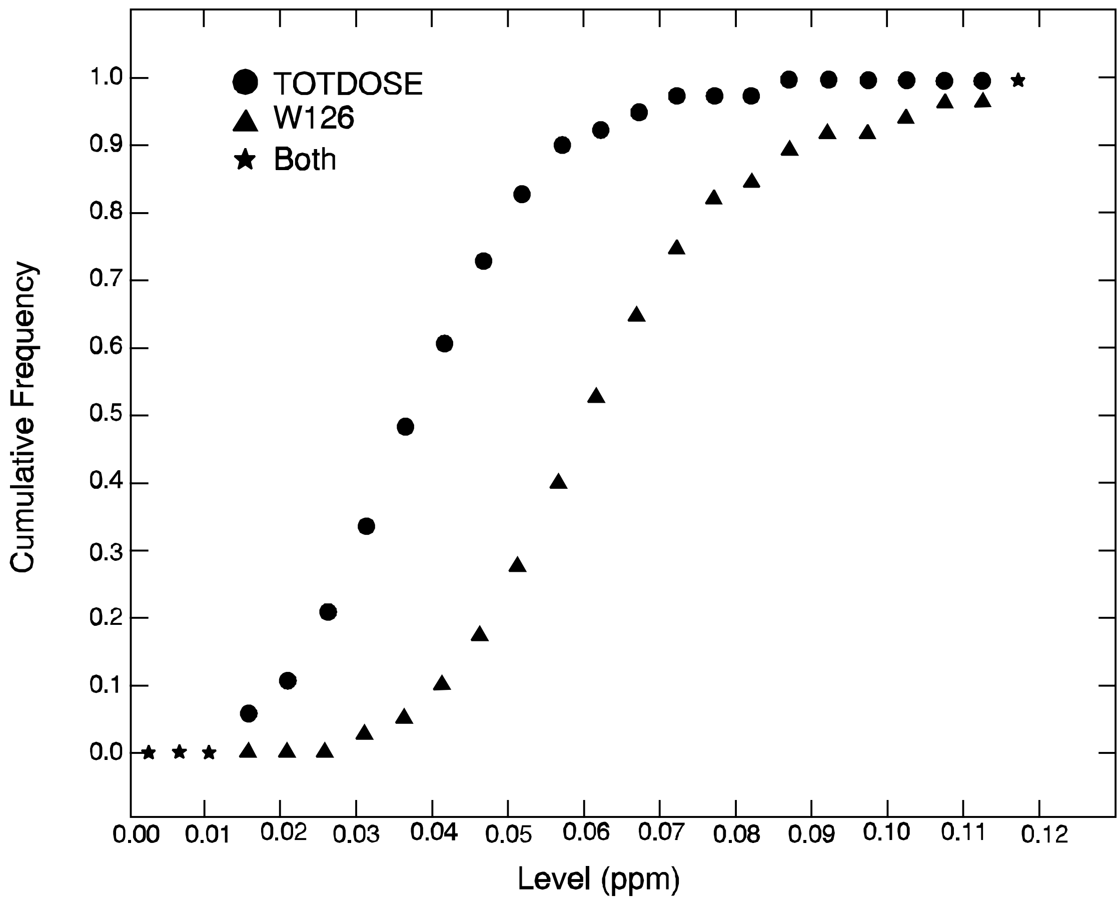


Figure 5-21. A comparison between the resulting cumulative frequencies for the exposure parameters, sum of all hourly average concentrations (SUM00) and the sigmoidally weighted integrated exposure index, W126. The ozone data were collected in 1981 at a site located in the Mark Twain National Forest, MO, EPA AIRS site number 291230001 (Lefohn et al., 1989).

another. This statement does not provide any insight concerning whether the magnitude of a SUM06 or a W126 value, calculated using monitoring data collected at a specific site over a specified time interval (i.e., months and hours of the day), is associated more with mid-level than high hourly average concentrations. The contribution of each range of hourly average concentrations to the magnitude of the cumulative index value is related to the distribution of the hourly average concentrations measured at the site.

5.5.2.5 Comparison of Effects on Vegetation of Cumulative "Peak" Versus "Mid-Level" Ozone Exposures

Not all studies dealing with the response of crop plants to O_3 exposures agree with the conclusions emphasized in the foregoing pages of this section that "higher" hourly concentrations should be given greater weight than "lower" concentrations. Based on their studies, Tonneijck (1994), Krupa et al., (1993, 1994, 1995), Grünhage et al. (1993b), and

Grünhage and Jäger (1994b) concluded that mid-level hourly average O_3 concentrations of 0.05 to 0.09 ppm are of greater importance than are higher hourly average concentrations in affecting vegetation.

It is clear from the studies over the years that the cumulative effects of exposure to all concentrations, peak and mid-range included, can play an important role in producing plant growth responses. The apparent difference in viewpoints is based on whether cumulative peak concentrations play a greater role in producing growth responses than do cumulative mid-range concentrations. As emphasized later, these views are based on experimental results that are not comparable. The studies that support the importance of peaks are chamber studies primarily using peak exposures, whereas the majority of the studies emphasizing that mid-range concentrations must be considered in plant response base their conclusions on both OTC and ambient field data. The key to plant response is timing because peak and mid-range concentrations do not occur at the same time. The greatest potential effect of O_3 on plants will occur when stomatal conductance is highest. If peaks do occur when stomatal conductance is greatest, the contribution of mid-range exposures will not be observable because they are masked. Associated with this is the importance of atmospheric conductivity (i.e., the O_3 concentration must reach the leaf surface if it is to be taken up by a plant).

Many studies over the years, depending on the duration of exposures and sensitivity of the plants have shown that injury to crops and other vegetation could occur when exposed to O_3 concentrations that ranged from 0.04 to either 0.4 or 0.5 ppm, with the higher concentration usually causing injury in the shortest period of time (Table 5-17; U.S. Environmental Protection Agency, 1978, 1986). This range encompasses both peaks and mid-range concentrations reported in the studies with the differing viewpoints cited above (Musselman et al., 1983, 1986b, 1994; Hogsett et al.,1985b; Tonneijck and Bugter, 1991; Tonneijck, 1994; Krupa et al., 1993, 1994, 1995; Grünhage et al., 1993b; Grünhage and Jäger, 1994b).

Unfortunately, the terms "high" and "low" concentrations and "peak" and "cumulative peak" concentrations are often used in publications (e.g., the majority of those cited above) without any explanation or the concentration being specified or, when specified, varying terminology has been applied with regard to what constitutes high concentrations or categories of lower values. For example, in an early paper discussing the development of vegetation effects exposure indices, Hogsett et al. (1988) termed 0.05 to 0.09 ppm as "mid-range", whereas >0.10 was considered as being "relatively high". In a recent paper, Krupa et al. (1995) term the concentrations of 0.05 to 0.09 as "moderately enhanced" and those >0.09 ppm as high. For consistency within this present review, concentrations ranging from 0.05 to 0.09 ppm are termed mid-range and those above 0.10 ppm as high or peaks.

When evaluating the results of the studies cited above, most attention has been focused on the concentrations used in the experiments (whether peaks or mid-range) by those espousing a particular viewpoint, whereas little mention has been accorded to duration of exposure, number of peaks during the exposure, whether or not there were peaks, and whether the experiments were conducted in chambers in the greenhouse, in the field, or in OTCs in the field. In the introduction to their paper, Musselman et al., (1983) describe the major problem plant scientists have encountered when attempting to relate exposures to plant responses in stating: "Pollutant dose, a quantitative description of pollutant exposure, has been defined as a product of concentration and exposure duration. The components of

Table 5-17. Ozone Concentrations for Short-Term Exposures That Produce 5 or 20% Injury to Vegetation Grown Under Sensitive Conditions[a]

	Ozone Concentrations That May Produce 5% (20%) Injury (ppm):		
Exposure time (h)	Sensitive Plants[b]	Intermediate Plants[c]	Less Sensitive Plants[d]
0.5	0.35 - 0.50 (0.45 - 0.60)	0.55 - 0.70 (0.65 - 0.85)	≥0.70 (0.85)
1.0	0.15 - 0.25 (0.20 - 0.35)	0.25 - 0.40 (0.35 - 0.55)	≥0.40 (0.55)
2.0	0.09 - 0.15 (0.13 - 0.25)	0.15 - 0.25 (0.25 - 0.35)	≥0.30 (0.40)
4.0	0.04 - 0.09 (0.10 - 0.15)	0.10 - 0.15 (0.15 - 0.30)	≥0.25 (0.35)
8.0	0.02 - 0.04 0.06 - 0.12	0.07 - 0.12 0.13 - 0.25	≥0.20 (0.30)

[a]The concentrations in parenthesis are for the 20% injury level.
[b]Examples of sensitive plants: oat, bean, and tobacco.
[c]Examples of intermediate plants: legumes, clover, and wheat.
[d]Examples of less sensitive plants: vegetables, woody plants, and cucumber.

Source: U.S. Environmental Protection Agency (1978, 1986).

pollutant dose are now recognized to be much more complex. Exposure concentration should consider distribution, peaks, and means, whereas exposure duration includes length of time exposed to zero concentration to indicate time intervals between exposures as well as the duration of individual exposures. Sequence and patterns of intermittent pollutant exposures also are involved when describing dose."

The papers on which the differing viewpoints are based represent attempts by the various scientists to address the problems noted in the preceding paragraph. When reading these papers, it soon becomes clear that each study is unique, some exposures were conducted in chambers in the greenhouse or in the field on plants growing in pots, and others were conducted in ambient air with plants grown in pots (See Table 5-18). None of the studies, even those in which the same scientists exposed the same plant species or cultivar, replicates a previous study. No two of the studies have exposed plants in the same manner or under similar conditions (Table 5-18). The O_3 concentrations, the duration, the conditions under which exposures were made, and the medium in which the plants were grown all vary. When similar exposure methods have been used, the exposures (concentration × duration [C × T]) and the plant species exposed have been different, and, when the same species or cultivar has been used, the exposure methods have been different, and plants were grown in a different medium. Therefore, the data presented in each paper were obtained under the particular set of circumstances applicable to that given study. Attempting to extrapolate the data from these studies to a broader scale causes many problems. Several of the authors of the above papers have recognized this fact (Musselman et al., 1983, 1986b, 1994; Tonneijck and Bugter, 1991; Krupa et al.,1993) and state that their studies have limited applicability,

Table 5-18. A Summary of Studies Reporting Effects of Peaks or Mid-Range Concentrations[a]

Species	Concentration (ppm)	Exposure Pattern	Exposure Duration	Methodology	Response	Reference
Kidney Bean cv. California Dark Red *Phaseolus vulgaris* L.	0.28 0.2 0.1-0.5 0.14-0.7	UH[b] UL[c] Simulated ambient: diurnal, variable diurnal, variable	One 6-h (0915-1515 h) exposure/week 1/3 plants: at 6 weeks; 1/3 plants: at 6 and 7 weeks; 1/3 at 6, 7, and 8 weeks plants harvested at end of exposure period	8 CSTR, in pots in soil	Greatest injury at 6 and 7 weeks; senescence at 8 weeks	Musselman et al. (1983)
Kidney Bean cv. California Dark Red *Phaseolus vulgaris* L.	0.3 0.4 0.06-0.3 0.08-0.4	UL "square wave" UH "square wave" Ambient, variable Ambient, variable	One 2-h (1051-1309 h) exposure/week for 6, 7, or 8 weeks One 6-h (900-1500) exposure/week 1/3 plants: at 6 weeks; 1/3 plants: at 6 and 7 weeks; 1/3 at 6, 7, and 8 weeks plants harvested at end of exposure period	8 negative pressure chambers, in pots in soil	Square wave vs. ambient: no difference in response if total dose equivalent	Mussleman et al. (1986b)
Kidney Bean cv. California Dark Red *Phaseolus vulgaris* L.	1. 0.12 2. 0.36 peak, max 1-h avg = 0.28 3. 0.24 4. 0.24 1-h peak	Uniform Narrow-based triangle Broad based pyramid Trapezoid	7 weeks 3 days/week 5 h daily	CSTR, 15 plants per chamber	Least injury: profiles 2 and 4 Greatest injury: 3 > 1 but less than 2 and 4	Musselman et al. (1994)
Alfalfa, *Medicago sativa* L.	Daily 7-h mean: 0.063, 0.064, 0.083, 0.084, peaks ≈ 0.2 7-h mean 0.074, 0.094, 0.099, peaks ≈ 0.10-0.15	Daily for 30 days: low episodic, high episodic, peaks at 1400-1500 h 30 days: low daily peak, high daily peak, peaks at 1400 h	0900-1600 h; 30 days × 5	8 OTC, in pots; alfalfa cut 3× during exposure period	Growth reduced more for alfalfa under episodic exposures Growth reduced less than with episodic exposures	Hogsett et al. (1985b)

Table 5-18 (cont'd). A Summary of Studies Reporting Effects of Peaks or Mid-Range Concentrations[a]

Species	Concentration (ppm)	Exposure Pattern	Exposure Duration	Methodology	Response	Reference
Tobacco cv. Bel W3 *Nicotiana tobacum* L.	Yearly mean range 1979-88: 0.025-0045	Ambient, daily not given	1 week	4 pots in soil in field: 17 locations	Foliar injury	Tonneijck and Bugter (1991)
	Weekly mean range 1988: 0.01-0.055	Ambient, daily not given	1 week	4 pots in soil in field: 17 locations	Foliar injury	
Tobacco cv. Bel W3, *Nicotiana tobacum* L.	Years, 1979-1983 0.005-0.15, combined in classes of 10 μg/m^3	Ambient, daily not given	1 week	4 pots in soil in field: 40 locations	Foliar injury	Tonneijck (1994)
Bean, *Phaseolus vulgaris* L. cv. Stratego cv. Groffy	Years 1982-1983 0.015-0.075, combined in classes of μg/m^3	Ambient, daily not given	1 week	4 pots in soil in field: 10 locations	Foliar injury on Stratego	
Tobacco cv. Bel W3 Bel B *Nicotiana tobacum* L.	0.06-0.100	Montague weekly max	1 week	OTC (CF); OTC (NF); ambient	Foliar injury on bottommost expanded leaf	Krupa et al. (1993)
	0.06-0.103	Mt. Equinox weekly max	1 week	6 plants in pots in peat and Perlite 6 plants in pots in peat and Perlite		

[a]See Appendix A for abbreviations and acronyms.
[b]UH = Uniform high.
[c]UL = Uniform low.

and that caution should be used in applying their results on a broader scale. Had this advice been adhered to, then many apparent discrepancies in conclusions across the papers would likely not have arisen.

Musselman et al. (1983) exposed bean plants (*Phaseolus vulgaris* cv. California Red Kidney) grown in pots in soil in CSTR chambers in a greenhouse with CF air to simulated ambient O_3 concentration distributions specific for their region (Riverside, CA), as well as to two uniform concentration levels (Table 5-18). Plants were exposed to a 6-h O_3 fumigation from 0915 to 1515 Pacific Standard Time (PST) at 6, 7, and 8 weeks of age. The four exposure regimes were (1) uniform high, 0.28 ppm; (2) uniform low, 0.2 ppm; (3) variable low concentrations ranging from 0.1 to 0.5 ppm that simulated ambient exposures distributions (i.e., O_3 concentrations increased during the morning, peaked in the afternoon, and then decreased in the evening); and (4) variable high exposures ranging from 0.14 to 0.71 ppm that also simulated ambient concentration distributions (Table 5-18; Figure 5-22). Six days after each of the three fumigations, one-third of the plants were measured for leaflet oxidant stipple and destructively analyzed for leaf area and dry weight of plant parts. Therefore, one-third of the plants received one fumigation, the second third received two fumigations, and the remaining third received three fumigations at 6, 7, and 8 weeks of age. Simulated ambient O_3 distribution treatment produced significantly greater leaf injury and reduced growth and yield response than the uniform low or high exposure patterns. In addition, the simulated Riverside ambient O_3 concentration distribution reduced the total dry weight at both the 6- and 7-week fumigations; both pod and seed weights were reduced. The reduction in dry weights of pods resulted after the first fumigation at 6 weeks and did not change with subsequent fumigations. At 8 weeks, plants had begun to senesce. In this experiment, levels of concentration ranged from the lowest, 0.1 ppm, to the highest, 0.5 ppm. No exposure concentration, therefore, was below the "peak" level. Musselman et al. (1983) pointed out that the simulated ambient pollutant distribution used in their studies was specific for their geographic region. They also suggested that other studies determining the responses of additional species at different developmental stages to ambient O_3 distributions typical of other regions of the country were needed to put their findings in perspective.

Exposures in the Musselman et al. (1986b) study were designed to compare plant response to simulated ambient and uniform O_3 concentration distributions at two equivalent dose levels under controlled conditions (Table 5-18; Figure 5-23). Plants were fumigated in eight negative pressure chambers located within the greenhouse and received either one ambient or one uniform O_3 treatment during Week 6, during Weeks 6 and 7, or during Weeks 6, 7, and 8. Therefore, as in the previous study, one-third received one fumigation, the second third received two fumigations, and the other third received three fumigations. Plants were harvested 6 days after their last fumigation (Musselman et al., 1986b).

The uniform distribution in the above study was selected so that the constant concentration matched the total dose and peak concentration of the ambient distribution. Matching the peak concentration and the total dose required that plants exposed to the uniform distribution be exposed to the peak concentration (either 0.3 or 0.4 ppm) during the entire fumigation period, whereas plants in the ambient distribution were exposed to the same peak for only half an hour. The O_3 concentrations during the ambient exposure distribution had a fluctuating rising and falling pattern and were of longer duration overall, and the time of the peak exposure was shorter when compared with the uniform O_3 concentration

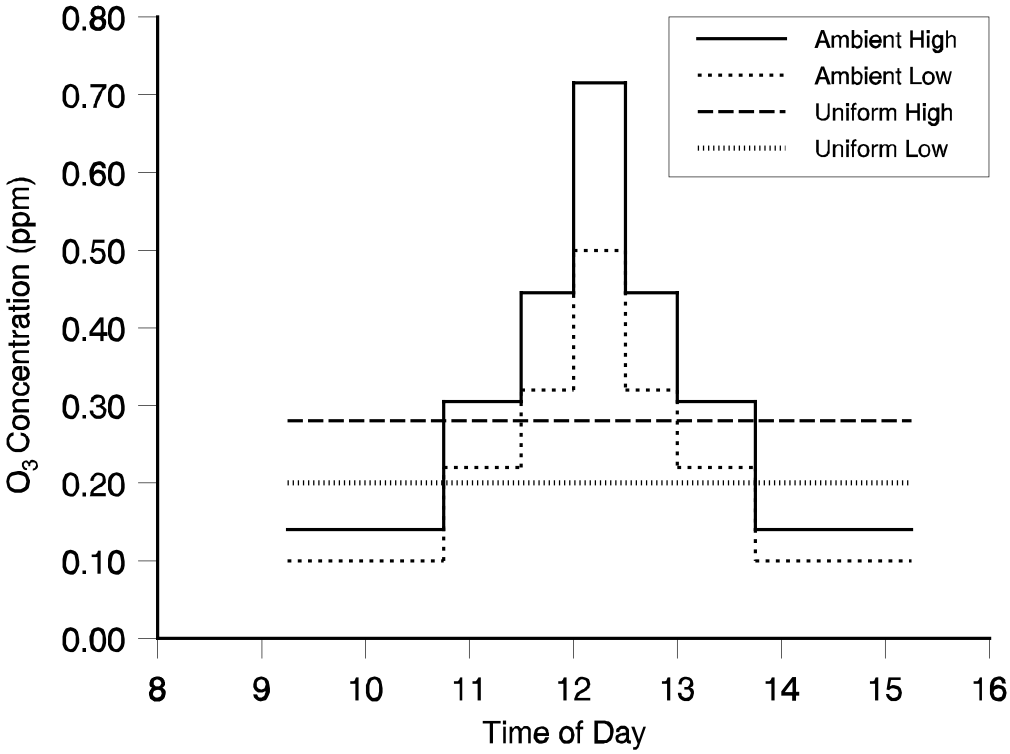


Figure 5-22. Fumigation schedule of uniform and simulated ambient ozone (O_3) concentration distributions at two equivalent dose levels.

Source: Musselman et al. (1983).

treatment. Total exposure time for the uniform distribution was 2 h and 18 min, and, for the ambient distribution, it was 6 h (Figure 5-23). Simulated ambient O_3 concentrations for the low dose ranged from 0.058 to 0.30 ppm, and for high dose, from 0.077 to 0.40 ppm.

The authors point out that ambient air quality data are generally reported as hourly average concentrations, and the dynamics of changes in O_3 concentrations during the hour are not considered in the summaries of air quality data, although these have been considered important in plant response. They also state that the results of this experiment demonstrate that, when peak O_3 concentrations and total dose are equivalent, the shape of the O_3 distribution (normal versus square wave) had no effect on the magnitude of response. Beans responded similarly to both an ambient and a uniform O_3 concentration distribution. No significant difference in injury, growth, or yield was observed. The authors conclude with the statement that "Further research is needed to examine whether peak concentration is the most important component of the concentration distribution causing plant response" (Musselman et al., 1986b).

In a further attempt to determine the response of plants to different exposure profiles but equal total exposures (C × T), Musselman et al. (1994) exposed the same bean cultivar, California Red Kidney, grown as in the previous studies, in CSTRs in a CF greenhouse to four different profiles having the same total cumulative exposure and the same

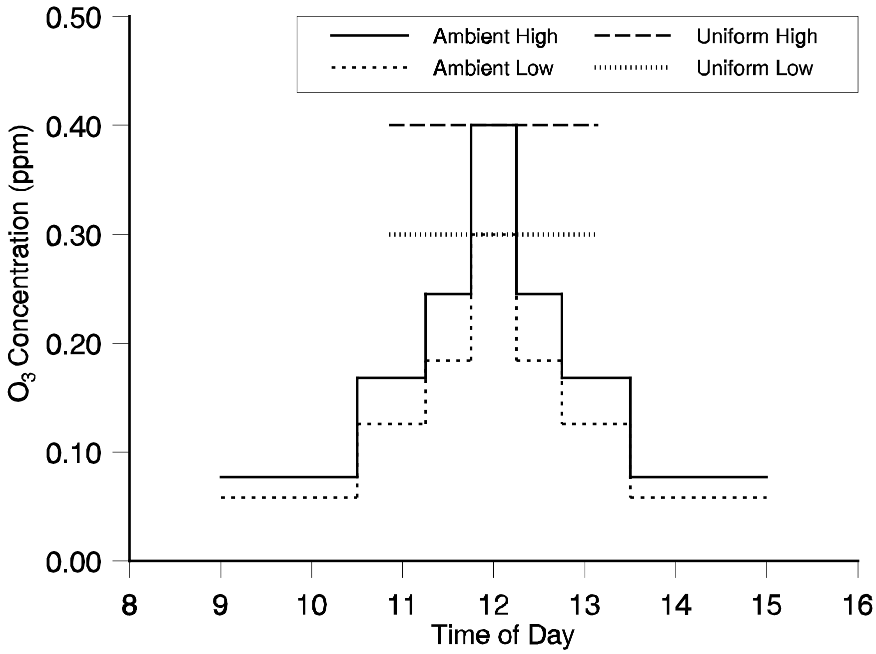


Figure 5-23. Fumigation schedule of uniform and simulated ambient ozone (O_3) concentration distributions at two dose levels.

Source: Musselman et al. (1986b).

7-, 12-, and 24-h seasonal means (Table 5-18; Figure 5-24). Ozone exposures began 21 days after germination. Plants were exposed for approximately 5 h, three times a week over the seven-week growing season. The first profile used was a "square-wave" concentration of 0.12 ppm; the second exposure resembled a narrow-based triangle, during which the O_3 concentrations rose rapidly to a peak of 0.36 ppm with a maximum 1-h average of 0.28 ppm and then dropped off rapidly; the third profile was in the shape of a broad-based pyramid, during which the O_3 concentration rose slowly to a peak of 0.24 ppm and then slowly dropped off; the fourth profile rose rapidly to a plateau with a peak of 0.24 ppm that lasted for 1 h and then dropped off slowly. The maximum 1-h average concentrations of 0.22 ppm for Profiles 3 and 4 simulated the more typical summer patterns for Southern California, where hourly peaks of >0.2 ppm occurred with regularity. Each of the last three profiles had the same total O_3 exposure, but at least 1 h of each daily exposure had at an average peak concentration that exceeded 0.12 ppm.

