euramericana*) shed their ozone-injured foliage while new foliage developed throughout the growing season resulting in the same total leaf number (compared to poplar exposed to ambient air) measured at the end of the growing season (Matyssek et al., 1993).

Height growth, cumulative leaf dry weight, and dormant pruning weight of Casselman plum all were unaffected by increased ozone partial pressures. As stated previously, this is probably due to the fact that the majority of height growth in fruit trees occurs early in the growing season before the ozone treatments affect photosynthesis (Retzlaff et al., 1991, 1992b), whereas fruit tree diameter growth continues throughout the entire growing season (DeJong et al., 1987). Further, there is no indication in this study that, as premature leaf senescence occurs in the highest ozone treatment, C is reallocated (from fruit sinks) to replace foliage (and photosynthesizing leaf area). Therefore, reallocation of available C is an unlikely scenario for the documented reduction in plum fruit yield in increased atmospheric ozone partial pressures.

Yield data indicate that increased ozone partial pressures reduced yield of 4, 5, and 6 year-old Casselman plum (Fig. 6). Previously, yield data from this study in 1990 (the first bearing year in this orchard) also indicated that increased ozone partial pressures decreased Casselman plum yield and that reduced fruit number was the initial factor implicated in the yield reduction (Retzlaff et al., 1992b). Similarly, yield of 'Valencia' orange [*Citrus sinensis* (L.) Osbeck] and 'Heritage' raspberry (*Rubus idaeus* L.) decreased with increasing ozone partial pressure (Olszyk et al., 1990; Sullivan et al., 1994). The present study confirmed that the ozone-induced yield reduction in Casselman plum is due entirely to the reduction in the number of fruit per tree that is different than reported in the Valencia orange study (reduced fruit number and fruit size), but similar to 'Heritage' raspberry (reduced fruit number) (Olszyk et al., 1990; Sullivan et al., 1994). The decrease in yield of Heritage raspberry in the second year of that study was attributed to decreases in berry count which suggested a reduction in yield potential due to fewer flowers; however, flowers were not counted (Sullivan et al., 1994). Flower and fruit drop counts, and percent fruit set responses of Casselman plum measured in the present study (Table 3), but not previously quantified (Retzlaff et al., 1992b), varied from year to year and gave no clear indication of the exact physiological mechanism that caused the measured yield reduction (lower fruit counts) in response to increased ozone partial pressure.

Table 4. Flower and fruit production and yield data of 'Casselman' plum trees exposed to different seasonal ozone partial pressures from 1989 through 1992, but not exposed in 1993 (i.e., PC Treatments).

1989–1992 Prior ozone treatment	Total no. flowers per tree	Total no. fruit set/tree†	Percentage set‡	Fruit abscised per tree	Percentage drop§
CF	9062 (639)	432 (36)	4.9 (0.6)	240 (16)	56 (4.5)
AA	8481 (404)	383 (33)	4.5 (0.2)	164 (12)	43 (0.9)
AO	7991 (765)	324 (40)	4.3 (0.8)	127 (14)	39 (1.2)
P > F	NS¶	NS	NS	*	*
NC	9623 (820)	416 (46)	4.3 (0.4)	157 (30)	37 (3.4)
P > F	NS#	NS	NS	NS	NS
	Total no. of fruit/tree at harvest[β]	Average fruit weight, g	Yield, kg/tree††		Yield, kg ha
CF	192 (17)	87 (1.8)	16.7 (1.5)		21 332 (1 949)
AA	219 (17)	82 (1.5)	17.9 (1.3)		22 907 (1 718)
AO	198 (19)	82 (1.2)	16.0 (1.5)		20 505 (1 900)
P > F	NS	NS	NS		NS
NC	258 (21)	80 (1.3)	20.4 (1.5)		26 084 (1 982)
P > F	NS	NS	NS		NS

† Total no. fruit set per tree = fruit no. at harvest (Table 2) + fruit abscised per tree.
‡ Percentage set = (total no. fruit set per tree/total no. flower per tree) × 100.
§ Percentage drop = (fruit abscised per tree/total no. fruit set per tree) × 100.
¶ A significant treatment effect(*) indicates that each mean from the CF, AA, and AO treatments is different at the 5% level. NS indicates not significant.
# A significant treatment effect(*) indicates that each mean from the AA and NC treatments is different at the 5% level. NS indicates not significant.
†† n = 16 for total no. of fruit and yield per tree.

