Table 5-8 title

Table 5-8. Field Studies of Ozone-Drought Stress Interactions in Crop Species[a]
(Adapted in part from Heagle et al., 1988a)

5-62

Crop/Cultivar	Year	Response	Significant Interaction[c]	0.04	0.05	0.06	0.07	0.08	Reference
Soybean									
Williams	1982	Yield	No	7	13	19	24	30	Heggestad et al. (1985) Heggestad and Lesser (1990)
Williams and Corsoy 79	1983	Yield	WW	7	13	18	24	30	
		Yield	DS	6	11	15	19	23	Heggestad and Lesser (1990)
Williams		Root length	WW		No significant O₃ effect				Heggestad et al. (1988)
		Root length	DS		[33	36	52][d]		
Forrest	1982	Yield	WW	3	9	21	39	60	Heggestad et al. (1985)
		Yield	DS	13	21	28	35	41	Heggestad and Lesser (1990)
Davis	1983	Yield DS	WW	4	7	12	16	21	Heagle et al. (1987a)
		Yield DS			No significant O₃ effect				
Davis	1984	Yield	No	4	7	12	18	24	Heagle et al. (1987a)
Corsoy 79	1986	Yield	WW	2	4	8	13	21	Irving et al. (1988)
		Yield	DS	0	0	0	0	1	
Young	1986	Yield	No	6	11	17	25	34	Miller et al. (1989b)
Cotton									
Acala SJ-2	1981	Yield	WW	3	7	13	21	30	Temple et al. (1985)
		Yield	DS	1	2	3	7	12	
Acala SJ-2	1982	Yield	No	6	15	26	40	55	Temple et al. (1985)
McNair 235	1985	Yield	No	7	13	21	30	40	Heagle et al. (1988b)
Acala SJ-2	1986	Shoot dry mass	WW[e]		[22	26	42][f]		Temple et al. (1988b)
		Shoot dry mass	DS[e]		[20	37	44][f]		
		Shoot dry mass	DS (severe)[e]		[+14	+22	27][f]		

Header: Estimated Yield Loss (%) per Seasonal Mean O₃ Concentration (ppm)[b]

Table 5-8 (cont'd). Field Studies of Ozone-Drought Stress Interactions in Crop Species[a]
(Adapted in part from Heagle et al., 1988a)

				Estimated Yield Loss (%) per Seasonal Mean O₃ Concentration (ppm)[b]					
Crop/Cultivar	Year	Response	Significant Interaction[c]	0.04	0.05	0.06	0.07	0.08	Reference
Alfalfa									
WL-514	1984	Yield	No	6	9	13	17	20	Temple et al. (1988a)
WL-514	1985	Yield	No[g]	4	7	10	14	18	
Tall Fescue-Ladino Clover									
Kentucky 31	1984	Yield	No	5	8	12	17	22	Heagle et al. (1989b)
and Regal	1984	Yield	No	6	11	17	24	32	

[a]See Appendix A for abbreviations and acronyms.

[b]Where a significant interaction was observed, separate responses are listed for well-watered (WW) and drought-stressed (DS) plants; otherwise, the pooled response is listed.

[c]Based on Weibull model estimates (Heagle et al., 1988a)

[d]Data presented are percent reductions in root length per soil core at seasonal mean O₃ exposures of 0.074, 0.107, and 0.132 ppm relative to 0.052 ppm. Increased root lengths in DS treatments ranged from 136 to 11% with increasing O₃ exposure.

[e]Interaction not significant by analysis of variance, but significant suppression of O₃ response in DS (severe).

[f]Weibull model data not available. Data presented are actual percent yield losses at seasonal mean O₃ exposures of 0.074, 0.094, and 0.111 ppm relative to 0.015 ppm.

[g]Polynomial regression analysis showed slightly greater response in WW than DS plots.

evidence from tree species to support the view that drought stress may reduce the impact of O_3. However, the work with trees provides no additional information to help in resolving the quantitative nature of the drought-O_3 interaction.