Significant differences were found for all measured variables. Plants exposed using the 0.12-ppm square-wave exposure (Profile 1) exhibited the least injury. Profile 3, with the mean hourly pyramidal peak of 0.22-ppm exposure, exhibited significantly less necrosis than did Profiles 2 and 4, which also had peak exposures. Plants responded similarly to Profiles 2 and 4. There were no significant differences in plant responses for any of the measured response variables, even though the mean 1-h peak for Profile 2 (0.28 ppm) was higher than the 1-h peak mean (0.22) for Profile 4. Both of these profiles had higher peaks or a longer duration of high concentrations, those above 0.16 ppm, than did

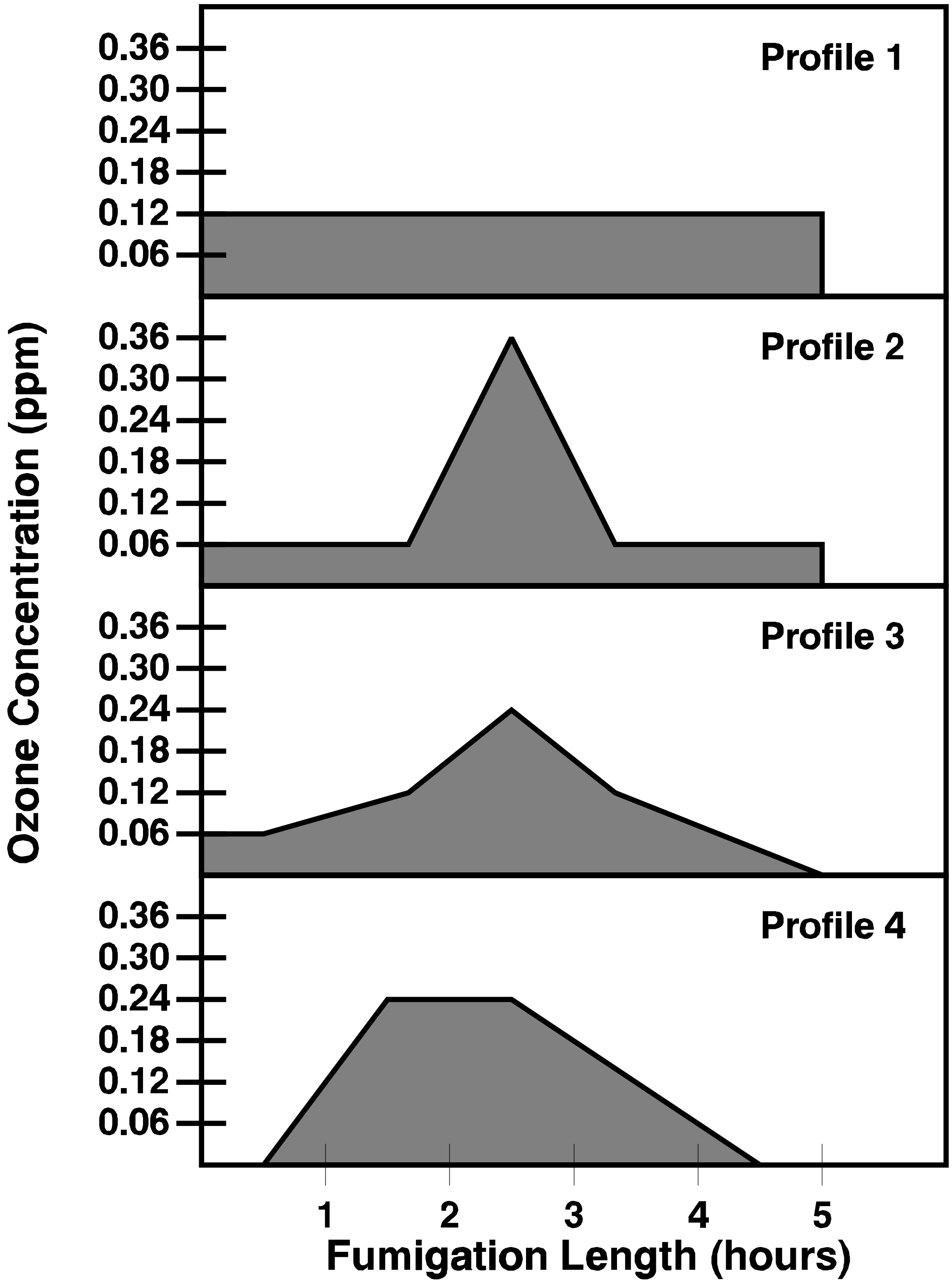


Figure 5-24. Experimental ozone exposure profiles.

Source: Musselman et al. (1994).

Profile 3. The three exposure profiles that incorporated peaks impacted plant response more severely than the steady-state profile, thus providing evidence of the importance of peak concentrations in defining an exposure index (Musselman et al., 1994). Total exposure, however, could not relate O_3 impact to plant response unless the exposure shape was held constant. The authors caution against the application of summary exposure statistics that do not give increased weight to higher concentrations for comparison of plant response in areas with differing exposure regimes. In addition, the authors state that, for Southern California, which experiences high peak O_3 levels, a descriptor of exposure that gives greater weight to peak concentrations is more useful when relating plant response to O_3 exposure. They also suggest that environmental conditions may influence stomatal conductance and O_3 uptake. Therefore, summary statistics might necessitate the inclusion of other parameters that relate to environmental factors. Finally, it is suggested that flattening out concentrations so that peaks remain lower than 0.10 ppm might be expected to benefit the vegetation of Southern California. Again, it should be noted that in all of the studies by Musselman et al. (1983, 1986b, 1994) peaks greatly exceed those in any of the other exposure studies.

The experiments of Hogsett et al. (1985a) were the initial studies using a newly designed modified OTC, with an automated control system in which plants were exposed to simulated ambient concentrations typical of the midwest. In the study, alfalfa and tall fescue growing in pots were exposed to generator-produced O_3 in OTCs using two different types of exposure profiles (Table 5-18). Concentrations used were based on a 1978 Storage and Retrieval of Aerometric Data (SAROAD) database for a selected midwestern site where a substantial acreage of hay was grown. This study used the longest exposures of any of the papers reviewed. The first exposure was a 30-day episodic profile of varying peak frequency, concentration, and duration; a profile that was repeated every 30 days throughout the growing season (Table 5-18; Figure 5-25). The second exposure was a daily peak profile of equivalent peak concentration and duration each day. Daily 7-h exposures of alfalfa were from 0900 to 1600 hours (9 a.m. to 4 p.m.) for the 133-day growing season. Episodic 7-h mean concentrations ranged from 0.064 to 0.084 ppm, with peaks of nearly 0.2 ppm occurring at 1400 to 1500 hours, whereas the profile for the mean daily peak concentrations varied from 0.074 to 0.099 ppm, with peaks ranging between 0.10 to 0.15 ppm occurring at 1400 hours. Reduction in alfalfa growth was reported under both exposure profiles; however, response to the episodic exposures was greater. Actual response data is not given in the paper. The response of tall fescue was reduced only slightly over a period of 90 days when exposed to either regime. Both alfalfa and fescue were cut three times during the exposure period. This is the only study exposing a perennial plant, alfalfa, and a grass. The growth habit of grasses differs from that of dicotyledonous plants because the growth of each leaf blade results from a meristem at the base of the leaf, not from the apical meristem. Therefore, cutting or injury to the leaf blade does not prevent its continued growth. Of the papers cited, this OTC experiment is the only long-term study in which plants were exposed to both mid-range and peak concentrations. The fluctuating episodic O_3 pattern in the Hogsett et al. (1985b) and the single 6-h/week exposure of the Musselman et al. (1983, 1986b) studies permit plants a brief recovery period between exposures to peak concentrations. Also, in the above studies, plant response to O_3 exposure resulted in a reduction in growth, whereas, in the studies discussed below, foliar injury is the plant response observed.

Tonneijck and Bugter (1991), Tonneijck (1994), and Krupa et al. (1993) were reviewed by Krupa et al. (1995) who cited these Bel W3 studies in support of the concept

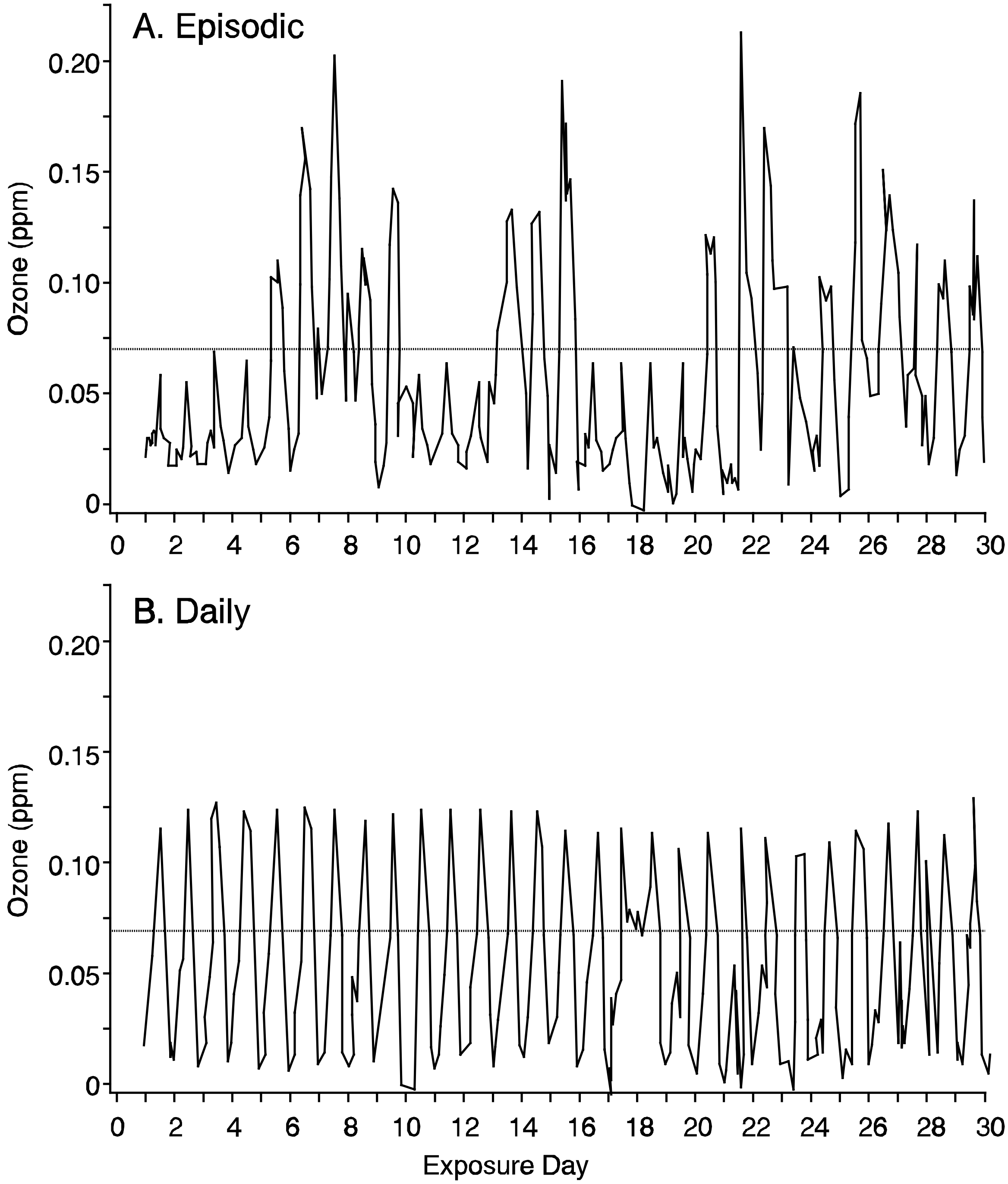


Figure 5-25. Ozone exposure profiles for the 1983 season.

Source: Hogsett et al. (1985b).

that "mid-range" concentrations (0.05 to 0.09 ppm) play a greater role than peak concentrations in causing plant response (Figures 5-5, A, B, and D, and 5-6). Bel W-3, is a variety of tobacco noted for its sensitivity to O_3 and has been used as a sensitive monitor for photochemical ambient air pollution for many years. Visible foliar injury is a clear and unequivocal indication of O_3 exposure. Heggestad and Middleton (1959) discovered Bel W3 and first reported on its sensitivity to O_3. Heggestad and Menser (1962), Heck et al. (1969) and Heck and Heagle (1970) all reported its value as a sensitive monitor of photochemical ambient air pollution. Both Heck et al. (1969) and Heck and Heagle (1970) reported, however, that there was no consistent relationship between oxidant values (O_3 concentrations measured as total oxidants) and foliar injury. They state, however, that a monitoring system such as they describe can provide a community with estimates of the frequency of phytotoxic levels of oxidants, of the relative severity of each episode, and of regional distribution of phytotoxic air pollution (Heck and Heagle, 1970).

The papers of Tonneijck and Bugter (1991) report on observations made in the Netherlands from 1984 to 1988, during which Bel W3 was used as a part of an extensive network for monitoring the effects of ambient air pollution along with the O_3-sensitive indicator plant subterranean clover cv. Geraldton (*Trifolium subterraneum*).

Indicator plants grown in the greenhouse in pots were taken to 17 field locations at weekly intervals and were exposed to ambient air for 1 week for Bel W3 tobacco and 2 weeks for clover. Foliar injury on the tobacco Bel W3 cultivar used in 1988 was greater than that on the variety used during the years 1984 through 1987 (Figure 5-5A), although mean O_3 concentrations to which the varieties were exposed were similar (Figure 5-26, B). The increased injury appeared to be associated with the new line of "relatively sensitive" tobacco used in 1988 when compared with the "rather tolerant" strains used from 1984 to 1987. Exposures were reported as mean weekly O_3 concentrations, 24-h means, daytime average concentrations, number of hours >80 µg m^3 (≈0.04 ppm), and cumulative dose of hourly values >120 µg m^3 (≈0.06 ppm). No peak concentrations were listed. The highest effect intensity, a mean O_3 concentration of 100 µg/m^3 (≈0.05 to 0.06 ppm), was observed during Week 22 of the exposures at the field site in 1988 (Figure 5-26, B). The mean O_3 concentration was the highest in Week 32.

The authors state that "foliar injury on tobacco Bel W3 was poorly related to the ambient ozone in the Netherlands" (Figure 5-26, A, B, and C), whereas foliar injury on subterranean clover correlated well with O_3 exposure concentrations (Figure 5-26, D). Ozone exposure indices emphasizing the importance of peak values did not correlate better with injury than those based on mean values (Figure 5-26, E). Even though no peaks, as previously defined above, were listed in their paper, foliar injury of tobacco was observed. Tobacco plants appeared to be "relatively" more sensitive to O_3 than did clover at the end of the season. The main reason for using Bel W3 was to demonstrate the occurrence of symptoms induced by O_3 and "not to examine the relationship between the level of ambient ozone and foliar injury intensity," as stated by Tonneijck and Bugter (1991). These authors further noted that care should be taken when comparing the responses of both species because of the difference in length of exposure and effect parameter. Even when both species of plants were exposed to ambient air at the same location for the same length of time (7 days), foliar injury on tobacco was not related to foliar injury on primary leaves of bean plants. Finally, the authors state, "From these results, it can be concluded that ozone injury on tobacco Bel W3 does not adequately indicate the concentration of ambient ozone nor is it a good indication of the risk of ozone to other plant species or to vegetation as a

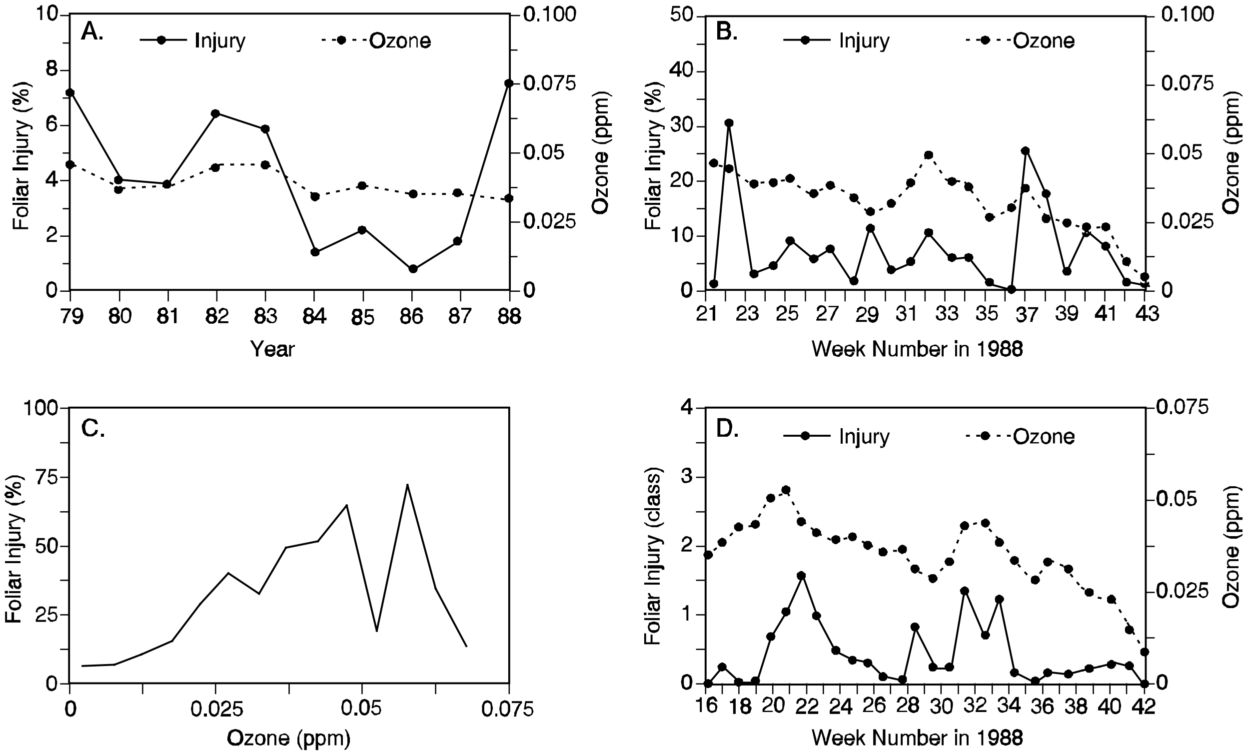


Figure 5-26. (A) Mean foliar injury on tobacco Bel W3 and mean ozone (O_3) concentrations for the years 1979 to 1988, (B) mean foliar injury on tobacco Bel W3 and O_3 concentrations for weekly exposures during the 1988 growing season, (C) maximal foliar injury on tobacco Bel W3 in relation to O_3 concentrations for 1988, and (D) mean foliar injury on subterranean clover cv. Geraldton and mean O_3 concentrations for two weekly exposures during the 1988 growing season.

Source: Tonneijck and Bugter (1991).

whole" (Tonneijck and Bugter, 1991). In other words, Tonneijck and Bugter (1991) concur with the reports of Heck et al. (1969) and Heck and Heagle (1970), who much earlier had reported similar views based on the results of their studies. Also, in their studies they observed that ratios of weekly tobacco injury indices to oxidant indices at an oxidant-monitoring site revealed no consistent relationship between weekly oxidant concentrations and weekly plant injury. In addition, they observed that, although considerable new injury was recorded each week of the season, the relationship between oxidant values and plant injury was not consistent. In other words, data from Bel W3 exposures is not a good basis from which to make extrapolations.

Tonneijck (1994) used data from the Dutch monitoring network for the years 1979 to 1983 (Figure 5-27, A) for Bel W3 and from 1982 to 1983 (Figure 5-27, B) for two bean cultivars, the O_3-sensitive "Stratego" and the O_3 tolerant "Groffy", to evaluate injury-response relationships among certain indicator plants. Various O_3 exposure indices were

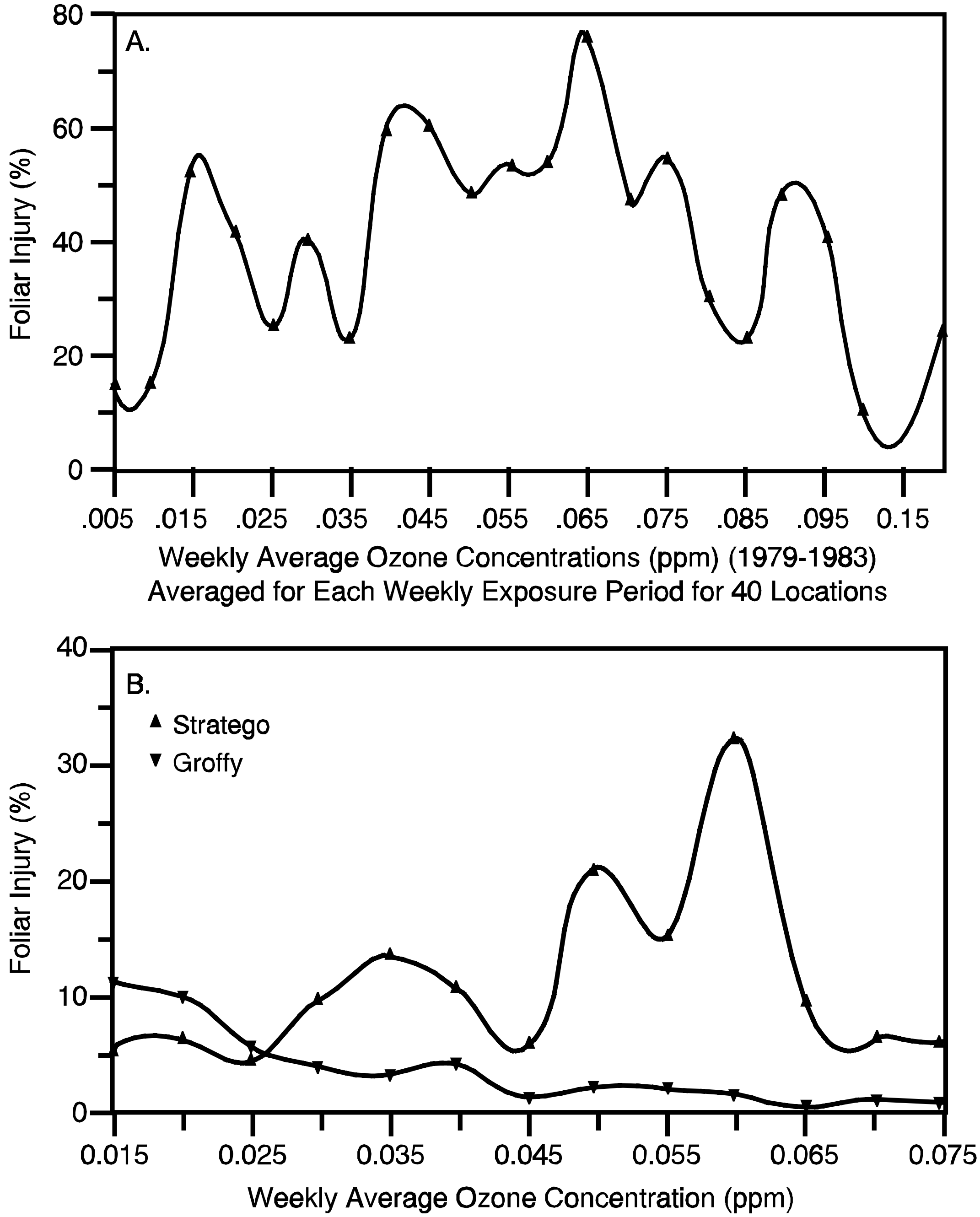


Figure 5-27. ***(A) Maximum foliar injury (percent of leaf area affected) on tobacco Bel W3 in relation to ozone (O_3) concentrations expressed in classes of 10 µg/m^3 for 1979 to 1983, and (B) maximum foliar injury (percent of leaf area affected) on two bean cultivars in relation to O_3 concentrations for 1982 to 1983.***

Source: Tonneijck (1994).

calculated from hourly O_3 concentrations for all exposure periods. Data of foliar injury to Bel W3 tobacco based on 20 to 22 weekly observations for 5 years (1979 to 1983) at 40 locations (Figure 5-27, A) were regressed against several exposure indices. Results of correlation analysis indicated that the weekly sum of all hourly concentrations >40 µg/m^3 (0.02 ppm) has a negligibly better linear association with maximum weekly foliar injury response than does the 24-h mean. Tonneijck (1994) does not present strong evidence in favor or against the importance of mid-range concentrations in causing foliar injury response due to low correlations (<0.28). The role of mid-range concentrations is difficult to substantiate using correlation analyses because the effects of O_3 on maximum foliar injury response are not linear (Figures 5-27, B and C) and are confounded with environmental factors. Tonneijck stated that the results of the Dutch monitoring network generally do not support the conclusion that hourly concentrations of ambient O_3 above 80 to 120 µg/m^3 (0.05 to 0.06 ppm) may be relatively more important in causing tobacco injury. Problems with weak associations between weekly pollutant concentrations and visible foliar injury that make the ability to discriminate among exposure indices difficult, which were reported by Tonneijck (1994), also were experienced by Tonneijck and Bugter (1991) and Heck et al. (1969), and Heck and Heagle (1970).

Based on his study, Tonneijck (1994) concluded that "the greatest injury to the ozone-sensitive indicators, tobacco Bel-W3 and bean cv. Stratego, seems to occur at moderate levels of ambient ozone." At relatively high O_3 concentrations (>115 to 135 µg/m^3; ≈0.055 to 0.065 ppm), less injury was observed than at "moderately enhanced concentrations". Results of the above study do not support the "concept that higher O_3 concentrations should be given more weight in terms of plant response than lower ones, since higher concentrations do not necessarily cause greater effects." In Figure 5-27, A, it can be noted that foliar injury on Bel W3 tobacco did not increase even when O_3 concentrations neared 0.15 ppm. However, the manner in which the data in the above study is presented makes it difficult to determine the actual concentrations to which the plants were exposed.

In neither the Tonneijck and Bugter (1991) nor Tonneijck (1994) papers are the actual O_3 concentrations to which the plants were exposed stated, except as mean values. Also, the terms "peak", "moderate", "moderately enhanced", and "circa" are used, but never defined. The problems associated with attempting to make extrapolations from Bel W3 have already been mentioned. In addition, Posthumus (1984) points out, in a paper describing the Dutch monitoring program, that plants grown in the greenhouse may be "more vulnerable" to ambient air pollutants than are crops grown in the field because those grown in a greenhouse have been grown under ideal circumstances.