It is clear, however, that ozone exposure did not reduce Casselman plum fruit size although ozone exposure can reduce Casselman plum fruit postharvest quality (Crisosto et al., 1993). In a recent review of C allocation in trees, Cannell and Dewar (1994) state that during the period of endosperm filling, the growth rate of seeds tends to be constant, and the final weight per seed is usually much less variable than the number of seeds produced per plant. Further, trees have developed several mechanisms to adjust the total number of seed or fruit that are set to ensure that the assimilate and nutrient resources are adequate to produce full-sized seed or fruit without threatening the survival of the vegetative structure. It appears in the present study that Casselman plum has the ability to adjust the total number of fruit per tree and alleviate the stress associated with less C assimilation (Retzlaff et al., 1991, 1992b) in response to increased ozone partial pressures.

Although we have implicated fruit load and C availability as the primary response factors, we have not been able to identify the exact mechanism of this response. If flower emergence and fruit set were the only response factors involved, then an ozone episode from the previous growing season would determine the current season fruit load. In fact, flower buds develop on Casselman plum during the latter portion of the previous growing season and fruit set occurs before current season photosynthate is available. Further, a recent simulation exercise (J.V.H. Constable and W.A. Retzlaff, 1996, personal communication) has identified that peak ozone episodes that correspond with the conclusion of the leaf expansion period in yellow poplar (*Liriodendron tulipifera* L.) and loblolly pine (*Pinus taeda* L.) are more detrimental than seasonal exposure with no peak episodes or peak episodes that occur at other times of the year. However, timing of ozone exposure must not be the only factor that influences the fruit load of Casselman plum, because yields of previously exposed CF and AO trees 'adjusted' to AA levels in one growing season following treatment exposure.

Growth and yield of Casselman plum trees grown outside the chamber (NC) in ambient partial pressures of ozone were approximately the same as those of trees grown in the AA chambers even though the ozone partial pressure was reduced by as much as 17% in AA compared to NC. In addition, yield of PC trees (previously exposed to various ozone partial pressures) in 1993 was similar to that of AA and NC trees. In a study of the effects of ambient air pollution in open-top chambers on bean (*Phaseolus vulgaris* L.) it was noted that the presence of the chamber had opposite effects on yield in successive years (Schenone et al., 1992). In one growing season the no-chamber bean yield was 30% less than that in the chamber, while in the next growing season bean yields in the chamber were 70% less than those in the no-chamber plots. The results indicate that chamber effects on bean yield may be related to different seasonal and plant maturity conditions. As reported previously (Retzlaff et al., 1992b) and in the present study, the open-top chambers apparently had little effect on the overall physiology and yield of Casselman plum trees over multiple growing seasons.

The average expected yield of 5 to 7 yr-old Casselman plum trees growing in the San Joaquin Valley of California in a high density commercial production system (similar to the experimental orchard in this study) is reported to range between 25 000+ to 33 000+ kg ha^{-1} (R. Scott Johnson, 1996, personal communication). Yield of 4, 5, and 6 yr-old Casselman plum trees in the present study in the CF, AA, NC, and PC treatment plots was near or slightly above the lower limit of this reported average range indicating that our experimental orchard had moved into the commercial bearing life stage. Yield of Casselman plum trees in the present study in the AO treatment was reduced to approximately one-half the reported minimum yield in commercial production orchards in 1991 and 1993, indicating that any increases in tropospheric ozone partial pressure in this region may significantly reduce Casselman plum yield. It appears from the results of our study that ozone does not affect the transition to reproductive growth in Casselman plum (our trees in the AA chambers achieved commercial yields in the expected time interval). Contrary to our initial hypothesis this study also showed that long-term exposure to ozone did not have an additive effect on yield of Casselman plum (i.e., the yield of the trees in the AA and AO chambers varied from year-to-year and the yield reduction did not increase yearly). Similarly, yield of 'Valencia' orange trees was reduced by increased atmospheric ozone during two 'on' production years, but yield was not affected by ozone in 'off' production years (Olszyk et al., 1990); further evidence that ozone may not have a cummulative effect on yield of perennial plants.

Yields of Casselman plum trees in the PC treatment were the same regardless of the previous four seasons' ozone exposure (Table 4). Yield data in the final year of the present study indicate that a decrease in air quality (increased seasonal ozone partial pressure) can reduce yield of Casselman plum trees because the yield of the PC trees previously exposed to the CF treatment was similar to the previous AA treatment. In addition, because the yield of the PC trees previously exposed to AO was similar to the previous AA treatment, this study also indicates that an improvement in air quality (decreased seasonal ozone partial pressure) can increase yield of Casselman plum trees.

Increased atmospheric ozone partial pressures reduced the yield of 4, 5, and 6 yr-old Casselman plum trees in the current study. This is the first report that documents that ozone affects production of fruit trees during the commercial production life stage. Further, our results indicate that Casselman plum has the ability to adjust the total fruit number and alleviate the stress associated with less C assimilation. Data also indicate that the previous year's ozone exposure level does not completely determine the yield of Casselman plum the following year, an important implication further indicating that a combination of factors determines the yield response of fruit tree crops to ozone air pollution.

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