Although drought stress may be the result of insufficient rainfall, conditions of effective SMD also may be induced by excessive soil salinity. Laboratory studies reviewed in the previous criteria document (U.S. Environmental Protection Agency, 1986) showed that increased salinity could reduce the impact of O_3 on injury and yield of various crops. However, in a more recent field study with alfalfa, Olszyk et al. (1988) found no overall interaction between O_3 and salinity on growth or yield. Although salinity decreased the number of empty nodes caused by exposure to above-ambient levels of O_3, the effect was statistically significant only for the second of four harvests. In general, salinity was found to be more harmful to alfalfa growth than exposure to O_3, but, as pointed out by Olszyk et al. (1988), the amount of information available is insufficient to permit the development of models for estimating losses due to O_3-salinity combinations.

The bulk of the available evidence supports the view that drought stress may reduce the impact of O_3 on plants. However, it must be emphasized that, in terms of growth and productivity, any "protective" benefit will be offset by the effects of SMD per se, as noted in the previous criteria document (U.S. Environmental Protection Agency, 1986).

The O_3-water interaction is not confined to the effects of SMD on direct plant response to O_3. Numerous studies have shown that O_3 may affect various aspects of plant water status, including water-use efficiency (WUE), the ratio of the rates of photosynthetic carbon gain and transpirational water loss. For example, Reich et al. (1985) observed that daily exposures to 0.13 ppm O_3 for 6.8 h resulted in a 25% reduction in WUE in well-watered Hodgson soybean, when compared to exposure to 0.01 ppm. Similar findings have been reported for alfalfa (Temple and Benoit, 1988) and radish (Barnes and Pfirrmann, 1992). However, WUE is a complex resultant of both stomatal conductance and the activity of the photosynthetic system, both of which may be independently affected by O_3. Genetic or environmentally induced difference in the relative sensitivities of the stomatal and photosynthetic components will dictate the nature and magnitude of any effect of O_3 on WUE. Thus, with radish and soybean, Greitner and Winner (1988) observed effects on stomatal conductance and photosynthetic CO_2 assimilation that translated into O_3-induced increases in WUE; however, they point out, that this advantageous increase far outweighed the adverse effects of O_3 on growth.

However, these reports concern herbaceous weedy species, and there appears to be only one report concerning tree species. Johnson and Taylor (1989) reported that exposure to higher than ambient levels of O_3 results in adaptation to a more efficient use of water by the foliage of loblolly pine seedlings. The corollary to this observation is that trees exposed continuously to low O_3 levels may be more sensitive to recurrent drought stress than are those grown under higher exposure levels. As with most studies of tree species, these observations were made on tree seedlings, and the relevance to mature trees is still to be established.

It therefore is clear that not only does drought have a pronounced effect on the response of most species to O_3, but that O_3 also may modify plant water relations, including conferring drought tolerance. However, more study will be needed before it will be possible to generalize about the implications of the latter effect and its importance to forest ecosystems.

5.4.5 Nutritional Factors

All land plants require an adequate supply of essential mineral elements from the soil in order to avoid adverse effects on growth and survival resulting from mineral deficiencies. Two of the essential elements needed for growth are nitrogen and sulfur, and although these are normally obtained from the soil through the root system, the plant's needs, at least in part, also can be met by the uptake of pollutant gases such as NO_2 and SO_2. Other nutrients such as phosphorus, potassium, magnesium, and calcium generally are available only from the soil.

A supply of elements such as nitrogen, potassium, phosphorus, sulfur, magnesium, and calcium is essential for plant growth, but optimal growth requires that the supply be balanced; with insufficiency (or excess) of any of them, growth will be suboptimal. Not surprisingly, therefore, nutrient imbalance has been shown to affect response to O_3, although the previous criteria document (U.S. Environmental Protection Agency, 1986) concluded that work to that date had not clarified the relationship between soil fertility and sensitivity to O_3, largely because of the differences in nutrients and species selected for study and the experimental conditions used. This conclusion is still valid, in spite of the results of a limited number of more recent studies, and is not surprising in view of the vast number of possible permutations and combinations of nutrient elements and their levels that may exert effects on O_3 response. A comprehensive summary of the relevant studies is presented in Table 5-9.