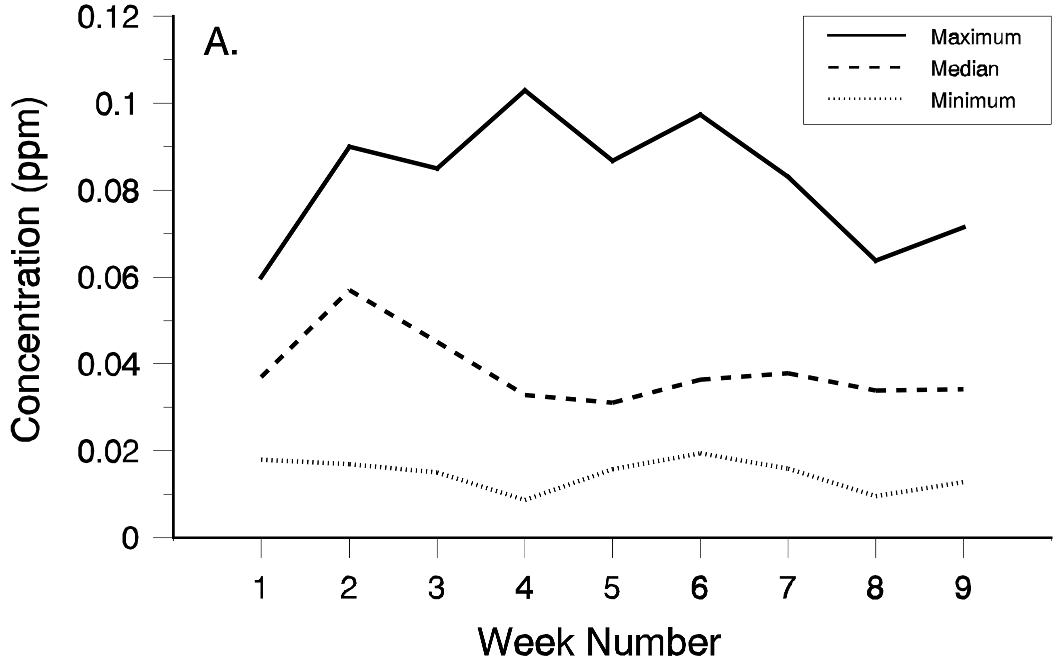
Krupa et al. (1993) used two tobacco cv. (the sensitive Bel W3 and the tolerant Bel B) as differential indicators of ambient O_3 pollution. When reviewing previous studies in the introduction to their paper, Krupa et al. (1993) mention that the tobacco cultivars Bel W3 and Bel B have been used for over 25 years and indicate that other studies using Bel W3 have produced conflicting results. The aim of their present study was to further examine this subject. Seedlings of the two cultivars grown in pots containing Fafard Mix No. 2 (screened peat + Perlite) in CF air and fertilized every 7 days with liquid fertilizer until the day prior to exposure were transferred to the two field sites when each set of plants reached its "true four-leaf stage" after removing the two juvenile leaves. Exposures to ambient O_3 concentrations were made at two different sites (near Amherst, MA, and in the Green Mountains of southern Vermont) from mid-June to August during the 9 weeks of the study (Figure 5-28, A and B). Ambient O_3 concentrations were measured continuously. Exposures occurred in an OTC with

CF air, an OTC with NF air, and a chamberless ambient-air field plot (Table 5-18). There were two replicates per treatment, with six plants of each cultivar in each replicate. Visual estimates of leaf area showing O_3 injury were made, beginning with the bottommost fully expanded leaf (leaf no. 1) at the end of each weekly exposure. Ratings were given a value from 1 to 10. A new set of plants was exposed each week. Maximum hourly average concentrations for the 9-week period ranged from 0.06 to 0.1 ppm, with the highest concentrations occurring during week seven.

Observations, based on foliar injury scores, indicated that injury to leaves no. 1 and 2 on Bel W3 was much greater than corresponding leaves on Bel B. Foliar injury on Bel W3 was much higher in the NF OTCs and chamberless ambient-air exposures than in the filtered-air OTC exposures. Injury scores indicated that leaf no. 1 on Bel W3 was more sensitive than leaf no. 2. Also, injury scores on leaf no. 1 were very similar in the NF OTC and the chamberless ambient field plot. Study results indicated that, in all cases, of the several O_3 descriptors tested, the number of hours with O_3 concentrations >40 ppb (N40) and >60 ppb (N60) or the number of hours with O_3 concentrations >40 ppb (SUM40) and >60 ppb (SUM60) were best predictors of O_3 injury. Neither the N40 or N60 nor the SUM40 or SUM60 performed well independently of the corresponding variable in the best regression.

The authors state that the results of the present study support the conclusions of Menser et al. (1963), who pointed out that mature leaves were more sensitive than over-mature and rapidly expanding younger leaves. Consequently, all subsequent analyses were based on the responses of leaf no. 1. The authors also point out that their analysis had two limitations: (1) the number of foliar injury observations was low (nine) on a per-site basis, and, hence, results had to be pooled; and (2) foliar injury observations each week involved new groups of plants, and the results on consecutive weeks were thus independent of each other. This is the only study, of those being discussed, in which plants were grown in an artificial medium.

Krupa et al. (1994) suggested that mid-level hourly average concentrations of O_3 (0.05 to 0.087 ppm) are more important than higher hourly average concentrations in affecting vegetation. The key result of Krupa et al. (1994) is questioned because the CF-NF and AA-NF (i.e., comparisons between CF and NF OTC plots and between ambient air nonchambered and NF chambered plots) differences, as reported by the authors, were inconsistent with earlier publications of the same NCLAN studies, which found few cases with significant CF-NF differences (e.g., Heagle et al., 1988a; Rawlings et al., 1988a; Kress et al., 1985; Kohut and Laurence, 1983). For three of the eight harvests, which Krupa et al. (1994) reported as having significant CF-NF difference, Kohut and Laurence (1983) reported a 2% yield reduction at NF for kidney bean plants at the Ithaca site in 1980; Heagle et al. (1987a) reported 0 and 34% yield reductions at NF for well-watered and water-stressed soybean plants, respectively, at the Raleigh, NC, site in 1983; and Kohut et al. (1987) reported an 11% yield reduction at NF for wheat plants at the Ithaca site in 1983, which was not significant at the 5% level. Another two harvests of clover in the 1985 Raleigh experiment should not have been used by Krupa et al. (1994) because Heagle et al. (1989b) reported significant chamber effects on total biomass, based on a 33% yield reduction at NF relative to AA. Two other inconsistencies were found in Krupa et al. (1994). First, the two clover studies conducted at Raleigh in 1984 and 1985 had six and seven harvests during each year of the studies (Heagle et al., 1989b), not 12 and 14 as reported by Krupa et al. (1994).



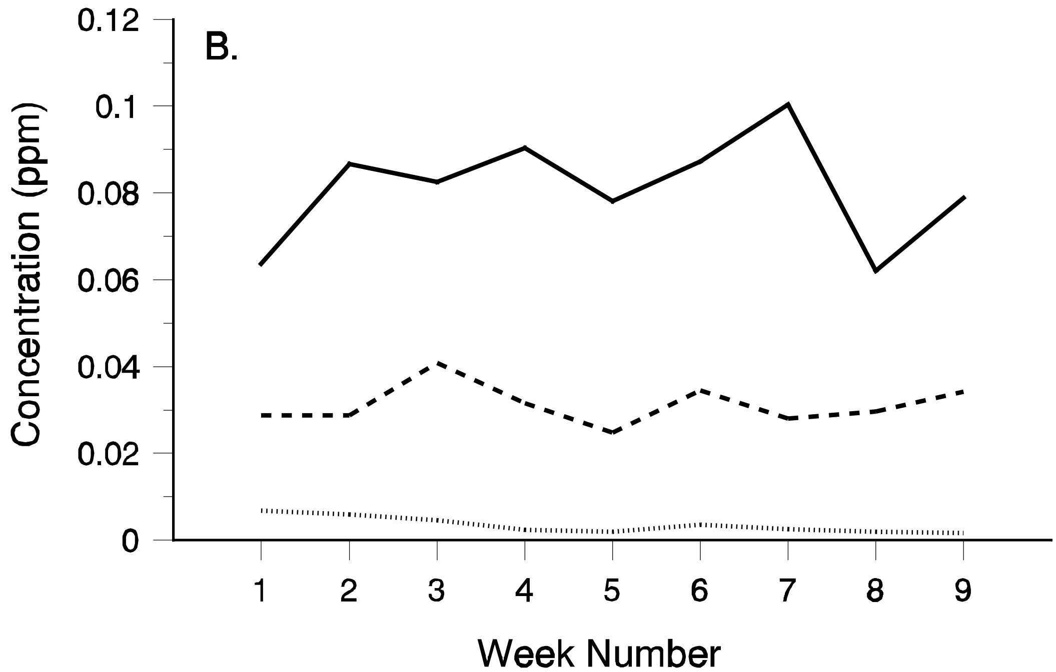


Figure 5-28. ***(A) Summary hourly ambient ozone (O_3) concentrations during 9 weeks of experimentation (1990) at Montague-Amherst, MA, and (B) summary hourly ambient O_3 concentrations during 9 weeks of experimentation (1990) at Mount Equinox.***

Source: Krupa et al. (1993).

Second, the two clover studies conducted at Ithaca in 1984 and 1985 had three harvests during each year of the studies (Kohut et al., 1988a), not six as reported by the authors.

Krupa et al. (1995) attempted in another paper to present "a cohesive view of the dynamics of ambient O_3 exposure and adverse crop response relationships, coupling the properties of photochemical O_3 production, flux of O_3 from the atmosphere into crop canopies and the crop response per se." The results from two independent approaches, (1) statistical and (2) micrometeorological, were analyzed for understanding cause and effect relationships of foliar injury responses of tobacco Bel W3 to the exposure dynamics of ambient O_3 concentrations. Additionally, other results from two independent approaches were analyzed to (1) establish a micrometeorological relationship between hourly ambient O_3 concentrations and their vertical flux from the atmosphere into a grassland canopy and (2) establish a statistical approach relationship between hourly O_3 concentrations in long-term, chronic exposures and crop yield reductions. Based on the above approaches, Krupa et al. (1995) noted that atmospheric conditions appeared to be most conducive and crop response appeared to be explained best statistically by the cumulative frequency of hourly ambient O_3 concentrations between 0.05 and 0.09 ppm. The diurnal occurrence of this concentration range, frequently between the hours 9:00 a.m. and 4:00 p.m. in a polluted agricultural environment, coincided with the optimal CO_2 flux from the atmosphere into the crop canopy, thus facilitating high uptake. The frequency of hourly concentration >0.90 ppm appeared to be of little importance. The higher concentrations, generally appeared to occur when atmospheric conditions did not facilitate optimal vertical flux into the crop canopy, therefore uptake was low.

Krupa et al. (1995) concluded, based on their overall results, that, if the cumulative frequency of hourly ambient O_3 concentrations between 0.05 and 0.062 ppm (100 and 124 µg m^3) occurred during 53% of the growing season, and the corresponding cumulative frequency of hourly concentrations between 0.05 and 0.074 ppm occurred during 71% of the growing season, a potential yield reduction in sensitive crops could be expected, if other factors supporting growth, such as adequate soil moisture, are not limiting. In summary, they concluded that these results need further verification.

High correlations can be obtained from chamber experiments because exchange properties inside chambers are more or less constant in time (Grünhage and Jäger, 1994b). Under ambient conditions, however, exposure indices obtained from the chamber studies frequently yield unsatisfactory results (Grünhage and Jäger, 1994a). Grünhage and Jäger (1994a,b) support this view by presenting the results of O_3 flux density measurements above a permanent grassland in Germany. Two years of observations demonstrate the influence of atmospheric conditions on O_3 exposure potential (i.e., how vertical flux and stomatal conductance change during the day). Diurnal flux densities of O_3 varied during the growing seasons of 1990 and 1991 (Grünhage et al., 1994). Vertical flux densities have to be calculated using micrometeorological approaches. Though similar in pattern, the higher flux densities in 1991 coincided with lower O_3 concentrations. Therefore, under ambient conditions, exposures cannot be expressed as a simple function of the concentration in the air. Flux densities and deposition velocities of O_3, as well as the biological activity of the canopy, need to be considered when determining the effects of ambient air exposures on vegetation. Grünhage and Jäger (1994a,b) and Grünhage et al. (1994), using the information obtained from the micrometeorological measurements of vertical flux densities of CO_2 and O_3 above the native grassland, developed a mathematical model. Grünhage and Jäger (1994b) fit this mathematical model to Bel W3 tobacco data to describe a dose-response relationship for leaf injury. They concluded that it is possible with this model to attribute the DLA on Bel W3 tobacco to O_4 flux densities. Correlations between O_3 fluxes and leaf injury to tobacco are significantly higher than those using exposure indices based on chamber studies. Grünhage and Jäger (1994b) emphasize the need for taking ambient conditions into account when developing exposure indices to determine critical levels that will prevent injury to vegetation.

Finally, it is not possible at this time, based on a comparison of data from the above mixed studies, to conclude whether the cumulative effects of mid-range concentrations are of greater importance than those of peak hourly average concentrations in determining plant response. The data are not comparable; exposure methods, concentrations and durations used, age of plants at exposure, length of exposure, the plants exposed, and the media in which they were grown all differ across experiments. Some exposures were in chambers in the greenhouse, others in OTCs and others in the ambient air. Many of the exposures in the studies supporting the importance of mid-level O_3 concentrations were only 1 week in duration. It is doubtful that an exposure duration of only 1 week and foliar response data from a sensitive plant species like Bel W3 or from any other plant species are sufficient to ascertain whether cumulative peaks or mid-range concentrations play a greater role in plant growth response. It should be noted, however, that plants are not exposed just to peak O_3 concentrations, therefore, response to O_3 involves the cumulative effect of all concentrations that enter the plants. The short-term exposures indicate that foliar injury can occur even in the absence of peaks. The timing is the key to plant response. Peak and mid-range concentrations do not occur at the same time. A plant effect is determined by which concentrations occur when stomatal conductance is highest. Peaks are important in plant response only where and when plants are exposed to them.

Most important of all is that the response parameters measured in the studies of Musselman et al. (1983, 1986b, 1994) and Hogsett et al. (1985b) differ from those of Tonneijck and Bugter (1991), Tonneijck (1994), and Krupa et al. (1993, 1994). The former measured both foliar injury and growth reductions; all but one of the latter based their conclusions on foliar injury alone. Although foliar injury in tobacco can result in important economic loss to the grower, for the majority of crops, reduction in growth and yield is the measure of importance. As stated in the previous criteria document (U.S. Environmental Protection Agency, 1986), foliar injury in crops does not necessarily signify growth or yield loss. Many studies can be cited to illustrate the inconsistency of relationship between foliar injury and yield loss when foliage is not the yield component.

The studies of Musselman et al. (1983, 1986b) and Hogsett et al. (1985b) have been cited previously (U.S. Environmental Protection Agency, 1986, 1992) as a basis for emphasizing the importance of episodic peak exposures. In addition, the conclusions discussed in previous sections that favored the concept that cumulative effects of hourly O_3 (>0.10 ppm) concentrations are of greater importance than seasonal mean exposures in causing vegetation injury are based on subsequent reanalyses of the NCLAN data. The information presented above in Section 5.5.2.5 does not alter the conclusions reached in the retrospective statistical analyses of NCLAN (Lee et al., 1987, 1991; Tingy et al., 1989; Lefohn and Foley, 1992) that episodic peaks are of importance in causing growth effects, nor does it rule out the possibility that mid-range exposures also could have had an effect.

5.5.3 Summary

The effects of O_3 on individual plants and the factors that modify plant response to O_3 are complex and vary with species and environmental soil and nutrient conditions. Because the effects of O_3 and its interactions with physical and genetic factors that influence response are complex, it is difficult to develop a measure of exposure that relates well with plant response based on experimental data. At best, experimental evidence of the impact of O_3 on biomass production can suggest the important factors of O_3 exposure that modify plant response, which should be considered when developing an exposure index.

Considerable evidence of the primary mode of action of O_3 on plants (injury to proteins and membranes, reduction in photosynthesis, changes in allocation of carbohydrate, and early senescence), which ultimately lead to reductions in biomass production, identifies O_3 uptake as an important factor (see Section 5.2). Ozone uptake is controlled by canopy conductance, stomatal conductance, O_3 concentration outside the leaf and gases emitted from the leaf (see Figure 5-2). Any factor that will affect stomatal conductance (e.g., light, temperature, humidity, soil and atmospheric chemistry and nutrients, time of day, phenology, biological agents) will affect O_3 uptake and, consequently, plant response.

The factors such as respite time, temporal variation, phenology, canopy structure, physiological processes, environmental conditions, and soil and nutrient conditions are important in determining the impact of O_3 on crops and trees but are not well understood and interact with concentration and duration in different fashions depending on species. Ozone uptake integrates these factors with atmospheric conditions and relates well with plant response, but is difficult to measure. Empirical functions to predict stomatal conductance have been developed for particular species (e.g., Lösch and Tenhunen, 1981) but have not been used to estimate O_3 uptake or used in development of exposure indices. Based on atmospheric measurement of deposition and diurnal patterns of O_3 and gas exchange in a natural grassland ecosystem, Grünhage and Jäger (1994a,b) and Grünhage et al. (1993a) proposed an ambient O_3 exposure potential for characterizing O_3 uptake and related it to the DLA of Bel W3 tobacco. Grünhage and Jäger (1994a,b) proposed a weighting scheme that preferentially weights the hourly O_3 concentrations occurring during periods of optimal vertical flux into the canopy. For the diurnal pattern of distribution at the natural grassland site in Germany, there was a greater frequency of concentrations in the 0.05- to 0.09-ppm range during the 0900 to 1559 period that matched the DLA of Bel W3 when atmospheric and canopy resistance was minimal.

Further, the biochemical mechanisms, discussed in Section 5.2, describe the mode of action of O_3 on plants as the culmination of a series of physical, biochemical, and physiological events leading to alterations in plant metabolism. Ozone-induced injury is cumulative, resulting in net reductions in photosynthesis, changes in allocation of carbohydrate, and early senescence, which lead to reductions in biomass production (Section 5.2). Increasing O_3 uptake will result in increasing reductions in biomass production.

The optimum exposure index that relates well with plant response should incorporate the factors (directly or indirectly) described above; unfortunately, such an index has not yet been identified. At this time, exposure indices that weight the hourly O_3 concentrations differentially appear to be the best candidates for relating exposure with predicted plant response. Peak concentrations in ambient air occur primarily during daylight, thus, these indices, by providing preferential weight to the peak concentrations, give greater weight to the daylight concentrations than to the nighttime concentrations (when stomatal conductance is minimal). The timing of peak concentrations and maximum plant uptake is critical in determining their impact on plants.

Some studies reported in the literature show that, when O_3 is the primary source of variation in response, year-to-year variations in plant response are minimized by the peak-weighted, cumulative exposure indices. However, the study of Fuhrer et al. (1992) illustrates some of the limitations in applying exposure indices. The study is significant for its use of the mean O_3 flux in minimizing the year-to-year variation in response when combining replicate studies, indicating the importance of environmental conditions in quantifying the relationship between O_3 exposure and plant response.

5.6 Exposure-Response of Plant Species

5.6.1 Introduction

Determining the response of plants to O_3 exposures continues to be a major challenge. The effects of exposure usually are evaluated by exposing various plant species under controlled experimental conditions, such as those discussed in Section 5.2, to known concentrations and exposure periods. Plant responses are influenced not only by the biochemical and physiological changes that may occur within the plant after O_3 entry (Section 5.3, Mode of Action, see also Figure 5-5) but also by the many factors (both internal and external) that modify plant response (Section 5.4). Of the internal factors discussed in Section 5.4, those that are most likely to apply under controlled experimental conditions are the genetic makeup and age of the plant at the time of exposure. Compensatory responses (Section 5.3.4.2) also will influence plant response. This section analyzes, summarizes, and evaluates what is known about the response of various plant species or cultivars, either as individuals or in populations, to O_3 exposure. Species as populations will be considered only in the case of pasture grasses, or forage mixes, which commonly occur as mixed stands. The response of forest and trees in their natural habitats is discussed in the next section. Emphasis will be placed on those studies conducted since the publication of the previous criteria document 1986 (U.S. Environmental Protection Agency, 1986). Much of the discussion of vegetation response to O_3 exposure in the current document is based on the conclusions of both the 1978 and 1986 criteria documents (U.S. Environmental Protection Agency, 1978, 1986); therefore, to provide a basis for understanding the effects presented below, the conclusions of the two documents are summarized.

Finally, the results of O_3 exposure-response presented in this section must be related to one or more assessment endpoints. Historically, the dollar value of lost production was the endpoint of interest; however, other endpoints (e.g., biodiversity, habitat, aesthetics, recreation) must be considered now, particularly as the impacts of O_3 on long-lived species of ecological importance are evaluated (Tingey et al., 1990).

5.6.2 Summary of Conclusions from the Previous Criteria Documents

The experimental data presented in the 1978 and 1986 criteria documents dealt with the effects of O_3 primarily on agricultural crops species (U.S. Environmental Protection Agency, 1978, 1986). The chapter on vegetation effects in the 1978 criteria document (U.S. Environmental Protection Agency, 1978) emphasized visible injury and growth effects;

however, the growth effects were not those that affected yield. This emphasis was dictated by the kind of data available at the time. The document also presented data dealing with the response of the San Bernardino forest ecosystem to O_3. This information also was discussed in the 1986 document (U.S. Environmental Protection Agency, 1986). It remains the best and most comprehensive study of forest ecosystem responses to O_3 stresses (see Section 5.7).

The 1986 document emphasized the fact that although foliar injury on vegetation is one of the earliest and most obvious manifestations of O_3 exposure, the effects of exposure are not limited to visible injury. Foliage is the primary site of plant response to O_3 exposures. Significant secondary effects include reduced growth, both in foliage and roots. Impacts range from reduced plant growth and decreased yield to changes in crop quality and alterations in plant susceptibility to biotic and abiotic stresses. Also, the 1986 document noted that O_3 exerts a phytotoxic effect only if a sufficient amount reaches sensitive sites within the leaf (see Section 5.3). Ozone injury will not occur if the rate of uptake is low enough that the plant can detoxify or metabolize O_3 or its metabolites or if the plant is able to repair or compensate for the effects (Tingey and Taylor, 1982; U.S. Environmental Protection Agency, 1986). Cellular disturbances that are not repaired or compensated are ultimately expressed as visible injury to the leaf or as secondary effects that can be expressed as reduced root growth or as reduced yield of fruits or seeds, or both. Ozone would be expected to reduce plant growth or yield if it directly impacts the plant process (e.g., photosynthesis) that limits plant growth or if it impacts another step to the extent that it becomes the step limiting plant growth (U.S. Environmental Protection Agency, 1986; Tingey, 1977). Conversely, if the process impacted is not or does not become rate-limiting, O_3 will not limit plant growth. These conditions also suggest that there are combinations of O_3 concentration and exposure duration that a plant can experience that will not result in visible injury or reduced plant growth and yield. Indeed, numerous studies have demonstrated this fact. This information is still pertinent today (Section 5.3)

Ozone can induce a diverse range of effects beginning with individual plants and then proceeding to plant populations and, ultimately, communities. The effects may be classified as either injury or damage. Injury encompasses all plant reactions, such as reversible changes in plant metabolism (e.g., altered photosynthesis), leaf necrosis, altered plant quality, or reduced growth that does not impair yield or the intended use or value of the plant (Guderian, 1977). In contrast, damage or yield loss includes all effects that reduce or impair the intended use or value of the plant. Thus, for example, visible foliar injury to ornamental plants, detrimental responses in native species, and reductions in fruit and grain production by agricultural species all are considered damage or yield loss. Although foliar injury can not always be classified as damage, its occurrence indicates that phytotoxic concentrations of O_3 are present, and, therefore, studies should be conducted to assess the risk to vegetation.

The concept of limiting values used to summarize visible foliar injury in the 1978 document also was considered valid in the 1986 document (U.S. Environmental Protection Agency, 1978, 1986). Jacobson (1977) developed limiting values by reviewing the scientific literature and identifying the lowest concentration and exposure duration reported to cause visible injury to a variety of plant species. Expressed in another way, limiting values were concentrations and durations of exposure below which visible injury did not occur.
A graphical analysis presented in both of the previous documents indicated the limit for reduced plant performance was an exposure to 0.05 ppm for several hours per day for more than 16 days. Decreasing the exposure period to 10 days increased the concentration required

to cause injury to 0.1 ppm, and a short, 6-day exposure further increased the concentration to cause injury to 0.3 ppm.

By 1986, a great deal of new information concerning the effects of O_3 on the yield of crops plants had become available, both through EPA's NCLAN and the results of research funded by other agencies. The NCLAN project was initiated by EPA in 1980, primarily to improve estimates of yield loss in the field and of the magnitude of crop losses caused by O_3 (Heck et al., 1982, 1991). The primary objectives were:

(1) to define the relationships between yields of major agricultural crops and O_3 exposure as required to provide data necessary for economic assessments and the development of National Ambient Air Quality Standards;
(2) to assess the national economic consequences resulting from the exposure of major agricultural crops to O_3; and
(3) to advance understanding of the cause and effect relationships that determine crop responses to pollutant exposures.

The cultural conditions used in the NCLAN studies approximated typical agronomic practices. The methodology used in these studies is described in Section 5.2.

Yield loss in the 1986 document was defined as "damage", an impairment in the intended use of the plant. This concept included reductions in aesthetic values, the occurrence of foliar injury (changes in plant appearance), and losses in terms of weight, number, or size of the plant part that is harvested. Yield loss also may include changes in physical appearance, chemical composition, or the ability to withstand quality storage (collectively termed crop quality). Losses in aesthetic values are difficult to quantify. Foliar injury symptoms can substantially reduce the marketability of ornamental plants or crops in which the foliage is the plant part (e.g., spinach, lettuce, cabbage) and constitute yield loss with or without concomitant growth reductions. At that time (1986), most studies of the relationship between yield loss and O_3 concentration focused on yields as measured by weight of the marketable organ of the plant.

The OTC studies conducted to estimate the impact of O_3 on the yield of various crop species (e.g., the NCLAN program) were grouped into two types, depending on the experimental design and statistical methods used to a analyze the data: (1) studies that developed predictive equations relating O_3 exposure to plant response and (2) studies that compared discrete treatment level to a control. The advantage of the regression approach is that exposure-response models can be used to interpolate results between treatment levels (see Section 5.2.2).

Using NCLAN data as an example of plant response, the O_3 concentrations that could be predicted to cause 10 or 30% yield loss were estimated using the Weibull function (Table 5-19). The data in Table 5-19 are based on yield-response functions for 38 species or cultivars developed from studies using OTCs. Review of that data indicated that 10% yield reductions could be predicted for 58% of the species or cultivars, when 7-h seasonal mean concentrations were below 0.05 ppm, and for 34%, when seasonal mean concentrations were between 0.04 and 0.05 ppm, but only 18% required 7-h seasonal mean concentrations in excess of 0.08 ppm to suffer a 10% loss in yield. Furthermore, approximately 11% of the 38 species or cultivars would be expected to have a yield reduction of 10% loss at 7-h seasonal mean concentrations below 0.035 ppm, suggesting that these plants are very sensitive to O_3.

Grain crops were apparently less sensitive than the other crops. The data also demonstrate that the sensitivity within species may be as great as differences between

Table 5-19. Estimates of the Parameters for Fitting the Weibull Model Using the 7-Hour Seasonal Mean Ozone Concentrations[a,b]

	Parameters for Weibull Model				Concentration for Predicted Yield Losses of:	
Crop	$\hat{\alpha}$	$\hat{\sigma}$	$\hat{c}$	CF[c]	10%[d]	30%[d]
LEGUME CROPS						
Soybean, Corsoy	2,785.00	0.133	1.952	0.022	0.048	0.082
Soybean, Davis (81)	5,593.00	0.128	0.872	0.025	0.038	0.071
Soybean, Davis (CA-82)[e]	4,931.00	0.12/	2.144	0.019	0.048	0.081
Soybean, Davis (PA-82)[e]	4,805.00	0.103	4.077	0.019	0.059	0.081
Soybean, Essex (81)	4,562.00	0.187	1.543	0.014	0.048	0.099
Soybean, Forrest (82-I)	4,333.00	0.171	2.752	0.017	0.076	0.118
Soybean, Williams (81)	4,992.00	0.211	1.100	0.014	0.039	0.093
Soybean, Williams (82-I)	5,884.00	0.162	1.577	0.017	0.045	0.088
Soybean, Hodgson	2,590.00	0.138	1.000	0.017	0.032	0.066
Bean, Kidney (FP)[f]	2,878.00	0.120	1.171	0.019	0.033	0.063
Peanut, NC-6	7,485.00	0.111	2.249	0.025	0.046	0.073
GRAIN CROPS						
Wheat, Abe (82)	5,363.00	0.143	2.423	0.023	0.059	0.095
Wheat, Arthur 71 (82)	4,684.00	0.148	2.154	0.023	0.056	0.094
Wheat, Roland	5,479.00	0.113	1.633	0.023	0.039	0.067
Wheat, Vona	7,857.00	0.053	1.000	0.022	0.028	0.041
Wheat, Blueboy II (T)	5.88	0.175	3.220	0.030	0.088	0.127
Wheat, Coker 47-27 (T)	5.19	0.171	2.060	0.030	0.064	0.107
Wheat, Holly (T)	4.95	0.156	4.950	0.030	0.099	0.127
Wheat, Oasis (T)	4.48	0.186	3.200	0.030	0.093	0.135
Corn, PAG 397	13,968.00	0.160	4.280	0.015	0.095	0.126
Corn, Pioneer 3780	12,533.00	0.155	3.091	0.015	0.075	0.111
Corn, Coker 16 (T)	240.00	0.221	4.460	0.020	0.133	0.175
Sorghum, DeKalb-28	8,137.00	0.296	2.217	0.016	0.108	0.186
Barley, Poco	1.99	0.205	4.278	0.020	0.121	0.161
FIBER CROPS						
Cotton, Acala SJ-2 (81-I)	5,546.00	0.199	1.228	0.018	0.044	0.096
Cotton, Acala SJ-2 (82-I)	5,872.00	0.088	2.100	0.012	0.032	0.055
Cotton, Stoneville	3,686.00	0.112	2.577	0.026	0.047	0.075
HORTICULTURAL CROPS						
Tomato, Murrieta (81)	32.90	0.142	3.807	0.012	0.079	0.108
Tomato, Murrieta (82)	32.30	0.082	3.050	0.012	0.040	0.059
Lettuce, Empire (T)	1,245.00	0.098	1.220	0.043	0.053	0.075
Spinach, America (T)	21.20	0.142	1.650	0.024	0.046	0.082
Spinach, Hybrid (T)	36.60	0.139	2.680	0.024	0.043	0.082
Spinach, Viroflay (T)	41.10	0.129	1.990	0.024	0.048	0.080
Spinach, Winter Bloom (T)	20.80	0.127	2.070	0.024	0.049	0.080

Table 5-19 (cont'd). Estimates of the Parameters for Fitting the Weibull Model Using the 7-Hour Seasonal Mean Ozone Concentrations[a,b]

	Parameters for Weibull Model				Concentration for Predicted Yield Losses of:	
Crop	$\hat{\alpha}$	$\hat{\sigma}$	$\hat{c}$	CF[c]	10%[d]	30%[d]
HORTICULTURAL CROPS (cont'd)						
Turnip, Just Right (T)	10.89	0.090	3.050	0.014	0.043	0.064
Turnip, Pur Top W.G. (T)	6.22	0.095	2.510	0.014	0.040	0.064
Turnip, Shogoin (T)	4.68	0.096	2.120	0.014	0.036	0.060
Turnip, Tokyo Cross (T)	15.25	0.094	3.940	0.014	0.053	0.072

[a]Data are from Heck et al. (1984) and are based on individual plot means unless the crop name is followed by "(T)". The "T" indicates that the parameters were based on treatment means and the data are from Heck et al. (1983). The parameters given in Heck et al. (1983, 1984) also contain the standard errors of the parameters.
[b]All estimates of $\hat{\sigma}$ are in ppm. The yield is expressed as kilograms per hectare for all crops except barley—see weight (grams per head); tomato (both years)—fresh weight (kilograms per plot); cotton—lint + seed weight (kilograms per hectare); peanut—pod weight (kilograms per hectare). In cases where the estimated $\hat{c}$ parameter is exactly 1.0, it has been bounded from below to obtain convergence in the nonlinear model fitting routine. Parameters were estimated from data not showing the expected Weibull form. Caution should be used in interpreting these Weibull models. Other models might better describe the behavior observed in these experiments. For those crops whose name is followed by "(T)", the yield is expressed as grams per plant.
[c]The ozone (O_3) concentration in the charcoal-filtered (CF) chambers expressed as a 7-h seasonal mean concentration.
[d]The 7-h seasonal mean O_3 concentration (parts per million) that was predicted to cause a 10 or 30% yield loss (compared to CF air).
[e]CA and PA refer to constant and proportional O_3 addition.
[f]Only the bean data from the full plots are shown. The partial plot data are given Heck et al. (1984).

Source: U.S. Environmental Protection Agency (1986).

species. For example, at 0.04 ppm O_3, estimated yield losses ranged from 2 to 15% in soybean and from 0 to 28% in wheat. Year-to-year variations in plant response also were observed during the studies.

Discrete treatments were used to determine yield loss in some studies. These experiments were designed to test whether specific O_3 treatments were different from the control rather than to develop exposure-response equations, and the data were analyzed using analyses of variance. When summarizing these studies using discrete treatment levels, as opposed to the variable concentrations used in NCLAN, the lowest O_3 concentration that significantly reduced yield was determined from analyses done by the authors. Frequently, the lowest concentration used in the study was the lowest concentration reported to reduce yield; hence, it was not always possible to estimate a no-effect exposure concentration.
In general, the data indicated that O_3 concentrations of 0.10 ppm (frequently the lowest concentration used in the studies) for a few hours per day for several days to several weeks generally caused significant yield reductions. The concentrations derived from the regression

studies were based on a 10% yield loss, whereas, in the studies using the analysis of variance, the 0.10-ppm concentration frequently induced mean yield losses of 10 to 50%.

A chemical protectant, EDU was used to provide estimates of yield loss. The impact of O_3 on yield was determined by comparing the yield data from plots treated with EDU with those that were not. Studies indicated that yields were reduced by 18 to 41% when ambient O_3 concentrations exceeded 0.08 ppm during the day for 5 to 18 days over the growing season.

In summary, the 1986 criteria document (U.S. Environmental Protection Agency, 1986) states that several general conclusions can be drawn from the various approaches used to estimate crop loss yield.

(1) Based on the comparison of crop yield in CF and unfiltered (ambient) exposures, data clearly indicate that O_3 at ambient levels is elevated sufficiently in several parts of the country to impair the growth and yield of plants. Data from the chemical protectant studies support the conclusion and extend it to other plant species.

(2) Both of the above-mentioned approaches indicate that effects occur with only a few O_3 occurrences above 0.08 ppm.

(3) The growth and yield data cited in the 1978 criteria document (U.S. Environmental Protection Agency, 1978) indicate that several plant species exhibited growth and yield effects when the mean O_3 concentration exceeded 0.05 ppm for 4 to 6 h/day for at least 2 weeks.

(4) The data obtained from regression studies conducted to develop exposure-response functions for estimating yield loss indicated that at least 50% of the species and cultivars tested were predicted to exhibit a 10% yield loss at 7-h season mean O_3 concentrations of 0.05 ppm or less.

Though most of the data from the discrete treatment studies (non-NCLAN studies) did not use concentrations low enough to support the values cited above, the magnitude of yield losses reported at 0.10 ppm under a variety of exposure regimes indicate that, to prevent O_3 effects, a substantially lower concentration is required (U.S. Environmental Protection Agency, 1986).

The limiting values established in 1978 were still deemed appropriate in the 1986 criteria document for ornamentals and certain vegetable crops where visible injury was still considered the response of interest because appearance is of importance (e.g., spinach, lettuce, cabbage) (U.S. Environmental Protection Agency, 1986). This remains the case today.

5.6.3 Information in the Published Literature Since 1986

The major question to be addressed in this section is whether the conclusions of the 1986 criteria document summarized in the previous section, remain valid, given the results of research published since 1988. In particular, whether the response of plants to experimental treatments at or near concentrations of 0.05 ppm (7-h seasonal mean), which are characteristic of ambient concentrations in many areas, can be compared to a control or to reduced O_3 treatment to establish a potential adverse effect.

The 1986 criteria document (U.S. Environmental Protection Agency, 1986) made the following statement: "The characterization and representation of plant exposures to O_3 has been and continues to be a major problem because research has not yet clearly identified which components of the pollutant exposure cause plant response." This is still true today, although some insight into the importance of peak concentrations versus long-term means has been gained (See Section 5.5). The importance of the timing of exposure during the growing season, the duration of peaks, the rate of increase of concentration, and the respite periods is unresolved.

The aim of most air pollution research experiments have been designed to quantify the relationship between pollutant exposure and agricultural crop yield. The problem is the incorporation of the concentration, duration, frequency, age, genetic composition, and respite time into an exposure statistic or index that may be used to predict yield loss. The correct exposure representation is the amount of pollutant entering the plant, not the ambient concentration to which the plant is exposed (Taylor et al., 1982; Tingey and Taylor, 1982). Unfortunately, it is rarely possible to know the amount of pollutant taken up by the plant, so therefore, an appropriate index of exposure must be chosen. Most indices were not developed from a biological basis, nor were they developed using an experimental approach specifically designed to address all key factors (Lee et al., 1991). A number of exposure indices have been developed in an attempt for depicting plant response to O_3 exposure (see Section 5.5). Much of the data in this section is evaluated using these indices. For this reason, several different exposure statistics are used to determine the effect of an exposure on plant response. It should be remembered that the SUM06, which is used more than any of the other indices, is the seasonal sum of hourly concentrations at or above 0.06 ppm (see Section 5.5).

Exposure indices calculated for each of 10 years (1982 to 1991) and two exposure periods, June through August (3 mo) and May through September (5 mo), are presented in Table 5-20 (modified from Tingey et al., 1991). The monitoring data, collected at nonurban sites, show that ambient O_3 is frequently at, or near, the 7-h seasonal mean that would be expected to cause a yield loss in crops, based on the conclusions of the 1986 criteria document. This table may be used for comparison of ambient-O_3 concentrations to those used in experiments. Although the examples here are based on 10% loss figures, losses below that level may occur and be important. Thirty-four percent of the 38 species or cultivars under consideration would be predicted to have a 10% yield loss at a 7-h mean concentration of between 0.04 and 0.05 ppm, but only 19% required a 7-h mean concentration of greater than 0.08 ppm to suffer a predicted 10% loss in yield. Furthermore, 11% of the 38 species or cultivars would be expected to have a yield reduction of 10% at a 7-h mean, or less than 0.028 to 0.035 ppm (Tables 6-17 and 6-19; U.S. Environmental Protection Agency, 1986). It also was concluded that grain crops (with the exception of a few very sensitive cultivars) were generally less sensitive than others, but that within-species variability in sensitivity may be as great or greater than between species. The preceeding results are similar to those previously obtained from Table 6-19 in the 1986 document. Lee et al. (1994a,b) have revised Table 6-19 in U.S. Environmental Protection Agency (1986) (see Table 5-19) using recalculated peak-weighted exposure indices (shown to be more appropriate than long-term means for relating effects to ambient concentrations) for the 54 studies (listed in Tables 5-21 and 5-22).

In 1992, the Supplement to the Air Quality Criteria Document for Ozone and Other Photochemical Oxidants (1986) reviewed effects of oxidant exposure on vegetation. Considerable emphasis was placed on the appropriate exposure index for relating biological effects of O_3 on plants (U.S. Environmental Protection Agency, 1992). An analysis of the data at that time indicated that a seasonal mean concentration (e.g., 7 or 24 h) might not be the best expression of the exposure because it did not weight high concentrations differently from low concentrations, and it did not account for the variable length of growing seasons or exposure durations. Unfortunately, it is often impossible to calculate the different possible exposure indices (means, cumulative peak- or threshold-weighted, or continuously weighted [sigmoid] cumulative) from information given in published papers. Thus, difficulties remain when comparing exposure-response studies that utilize different exposure indices. However, reported responses and concentrations of O_3 can be compared to those that occur at ambient concentrations and then to other exposure indices (Table 5-20).

5.6.3.1 Effects of Ozone on Short-Lived (Less Than One Year) Species

Plant species can be characterized by their life span. They are either short-lived annual species or longer lived perennials and trees. Physiological processes may be related to life span (for instance, leaf gas exchange tends to be lower in longer-lived trees than in crop species), so the response to O_3 may be different (Reich, 1987). In addition, multiple-year exposures and carry-over effects may be of importance in long-lived species, but of no concern in annuals. Accordingly, annuals and perennials will be discussed separately. The response of plants to O_3 also is affected by interactions with other physical, chemical, and biological factors. Those interactions are discussed elsewhere in this document (Section 5.3). In most cases, the research analyzed here was conducted under near-optimal conditions of water and nutrient availability. Although deviations from these conditions may affect the magnitude of response, it is important to understand the potential of O_3 exposure and its consequences.

Several papers (Lee et al., 1988, 1991, 1994a,b; Lefohn et al., 1988a; Lesser et al., 1990; Tingey et al., 1991) present a reanalysis of NCLAN data and data from field studies conducted on potato that were not part of the NCLAN project. Lee et al. (1988, 1991) examined a number of measures of O_3 exposure in relation to response data collected in the experiments. The investigators were particularly interested in examining the ability of a seasonal mean, a cumulative exposure index, and the second-highest daily maximum concentration (2HDM) to predict the biological response of the plant. They found that no particular index of O_3 concentration dominated as best in all studies, but that cumulative indices that weighted high concentrations at the "grain-filling" stage of the life cycle were better than a seasonal mean. Seasonal means did work well within a given experiment where treatments were highly correlated. The 2HDM was consistently a poor predictor of plant response.

In a reanalysis of NCLAN data, Lesser et al. (1990) presented composite exposure-response functions for a number of crop species, or groups of species. Predicted yield losses (compared to yield at an assumed background concentration of 0.025 ppm) of up to 20% occurred at a 12-h seasonal mean of 0.06 ppm, with a loss of 10% at a 12-h mean concentration of about 0.045 ppm.

Tingey et al. (1991) and Lee et al. (1991) went on to reanalyze the crop response data using three measures of exposure: (1) the SUM06, (2) the 7-h seasonal mean, and (3) the 2HDM. Their analysis included crops that account for 70% of all crop land in the United States and 73% of the agricultural receipts. The analysis included 31 field experiments with 12 crop species, conducted in OTCs and resulted in composite exposure-response functions. The results of their studies and additional reanalyses done since then are summarized in Tables 5-23 and 5-24. They concluded that to limit yield loss to 10% or less in 50% of the cases (all experiments and crops), a SUM06 of 24.4 ppm·h (or 26.4 ppm·h,

Table 5-20. Summary of Ozone Exposure Indices Calculated for 3- or 5-Month Growing Seasons from 1982 to 1991[a]

3 mo (June-August)

Year	No. of Sites[b]	HDM2[c] ppm Mean	HDM2[c] ppm CV[d]	M7 ppm Mean	M7 ppm CV	SUM00 ppm·h Mean	SUM00 ppm·h CV	SUM06 ppm·h Mean	SUM06 ppm·h CV	SIGMOID ppm·h Mean	SIGMOID ppm·h CV
1982	99	0.114	23.7%	0.052	18.7%	82.9	19.1%	26.8	68.8%	26.3	56.7%
1983	102	0.125	24.9%	0.056	21.9%	86.1	22.1%	34.5	58.1%	33.0	52.3%
1984	104	0.117	24.6%	0.052	18.2%	84.1	19.9%	27.7	58.4%	27.4	47.9%
1985	117	0.117	24.6%	0.052	17.1%	84.6	18.0%	27.4	59.6%	27.4	47.6%
1986	123	0.115	21.8%	0.052	19.1%	85.3	18.0%	27.7	65.0%	27.7	51.8%
1987	121	0.119	22.9%	0.055	17.6%	86.9	17.3%	31.2	56.4%	30.4	46.8%
1988	139	0.129	21.3%	0.060	17.8%	97.6	19.6%	45.2	46.8%	42.9	42.4%
1989	171	0.105	23.1%	0.051	17.5%	86.4	19.9%	24.8	78.7%	25.8	59.4%
1990	188	0.105	21.6%	0.053	18.3%	85.7	21.0%	25.8	76.2%	26.6	59.2%
1991	199	0.106	22.0%	0.054	18.4%	87.7	21.3%	28.3	74.2%	28.9	59.5%
Among Years		0.113	11.1%	0.054	10.0%	87.0	9.9%	29.5	42.1%	29.4	31.0%

5 mo (May-September)

Year	No. of Sites	M7 ppm Mean	M7 ppm CV	SUM00 ppm·h Mean	SUM00 ppm·h CV	SUM06 ppm·h Mean	SUM06 ppm·h CV	SIGMOID ppm·h Mean	SIGMOID ppm·h CV
1982	88	0.048	20.6%	122.9	22.3%	37.3	70.9%	37.1	57.8%
1983	87	0.051	22.1%	129.6	24.4%	44.4	61.9%	43.8	52.7%
1984	95	0.048	18.0%	126.2	19.1%	36.7	60.8%	37.6	46.9%
1985	114	0.048	18.4%	124.5	19.4%	36.2	63.8%	37.0	50.3%
1986	118	0.048	20.3%	123.3	21.4%	34.9	70.7%	35.6	55.7%
1987	116	0.050	20.3%	128.7	20.4%	42.2	62.0%	41.8	50.3%
1988	134	0.054	18.7%	141.7	22.0%	58.0	50.5%	55.6	45.0%
1989	158	0.047	18.6%	127.8	22.5%	32.7	87.8%	35.2	64.1%
1990	172	0.049	19.8%	129.4	22.7%	34.6	82.7%	37.0	62.1%
1991	190	0.050	19.8%	130.6	23.6%	36.8	80.7%	38.8	62.9%
Among Years		0.049	9.8%	129.0	9.9%	38.7	42.5%	39.6	29.8%

[a]Updated and additional years from data given in Table III of Tingey et al. (1991), where the spatial and temporal variation in ambient O_3 exposures is expressed in terms of several exposure indices.
[b]Indicates the number of separate monitoring sites included in the analysis; fewer sites had 5 mo of available data than had 3 mo of available data.
[c]The 2HDM index is calculated for sites with at least 3 mo of available data. SUM00, SUM06, M7, SIGMOID, and 2HDM are the cumulative sum above 0.0 ppm, the cumulative sum above 0.06 ppm, the 7-h seasonal mean, the sigmoid weighted summed concentration, and the second highest daily maximum 1-h concentration, respectively.
[d]CV = coefficient of variation.

Source: Tingey et al. (1991).