Most information concerns nitrogen. However, inspection of Table 5-8 shows that, in four of the 13 studies, increased nitrogen supply increased susceptibility to foliar injury or enhanced adverse effects on growth; two of the studies showed opposite effects; in three studies, injury was greatest at normal nitrogen levels and less at higher or lower levels; and, in one study, injury was least at normal nitrogen levels. No interactions were observed with soil nitrogen in three studies. Knowledge of the tissue nitrogen levels resulting from the fertilizer treatments, as recommended by Harkov and Brennan (1980), might resolve these contradictions, but these were not reported in most studies. The contradictory evidence for tobacco may reflect different responses of different cultivars, as suggested by Menser and Hodges (1967).

The possibilities of response to O_3 being modified as a result of significant dry deposition of nitric acid (HNO_3) vapor or of wet deposition of nitrate ion in acid precipitation are discussed in Sections 5.4.6.3 and 5.4.6.5, respectively.

The limited evidence for phosphorus, potassium, and sulfur consistently indicated a decrease in sensitivity with increased nutrient level. With respect to general fertility, both studies listed in Table 5-8 revealed decreased sensitivity to O_3 at high levels of nutrient supply, although, with soybean, nutrient-deficient plants also showed decreased sensitivity. Heagle (1979) found that, although injury and growth reductions tended to be greatest at normal levels of fertility, the effects were dependent on the rooting medium used; in media containing peat, the impact of O_3 on growth was least at the lowest fertility level.

Cowling and Koziol (1982) have suggested that, in spite of the apparent contradictory evidence regarding the effects of nutrition on O_3 response, there is evidence to support the hypothesis that differences in sensitivity are ultimately linked to changes in the status of soluble carbohydrates in the plant tissues (Dugger et al., 1962). However, this hypothesis has yet to be tested systematically.

Table 5-9. Ozone-Soil Nutrient Interactions
(Based in part on Cowling and Koziol, 1982)[a]

Species	Response to Increase in Nutrient Level	Reference
Nitrogen		
Loblolly pine	Decreased reduction of growth due to O_3	Tjoelker and Luxmoore (1991)
Ponderosa pine	No injury or growth interactions	Bytnerowicz et al. (1990)
Poplar	Maximum injury in mid-range but no growth interaction	Harkov and Brennan (1980)
Yellow poplar	No growth interaction	Tjoelker and Luxmoore (1991)
Ladino clover/tall fescue	No growth interaction	Montes et al. (1982)
Mangel	Increased injury	Brewer et al. (1961)
Radish	Increased reduction of growth due to O_3	Ormrod et al. (1973)
	Increased reduction of growth due to O_3	Pell et al. (1990)
Spinach	Increased injury	Brewer et al. (1961)
Tobacco	Decreased injury	Menser and Street (1962)
	Minimum injury in mid-range	MacDowall (1965)
	Maximum injury in mid-range	Leone et al. (1966)
	Maximum injury in mid-range	Menser and Hodges (1967)
Phosphorus		
Radish	No growth interaction	Ormrod et al. (1973)
Tomato	Increased injury	Leone and Brennan (1970)
Potassium		
Norway spruce	Decreased reduction of CO_2 assimilation due to O_3	Keller and Matyssek (1990)
Pinto bean	Decreased injury	Dunning et al. (1974)
Soybean	Decreased injury	Dunning et al. (1974)
Sulfur		
Bush bean	Decreased injury	Adedipe et al. (1972)
Magnesium		
Loblolly pine	No growth interaction	Edwards et al. (1992b)
General Fertility (nitrogen, phosphorus, and potassium)		
Bush bean	Decreased injury	Heck et al. (1965)
Soybean	Maximum injury and growth reduction in mid-range	Heagle (1979)

[a]See Appendix A for abbreviations and acronyms.

Nutritional nitrogen and sulfur also can be supplied directly to foliage in the form of nitrogen and sulfur oxides. The interactions of these gaseous pollutants with O_3, dealt with in the next section, focus on toxic rather than nutritional effects. However, one example of a beneficial effect concerns N_2O_5. Because N_2O_5 is produced in trace amounts by high-voltage, corona-discharge O_3 generators, it may contaminate O_3 produced from air by such generators for use in studies of effects of O_3 on vegetation, unless the O_3 stream is passed first through a water scrubber. Brown and Roberts (1988) reported that deposition of the nitrate formed by hydration of trace amounts of N_2O_5 in unscrubbed O_3 significantly increased the nitrogen status of the exposed plants, which may have confounded the effects attributed to O_3.