Table 5-21. Comparison of Exposure-Response Curves Calculated Using the 3-Month, 24-Hour SUM06 Values for 54 National Crop Loss Assessment Network Cases[a]

			Wiebull/Linwear Model Parameters[c]					3 mo 24-h SUM06[f] Values for Yield Losses of	
Species	Cultivar	Moisture[b]	A	B	C	RMSE[d]	R^{2e}	10%	30%
Barley (Linear)	CM-72	Dry	7,741.1	−4.412		1,215	0.12	175.5	526.4
Barley (Linear)	CM-72	Wet	8,776.6	15.485		1,175	NA	250.0	250.0
Corn (L)	Pio		9,627.4	92.61	2.823	680	0.93	41.7	64.3
Corn (L)	Pag		10,730.1	94.36	4.316	1,248	0.80	56.0	74.3
Cotton (L)	Acala	Dry	6,465.0	92.59	2.361	1,097	0.45	35.7	59.8
Cotton (L)	Acala	Wet	9,808.0	71.17	1.997	521	0.96	23.1	42.5
Cotton (L)	Acala	Dry	7,009.8	83.78	1.849	949	0.80	24.8	48.0
Cotton (L)	Acala	Wet	7,858.8	78.01	1.311	937	0.85	14.0	35.5
Cotton (L, Linear)	Acala	Dry	5.693	−0.0011		104	0.06	94.9	321.3
Cotton (L, Linear)	Acala	Wet	5.,883	−0.0017		90	0.20	60.3	204.0
Cotton	Stoneville		3,576.1	94.6	2.012	226	0.91	30.9	56.7
Cotton	McNair	Dry	3,698.8	165.81	2.778	342	0.46	73.8	114.4
Cotton	McNair	Wet	4,811.0	117.02	1.534	366	0.89	27.0	59.7
Kidney Bean	California Light Red		2,488.2	27.41	3.885	333	0.72	15.4	21.0
Kidney Bean (L)	California Light Red		2,484.3	44.24	2.691	397	0.71	19.2	30.2
Lettuce (T)	Empire		7,196.6	54.87	5.512	613	0.74	36.5	45.5
Peanut (L)	NC-6		6,402.5	100.12	2.226	351	0.97	36.4	63.0
Potato	Norchip		5,900.7	93.84	1.000	742	0.63	9.9	33.5
Potato	Norchip		5,755.6	79.26	1.654	675	0.49	20.3	42.5
Sorghum	Dekalb		8,046.2	178.05	2.338	441	0.48	68.0	114.6
Soybean	Corsoy		2,652.6	57.1	1.726	166	0.91	15.5	31.4
Soybean	Corsoy		1,891.7	65.21	5.160	282	0.63	42.2	53.4
Soybean	Amsoy		1,907.2	75.91	2.739	390	0.41	33.4	52.1
Soybean	Pella		2,619.9	174.13	1.000	311	0.51	18.3	62.1

Table 5-21 (cont'd). Comparison of Exposure-Response Curves Calculated Using the 3-Month, 24-Hour SUM06 Values for 54 National Crop Loss Assessment Network Cases[a]

			Wiebull/Linwear Model Parameters[c]					3 mo 24-h SUM06[f] Values for Yield Losses of	
Species	Cultivar	Moisture[b]	A	B	C	RMSE[d]	R^{2e}	10%	30%
Soybean	Williams		2,368.4	146.37	1.000	527	0.27	15.4	52.2
Soybean	Corsoy	Dry	2,229.8	92.0	9.593	193	0.16	72.8	82.6
Soybean	Corsoy	Wet	2,913.8	311.04	1.527	330	0.38	71.3	158.4
Soybean	Corsoy	Dry	3,528.1	103.83	15.709	400	0.55	90.0	97.2
Soybean	Corsoy	Wet	4,905.0	117.98	3.590	401	0.80	63.0	88.5
Soybean	Corsoy	Dry	5,676.1	97.46	1.000	508	0.81	10.3	34.8
Soybean	Corsoy	Wet	5,873.9	65.73	1.319	512	0.89	11.9	30.1
Soybean	Williams	Dry	6,305.2	99.18	1.456	389	0.87	21.1	48.8
Soybean	Williams	Wet	7,338.4	78.71	1.344	377	0.94	14.8	36.5
Soybean	Hodgson		2,052.4	79.97	1.000	361	0.78	8.4	28.5
Soybean	Davis		3,929.7	131.57	1.000	524	0.64	13.9	46.9
Soybean	Davis		4,815.5	85.71	1.734	346	0.87	23.4	47.3
Soybean	Davis	Dry	2,007.1	542.36	1.000	556	0.04	57.1	193.4
Soybean	Davis	Wet	4,568.0	158.57	1.539	495	0.61	36.8	81.2
Soybean	Davis	Dry	5,775.6	90.18	3.348	920	0.55	46.0	66.3
Soybean	Davis	Wet	8,082.7	113.89	1.442	927	0.71	23.9	55.7
Soybean	Young	Dry	5,978.8	183.63	1.448	244	0.93	38.8	90.1
Soybean	Young	Wet	7,045.0	145.63	1.277	424	0.93	25.0	65.0
Tobacco (L)	McNair		5,177.4	172.55	1.186	306	0.81	25.9	72.3
Turnip (T)	Just Right		12.7	25.68	1.806	0.810	0.96	7.4	14.5
Turnip (T)	Purple Top		5.7	29.26	1.437	0.590	0.92	6.1	14.3
Turnip (T)	Shogon		4.4	29.18	1.548	0.660	0.81	6.8	15.0
Turnip (T)	Tokyo Cross		11.7	27.83	2.142	3.250	0.78	9.7	17.2
Wheat	Abe		5,149.8	52.89	3.077	399	0.90	25.5	37.8
Wheat	Arthur		4,455.8	60.87	2.176	264	0.92	21.6	37.9

Table 5-21 (cont'd). Comparison of Exposure-Response Curves Calculated Using the 3-Month, 24-Hour SUM06 Values for 54 National Crop Loss Assessment Network Cases[a]

Species	Cultivar	Moisture[b]	Wiebull/Linwear Model Parameters[c] A	B	C	RMSE[d]	R^{2}[e]	3 mo 24-h SUM06[f] Values for Yield Losses of 10%	30%
Wheat	Roland		5,028.9	52.32	1.173	405	0.91	7.7	21.7
Wheat	Abe		6,043.1	47.39	7.711	226	0.74	35.4	41.5
Wheat	Arthur		5,446.9	72.34	2.462	349	0.57	29.0	47.6
Wheat	Vona		5,384.0	27.74	1.000	608	0.88	2.9	9.9
Wheat	Vona		4,451.0	33.5	1.818	654	0.64	9.7	19.0

[a]See Appendix A for abbreviations and acronyms.
[b]Wet refers to experiments conducted under well-watered conditions, whereas dry refers to experiment conducted under some controlled level of drought stress.
[c]For those studies whose species name is followed by "Linear", a linear model was fit. A Weibull model was fit to all other studies, and estimates of "B" parameter are in parts per million per hour. The yield is expressed in kilograms per hectare for all crops except turnip (grams per meter per plant) and lettuce (grams per meter). In cases where the estimated "C" parameter is exactly 1.0, the shape parameter has been bounded from below to obtain convergence in the nonlinear-model-fitting routine. For those studies whose species name is followed by "L", a log transformation was used to stabilize the variance. For those crops whose name is followed by "T", the yield is expressed as either grams per plant or grams per meter.
[d]The root mean square error, based on individual plot means.
[e]Multiple correlation coefficient (R^2) measures the proportion of total variation about the mean response explained by the regression on individual plot means.
[f]The 24-h SUM06 value (ppm-h) that was predicted to cause a 10 or 30% yield loss (compared to zero SUM06).

Source: Based on analyses by Lee et al. (1991, 1994a,b).

based on 24 h), a 7-h seasonal mean of 0.049 ppm, or a 2HDM of 0.094 ppm would be required. A SUM06 of about 37 ppm·h should limit yield losses to 20% in 50% of the cases. If one standard error were added to or subtracted to account for the variability, the metrics would be reduced to 21 ppm·h, 0.046 ppm, and 0.088 ppm or increased to 27.8 ppm·h, 0.049 ppm, and 0.10 ppm, respectively. To limit the loss to 10% or less in 75% of the cases would require 14.2 ppm·h, 0.040 ppm, and 0.051 ppm, respectively (Table 5-23). These values are based on studies of both well-watered and drought stressed plants.

Further analyses by Lee et al. (1991, 1994a,b) provides composite exposure-response functions for all NCLAN studies, as well as for soybean and wheat experiments (Table 5-22). In the analysis, they calculated the SUM06 based on 24-h/day O_3 concentrations, and the resulting exposure to prevent crops from yield loss is slightly higher than they previously calculated (26.4 ppm·h versus 24.4 ppm·h; Table 5-23).

Table 5-22. Comparison of Exposure-Response Curves Calculated Using the 24-Hour W126 Values for 54 National Crop Loss Assessment Network Cases[a]

Species	Cultivar	Moisture[b]	Weibull[c] A	Weibull[c] B	Weibull[c] C	RMSE[d]	R^2[e]	24-h W126[f] Values for Yield Losses of 10%	24-h W126[f] Values for Yield Losses of 30%
Barley	CM-72	Dry	8,133.2	1,109.6	1.000	1,214	0.13	116.9	395.8
Barley	CM-72	Wet	8,927.2	57,439.6	1.000	1,175	NA	6,051.9	20,487.3
Corn (L)	Pio		9,605.0	92.9	2.594	650	0.93	39.0	62.4
Corn (L)	Pag		10,686.7	94.5	4.190	1,253	0.80	55.2	73.9
Cotton (L)	Acala	Dry	6,482.8	89.9	1.949	1,075	0.47	28.3	53.0
Cotton (L)	Acala	Wet	9,817.3	66.6	1.603	514	0.96	16.4	35.0
Cotton (L)	Acala	Dry	7,022.7	81.3	1.540	948	0.80	18.8	41.6
Cotton (L)	Acala	Wet	7,927.1	74.7	1.070	943	0.85	9.1	28.5
Cotton (L)	Acala	Dry	310.1	174.1	2.189	104	0.06	62.3	108.7
Cotton (L)	Acala	Wet	393.2	582.6	1.000	90	0.20	61.4	207.8
Cotton	Stoneville		3,592.1	94.1	1.582	223	0.91	22.7	49.1
Cotton	McNair	Dry	3,700.9	174.1	2.430	344	0.45	68.9	113.9
Cotton	McNair	Wet	4,817.6	113.5	1.410	360	0.89	23.0	54.6
Kidney bean	California Light Red		2,484.7	28.0	3.706	332	0.72	15.3	21.2
Kidney bean (L)	California Light Red		2,475.2	44.2	2.353	401	0.70	17.0	28.5
Lettuce (T)	Empire		7,197.4	54.6	4.921	614	0.74	34.6	44.3
Peanut (L)	NC-6		6,386.0	97.4	1.905	370	0.96	29.9	56.7
Potato	Norchip		5,867.2	96.3	1.000	754	0.62	10.1	34.3
Potato	Norchip		5,777.9	113.9	1.299	675	0.48	20.1	51.5
Sorghum	Dekalb		8,049.7	205.9	1.963	439	0.48	65.4	121.8
Soybean	Corsoy		2,660.3	58.8	1.455	169	0.91	12.5	28.9
Soybean	Corsoy		1,895.6	63.3	4.032	280	0.63	36.2	49.0
Soybean	Amsoy		1,926.1	79.0	1.977	390	0.41	25.3	46.9
Soybean	Pella		2,602.4	161.5	1.000	314	0.50	17.0	57.6
Soybean	Williams		2,341.8	138.6	1.000	533	0.25	14.6	49.4
Soybean	Corsoy	Dry	2,229.3	88.2	8.632	192	0.16	67.9	78.2

Table 5-22 (cont'd). Comparison of Exposure-Response Curves Calculated Using the 24-Hour W126 Values for 54 National Crop Loss Assessment Network Cases[a]

				Weibull[c]				24-h W126[f] Values for Yield Losses of	
Species	Cultivar	Moisture[b]	A	B	C	RMSE[d]	R^{2e}	10%	30%
Soybean	Corsoy	Wet	2,929.7	470.2	1.128	329	0.39	64.0	188.6
Soybean	Corsoy	Dry	3,533.5	113.2	11.095	403	0.54	92.4	103.1
Soybean	Corsoy	Wet	4,909.5	126.5	2.803	405	0.80	56.7	87.6
Soybean	Corsoy	Dry	5,597.1	95.7	1.000	526	0.80	10.1	34.1
Soybean	Corsoy	Wet	5,884.8	65.6	1.139	515	0.88	9.1	26.6
Soybean	Williams	Dry	6,314.1	106.3	1.243	391	0.87	17.4	46.4
Soybean	Williams	Wet	7,352.3	80.7	1.162	368	0.95	11.6	33.2
Soybean	Hodgson		2,044.6	76.2	1.000	361	0.78	8.0	27.2
Soybean	Davis		3,837.6	130.3	1.000	530	0.63	13.7	46.5
Soybean	Davis		4,810.8	87.5	1.494	352	0.86	19.4	43.9
Soybean	Davis	Dry	1,992.3	537.6	1.000	558	0.03	56.6	191.7
Soybean	Davis	Wet	4,595.4	170.9	1.253	496	0.61	28.4	75.1
Soybean	Davis	Dry	5,770.1	90.6	2.796	928	0.54	40.5	62.7
Soybean	Davis	Wet	8,101.3	118.2	1.220	939	0.70	18.7	50.8
Soybean	Young	Dry	5,994.2	199.8	1.251	244	0.93	33.1	87.7
Soybean	Young	Wet	7,075.0	149.7	1.133	418	0.93	20.5	60.2
Tobacco (L)	McNair		5,223.9	179.8	1.018	291	0.83	19.7	65.3
Turnip (T)	Just Right		12.7	24.1	1.473	1.0	0.96	5.2	12.0
Turnip (T)	Purple Top		5.8	28.2	1.155	1	0.92	4.0	11.6
Turnip (T)	Shogon		4.4	28.2	1.174	1	0.82	4.1	11.7
Turnip (T)	Tokyo Cross		11.7	26.8	1.710	3	0.78	7.2	14.7
Wheat	Abe		5,138.1	53.3	2.602	407	0.89	22.4	35.8
Wheat	Arthur		4,467.4	63.8	1.747	264	0.92	17.6	35.4
Wheat	Rol		5,074.4	51.2	1.000	397	0.91	5.4	18.3
Wheat	Abe		6,042.8	48.5	5.843	225	0.75	33.0	40.6

Table 5-22 (cont'd). Comparison of Exposure-Response Curves Calculated Using the 24-Hour W126 Values for 54 National Crop Loss Assessment Network Cases[a]

			Weibull[c]					24-h W126[f] Values for Yield Losses of	
Species	Cultivar	Moisture[b]	A	B	C	RMSE[d]	R^{2e}	10%	30%
Wheat	Arthur		5,440.0	76.1	2.100	349	0.57	26.1	46.6
Wheat	Vona		5,300.8	25.0	1.000	679	0.85	2.6	8.9
Wheat	Vona		4,462.7	32.3	1.517	665	0.63	7.3	16.4

[a]See Appendix A for abbreviations and acronyms.
[b]Wet refers to experiments conducted under well-watered conditions, whereas dry refers to experiments conducted under some controlled level of drought.
[c]All estimates of "B" parameter are in parts per million per hour. The yield is expressed in kilograms per hectare for all crops except turnip (grams per plant) and lettuce (grams per meter). In cases where the estimated "C" parameter is exactly 1.0, the shape parameter has been bounded from below to obtain convergence in the nonlinear-model-fitting routine. For those studies whose species name is followed by "L", a log transformation was used to stabilize the variance. For those crops whose name is followed by "T", the yield is expressed as either grams per plant or grams per meter.
[d]The root mean square error, based on individual plot means.
[e]Multiple correlation coefficient (R^2) measures the proportion of total variation about the mean response explained by the regression on individual plot means.
[f]The 24-h W126 value (parts per million per hour) that was predicted to cause a 10 or 30% yield loss (compared to zero W126).

Source: Based on analyses by Lee et al. (1991, 1994a,b).

Research since 1986 has focused largely on understanding the response of trees and other perennials to O_3 (covered in the next section) and of five crop species: (1) cotton, (2) wheat, (3) spring rape, (4) bean, and (5) soybean. A number of the studies were conducted as part of NCLAN, but many also were the result of research activity in Europe. Results of these studies, as well as those species studied less intensively, are summarized in Table 5-25. A composite exposure-response function is illustrated in Figure 5-29.

Yield losses in cotton of 13 to 19% have been reported at 12-h mean concentrations of 0.050 or 0.044 ppm by Heagle et al. (1988a) and Temple et al. (1988b) (Table 5-25). These are typical ambient concentrations, as listed under M7 (Table 5-20). The same experiments showed that drought stress reduced the predicted yield loss due to O_3, but did not eliminate it.

Wheat yields have been reduced by 0 to 29%, depending on the cultivar and exposure conditions (Adaros et al., 1991a; Fuhrer et al., 1989; Grandjean and Fuhrer, 1989; Kohut et al., 1987; Pleijel et al., 1991) (Table 5-25). In no case was a 7-h average of greater than 0.062 ppm required to cause the reported loss, but Slaughter et al. (1989) suggest that hourly concentrations above 0.06 ppm during the period following anthesis may be particularly effective in reducing yield.

Table 5-23. The Exposure Levels (Using Various Indices) Estimated To Cause at Least 10% Crop Loss in 50 and 75% of Experimental Cases[a]

50th PERCENTILE[b]	SUM06	SE[c]	SIGMOID	SE	M7	SE	2HDM	SE
NCLAN Data (N = 49; wet and dry)[d]	24.4	3.4	21.5	2.0	0.049	0.003	0.094	0.006
NCLAN Data (N = 39; wet only)	22.3	1.0	19.4	2.3	0.046	0.003	0.090	0.010
NCLAN Data (N = 54; wet and dry)[e]	26.4	3.2	23.5	2.4	NA	NA	0.099	0.011
NCLAN Data (N = 42; wet only)[e]	23.4	3.1	22.9	4.7	NA	NA	0.089	0.008
NCLAN Data (N = 10; wet)	25.9	4.5	23.4	3.2	0.041	0.001	0.110	0.042
NCLAN Data (N = 10; dry)	45.7	23.3	40.6	0.1	0.059	0.014	0.119	0.017
Cotton Data (N = 5)	23.6	2.3	19.3	2.3	0.041	0.001	0.066	0.032
Soybean Data (N = 13)	26.2	5.4	22.6	3.6	0.044	0.005	0.085	0.013
Wheat Data (N = 6)	21.3	15.2	19.3	12.7	0.061	0.018	0.098	0.059
Cotton Data (N = 5)[e]	30.0	12.7	27.2	12.8	NA	NA	0.075	0.012
Soybean Data (N = 15)[e]	23.9	6.5	22.0	8.0	NA	NA	0.088	0.008
Wheat Data (N = 7)[e]	25.9	10.5	21.4	9.4	NA	NA	0.097	0.028
75th PERCENTILE[b]								
NCLAN Data (N = 49; wet and dry)	14.2	4.2	11.9	5.6	0.040	0.007	0.051	0.010
NCLAN Data (N = 39; wet only)	14.3	2.7	12.6	2.3	0.039	0.005	0.056	0.006
NCLAN Data (N = 54; wet and dry)[e]	16.5	4.3	14.5	3.2	NA	NA	0.073	0.006
NCLAN Data (N = 42; wet only)[e]	17.2	3.0	14.7	2.4	NA	NA	0.070	0.006
NCLAN Data (N = 10; wet)	16.4	3.7	13.7	3.2	0.040	0.001	0.080	0.032
NCLAN Data (N = 10; dry)	24.0	0.8	22.3	0.1	0.053	0.022	0.093	0.003
Cotton Data (N = 5)	21.8	5.0	17.5	2.8	0.041	0.001	0.065	0.014
Soybean Data (N = 13)	14.2	0.1	12.4	0.1	0.041	0.006	0.069	0.004
Wheat Data (N = 6)	11.7	2.5	10.9	2.4	0.054	0.032	0.062	0.035
Cotton Data (N = 5)[e]	21.1	6.0	16.7	5.7	NA	NA	0.070	0.034
Soybean Data (N = 15)[e]	15.3	4.1	13.4	4.1	NA	NA	0.078	0.007
Wheat Data (N = 7)[e]	5.1	2.6	8.5	3.4	NA	NA	0.054	0.027

[a]See Appendix A for abbreviations and acronyms.
[b]The numbers in parentheses are the number of cases used in deriving the various exposure levels.
[c]Standard error (SE).
[d]NCLAN data refers to studies conducted as part of the NCLAN project. Wet and dry refer to watery regimes used in the studies, wet being well-watered, and dry meaning some level of drought stress was imposed.
[e]24-h exposure statistics reported in Lee et al. (1994b). Relative yield loss for 2HDM is relative to yield at 0.04 ppm rather than 0.00 ppm as was used in Tingey et al. (1991).

Source: Modified from Tingey et al. (1991).

Studies with spring rape in Europe have documented yield losses of 9.5 to 26.9% at 8-h growing season average concentrations ranging from 0.03 to 0.06 ppm (Adaros et al., 1991b,c) (Table 5-26).

The yield of beans (fresh pods) was reduced by 17% at a 7-h average of 0.045 ppm (Schenone et al., 1992) or 20% at an 8-h growing season average of 0.080 ppm (Bender et al., 1990). In a similar study, Heck et al. (1988) found that the predicted yield of sensitive cultivars was reduced an average of 17.3% by exposure to a 7-h growing season

Table 5-24. SUM06 Levels Associated with 10 and 20% Yield Loss for 50 and 75% of the National Crop Loss Assessment Network (NCLAN) Crop Studies[a]

Weibull Equations (all 54 NCLAN studies):
50th Percentile[b] PRYL = 1 − exp(−[SUM06/89.497]**1.84461)
75th Percentile PRYL = 1 − exp(−[SUM06/60.901]**1.72020)

Weibull Equations (all 22 NCLAN soybean studies; 15 well-watered, 7 water-stress):
50th Percentile PRYL = 1 − exp(−[SUM06/117.68]**1.46509)
75th Percentile PRYL = 1 − exp(−[SUM06/88.99]**1.47115)

Weibull Equations (15 NCLAN well-watered soybean studies):
50th Percentile PRYL = 1 − exp(−[SUM06/112.75]**1.46150)
75th Percentile PRYL = 1 − exp(−[SUM06/79.62]**1.36037)

Weibull Equations (7 NCLAN wheat studies):
50th Percentile PRYL = 1 − exp(−[SUM06/49.02]**3.52788)
75th Percentile PRYL = 1 − exp(−[SUM06/29.56]**1.29923)

SUM06 Levels Associated with 10 and 20% Yield Loss for 50 and 75% of the Crops:

All 54 NCLAN Cases

		Percent of Crops	
		50%	75%
Relative	10%	26.4	16.5
Yield Loss	20%	39.7	25.5

All 22 NCLAN Soybean Cases

		Percent of Crops	
		50%	75%
Relative	10%	25.3	19.3
Yield Loss	20%	42.3	32.1

15 Well-Watered Soybean Cases

		Percent of Crops	
		50%	75%
Relative	10%	24.2	15.2
Yield Loss	20%	40.4	26.4

All Seven NCLAN Wheat Cases

		Percent of Crops	
		50%	75%
Relative	10%	25.9	5.2
Yield Loss	20%	32.0	9.3

[a]See Appendix A for abbreviations and acronyms.
[b]50th and 75th percentiles refer to the percentage of studies analyzed in which loss of the stated magnitude would have been prevented.

Source: Based on analyses by Lee et al. (1994b).

Table 5-25. A Summary of Studies Reporting the Effects of Ozone on the Growth, Productivity, or Yield of Annual Plants Published Since U.S. Environmental Protection Agency (1986)[a]

Species	Concentration[b]	Duration	Facility[c]	Variable[d]	Effect[e]	Reference
Soybean	18 or 24 ppb vs. 59 or 72 ppb 9-h mean	13 weeks, two growing seasons	OTC	Seed yield	12.5% reduction over filtered air averaged over cultivars. Between-cultivar differences as great as ozone effect.	Mulchi et al. (1988)
Soybean	23, 40, and 66 ppb 7-h mean	84 days	OTC	Seed yield	15.8 and 29% reduction over 23 ppb.	Mulchi et al. (1992)
Soybean	97 ppb vs. 38, 23, 16, and 23 ppb 7-h mean	Four 31-day periods, one growing season	OTC in pots	Seed yield	30 to 56% reduction over control, most loss in mid- to late-growth stage.	Heagle et al. (1991b)
Soybean	17 to 122 ppb 7-h mean	69 days	OTC	Seed yield	8% at 35 ppb to 41% at 122 ppb.	Kohut et al. (1986)
Soybean	25 and 50 ppb 7-h mean	About 90 days	OTC	Seed yield	Predicted loss of 10%.	Heagle et al. (1986b)
Soybean	20 and 50 ppb 12-h mean	107 days	OTC	Seed yield	Predicted loss of 13%.	Miller et al. (1989b)
Soybean	25 and 55 ppb 7-h mean	64, 70, and 62 days, three growing seasons	OTC	Seed yield	Predicted loss of 15%.	Heggestad and Lesser (1990)
Soybean	27 and 54 ppb 7-h means	About 109 and 103 days, two growing seasons	OTC	Seed yield	Predicted loss of 12 and 14%.	Heagle et al. (1987a)
Soybean	Filtered and nonfiltered air-concentration not reported	About 125 days, two growing seasons	OTC	Seed yield	No difference.	Johnston and Shriner (1986)
Soybean	10 to 130 ppb	8 weeks, 6.8 h/day	GC	Biomass	Predicted reduction of 16 or 33% at 60 and 100 ppb vs. 25 ppb.	Amundson et al. (1986)
Soybean	200 ppb	12 h, up to four times	GC	Shoot and root weight	No effect at maturity.	Smith et al. (1990)

Table 5-25 (cont'd). A Summary of Studies Reporting the Effects of Ozone on the Growth, Productivity, or Yield of Annual Plants Published Since U.S. Environmental Protection Agency (1986)[a]

Species	Concentration[b]	Duration	Facility[c]	Variable[d]	Effect[e]	Reference
Cotton	15 to 111 ppb 12-h mean	123 days	OTC	Leaf, stem, and root weight	Up to 42% reduction in leaf and stem and 61% reduction in root weights.	Temple et al. (1988c)
Cotton	10 to 90 ppb 12-h mean	102 days	OTC	Lint weight	40 to 71% reduction at highest concentration determinant cultivars more susceptible.	Temple (1990b)
Cotton	25 to 74 ppb 12-h mean	123 days	OTC	Lint weight	Predicted loss of 26.2% at 74 ppb.	Temple et al. (1988b)
Cotton	22 to 44 ppb 12-h mean	124 days	OTC	Lint weight	Predicted loss of 19% at 44 ppb.	Heagle et al. (1988a)
Cotton	26 to 104 ppb 7-h mean	119 days	OTC	Lint weight	Predicted loss of 11% at 53 ppb.	Heagle et al. (1986a)
Bean, fresh	35 to 132 ppb 7-h mean	42 days	OTC in pots	Green pod weight	Significant yield reductions of >10% in eight lines at 63 ppb 7-h mean.	Eason and Reinert (1991)
Bean, fresh	11 to 40 ppb 12-h mean, 7 to 42 ppm·h	69 days	OTC	Pod weight	15.5% reduction at 45 ppb (39 ppm·h).	Schenone et al. (1992)
Bean, fresh	26 to 126 ppb 7-h mean	26 days and 44 days, early and late in season	OTC in pots	Pod weight	3.5 to 26% reduction in resistant and sensitive cultivars at 55 to 60 ppb.	Heck et al. (1988)
Bean, fresh	24 to 109 ppb 8-h mean	43 days 34 days, two growing seasons	OTC	Pod weight	20% reduction at 80 ppb.	Bender et al. (1990)
Bean, dry	15 to 116 ppb 12-h mean, 339 ppb highest hour	54 days	OTC	Seed yield	55 to 75% reduction at 72 ppb 12-h mean, 198 highest hour.	Temple (1991)

Table 5-25 (cont'd). A Summary of Studies Reporting the Effects of Ozone on the Growth, Productivity, or Yield of Annual Plants Published Since U.S. Environmental Protection Agency (1986)[a]

Species	Concentration[b]	Duration	Facility[c]	Variable[d]	Effect[e]	Reference
Bean, dry	10 to 50 ppb 7-h mean	86 days	OTC	Seed weight	26 to 42% reduction at 38 to 50 ppb.	Sanders et al. (1992)
Bean, dry	300 ppb	3 h, two exposures	GC	Dry weight	Growth response detected if exposure separated by 3 to 5 days.	McCool et al. (1988)
Wheat, spring	14 to 46 ppb 24-h mean	79, 92, and 79 days in three growing seasons	OTC	Seed weight	13% reduction at 40 ppb.	Fuhrer et al. (1989)
Wheat, spring	21.6 to 80 and 24.6 to 93.5 ppm·h	82 and 88 days in two growing seasons	OTC	Seed weight	48 to 54% reduction at 80 and 93.5 ppm·h.	Grandjean and Fuhrer (1989)
Wheat, spring	3 to 56 ppb 7-h mean	61 and 55 days in two growing seasons	OTC	Seed weight	7% reduction at 15 and 22 ppb.	Pleijel et al. (1991)
Wheat, spring	8 to 101 and 20 to 221 ppb 8-h mean	118 and 98 days in two growing seasons	OTC	Seed weight	10% reduction at 17 to 23 ppb.	Adaros et al. (1991a)
Wheat, spring	0 to 38 ppb 8-h mean	Entire growing season	OTC	Seed weight	5% reduction at 38 ppb.	De Temmerman et al. (1992)
Wheat, spring	17 to 77 ppb 7-h mean	90 and 87 days in two growing seasons	OTC	Seed weight	9.5 to 11.6 reduction at 37 and 45 ppb.	Fuhrer et al. (1992)
Wheat, spring	25 to 75 ppb 8-h mean	40 days	OTC	Total weight	Reductions at 75 ppb.	Johnsen et al. (1988)
Wheat, spring	6 to 10 ppb, 6 h/day	21 days	GC	Shoot dry weight	Decreased 35 to 60% at 101 ppb in low and high light.	Mortensen (1990b)
Wheat, spring	10 to 125 ppb, 6 h/day	21 and 17 days	GC	Top dry weight	Reduced by up to 35%.	Mortensen (1990c)

Table 5-25 (cont'd). A Summary of Studies Reporting the Effects of Ozone on the Growth, Productivity, or Yield of Annual Plants Published Since U.S. Environmental Protection Agency (1986)[a]

Species	Concentration[b]	Duration	Facility[c]	Variable[d]	Effect[e]	Reference
Wheat, winter	11 to 42 ppb 14-week mean	109 days	OTC	Seed weight	No effect.	Olszyk et al. (1986b)
Wheat, winter	30 to 93 ppb 4-h mean	39 and 40 days in two growing seasons 5 days/week 4 h/day	OTC	Seed weight	Exposures >60 ppb during anthesis reduce yield.	Slaughter et al. (1989)
Wheat, winter	27 to 96 ppb 7-h mean	36 days	OTC	Seed weight/ head	50% reduction at 96 ppb.	Amundson et al. (1987)
Wheat, winter	22 to 96 ppb 7-h mean	65 days and 36 days in two growing seasons	OTC	Seed weight	33 and 22% reductions at 42 and 54 ppb, respectively.	Kohut et al. (1987)
Wheat, winter	23 to 123 ppb 4 h/day	5 days at anthesis	OTC	Seed weight	Up to 28% reduction.	Mulchi et al. (1986)
Barley, spring	6 to 45 ppb 7-h mean	96 days	OTC	Seed weight	No effect.	Pleijel et al. (1992)
Barley, spring	0.6 to 27 ppb monthly mean	Growing season	OTC	Seed weight	No effect.	Weigel et al. (1987)
Barley, spring	0.8 to 83 ppb 8-h mean	97, 108, and 98 days in three growing seasons	OTC in pots	Seed weight	0 to 13% reduction at highest.	Adaros et al. (1991b)
Rape, spring	25 to 75 ppb 8-h mean	31 days	OTC	Premature senescence	Increased at 75 ppb.	Johnsen et al. (1988)
Rape, spring	0.8 to 83 ppb 8-h mean	89, 113, and 84 days in three growing seasons	OTC in pots	Seed weight	9.4 to 16% reduction at 30 or 51 ppb.	Adaros et al. (1991b)

Table 5-25 (cont'd). A Summary of Studies Reporting the Effects of Ozone on the Growth, Productivity, or Yield of Annual Plants Published Since U.S. Environmental Protection Agency (1986)[a]

Species	Concentration[b]	Duration	Facility[c]	Variable[d]	Effect[e]	Reference
Rape, spring	43 to 60 ppb 8-h mean	89, 113, and 84 days in three growing seasons	OTC in pots	Seed weight	12 to 27% reduction.	Adaros et al. (1991c)
Tomato	13 to 0.109 ppm 12-h mean, 79.5 ppm-h	75 days	OTC	Fresh weight	17 to 54% reduction at 0.109 ppm; no reduction at ambient.	Temple (1990a)
Tomato	10 to 85 ppb, 6 h/day	12 to 21 days	GC	Shoot dry weight	35 to 62% reduction.	Mortensen (1992b)
Tomato	18 to 66 ppb 12-h mean	11 weeks	OTC	Fresh fruit weight	No effect.	Takemoto et al. (1988c)
Moss campion	5 to 80 ppb, 8 h/day	Up to 90 days	GC	Dry weight	25% reduction at 80 ppb.	Mortensen and Nilsen (1992)
Buckhorn	5 to 80 ppb, 8 h/day	Up to 90 days	GC	Dry weight	14% reduction at 50 ppb.	Mortensen and Nilsen (1992)
16 Other species	5 to 80 ppb, 8 h/day	Up to 90 days	GC	Dry weight	No effect.	Mortensen and Nilsen (1992)
Radish	20 or 70 ppb 24-h mean	27 days	GC	Shoot and root growth	36 and 45% reduction at 70 ppb.	Barnes and Pfirrman (1992)
Lettuce	21 to 128 ppb 7-h mean	52 days	OTC	Head weight	Significant reduction at 83 ppb, 35% at 128 ppb.	Temple et al. (1986)
Lettuce	10 to 34 ppb 7-week mean	64 days	OTC	Fresh weight	No effect.	Olszyk et al. (1986b)
Faba bean	6 or 15 ppb 24-h mean	134 days	OTC	Seed weight	No effect.	Sanders et al. (1990)
Fenugreek	120 ppb, 7 h/day	4 weeks	CC	Dry weight	No significant effect.	Kasana (1991)

Table 5-25 (cont'd). A Summary of Studies Reporting the Effects of Ozone on the Growth, Productivity, or Yield of Annual Plants Published Since U.S. Environmental Protection Agency (1986)[a]

Species	Concentration[b]	Duration	Facility[c]	Variable[d]	Effect[e]	Reference
Chickpea	120 ppb, 7 h/day	4 weeks	CC	Dry weight	No significant effect.	Kasana (1991)
Gram, black	120 ppb, 7 h/day	4 weeks	CC	Dry weight	No significant effect.	Kasana (1991)
Rice	0 to 200 ppb, 5 h/day	5 days/week 15 weeks	OTC	Seed weight	12 to 21% reduction at 200 ppb.	Kats et al. (1985)
Rice	50 ppb 24-h mean	8 weeks	GC	Dry weight	No effect at 50 ppb.	Nouchi et al. (1991)
Watermelon	15 to 27 ppb 7-h mean	81 days	OTC	Fresh weight and number (marketable)	20.8 and 21.5% reduction at 27 ppb.	Snyder et al. (1991)
Pea	10 to 35 ppb 12-h mean	58 and 52 days in two growing seasons	OF	Fresh weight	Linear decrease in yield with increasing O_3.	Runeckles et al. (1990)
Green pepper	19 to 66 ppb 12-h mean	77 days	OTC	Fresh fruit weight	12% reduction at 66 ppb.	Takemoto et al. (1988c)
Green pepper	18 to 66 ppb 12-h mean	11 weeks	OTC	Fresh fruit weight	13% reduction in fruit weight at 66 ppb.	Takemoto et al. (1988c)
Celery	18 to 66 ppb 12-h mean	11 weeks	OTC	Shoot dy weight	12% reduction at 66 ppb.	Takemoto et al. (1988c)

[a]See Appendix A for abbreviations and acronyms.
[b]Means are seasonal means unless specified. Maximums are 1-h seasonal maxima unless otherwise specified. Cumulative exposures are SUM00 unless otherwise specified; accumulation based on 24 h/day unless otherwise noted.
[c]OTC = open-top chamber with plants in ground unless specified in pots; CC = closed chamber, outside; GC = controlled environment growth chamber or CSTR; OF = open-field fumigation.
[d]The effect reported in the study that is a measure of growth, yield, or productivity.
[e]Effect measured at specified ozone concentration, over the range specified under concentration, or predicted (if specified) to occur based on relationships developed in the experiment.

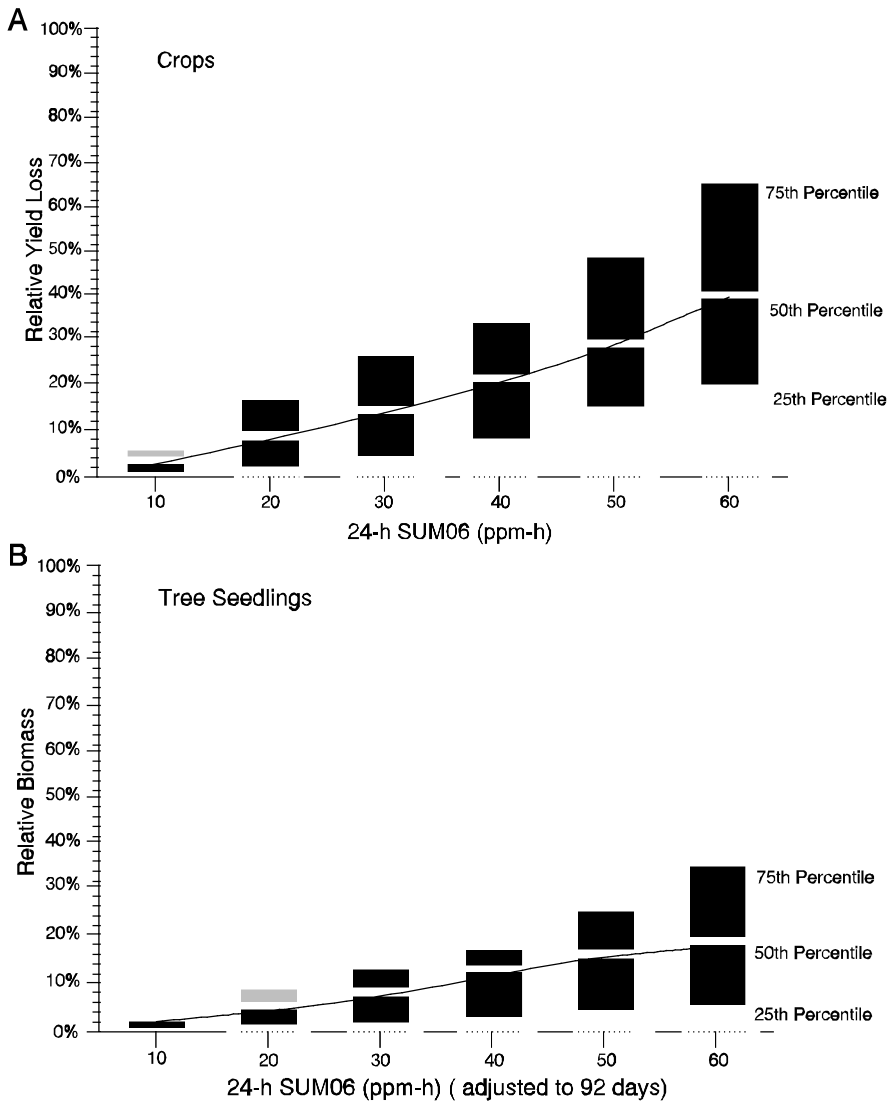


Figure 5-29. Box-plot distribution of biomass loss predictions from Weibull and linear exposure-response models that relate biomass and ozone exposure as characterized by the 24-h SUM06 statistic using data from (A) 31 crop studies from National Crop Loss Assessment Network (NCLAN) and (B) 26 tree seedling studies conducted at U.S. Environmental Protection Agency's Environmental Research Laboratory in Corvallis, OR; Smoky Mountains National Park, TN; Michigan; Ohio; and Alabama. Separate regressions were calculated for studies with multiple harvests or cultivars, resulting in a total of 54 individual equations from the 31 NCLAN studies and 56 equations from the 26 seedling studies. Each equation was used to calculate the predicted relative yield or biomass loss at 10, 20, 30, 40, 50, and 60 ppm·h, and the distributions of the resulting loss were plotted. The solid line is the calculated Weibull fit at the 50th percentile (from Hogsett et al., 1995).

Table 5-26. A Summary of Studies Reporting the Effects of Ozone on the Growth, Productivity, or Yield of Perennial Crop Plants Published Since U.S. Environmental Protection Agency (1986)[a]

Species	Concentration[b]	Duration	Facility[c]	Variable[d]	Effect[e]	Reference
Strawberry	18 to 66 ppb 12-h mean	11 weeks	OTC	Fresh fruit weight	20% increase in fruit weight at 66 ppb.	Takemoto et al. (1988c)
Timothy	10 to 55 ppb 7-h mean	5 weeks	GC	Shoot dry weight	45% reduction at 55 ppb.	Mortensen (1992a)
Orchard grass	10 to 55 ppb 7-h mean	5 weeks	GC	Shoot dry weight	28% reduction at 55 ppb.	Mortensen (1992a)
Kentucky blue grass	10 to 55 ppb 7-h mean	5 weeks	GC	Shoot dry weight	28% reduction at 55 ppb.	Mortensen (1992a)
Red grass	10 to 55 ppb 7-h mean	5 weeks	GC	Shoot dry weight	23% reduction at 55 ppb.	Mortensen (1992a)
Tall fescue	10 to 55 ppb 7-h mean	5 weeks	GC	Shoot dry weight	16% reduction at 55 ppb.	Mortensen (1992a)
Colonial bent grass	10 to 55 ppb 7-h mean	5 weeks	GC	Shoot dry weight	No effect.	Mortensen (1992a)
Rye grass	62 ppb 7-h mean	5 weeks	GC	Shoot dry weight	No effect.	Mortensen (1992a)
Red clover	6 to 59 ppb 7-h mean	5 weeks	GC	Shoot dry weight	30% reduction at 59 ppb.	Mortensen (1992a)
Common plantain	70 ppb 7-h mean	8 weeks	GC	Total dry weight	Reduced up to 36% depending on growth stage.	Reiling and Davison (1992c)
Red clover	19 to 62 ppb 12-h mean	83 and 91 days in two growing seasons	OTC	Dry weight	11% reduction at 62 ppb.	Kohut et al. (1988a)
Timothy	19 to 62 ppb 12-h mean	83 and 91 days in two growing seasons	OTC	Dry weight	No effect.	Kohut et al. (1988a)

Table 5-26 (cont'd). A Summary of Studies Reporting the Effects of Ozone on the Growth, Poductivity, or Yield of Perennial Crop Plants Published Since U.S. Environmental Protection Agency (1986)[a]

Species	Concentration[b]	Duration	Facility[c]	Variable[d]	Effect[e]	Reference
Ladino clover-tall fescue pasture	22 to 114 ppb 12-h mean	Five 3- to 4-week exposure periods. Six 3- to 4-week exposures in 2 years	OTC	Shoot dry weight, root dry weight	18 to 50% reduction in shoot dry weight (SDW) at 40 to 47 ppb clover; 25% reduction root dry weight at 40 to 47 ppb. SDW increased by up to 50% in fescue.	Rebbeck et al. (1988)
Ladino clover	28 to 46 ppb 12-h mean	180 and 191 days in two growing seasons	OTC	Dry weight	Predicted yield of mix reduced 10%, with 19% decrease in clover and 19% increase in fescue at 46 ppb.	Heagle et al. (1989b)
Alfalfa	14 to 98 ppb 12-h mean	32 days	OTC	Dry weight	2.4% reduction at 40 ppb, 18.3% reduction at 66 ppb.	Temple et al. (1987)
Alfalfa	20 to 53 ppb 12-h mean	11 weeks	OTC	Dry weight	22% reduction at 53 ppb.	Takemoto et al. (1988a)
Alfalfa	18 to 66 ppb 12-h mean	11 weeks	OTC	Shoot dry weight	22% reduction at 36 ppb.	Takemoto et al. (1988c)
Alfalfa	10 to 109 ppb 12-h mean	208 and 200 days in two growing seasons	OTC	Dry weight	0 to 25% reduction at levels of 38 ppb and above.	Temple et al. (1988a)
Alfalfa	60 to 80 ppb 6-h day	5 days/week for 8 weeks	GH	Relative growth rate	Reduced up to 40% in Saranac.	Cooley and Manning (1988)
Grape	Not reported	Two growing seasons	OTC	Yield	No effects of ambient air vs. filtration.	Musselman et al. (1985)

[a]See Appendix A for abbreviations and acronyms.
[b]Means are seasonal means unless specified. Maximums are 1-h seasonal maxima unless otherwise specified. Cumulative exposures are SUM00 unless otherwise specified; accumulation based on 24 h/day unless otherwise noted.
[c]OTC = open-top chamber with plants in ground unless specified in pots; GC = controlled environment growth chamber or CSTR; GH = greenhouse.
[d]The effect reported in the study that is a measure of growth, yield, or productivity.
[e]Effect measured at specified ozone concentration, over the range specified under concentration, or predicted (if specified) to occur based on relationships developed in the experiment.

mean of 0.05 ppm, but resistant cultivars suffered only a 1.6% loss. Temple (1991) reported reductions in dry bean yield of 44 to 73% in three cultivars grown in California and exposed to a 12-h seasonal mean of 0.072 ppm. One other cultivar increased in yield in NF chambers but was severely affected in higher concentration O_3 treatments. Sanders et al. (1992) also observed yield stimulation at a 7-h growing season mean of 0.025 ppm; however, significant yield reductions were measured as O_3 concentrations increased to 50 ppb (7-h seasonal mean).

Several studies have shown soybean yields to be reduced by 10 to 15% at 7- or 12-h seasonal mean concentrations of 0.05 to 0.055 ppm (Table 5-26; Heagle et al., 1986b, 1987a; Heggestad and Lesser, 1990; Miller et al., 1989b).

A number of the studies cited above and some of those in Table 5-26 were conducted as part of NCLAN and are considered in the discussions of Tingey et al. (1991), Lee et al. (1993), and Lesser et al. (1990), but many of the experiments (primarily those not part of NCLAN) were not included in their analyses. Although the range of variability in species response to O_3 is apparent, these studies support, for the most part, the conclusions of U.S. Environmental Protection Agency (1986), Tingey et al. (1991), and Lesser et al. (1990). Table 5-24 summarizes the studies reporting the response of annual plants, particularly crops, as growth, dry weight, or yield to O_3 exposures ($C \times T$) under experimental conditions since the previous criteria document (U.S. Environmental Protection Agency, 1986). Based on the results of the studies reviewed in this section, including the reanalysis of NCLAN, exposures for a 3-mo period to O_3 concentrations currently occurring in the ambient air (0.048 to 0.06 ppm, 7-h seasonal mean; see M7, Table 5-20) have been shown to cause losses of 10% or more in the yield of the majority of major crop plants grown in the country. A number of crop species are more sensitive, and greater losses could be expected (Tables 5-21 through 5-25). It should be noted that a variety of methodologies has been used to generate these data. Generally speaking, data obtained through growth chamber experiments and experiments conducted using potted plants, in fact, are more scientifically reliable but less relevant to ambient conditions when assessing the effects of O_3 than are results from field growth plants.

5.6.4 Effects of Ozone on Long-Lived Plants

Quantifying exposure-response in the case of perennial plants (agricultural crops such as pastures, alfalfa, and shrubs and trees) is complicated by they fact that they can receive multi-year exposures and because the results of exposures in a previous year, or over a number of years, may be cumulative. Reduction in growth and productivity, a result of altered carbon allocation, may appear only after a number of years or when carbohydrate reserves are depleted (U.S. Environmental Protection Agency, 1986; Laurence et al., 1993; Garner, 1991; Garner et al., 1989). A further complication is that, in the case of evergreen plants, the life span of a leaf exceeds 1 year and usually persists for several years. In such cases, loss of a leaf or a reduction in photosynthetic performance may have a large effect on a plant's ability to survive and grow. Physiological differences among species (rates of gas exchange, for instance) may have a tendency to equalize exposure over a number of years, however, as shown in Reich's (1987) analysis of crops, hardwoods, and conifers and in Pye's analysis of tree species (1988). Unfortunately, there is little experimental data regarding the effects of long-term O_3 exposure on perennial plants, because only a few experimental studies have extended exposures beyond a single growing season. Most of what is known regarding the effects of O_3 on mature trees is from field observations. There have been some studies that have extended observation of growth alterations into the season following exposures and, thus, observed "carry-over effects" in several species. Hogsett et al. (1989) reported altered bud elongation in ponderosa pine, lodgepole pine (*Pinus contorta*), and western hemlock (*Tsuga heterphylla*), following a season of O_3 exposure. Altered root regrowth in ponderosa pine in the season following exposure that was correlated with root storage carbohydrate was observed by Andersen et al. (1991). Most studies have used seedlings because of the difficulty of exposing large trees. The extrapolation from seedlings to large trees and to forest stands is not straight-forward and, most likely, will depend on the use of models (Hogsett et al., 1995; Laurence et al., 1993; Taylor and Hanson, 1992). Correlative studies, such as those conducted in the San Bernardino Mountains of California, indicate potentially large impacts on ecosystems (U.S. Environmental Protection Agency, 1986). Cregg et al. (1989), however, point out that notable differences between trees and seedlings are their carbon allocation and use patterns. There is a significantly higher ratio of respiring to photosynthetic tissue in mature trees. This section will address three distinct types of long-lived plants: (1) multiple-year agricultural crops, (2) deciduous shrubs and trees, and (3) evergreen coniferous trees.

5.6.4.1 Perennial Agricultural Crops

Cooley and Manning (1988) conducted a greenhouse study of the response of alfalfa to O_3 applied at 0.06 to 0.08 ppm for 6 h/day, 5 days/week for 8 weeks during 2 different years (to different plants). Ozone treatment reduced the growth and relative growth rate (by about 15 to 20% for tops and 20 to 40% for roots) of plants before cutting, when compared to a filtered-air control. The growth of roots was affected more than the growth of tops, with a shift in the allocation pattern. In the second year of the study, O_3 exposure was continued after the plants were harvested and the impact of exposure on regrowth was determined. In this case, they found that the relative growth rate in O_3 exposed plants was higher, perhaps because of an increased demand for carbon by the root systems of the O_3-stressed plants. It is unclear whether these plants would sustain their increased growth, and, in fact, the authors speculate that the increased growth, in lieu of partitioning carbon to other compounds, might alter the cold hardiness of the plants.

Ozone has been demonstrated to affect the growth of field grown alfalfa. Temple et al. (1988a) reported a 2-year study of alfalfa in which O_3 at ambient concentrations (0.049 in 1984 and 0.042 ppm in 1985 for the seasonal 12-h means, April to October) did not affect the growth and yield of the plants, but at 12-h seasonal means of 0.063 and 0.078 ppm, yield was reduced by about 15 and 19%, respectively. The exposure-response functions for the 2 years were homogeneous; there was no indication of cumulative effect of O_3 exposure; however, crown weight (an indicator of health and vigor) of exposed plants was reduced significantly.

In a different field experiment conducted to determine the interactive effects of O_3 and simulated acid fog on stomatal conductance, photosynthesis, foliar injury, and yield of an established stand of alfalfa, plants were exposed 12 h daily for 4 weeks (Temple et al., 1987). Ozone was added in proportion to its concentration in the ambient air. Ambient O_3 concentrations during the experiment were 0.043 ppm. Ozone injury symptoms appeared on the alfalfa exposed to 0.098 ppm (NF × 2.0), 1 week after the start of the regrowth period. When exposures were at 0.081 and 0.066 ppm (NF × 1.7 and NF × 1.3), more than a week was required for injury to appear. A 1-mo exposure of the plants at the end of the growing season resulted in a reduction of about 2.5% in aboveground yield at a 12-h seasonal mean concentration of 0.04 ppm. At a concentration of 0.066 ppm, the exposure resulted in a reduction in yield of approximately 18%. It should be noted that the whole plant was exposed to ambient O_3 for the growing season, only new leaves that had developed after harvest received the 1-mo exposure. Ozone exposures could shorten the productive life of alfalfa stands, in addition to its affecting yield.

Kohut et al. (1988a) and Heagle et al. (1989b) experimented with forage mixtures characteristic of the northeast and southeast, respectively. In both cases, exposure to O_3 resulted in a reduction in total forage yield of about 10 to 20% at 12-h seasonal mean O_3 concentrations of 0.045 to 0.05 ppm. In both cases, the clover component of the mix was more sensitive than the grass and was reduced in prevalence in the stand. The relevance of these studies to competition and species composition is discussed in the section on ecosystem response (Section 5.7).

Results of studies on perennial plants conducted since 1986 are summarized in Table 5-26. As with single-season agricultural crops, yields of multiple-year forage crops are reduced at concentrations at or near ambient (0.05 to 0.06 ppm for 5 weeks) in many parts of the country.

5.6.4.2 Effects of Ozone on Deciduous Shrubs and Trees

Most of the information concerning the response of deciduous shrubs and trees to episodes or season-long or multiple-year exposures to O_3 is based on field observations. The longevity of perennial plants and their size, in the case of trees, makes their study under experimental conditions difficult. For this reason, there is little experimental data concerning the response of deciduous shrubs and trees.