5.4.6 Interactions with Other Pollutants

The concurrent or sequential exposure of vegetation to different gaseous air pollutants has been found to modify the magnitude and nature of the response to individual pollutants. Some of the early work reviewed in the previous criteria document (U.S. Environmental Protection Agency, 1986) on the effects of gaseous pollutant combinations is of academic interest, with little relevance to the present review because of the levels of exposure and the exposure profiles used and the fact that the experimental regimes usually involved concurrent exposures to two or more pollutants repeated daily. Lefohn and Tingey (1984) and Lefohn et al. (1987b) reviewed the patterns of co-occurrence of O_3, SO_2, and NO_2 in urban, rural, and remote sites in the United States for the years 1978 to 1982 and found that co-occurrences were usually of short duration and occurred infrequently. They noted that the most frequent types of co-occurrence were either purely sequential or a combination of sequential and overlapping exposures of short duration. Accordingly, the present review will focus on the evidence from experiments that simulated these naturally occurring patterns of combined exposure or, at least, that used exposure levels in the ranges of those occurring in polluted air. An exception is the co-occurrence of O_3 and PAN, which are both components of photochemical oxidant.

Over the past decade, the effects of pollutant mixtures have been reviewed by Wolfenden et al. (1992), Shriner et al. (1991), Mansfield and McCune (1988), Torn et al. (1987), Lefohn and Ormrod (1984), Reinert (1984), and Runeckles (1984).

5.4.6.1 Oxidant Mixtures

Because of their photochemical origins, elevated levels of O_3 and PAN can occur simultaneously. There appear to have been no further investigations of the effects of simultaneous or sequential exposures since the limited number of studies reviewed in the previous criteria document (U.S. Environmental Protection Agency, 1986). Hence, there is no reason to question the general conclusion, based on the work of Tonneijck (1984) and Nouchi et al. (1984), that the two gases tend to act antagonistically in both concurrent and sequential exposures. Hydrogen peroxide (H_2O_2) is also a component of photochemically polluted atmospheres. Although Ennis et al. (1990) reported reduced stomatal conductances in red spruce needles exposed to a mixture of O_3, SO_2, and H_2O_2, no studies have been made of O_3/H_2O_2 interactions.

5.4.6.2 Sulfur Dioxide

Because SO_2 originates from point sources of combustion, the occurrence of high ambient concentrations at a given location is usually episodic because of its dependence on wind speed and direction and the distance from the source. However, aggregations of point sources can lead to more widespread but less marked increases in ambient SO_2 levels. Thus, the potential exists for elevated O_3 exposures to be superimposed on patterns of SO_2, ranging from severe fluctuations to almost steady low-level concentrations. Concern over the importance of O_3-SO_2 interactions dates from the observations of Menser and Heggestad (1966) that simultaneous exposures of tobacco to SO_2 and O_3 acted synergistically (i.e., the effects of the mixture were greater than the sum of the responses to either pollutant alone). Indeed, in the Menser and Heggestad study, foliar injury was found to result from exposure to mixtures, although exposures to either gas alone at the same concentrations as in the mixtures did not result in injury.

Although much of the early work was concerned with foliar injury responses to simultaneous exposures to high levels of O_3 and SO_2, more recent studies have tended to focus on the consequences of growth and yield of repeated exposures to lower level mixtures or sequences. Several studies have been aimed at obtaining statistical evidence for the existence of interactions. For example, Ashmore and Onal (1984), studying six cultivars of barley, found that SO_2 at 0.065 ppm for 6 h, an exposure that induced no adverse effects, acted antagonistically to a 6-h exposure to 0.18 ppm O_3, causing significant decreases in foliar injury, ranging from 46% to as much as 95%. However, only one cultivar, Golden Promise, showed a significant interaction on yield, with SO_2 completely reversing the decrease caused by O_3 alone. The results could not be explained by effects on stomatal uptake because stomatal conductances were found to be highest in the mixture. In contrast, with pea, Olszyk and Tibbitts (1981) reported that O_3 + SO_2 caused the same degree of stomatal closure as SO_2 alone. An antagonism similar to that observed on Golden Promise also was observed in field studies of Arena barley (Adaros et al., 1991a) and spring rape (*Brassica napus*) (Adaros et al., 1991b). However, with Tempo spring wheat, a synergistic interaction was observed: the adverse effect of O_3 on yield (-26%) was increased to -38% by SO_2, which, by itself, only reduced yield by 7% (Adaros et al., 1991a). On the other hand, neither Amundson et al. (1987) nor Kohut et al. (1987) observed any interaction in a field study with Vona winter wheat. Irving et al. (1988) observed no interaction on field corn.