Trees, because of their size, are difficult to study under controlled conditions, therefore, most experiments have used seedlings in pots or in OTCs. Most of the hardwood experiments included in Reich's analysis (1987), for example, were exposed under laboratory or greenhouse conditions to relatively high concentrations for short periods of time. Although exposure durations of weeks were used, square-wave exposure regimes that do not capture important characteristics of ambient exposure were used. In addition, in Pye (1988), the majority of the studies were conducted in a laboratory or greenhouse. The results of a few OTC studies are cited; however, the majority of these studies used O_3 concentrations of 0.10 ppm or higher, a condition found only during peak exposures in the ambient air. Although the studies reported in the previous criteria document (U.S. Environmental Protection Agency, 1986) (see Section 5.6.2) support the sensitivity of the seedlings of some species grown in chambers, little information of value with regard to tree growth or biomass production in the long-term can be extrapolated from the experiments. Since 1986, a number of studies have been conducted documenting the sensitivity of hardwoods to O_3 (Table 5-27). Some species, such as black cherry, are very sensitive, although great variability in foliar injury was observed among individual trees, indicating that sensitivity varies greatly within species (Davis and Skelly, 1992a,b; Simini et al., 1992). No significant reductions in basal diameter and height growth were observed during the 3 years of the study, although growth was reduced during 1988 at two sites where O_3 concentrations exceeded 0.12 ppm (Simini et al., 1992), with SUM06 exposures as low as 12.9 ppm·h over 92 days (concentrations not given) predicted to cause a 10% yield loss (Hogsett et al., 1995; Table 5-28).

Based on studies previously reviewed, the growth of some hardwood species, particularly those of the genus *Populus*, may be affected by ambient concentrations of

Table 5-27. A Summary of Studies Reporting the Effects of Ozone on the Growth or Productivity of Deciduous Shrubs and Trees Published Since U.S. Environmental Protection Agency (1986)[a]

Species	Concentration[b]	Duration	Facility[c]	Variable[d]	Effect[e]	Reference
Almond	38 to 112 ppb 12-h mean	153 days	OTC	Total dry weight	Linear reduction in two cultivars, no effect in three.	Retzlaff et al. (1992a)
Almond	30 to 117 ppb 12-h mean	3.5 mo	OTC	Cross-sectional area	6% reduction at 51 ppb.	Retzlaff et al. (1991)
Almond	250 ppb, 4 h/week	16 weeks in each of two growing seasons	CC	Net growth	28 and 36% reduction in years 1 and 2.	McCool and Musselman (1990)
Plum	44 to 111 ppb 12-h mean	191 and 213 days	OTC	Number of fruit per tree	29% fewer fruit at ambient and above.	Retzlaff et al. (1992b)
Plum	30 to 117 ppb 12-h mean	3.5 mo	OTC	Cross-sectional area	19% reduction at 51 ppb.	Retzlaff et al. (1991)
Pear	30 to 117 ppb 12-h mean	3.5 mo	OTC	Cross-sectional area	8% reduction at 51 ppb.	Retzlaff et al. (1991)
Apricot	30 to 117 ppb 12-h mean	3.5 mo	OTC	Cross-sectional area	53% reduction at 117 ppb.	Retzlaff et al. (1991)
Skunk bush	10 to 75 ppb 12-h mean	3 mo	OTC in pots	Growth	Increase in leaf weight in ambient air; no other effect.	Temple (1989)
Black cherry	16 to 67 ppb 12-h mean	Three growing seasons	OTC	Growth and leaf dynamics	Leaf abscission increased with increasing ozone.	Simini et al. (1992)
Black cherry	40 or 80 ppb, 7 h/day, 5 days/week	8 or 12 weeks	GC	Growth	Reduced leaf, stem, and root dry weight, and height at 80 ppb.	Davis and Skelly (1992b)
Red oak	18 to 87 ppm·h 15 to 69 ppb 7-h mean	177 days	OTC	Tree canopy	Reduced 41% at 82 ppm·h or 69 ppb 7-h mean.	Samuelson and Edwards (1993)
Red oak	16 to 67 ppb 12-h mean	Three growing seasons	OTC	Growth and leaf dynamics	No effect.	Simini et al. (1992)

Table 5-27 (cont'd). A Summary of Studies Reporting the Effects of Ozone on the Growth or Productivity of Deciduous Shrubs and Trees Published Since U.S. Environmental Protection Agency (1986)[a]

Species	Concentration[b]	Duration	Facility[c]	Variable[d]	Effect[e]	Reference
Red oak	40 or 80 ppb, 7 h/day, 5 days/week	8 or 12 weeks	GC	Growth	Reduced root dry weight at 80 ppb.	Davis and Skelly (1992b)
Red maple	16 to 67 ppb 12-h mean	Three growing seasons	OTC	Growth and leaf dynamics	No effect.	Simini et al. (1992)
Red maple	40 or 80 ppb, 7 h/day, 5 days/week	8 or 12 weeks	GC	Growth	Reduced stem diameter and dry weight at 80 ppb.	Davis and Skelly (1992b)
Tulip poplar	16 to 67 ppb 12-h mean	Three growing seasons	OTC	Growth and leaf dynamics	Leaf abscission increased with increasing ozone.	Simini et al. (1992)
Yellow poplar	40 or 80 ppb, 7 h/day, 5 days/week	8 or 12 weeks	GC	Growth	Reduced leaf dry weight and stem diameter at 80 ppb.	Davis and Skelly (1992b)
European beech	10 to 90 ppb weekly mean	5 years	OTC	Growth	Reduced shoot growth and leaf area.	Billen et al. (1990)
Aspen	80 ppb, 6 h/day, 3 days/week	70 and 92 days in two growing seasons	OTC	Stem weight	No effect on tolerant clones; 46% reduction for sensitive clones in 1 year 5% (tolerant), and 74% (sensitive) reductions in the second year.	Karnosky et al. (1992b)
Aspen	Filtered air or 80 ppb, 6 h/day, 3 days/week	93 days at two sites in Michigan	OTC	Growth	18 to 26% reduction in diameter growth.	Karnosky et al. (1992a)
Aspen	Ambient + 27, 51, or 102-ppb exposure period mean	105 days	CC	Dry weight	40% reduction; 44% reduction in early growth the following year.	Keller (1988)

Table 5-27 (cont'd). A Summary of Studies Reporting the Effects of Ozone on the Growth or Productivity of Deciduous Shrubs and Trees Published Since U.S. Environmental Protection Agency (1986)[a]

Species	Concentration[b]	Duration	Facility[c]	Variable[d]	Effect[e]	Reference
Yellow poplar	0 to 200 ppb, 8 h/day, 3 days/week	4.5 mo	GC	Growth	Up to a 24% reduction at 200 ppb but moderated by pH treatment.	Jensen and Patton (1990)
Paper birch	60 to 80 ppb, 7 h/day, 5 days/week	12 weeks	GH	Dry weight	Decreased shoot and root weight and leaf area.	Keane and Manning (1988)
Downy birch	25 to 82 ppb, 7 h/day	50 days	GC	Dry weight	Shoot and root dry weight decreased linearly with ozone.	Mortensen and Skre (1990)
Downy birch	25 to 82 ppb, 7 h/day	50 days	GC	Dry weight	Shoot and root dry weight decreased linearly with ozone.	Mortensen and Skre (1990)
Red alder	25 to 82 ppb, 7 h/day	50 days	GC	Dry weight	Shoot and root dry weight decreased linearly with ozone.	Mortensen and Skre (1990)

[a]See Appendix A for abbreviations and acronyms.
[b]Means are seasonal means unless specified. Maximums are 1-h seasonal maxima unless otherwise specified. Cumulative exposures are SUM00 unless otherwise specified, accumulation based on 24 h/day unless otherwise noted.
[c]OTC = open-top chamber with plants in ground unless specified in pots; CC = closed chamber, outside; GC = controlled environment growth chamber or CSTR; GH = greenhouse.
[d]The effect reported in the study that is a measure of growth, yield, or productivity.
[e]Effect measured at specified ozone concentration, over the range specified under concentration, or predicted (if specified) to occur based on relationships developed in the experiment.

Table 5-28. Exposure-Response Equations That Relate Total Biomass (Foliage, Stem, and Root) to 24-Hour SUM06 Exposures (C) Adjusted to 92 Days (ppm-h/year)[a]

Rate of Growth	Habit	Study	Species	Location (State)	Exposure[b] Days	Year	Harvests[c]	Weibull Parameters A	B	C	SUM06 for Loss of[d] 10%	30%
Fast	D	1	Aspen, wild	OR	84	1989	1	9.9	96.3	1.316	19.09	48.21
Fast	D	1	Aspen, wild	OR	84	1989	2	17.7	165.2	1.000	19.06	64.54
Fast	D	2	Aspen, wild	OR	118	1991	1	31.0	130.0	3.062	48.62	72.41
Fast	D	2	Aspen, wild	OR	118	1991	2	75.6	124.9	5.529	64.80	80.79
Fast	D	3	Aspen, wild	OR	112	1990	1	67.8	111.0	6.532	64.60	77.86
Fast	D	3	Aspen, wild	OR	112	1990	2	96.9	142.1	1.257	19.48	51.40
Fast	D	4	Aspen 216	MI	82	1990	1	54.5	121.1	1.609	33.56	71.60
Fast	D	4	Aspen 253	MI	82	1990	1	73.1	265.5	1.000	31.38	106.23
Fast	D	4	Aspen 259	MI	82	1990	1	79.1	92.7	1.000	10.96	37.10
Fast	D	4	Aspen 271	MI	82	1990	1	91.3	44.9	8.964	39.20	44.91
Fast	D	5	Aspen 216	MI	98	1991	1	37.4	128.6	1.000	12.72	43.06
Fast	D	5	Aspen 259	MI	98	1991	1	35.2	95.9	1.000	9.49	32.11
Fast	D	5	Aspen 271	MI	98	1991	1	35.7	73.1	4.012	39.16	53.07
Fast	D	6	Aspen, wild	MI	98	1991	1	19.0	263.1	1.000	26.02	88.08
Slow	E	7	Douglas fir	OR	113	1989-90	1	16.8	462.7	1.844	111.17	215.37
Slow	E	7	Douglas fir	OR	113	1989-90	2	27.9	3.8E+17	1.000	250.00	250.00
Slow	E	7	Douglas fir	OR	234	1989-90	3	33.3	438.9	5.383	113.61	142.49
Slow	E	7	Douglas fir	OR	234	1989-90	4	83.5	2,887.0	1.000	119.61	404.91
Slow	E	8	Douglas fir	OR	118	1991-92	1	26.7	109.5	57.655	82.13	83.88
Slow	E	8	Douglas fir	OR	118	1991-92	2	85.9	-0.0058	(lin)	250.00	250.00
Slow	E	8	Douglas fir	OR	230	1991-92	3	119.1	218.7	12.254	72.80	80.42
Slow	E	9	Ponderosa pine	OR	111	1989	1	12.8	246.9	1.000	21.56	73.00
Slow	E	9	Ponderosa pine	OR	111	1989	2	25.8	365.2	1.000	31.89	107.95
Slow	E	10	Ponderosa pine	OR	113	1989-90	1	12.9	233.7	1.000	20.05	67.87
Slow	E	10	Ponderosa pine	OR	113	1989-90	2	25.7	358.8	1.000	30.77	104.18
Slow	E	10	Ponderosa pine	OR	234	1989-90	3	32.1	327.8	1.000	13.58	45.97
Slow	E	10	Ponderosa pine	OR	234	1989-90	4	90.1	634.3	1.000	26.27	88.94
Slow	E	11	Ponderosa pine	OR	118	1991-92	1	20.2	266.4	1.000	21.88	74.09
Slow	E	11	Ponderosa pine	OR	118	1991-92	2	47.1	206.5	1.000	16.96	57.42
Slow	E	11	Ponderosa pine	OR	230	1991-92	3	44.5	458.5	1.257	30.61	80.77
Slow	E	12	Ponderosa pine	OR	140	1992	1	134.6	235.8	2.570	64.56	103.76
Slow	E	13	Ponderosa pine	OR	84	1991	1	136.0	442.8	1.000	51.10	172.98
Fast	D	14	Red alder	OR	121	1990	1	42.4	217.0	1.427	34.08	80.10
Fast	D	15	Red alder	OR	113	1989	1	84.4	253.0	1.000	21.70	73.46
Fast	D	15	Red alder	OR	113	1989	2	206.8	179.9	5.294	95.76	120.57
Fast	D	16	Red alder	OR	118	1991	1	63.5	501.7	1.000	41.21	139.51
Fast	D	16	Red alder	OR	118	1991	2	248.8	2.0E+13	1.000	250.00	250.00
Fast	D	17	Red alder	OR	112	1992	1	54.1	274.4	1.107	29.50	88.79
Fast	D	18	Black cherry	TN	76	1989	1	53.7	79.1	1.123	12.91	38.23
Fast	D	19	Black cherry	TN	140	1992	1	37.1	176.6	1.168	16.90	48.00
Slow	D	20	Red maple	TN	55	1988	1	28.5	387.1	1.537	149.75	331.07
Fast	D	21	Tulip poplar	TN	75	1990-91	1	45.8	46.4	4.518	34.56	45.27
Fast	D	21	Tulip poplar	TN	184	1990-91	3	334.1	623.5	1.000	32.85	111.19
Fast	D	22	Tulip poplar	TN	81	1992	1	150.1	50.8	1.852	17.12	33.07

Table 5-28 (cont'd). Exposure-Response Equations That Relate Total Biomass (Foliage, Stem, and Root) to 24-Hour SUM06 exposures (C) Adjusted to 92 days (ppm-h/year)[a]

Rate of Growth	Habit	Study	Species	Location (State)	Exposure[b] Days	Year	Harvests[c]	Weibull Parameters A	B	C	SUM06 for Loss of[d] 10%	30%
Fast	E	23	Loblolly GAKR 15-91	AL	555	1988-89	3	22.7	4,402.5	1.000	76.89	260.30
Fast	E	23	Loblolly GAKR 15-23	AL	555	1988-89	3	20.4	13,125.4	1.000	229.24	250.00
Slow	D	24	Sugar maple	MI	83	1990-91	1	4.12	100.0	40.069	104.79	108.03
Slow	D	24	Sugar maple	MI	180	1990-91	3	24.63	110.2	5.987	38.68	47.42
Slow	E	25	Eastern white pine	MI	83	1990-91	1	0.35	63.1	4.191	40.90	54.72
Slow	E	25	Eastern white pine	MI	180	1990-91	3	1.21	719.5	1.000	38.74	131.16
Slow	E	26	Virginia pine	MI	98	1992	1	78.3	3,045.1	1.000	250.00	250.00

[a]See Appendix A for abbreviations and acronyms.
[b]Duration corresponds to the length in days of the first year of exposure for Harvests 1 and 2 and to the total length of the first and second years of exposure for Harvests 3 and 4.
[c]Harvest 1 occurs immediately following the end of the first year of exposure. Harvest 2 occurs in the spring following the first year of exposure. Harvest 3 occurs immediately following the end of the second year of exposure. Harvest 4 occurs in the spring following the second year of exposure.
[d]To compare the results from seedling studies of varying exposure duration, the SUM06 value is calculated for an exposure of fixed period of 92 days per year. For example, Study 1 Harvest 1 has an exposure duration of 84 days and a SUM06 value of 19.09 ppm-h over 92, days which corresponds to a SUM06 value of 19.09*84/92 = 17.43 ppm-h over 84 days, at which biomass loss is 10%. The calculation assumes that exposures can be scaled up or down in uniform fashion.
[e]Based on GIS, TREGRO, and ZELIG models projections. No data given in paper.

Source: Hogsett et al. (1995).

O_3 (U.S. Environmental Protection Agency, 1978, 1986). In studies of the response of aspen clones to O_3 at two field sites in Michigan, Karnosky et al. (1992a,b) documented reductions in stem weight of up to 46% in sensitive aspen clones after 70 days of exposure in OTCs to 0.08 ppm for 6 h/day, 3 days/week.

Tjoelker and Luxmoore (1991) found leaf abscission on tulip poplar (*Liriodendron tulipifera*) seedlings to be increased by exposure to a 7-h seasonal mean concentration of 0.108 ppm, resulting in a doubling of the leaf turnover rate, but this was not translated into an effect on growth, perhaps due to the indeterminate growth habit of the plant. In such plants, leaf production continues throughout the growing season, which may permit the tree to maintain an optimal leaf area; however, continued leaf growth could deplete carbon or nitrogen reserves.

Samuelson and Edwards (1993), in a study to determine if seedlings and trees responded similarly to O_3, found canopy weight of 30-year-old northern red oak, exposed in large OTCs, to be reduced by 41% after exposure for 177 days at a 7-h seasonal mean of 0.069 ppm (87 ppm·h SUM08), compared to a subambient treatment at a 7-h seasonal mean of 0.015 ppm (18 ppm·h SUM00). Two-year-old seedlings were not affected by similar exposures. Trees produced only one flush of leaves, seedlings produced as many as three.

Hogsett et al. (1995) developed exposure-response functions for aspen, red alder (*Alnus rubra*), black cherry (*Prunus serotina*), red maple (*Acer rubrum*), and tulip poplar (Table 5-28), as well as composite functions for deciduous tree seedlings (Table 5-29). Their results suggest that, for 28 deciduous seedling cases, a SUM06 exposure of 31.5 ppm·h over 92 days with a mean concentration of approximately 0.055 ppm could result in less than a

Table 5-29. SUM06 Levels Associated with 10 and 20% Total Biomass Loss for 50 and 75% of the Seedling Studies (The SUM06 value is adjusted to an exposure length of 92 days per year.)[a]

Weibull Equations (all 51 seedling studies):
50th Percentile PRYL = 1 − exp(−[SUM06/176.342]**1.34962)
75th Percentile PRYL = 1 − exp(−[SUM06/104.281]**1.46719)

Weibull Equations (27 fast-growing seedling studies):
50th Percentile PRYL = 1 − exp(−[SUM06/150.636]**1.43220)
75th Percentile PRYL = 1 − exp(−[SUM06/89.983]**1.49261)

Weibull Equations (24 slow to moderate growing seedling studies):
50th Percentile PRYL = 1 − exp(−[SUM06/190.900]**1.49986)
75th Percentile PRYL = 1 − exp(−[SUM06/172.443]**1.14634)

Weibull Equations (28 deciduous seedling studies):
50th Percentile PRYL = 1 − exp(−[SUM06/142.709]**1.48845)
75th Percentile PRYL = 1 − exp(−[SUM06/87.724]**1.53324)

Weibull Equations (23 evergreen seedling studies):
50th Percentile PRYL = 1 − exp(−[SUM06/262.911]**1.23673)
75th Percentile PRYL = 1 − exp(−[SUM06/201.372]**1.01470)

Levels Associated with Prevention of a 10 and 20% Total Biomass Loss for 50 and 75% of the Seedlings:

All 51 Seedling Cases

		Percent of Seedlings	
		50%	75%
Relative	10%	33.3	22.5
Biomass Loss	20%	58.0	37.5

27 Fast-Growing Seedling Cases

		Percent of Seedlings	
		50%	75%
Relative	10%	31.3	19.4
Biomass Loss	20%	52.9	32.4

24 Slow-to-Moderate-Growth Seedling Cases

		Percent of Seedlings	
		50%	75%
Relative	10%	42.6	24.2
Biomass Loss	20%	70.2	46.6

28 Deciduous Seedling Cases

		Percent of Seedlings	
		50%	75%
Relative	10%	31.5	20.2
Biomass Loss	20%	52.1	33.0

Table 5-29 (cont'd). SUM06 Levels Associated with 10 and 20% Total Biomass Loss for 50 and 75% of the Seedling Studies (The SUM06 value is adjusted to an exposure length of 92 days per year.)[a]

23 Evergreen Seedling Cases

		Percent of Seedlings	
		50%	75%
Relative	10%	42.6	21.9
Biomass Loss	20%	78.2	45.9

[a]See Appendix A for abbreviations and acronyms.

Hogsett et al. (1995).

10% growth (biomass) reduction in 50% of the cases. A 20% reduction in growth should result from a SUM06 exposure of greater than 52.1 ppm·h. Comparison with Table 5-20 shows a SUM06 for 3 mo of 29.5 ppm·h at ambient concentrations, a value near that (33.3 ppm·h) expected to prevent a 10% growth reduction in 50% of the cases (Table 5-27). An individual year, such as 1988, might be significantly above the no-injury exposure value (Table 5-20). By further grouping the seedlings by rate of growth (fast or slow), the investigators were able to refine estimates of the SUM06 exposure that would protect seedlings, based on growth strategy. Deciduous seedlings, and fast-growing species are more sensitive than evergreen and slow-growing seedlings (Table 5-27). Seedlings utilize more of the carbon compounds formed during photosynthesis for growth, whereas mature trees use more for maintenance; therefore, extrapolation of exposure response from seedlings to mature trees may lead to inaccurate assumptions.

The response of a number of fruit and nut trees to O_3 has been reported (McCool and Musselman, 1990; Retzlaff et al., 1991, 1992a,b). Almond (*Prunus amygdalis* Batsch) has been identified as the most sensitive, but peach (*Prunus persica*), apricot, pear, and plum (*Prunus domestica*) also have been affected. Net growth of almond, the stem diameter of peach, and the stem diameter and number of shoots produced on apricot were reduced by 4 mo (the exposure duration specified by the authors) of once-weekly exposure to 0.25 ppm for 4 h (an exposure found only in California), a relatively small exposure cumulatively (16 ppm·h as a SUM00 or as a SUM06) (McCool and Musselman, 1990), but one with a high peak value. Cross-sectional area of almond, plum, apricot, and pear stems decreased linearly with increasing O_3, with a significant reduction at a 12-h seasonal mean of 0.051; dry weight of roots, trunk, and foliage also was reduced in one variety of almond (Retzlaff et al., 1992a).

Finally, two studies report the response of citrus and avocado to O_3 (Eissenstat et al., 1991a; Olszyk et al., 1990b). These species retain their leaves for more than 1 year, but fit best in the deciduous category because, although evergreen, leaves are replaced more frequently than in most evergreen species. Valencia orange trees (*Citrus sinensis*), exposed during a production year to a seasonal 12-h mean of 0.04 or 0.075 ppm, had 11 and 31% lower yields than trees grown in filtered air at 0.012 ppm and atypical concentration. During an off-production year, yield was not affected. Growth of Ruby Red grapefruit (*Citrus paradisi*) was not affected by concentrations of three times that of the ambient concentration

(Eissenstat et al., 1991b). Avocado growth was reduced by 20 or 61% by exposure during two growing seasons at 12-h seasonal mean concentrations of 0.068 and 0.096 ppm.

In summary, deciduous trees appear to be less sensitive to O_3 than are most crop plants, but there are species that are as sensitive or more so because of their genetic composition than are crops (e.g., *Populus* species and perhaps black cherry; see discussion in Section 5.4.2). Analysis of the shrub and tree data presented in Table 5-25 and discussed above suggests that a 7-h seasonal mean exposure of approximately 0.055 ppm over a 3-mo period would not result in injury to tree seedlings. However, the absence of multiple-year studies, or studies using older, more mature trees, leaves unanswered the question of long-term and cumulative effects.

5.6.4.3 Effects of Ozone on Evergreen Trees

As with hardwoods, little long-term data from controlled studies of evergreen trees were available at the time the literature was reviewed for the previous criteria document (U.S. Environmental Protection Agency, 1986). The 1986 document did point out, however, that studies conducted on eastern white pine on the Cumberland Plateau in Tennessee indicated that ambient O_3 may have reduced the radial growth of sensitive individuals by as much as 30 to 50% annually over a period of 15 to 20 years (Mann et al., 1980). Also, field studies in the San Bernardino National Forest indicated that, over a period of 30 years, O_3 may have reduced the growth in height of ponderosa pine by as much as 25%, radial growth by 37%, and total volume of wood produced by 84% (Miller et al., 1982). Calculations of biomass in these studies were based on apparent reductions in radial growth without standardization of the radial growth data with respect to tree age. Since 1986, studies on the effects of O_3 on evergreen trees have focused primarily on three species or groups: (1) red spruce in the eastern United States, (2) southern pines (loblolly and slash), and (3) western conifers (primarily ponderosa pine). For the most part, the research has been conducted with tree seedlings or saplings and has involved exposures lasting one to four growing seasons. In many cases, the research has concentrated on defining the mode of action of O_3 in conifers and is discussed elsewhere in this document (Section 5.3). Results of studies with evergreen trees are summarized in Table 5-30.

Studies of the response of red spruce to O_3 exposures, regardless of whether they have been conducted in growth chambers (Lee et al., 1990a,b; Patton et al., 1991; Taylor et al., 1986) or in the field (Kohut et al., 1990; Laurence et al., 1993; Thornton et al., 1992) have failed to detect effects on growth of seedlings or saplings, even after exposure to 12-h seasonal means of up to approximately 0.09 ppm (concentrations that are considerably greater than those expected in ambient air) each year for up to 4 years. There was an indication that total nonstructural carbohydrate content was reduced by O_3, which might be an indicator of cumulative stress (Woodbury et al., 1992). However, results of these studies indicate red spruce is tolerant of O_3, at least for exposures of a few years.

Growth of seedlings of loblolly pine (a much faster growing species than red spruce) has been reduced by O_3 under some conditions. In growth chamber experiments, height growth was reduced after exposure to 0.10 ppm for 4 h/day, 3 days/week for 10 weeks, but only in combination with a "control" rain treatment. The effect was not observed in trees that received significant inputs of potential nutrients in simulated rain. Conversely, Tjoelker and Luxmoore (1991) reported a significant reduction in the weight of current year needles following an OTC exposure to O_3 at a 7-h seasonal mean of 0.056 or 0.108 ppm, only in a high-nitrogen treatment.

Table 5-30. A Summary of Studies Reporting the Effects of Ozone on the Growth or Productivity of Evergreen Trees Published Since U.S. Environmental Protection Agency (1986)[a]

Species	Concentration[b]	Duration	Facility[c]	Variable[d]	Effect[e]	Reference
Avocado	0.010 to 0.108 ppm 12-h mean	4 and 8 mo in two growing seasons	OTC in pots	Leaf mass	20 and 61% reduction in leaf mass at 86 and 108 ppb.	Eissenstat et al. (1991a)
Orange	0.010 to 0.108 ppm 12-h mean	4 and 8 mo in two growing seasons	OTC in pots	Leaf mass	No effect.	Eissenstat et al. (1991a)
Orange	0.012 to 0.075 ppm 12-h mean	7 mo/season for 5 years	OTC	Fruit weight	"On" production year: 11 and 31% reduction at 40 and 75 ppb; "off" year: no effect.	Olszyk et al. (1990b)
Ponderosa pine	0.036 to 0.051 ppm 24-h mean	June to August	F	Radial growth rate	No change in growth rate on symptomatic trees.	Peterson and Arbaugh (1988)
Ponderosa pine	0.013 to 0.095 ppm 12-h mean, 0.047 to 0.0350 ppm·h over 3 years	Three growing seasons	OTC	Growth	19.5% reduction at 95 ppb.	Beyers et al. (1992)
Ponderosa pine	0.011 to 0.087 ppm 12-h mean	Three growing seasons	OTC	Leaf weight	70 and 48% loss of 1- and 2-year-old needles at 87 ppb.	Temple et al. (1993)
Ponderosa pine	5, 122, or 169 ppm·h	112 days	OTC in pots	Root growth	43% reduction in coarse and fine nongrowing roots; 50, 65, and 62% reduction in coarse, fine, and new growing roots, respectively.	Andersen et al. (1991)
Ponderosa pine	0.067 to 0.071 ppm 7-h mean	134 days	OTC in pots	Leaf, stem, and root dry weight	20 to 33% reduction from filtered air at 67 ppb.	Hogsett et al. (1989)
Lodgepole pine	0.067 to 0.071 ppm 7-h mean	134 days	OTC in pots	Leaf, stem, and root dry weight	No effect.	Hogsett et al. (1989)
Jeffrey pine	0 to 0.0200 ppm, 4 h/day, 3 days/week	44 and 58 days in two growing seasons	GC	Root, stem, and needles dry weight	Reduced 10 to 20% ppb in 1 year.	Temple (1988)

Table 5-30 (cont'd). A Summary of Studies Reporting the Effects of Ozone on the Growth or Productivity of Evergreen Trees Published Since U.S. Environmental Protection Agency (1986)[a]

Species	Concentration[b]	Duration	Facility[c]	Variable[d]	Effect[e]	Reference
Jeffrey pine	>0.10 ppm	On 34 days of 1985	F	Radial growth	11% reduction in symptomatic trees.	Peterson et al. (1987)
Western hemlock	0.067 to 0.071 ppm 7-h mean	134 days	OTC in pots	Leaf, stem, and root dry weight	11 to 30% reduction at 71 ppb.	Hogsett et al. (1989)
Western red cedar	0.067 to 0.071 ppm 7-h mean	134 days	OTC in pots	Leaf, stem, and root dry weight	No effect.	Hogsett et al. (1989)
Douglas fir	0.067 to 0.071 ppm 7-h mean	134 days	OTC in pots	Leaf, stem, and root dry weight	No effect.	Hogsett et al. (1988)
Giant sequoia	0-0.0200 ppm, 4 h/day, 3 days/week	44 and 58 days in two growing seasons	GC	Root, stem, and needles dry weight	No effect.	Temple (1988)
Red spruce	0.08 to 0.0166 ppm 8-h mean, 8 to 156 ppm·h	135 days	OTC	Scion growth	No effect on juvenile or mature scion growth.	Rebbeck et al. (1992)
Red spruce	0.023 to 0.087 ppm 12-h mean	Two growing seasons	OTC in pots	Dry weight	No effect.	Kohut et al. (1990)
Red spruce	0.120 ppm, 4 h/day, twice per week	4 mo	GC	Growth	No effect.	Taylor et al. (1986)
Red spruce	0, 0.150 ppm, 6 h/day or 150 ppb, 6 h, plus 70 ppb 18 h/day	195 days	GC	Dry weight	No effect.	Patton et al. (1991)
Red spruce	0.025 or 0.100 ppm, 4 h/day, 3 day/week	10 weeks	GC	Growth	No effect.	Lee et al. (1990b)

Table 5-30 (cont'd). A Summary of Studies Reporting the Effects of Ozone on the Growth or Productivity of Evergreen Trees Published Since U.S. Environmental Protection Agency (1986)[a]

Species	Concentration[b]	Duration	Facility[c]	Variable[d]	Effect[e]	Reference
Red spruce	0.027 to 0.054 ppm 12-h mean	Three growing seasons	OTC in pots	Dry weight, diameter, and height	No effect.	Thornton et al. (1992)
Norway spruce	0.080 to 0.100 ppm, 7 to 8 h/day	100 days	GC	Dry weight	0 to 14% reduction vs. filtered air, five provenances.	Mortensen (1990a)
Norway spruce	0.014 to 0.070 ppm 8-h mean	5 to 6 mo in two growing seasons	OTC in pots	Growth	No effect.	Nast et al. (1993)
Norway spruce	0.010- to 0.090-ppm weekly mean	5 years	OTC	Growth	Reduced lateral shoot growth in last year.	Billen et al. (1990)
Sitka spruce	0.05 to 0.170 ppm, 7 h/day, 5 days/week	65 days	GH	Growth and winter hardiness	No effect on growth, reduced winter hardiness.	Lucas et al. (1988)
Silver fir	0.010- to 0.090-ppm weekly mean	5 years	OTC	Growth	Increased dry matter production.	Billen et al. (1990)
Fraser fir	0.020 to 0.100 ppm, 4 h/day, 3/week	10 weeks	GC	Biomass	No effect.	Tseng et al. (1988)
White pine	0.020 to 0.140 ppm, 7 h/day, 3 day/week	3.5 mo	GC	Dry weight	No effect.	Reich et al. (1987)
Loblolly pine	0.021 to 0.086 ppm 7-h mean	96 days	OTC in pots	Dry weight	18% reduction at 86 ppb; 20% reduction in foliage at 40 or 86 ppb.	Adams et al. (1988)
Loblolly pine	0.021 to 0.117 ppm 7-h mean	Three growing seasons	OTC in pots	Growth	No effect on five families.	Adams et al. (1990b)
Loblolly pine	0.022 to 0.094 ppm 7-h mean	Three growing seasons	OTC in pots	Dry weight	4% reduction at 30 to 38 ppm; 8% reduction at 51 to 65 ppm.	Edwards et al. (1992a)
Loblolly pine	0.032 to 0.108 ppm 7-h mean	18 weeks	OTC in pots	Dry weight	20% reduction in needles at 108 ppm.	Tjoelker and Luxmoore (1991)
Loblolly pine	0.023 to 0.090 ppm 12-h mean, 46 to 0.209 max 12-h	150 days	OTC in pots	Growth	10% reduction at 46 ppm.	Shafer et al. (1987)

Table 5-30 (cont'd). A Summary of Studies Reporting the Effects of Ozone on the Growth or Productivity of Evergreen Trees Published Since U.S. Environmental Protection Agency (1986)[a]

Species	Concentration[b]	Duration	Facility[c]	Variable[d]	Effect[e]	Reference
Loblolly pine	0.022 to 0.092 ppm 12-h mean, 37 to 0.143 ppm 1-h max	Three growing seasons	OTC in pots	Dry weight	0 to 13% reduction after 3 years at about 45 to 50 ppm 12-h seasonal mean, depending on family.	Shafer and Heagle (1989)
Loblolly pine	0.007 to 0.166 ppm 12-h mean, 12-h max 248 ppm	245 days	OTC in pots	Foliar weight	35% reduction at 166 ppm.	Qiu et al. (1992)
Loblolly pine	0.007 to 0.132 ppm 12-h mean 17 to 382 ppm·h	Three growing seasons	OTC	Foliage abscission	Initiated above 130 to 220 ppm·h in trees exposed to ambient or above.	Stow et al. (1992)
Loblolly pine	0.021 to 0.137 ppm 12-h mean 60 to 397 ppm·h	241 days	OTC	Shoot growth	Shoot length reduced 30% at 137 ppm.	Mudano et al. (1992)
Loblolly pine	0.020 to 0.137 ppm 12-h mean 0.050 to 0.286 ppm max 12-h mean	Two growing seasons	OTC	Needle retention and fascicle length	Needle retention decreased in elevated ozone—fascicle length reduced by ozone in early flushes, increased in later flushes.	Kress et al. (1992)
Loblolly pine	0 to 0.150 ppm, 5 h/day, 5 days/week	6 to 12 weeks	GC	Dry weight	8% reduction at 150 ppm.	Meier et al. (1990)
Loblolly pine	0 to 0.320 ppm, 6 h/day, 4 days/week	8 weeks	GC	Height and diameter growth	20% reduction in height growth; 36% reduction in diameter growth in three open-pollinated families.	Horton et al. (1990)
Loblolly pine	0 to 0.120 ppm, 7 h/day, 5 days/week	12 weeks	GC	Dry weight	Top dry weight increased up to 60%; root dry weight reduced 6%.	Spence et al. (1990)
Loblolly pine	0 to 0.320 ppm, 8 h/day, 4 days/week	9 weeks	GC	Relative growth rate (RGR)	36% reduction in height RGR; 10% reduction in diameter RGR.	Wiselogel et al. (1991)

Table 5-30 (cont'd). A Summary of Studies Reporting the Effects of Ozone on the Growth or Productivity of Evergreen Trees Published Since U.S. Environmental Protection Agency (1986)[a]

Species	Concentration[b]	Duration	Facility[c]	Variable[d]	Effect[e]	Reference
Loblolly pine	0.020 to 0.100 ppm, 4 h/day, 3 days/week	10 weeks	GC	Dry weight	No effect.	Lee et al. (1990a)
Slash pine	0.076 to 0.104 ppm 7-h mean 0.126 ppm 1-h max 122 and 155 ppm·h	112 days	GC	Top and root dry weight	18% reduction in top dry weight and 39% reduction in root dry weight at 122 ppm·h.	Hogsett et al. (1985a)
Slash pine	200 to 1,000 ppm·h	28 mo	OTC	Litterfall	Twice as much litterfall at ozone above 220 ppm·h.	Byres et al. (1992)
Slash pine	179 to 443 ppm·h 24-h SUM00 multiples of ambient	28 mo	OTC	Leaf area	Reduced up to 33% by 443 ppm·h.	Dean and Johnson (1992)

[a]See Appendix A for abbreviations and acronyms.
[b]Means are seasonal means unless specified. Maximums are 1-h seasonal maxima unless otherwise specified. Cumulative exposures are SUM00 unless otherwise specified, accumulation based on 24 h/day unless otherwise noted.
[c]OTC = open-top chamber with plants in ground unless specified in pots; GC = controlled-environment growth chamber or CSTR; GH = greenhouse; F = field.
[d]The effect reported in the study that is a measure of growth, yield, or productivity.
[e]Effect measured at specified ozone concentration, over the range specified under concentration, or predicted (if specified) to occur based on relationships developed in the experiment.

Multiple-year OTC exposures of loblolly pine have resulted in decreased foliar weight, partly through accelerated abscission, and decreased root surface area in the first year following exposure to a 2.5-times-ambient O_3 treatment (0.10 ppm 12-h seasonal average, 318 ppm·h) (Qiu et al., 1992). In a 2-year study, Kress et al. (1992) found that fascicle length and number of early season needle flushes decreased linearly with increasing O_3, but the reverse was true in flushes produced later in the season. This may occur only in seedlings that produce more than two leaf flushes per year. Foliage retention decreased with O_3, and fewer fascicles were retained on trees exposed to ambient concentrations of O_3 (12-h seasonal mean of 0.045 ppm averaged over 2 years). Shafer and Heagle (1989) exposed seedlings of four families of loblolly pine to O_3 over three growing seasons and, based on their data, predicted growth suppressions of above ground plant parts of 0 to 19% (depending on the sensitivity of the family) at a 12-h seasonal mean of 0.05 ppm, after 2 years; after 3 years, suppressions of 13% were predicted in the most sensitive family. Cumulative effects of multiple-year exposures were not apparent from the above study, but no measures of root growth, which has been reported to be affected in other species (Andersen et al., 1991; Edwards et al., 1992a; Temple et al., 1993), were reported. Edwards et al. (1992a) also conducted a 3-year exposure and found a 4% reduction in whole plant biomass after exposure to a 7-h seasonal concentration of about 0.050 ppm. An 8% reduction was associated with a 7-h concentration of about 0.10 ppm. Growth reductions occurred in both above- and belowground plant parts.

Many studies with loblolly pine have used multiple families with a range of reported tolerance to O_3 (Adams et al., 1988, 1990b; Kress et al., 1992; Qiu et al., 1992; Shafer and Heagle, 1989; Wiselogel et al., 1991). These studies have demonstrated the range of response, from tolerant to sensitive, in the species. Adams et al. (1990b) suggest that resistance to natural stresses, such as drought, may be linked to tolerance to O_3, thereby affecting the response of the species to multiple stresses.

The response of slash pine to O_3 also has been characterized. Dean and Johnson (1992) found leaf area to be reduced by O_3 in all three growing seasons studied, with an intensification of the effect each year at an O_3 exposure of about 0.03 to 0.04 ppm (12-h seasonal means) or 77 to 216 ppm·h (SUM00). Leaf litterfall also was increased by O_3 (Byres et al., 1992a,b). Volume increment of the trees was affected, with an increased sensitivity to simulated acid rain in trees exposed to twice the ambient concentration. Hogsett et al. (1985a) found reduced height (22%), diameter (25%), top (18%), and root growth (39%) in slash pine exposed to a 7-h seasonal mean of 0.076 ppm, with a maximum concentration of 0.094 ppm. From these studies, it is clear that slash pine is relatively sensitive to O_3 on an annual basis.

Hogsett et al. (1989) report the results of exposing five western conifers to O_3 at a seasonal 7-h mean concentration of 0.067 or 0.071 ppm (SUM06 for 134 days was 49.5 and 63 ppm·h, respectively; SUM00 was 140 and 153 ppm·h, respectively). Ponderosa pine and western hemlock had reduced needle, stem, and root dry weight after 134 days of exposure. Douglas fir (*Pseudotsuga menziesii*) and western red cedar (*Thuja plicata* D. Don) were not different from the CF air control, but Douglas fir showed consistent decreases in weight of plant components. Lodgepole pine was not affected by either O_3 treatment. Carry-over effects were observed in bud elongation in the following spring in lodgepole pine, ponderosa pine, and hemlock. Andersen et al. (1991) also observed reduced root dry weight in ponderosa pine after exposure to SUM00 of 122 or 169 ppm·h during a 120-day growing season. In addition, they observed a reduction in the weight of newly formed roots the following spring, possibly due to reduced levels of root starch.

In a 3-year field study, Temple et al. (1993) and Beyers et al. (1992) found that ponderosa pine trees exposed to a 24-h seasonal mean of 0.087 ppm had a 48 and 70% loss of 2- and 3-year-old needles, respectively. Radial stem growth and coarse root growth also were reduced but not as severely as needle weight (due to abscission). After three seasons of exposure, current-year needles in elevated O_3 treatments had a higher photosynthetic performance than those in filtered air. The compensation was apparently due to higher foliar nitrogen in O_3-exposed needles, a product of redistribution of nitrogen before abscission of needles. Cumulative responses would suggest that, eventually, reductions in growth of the trees would occur at lower concentrations of O_3.

A number of field studies have been conducted in North America in which an attempt was made to relate air quality to growth or injury of forest trees. Two field studies have correlated radial growth with visible injury in ponderosa and Jeffrey pine in California (Peterson and Arbaugh, 1988; Peterson et al., 1987). An 11% reduction in radial growth was measured in symptomatic Jeffrey pine, compared to trees that did not show symptoms of O_3 injury, but no reduction could be demonstrated in ponderosa pine; however, the authors point out that the trees they measured were not under competitive stress, which might alter their response.

The response of evergreen trees varies widely, depending on species and genotype within species. It is clear, however, that major forest species, such as ponderosa, loblolly, and slash pine are sensitive to O_3 (depending on length of exposure, based on seedling studies) at or slightly above the concentrations of O_3 (0.04 to 0.05 ppm) that occur over wide areas of the United States. Furthermore, because of the long life span of these trees, including those that have not been reported sensitive to O_3, there is ample opportunity for a long-term, cumulative effect on growth of the trees. Most of the experiments are conducted over only 2% or less of the life expectancy of the tree; an equivalent exposure in field crop plants would be 2 to 3 days. Consideration also must be given to the fact that most of these trees grow as part of mixed forests, in competition with many other species. Small changes in growth might be translated into large changes in stand dynamics, with concomitant effects on the structure and function of the ecosystem.

5.6.5 Assessments Using Ethylene Diurea as a Protectant

A chemical protectant, EDU (*N*-[2-(2-oxo-1-imidagolidinyl)ethyl]-*Ń*-phenylurea), has been used to study the response of plants to O_3 without attempting to control the concentration of the pollutant during the exposure (Table 5-31) (U.S. Environmental Protection Agency, 1986).

Disadvantages of the use of OTCs for assessing the effects of O_3 on the growth of plants include relatively high cost, the need for electrical power, and potential effects of the chambers themselves on the growth of the plants. In many cases, no chamber effects can be detected, and because most studies compare against a control, chamber effects would have a minimal effect on interpretation of results. Although, the number of experiments conducted with OTCs has led to a firm understanding of plant response to a chamber environment, the possibility of interactions with treatment cannot be ruled out. The use of EDU is attractive due to low cost and ease of application; however, it is essential to establish the correct dosage for protection from O_3, without direct effects of EDU on the plant, and an estimate of

Table 5-31. Effects of Ethylene Diurea (EDU) on Ozone Responses[a]

Crop/Species	EDU Application	O_3 Exposure	Effects of EDU	Reference
White bean	Spray to runoff, 2,000 ppm	Field; 34 h > 0.08 ppm	Reduced O_3 injury, 38%; delayed defoliation; increased yield, 24%.	Temple and Bisessar (1979)
	Spray to runoff, 2,000 ppm	Field; hours > 0.08 ppm = 518 ppm·h	Reduced O_3 injury, 20 to 80%; increased yield up to 35%.	Toivonen et al. (1982)
	Soil drench, 500 ppm, 0.5 L/pot	Greenhouse (charcoal-filtered)	No effect on growth.	Brennan et al. (1990)
	Soil drench, 500 ppm, 4 L/6 m row	Field; 78 h > 0.12 ppm (0.2 ppm max)	Reduced O_3 injury up to 50%; retarded maturation.	Brennan et al. (1990)
Corn	Spray to runoff, 500 ppm	Field (no details)	19% yield reduction.	Heggestad (1988)
Cotton	Spray to runoff, 500 ppm	Greenhouse (no details)	Increased yield in nonfiltered air; reduced yield in filtered air.	Heggestad (1988)
Potato	Spray to runoff, 1.1 kg/ha, five applications	Field; > 0.08 ppm on 18 days (0.138 ppm max)	Reduced O_3 injury, 50%; increased tuber weight, 35%.	Bisessar (1982)
	Soil drench, 6.7 kg/ha, four applications	Field; 282 h > 0.08 ppm	Reduced O_3 injury; increased tuber weight, 20 to 30%.	Clarke et al. (1990)
Radish	Soil drench, 100 mg/L, 2 L/m of row	Field; 0 h > 0.1 ppm, hours > 0.05 ppm = 0.76 ppm·h	No response to O_3. Reduced growth rates at low O_3 exposures.	Kostka-Rick and Manning (1992a)
	Soil drench, up to 800 mg/L, 100 mL/pot	Greenhouse, < 0.025 ppm	Increased shoot growth at <300 mg/L; reduced shoot growth at >300 mg/L. Reduced hypocotyl growth at all EDU levels.	Kostka-Rick and Manning (1993)
	Soil drench, up to 400 mg/L, 100 mL/pot	Greenhouse, 0.075 ppm/7 h, 6 days/week, with one weekly peak to 0.14 ppm	Complete protection against O_3 injury at 100 mg/L.	Kostka-Rick and Manning (1993)

Table 5-31 (cont'd). Effects of Ethylene Diurea (EDU) on Ozone Responses[a]

Crop/Species	EDU Application	O_3 Exposure	Effects of EDU	Reference
Radish (cont'd)	Soil drench, 150 mg/L, 60 mL/pot	Greenhouse, 0.07 ppm/7 h, 5 days/week, with two weekly peaks to 0.12 ppm	Reduced O_3 injury, 90 to 100%; less reduction in hypocotyl weight.	Kostka-Rick and Manning (1992b)
Soybean	Soil drench, 500 ppm, 0.5 L/pot	Greenhouse; 0.2 ppm, 6 h/day, 2 days	Reduced O_3 injury, 80 to 90%.	Brennan et al. (1987)
	Soil drench, 500 ppm, 4 L/6 m row	Field; 78 h > 0.12 ppm (0.2 ppm max)	No effect on loss of chlorophyll; no effect on seed weight.	Smith et al. (1987) and Brennan et al. (1990)
Tobacco	Spray to runoff, 1 kg/ha, seven applications	Field; > 0.08 ppm on 2 days	Increased growth, 22%.	Bisessar and Palmer (1984)
Beech	Stem injection 1 g/L; 0.25 mL	OTC; ambient and ambient +0.08 ppm, 8 h/day	No consistent effect.	Ainsworth and Ashmore (1992)
Black cherry	Spray to runoff, 1,000 ppm, seven applications per year	Field; 75 h > 0.08 ppm (over 4 years)	Twofold increase in growth.	Long and Davis (1991)
Other woody species:				
Red maple	Spray to runoff, 500 ppm or soil drench, 500 or 2,000 ppm, 250 mL/pot	Up to 0.95 ppm, 3 h	Reduced O_3 injury.	Cathey and Heggestad (1982)
Paper birch			Reduced O_3 injury.	
White ash			Reduced O_3 injury.	
Honey locust			Reduced O_3 injury.	
Golden-rain			Reduced O_3 injury.	
London plane			Reduced O_3 injury.	
Lilac			Reduced O_3 injury.	
Basswood			Reduced O_3 injury.	

[a]See Appendix A for abbreviations and acronyms.

the level of protection from O_3 achieved (Kostka-Rick and Manning, 1992a,b, 1993). Ethylene diurea is known to be phytotoxic, so studies under controlled O_3 conditions to establish an effective level of protection without phytotoxicity are essential before EDU can be used as an assessment tool.

Previous studies with EDU led to the conclusion, as did experiments with OTCs, that ambient concentrations of O_3 were sufficient to reduce crop yields (U.S. Environmental Protection Agency, 1986). If hourly O_3 concentrations exceeded 0.08 ppm for 5 to 18 days during the growing season, yields of crops might be reduced 18 to 41% (U.S. Environmental Protection Agency, 1986).

Inspection of Table 5-31 shows that in many cases there were clear-cut reductions in O_3-induced injury and increases in yield resulting from the application of EDU. However, the conflicting results for field-grown soybean indicated that, at the rate of EDU application used, no beneficial effects could be demonstrated. Similarly, experiments with corn and cotton suggest that any possible effects of O_3 may have been confounded by direct effects of EDU on growth.

A few studies using EDU have been conducted since 1986. Kostka-Rick and Manning (1992a,b, 1993) conducted studies to determine the direct effects of EDU on growth and to develop an understanding of dose-response to EDU itself. Their studies used EDU and radish (*Raphanus sativus*) in the presence or absence of a controlled O_3 fumigation in a greenhouse and found that the chemical did suppress O_3-induced reductions in belowground plant organs; it also protected the plants from foliar injury. The EDU itself did not cause effects on growth at a concentration of 150 mg L^{-1} applied as a 60-mL drench to each plant, a dosage much lower than often has been used (e.g., Long and Davis, 1991; Smith et al., 1987; discussed below). Kosta-Rick and Manning emphasize that it is essential to establish the appropriate dose for the species under consideration. Armed with this background, the investigators used EDU in a field study and found an O_3-induced decrease in the relative growth rates of sink organs of field-grown radish plants above a threshold level of about 0.052 to 0.058 ppm (7-h daily mean), an exposure that is near ambient O_3 concentrations.

Ethylene diurea also has been used to estimate the effect of O_3 on field-grown soybean in New Jersey (Smith et al., 1987; Brennan et al., 1990). In this case, the researchers did not establish the appropriate dose level for O_3 protection, as was done by Kostka-Rick and Manning. No differences in yield were found, and the authors concluded that O_3 does not impact soybean yield of the tested cultivars in New Jersey. However, they did not demonstrate that EDU was an effective protectant at the concentrations used and on the cultivars grown.

In a similar study, potato yields were measured and related to foliar injury in EDU-treated and nontreated plots over a 4-year period (Clarke et al., 1990). The cumulative O_3 dose ranged from 45 to 110 ppm·h, depending on the year, producing a range of foliar injury from 1 to 75%. The authors found that significant differences in yield between EDU-treated and control plants occurred only when foliar injury on untreated plants was 75% of leaf area. No level of protection, other than from foliar injury, could be assessed.

In a 3-year study of potted green ash, no significant effects on growth were measured using EDU (2 years) or by comparison of filtered and NF air in OTCs (1 year) (Elliot et al., 1987). Foliar injury was observed only late in the season of the first year in the NF chambers.