In a series of experiments in which exposure to O_3 or an O_3/SO_2 mixture was preceded by exposures to SO_2 alone, an antagonistic response was observed on foliar injury to white bean (Hofstra and Beckerson, 1981). In contrast, the responses of cucumber (*Cucumis sativus*) and radish were synergistic, whereas there was no interaction on soybean or tomato. However, when followed by exposure to an O_3/SO_2 mixture, SO_2 pretreatment resulted in an increase in injury to white bean, decreases in cucumber and tomato, and no effect on soybean and radish.

Field studies with soybean using an air-exclusion system to provide a range of exposures to O_3 and SO_2 at ambient and subambient levels revealed an antagonistic interaction on yield at low concentrations (Jones et al., 1988). However, Kress et al. (1986) found no interaction in a soybean field study using OTCs. No interactions were found with potato (Pell et al., 1988) or with a red clover-timothy (*Phleum pratense*) forage mixture (Kohut et al., 1988b).

From the foregoing, it is apparent that no clearer pattern of the interactive effects of O_3 and SO_2 on crops has emerged since the previous criteria document (U.S. Environmental Protection Agency, 1986). The same is true for the responses of tree species.

With tree seedlings, Chappelka et al. (1988a) observed no interaction on white ash. Although a synergistic interaction was found on root growth of yellow poplar (Chappelka et al., 1985), only additive interactions were found on the growth of other parts of the plant. In a unique study, Kargiolaki et al. (1991) noted that SO_2 reduced the accelerated leaf senescence caused by O_3 on two poplar clones, but had no effect on other clones. They also observed additive or less than additive interactions on the formation of intumescences, due to hypertrophy of the stems and bark cracking. They attributed the differences in clonal response to differences in the levels of pollutant-induced ethylene evolution.

Sulfur dioxide reversed the inhibition of photosynthesis caused by exposure to O_3 in two lichen species, *Flavoparmelia caperata* and *Umbilicaria mammulata* (Eversman and Sigal, 1987).

Several studies have attempted to quantify the magnitudes of joint responses to O_3 and SO_2. The earliest (Macdowall and Cole, 1971) showed that the synergistic injury response of tobacco occurred at concentrations of SO_2 less than the threshold for SO_2 injury, but not less than the O_3 threshold. Oshima (1978), working with kidney bean, found that the synergistic reduction due to intermittent exposures to O_3 was linear through a range of O_3 concentrations achieved by varying degrees of filtration of ambient air (expressed as 10 to 90 ppm-h of concentrations greater than zero), although the threshold for an O_3 response was approximately 47 ppm-h.

A selection of statistical models of injury- or yield responses to O_3/SO_2 is listed in Table 5-10. It is immediately apparent that the models reveal no consistent patterns of response. In part, this is because they were developed on the basis of individual experiments conducted under different environmental conditions at different locations in different years. Although each model was statistically significant, it was based on a unique data set. One study with soybean indicated an antagonistic interaction (Heagle et al., 1983b), but another indicated no interaction (Kress et al., 1986). Cucumber (Hofstra et al., 1985) and snap bean (Heggestad and Bennett, 1981) were reported to respond synergistically, whereas white bean responded antagonistically (Hofstra et al., 1985).

All that can be concluded from these studies is that the type of interaction, and whether or not one exists, is probably highly dependent on species and cultivar, and possibly dependent on other environmental variables. The available evidence is insufficient to be able to decide in which way, and to what extent, SO_2 exposure will influence the effects of O_3 on a particular species or cultivar at a particular location. The synergism originally observed (Menser and Heggestad, 1966) is not a general response.

5.4.6.3 Nitrogen Oxides, Nitric Acid Vapor, and Ammonia

As discussed in Chapter 3, the photochemical formation of O_3 involves a complex series of reactions in which NO, NO_2, and HNO_3 participate as intermediates or reaction products. Of these, the limited number of reports of interactive effects with O_3 is confined to NO_2. Some of the few studies of O_3/NO_2 interactions that have utilized realistic concentrations have involved mixtures of the pollutants. Adaros et al. (1991a) found in a 2-year study of two cultivars each of barley and spring wheat that significant interactions could be detected only on wheat yield in one growing season. With both cultivars, the

Table 5-10. Some Statistical Models of Combined Ozone and Sulfur Dioxide Responses[a]

Species	Type of Interaction	Model	Reference
Corn			
Golden Jubilee	Synergistic	Injury = −11.39 + 5.471ln(IHT) − 9.59[O_3] + 11.81[SO_2] − 86.63[SO_2]^2 + 428.95[O_3][SO_2] (IHT = initial plant height, used as a covariate; [O_3] and [SO_2], ppm)	Deveau et al. (1987)[b]
Cucumber			
National Pickling	Synergistic	Injury = 2.70 + 1.95 n; at [SO_2] = 0.10 ppm Injury = 2.40 + 0.21 n; at [SO_2] = 0.05 ppm Injury = 2.39 + 0.39 n; at [SO_2] = 0.03 ppm Injury = 1.86 + 0.166 n; at [SO_2] = 0.02 ppm (n = number of daily 8-h SO_2 exposures; O_3 exposure, 0.15 ppm, 6 h)	Hofstra et al. (1985)
Snap Bean			
Maple Arrow	Additive; no interaction	Injury = 4.44 + 34.19[O_3] + 19.98[SO_2]([O_3] and [SO_2], ppm)	Deveau et al. (1987)[b]
White Bean			
Seafarer	Antagonistic	Injury = 6.31 − 0.90 n; at [SO_2] = 0.10 ppm Injury = 5.95 − 0.45 n; at [SO_2] = 0.05 ppm (n = number of daily 8-h SO_2 exposures; O_3 exposure: 0.15 ppm, 6 h)	Hofstra et al. (1985)
Potato			
Norchip	Additive; no interaction	Yield = 1.27 − 0.0037[O_3] + 0.00092[SO_2] (Yield = number of Grade No. 1 tubers per plant; [O_3]: ppm, 10 h/day seasonal mean; [SO_2], ppm, 3 h/day)	Pell et al. (1988)
Soybean			
Davis	Antagonistic	Polynomial model: Yield = 534.5 − 3988.6[O_3] − 479.7[SO_2] + 2661.0[O_3][SO_2] + 1,0960[O_3]^2 Weibull model: Yield = 531 × exp[−([O_3]/0.133)] × exp[−([SO_2]/0.892)] (Yield = g/m of row; [O_3]: ppm, seasonal 7 h/day mean; [SO_2]: ppm, seasonal 4 h/day mean)	Heagle et al. (1983b)
Amsoy-71 and Corsoy-79 (pooled)	No interaction	Yield = 1934.4*exp[−([O_3]/0.124)$^{2.666}$]* exp[−([SO_2]/1.511)$^{1.044}$] (Yield = kg/ha; [O_3]: ppm, seasonal 7 h/day mean; [SO_2]: ppm, seasonal 4 h/day mean)	Kress et al. (1986)

Table 5-10 (cont'd). Some Statistical Models of Combined Ozone and Sulfur Dioxide Responses[a]

Species	Type of Interaction	Model	Reference
Tomato			
New Yorker		Injury = $-75.78 + 20.48\ln[PI] - 29.16[O_3] + 1,016[O_3]^2 + 9.02[SO_2] - 17.29[SO_2]^2 + 258.76$ $[O_3][SO_2]$ (PI = plastochron index, used as a covariate; $[O_3]$ and $[SO_2]$: ppm)	Deveau et al. (1987)[b]

[a]See Appendix A for abbreviations and acronyms.
[b]Report includes models for other growth variables.

interaction was antagonistic. Nitrogen dioxide also reduced the adverse effect of O_3 on the yield of spring rape (Adaros et al., 1991b). Foliar injury to sunflower (*Helianthus annuus*) caused by daily exposures to O_3 (0.1 ppm, 8 h) was increased by continuous exposure to 0.1 ppm NO_2 (Shimizu et al., 1984). Plant dry weight was decreased by $O_3 + NO_2$ relative to growth in O_3 alone, but because O_3 exposure resulted in a slight increase in dry weight relative to the controls, the growth in the mixture and in the controls did not differ significantly.

The results of a study of seven tree species exposed to 0.1 ppm O_3 and/or 0.1 ppm NO_2 for 6 h/day for 28 days (Kress and Skelly, 1982) were reported in detail in the previous criteria document (U.S. Environmental Protection Agency, 1986). However, although several growth interactions were noted in the review, the only statistically significant effect was on top growth of pitch pine (*Pinus rigida*), in which NO_2 reversed a growth stimulation caused by exposure to O_3. In contrast, although Yang et al. (1982) also observed an antagonistic interaction on the needle dry weights of two eastern white pine clones, in these cases NO_2, reversed the adverse effect of O_3.

There appear to have been only three studies using sequential exposures of O_3 and NO_2. Runeckles and Palmer (1987) exposed radish, wheat, bush bean, and mint (*Mentha piperita*) daily to 0.08 to 0.1 ppm NO_2 for 3 h (0900 to 1200 hours), to 0.08 to 0.1 ppm O_3 for 6 h (1200 to 1800 hours), or to the two gases in sequence. With each species except mint, pretreatment with NO_2 significantly modified the growth responses to O_3. In radish and wheat, the two gases acted conjointly to reduce growth more than O_3 alone, whereas in bean NO_2 was antagonistic. In studies with tomato, Goodyear and Ormrod (1988) found that sequential exposure to 0.08 ppm O_3 for 1 h, followed by 0.21 ppm NO_2 for 1 h, significantly reduced growth. No significant effects were found when the sequence was reversed or the two gases were used as a mixture. However, because the study did not include a treatment with O_3 alone, no information was obtained as to how NO_2 may have influenced the response to O_3. Bender et al. (1991) exposed kidney beans in OTCs in the field to the sequence: O_3 (0800 to 1600 hours, ambient + 0.50 ppm) followed by NO_2 (1600 to 0800 hours, ambient + 0.3 ppm), during two growing seasons. No significant treatment effects on growth were observed in 1988, but in 1989 a significant interaction on total plant biomass was noted after 48 days; the overnight NO_2 exposures negated the inhibition caused by O_3 with a change from -32 to $+14\%$, relative to the controls. This type of response is similar to that observed on bean by Runeckles and Palmer (1987).

With such limited information, it is not possible to generalize, particularly because antagonistic and additive responses have been reported even for individual species. However, because, on a daily basis, changes in NO_2 levels tend to lead to maxima at times when O_3 levels are lowest, the evidence is sufficiently compelling to indicate that modifications of the O_3 response, as a result of increased NO_2, are highly probable. Direct interactive effects of O_3 and NO virtually are precluded because of their rapid reaction to form NO_2.

In Southern California, O_3 levels have been correlated with levels of HNO_3 vapor (Fenn and Bytnerowicz, 1993). No studies of possible interactive effects between O_3 and HNO_3 have been reported. However, Taylor et al. (1988a) suggest that HNO_3 is largely deposited on foliar surfaces and, hence, may be leached to the soil by rainfall. Such leaching, together with rates of dry deposition to soil that have been conservatively estimated to range between 5.7 and 29.1 kg nitrogen ha^{-1} year^{-1}, would lead to nitrogen additions to the soil at rates considerably less than agricultural rates of nitrogen-application to crops. However, such

additions to forest soils could increase nitrogen levels significantly and lead to interactive effects with O_3 via changes in soil fertility, as discussed in Section 5.4.5.

Ammonia (NH_3) can contribute significantly to total nitrogen deposition in some locations. However, virtually nothing is known of its interactive effects with O_3. Tonneijck and van Dijk (1994) reported that, although NH_3 and O_3 showed a significant antagonism with regard to foliar injury of O_3-sensitive bean cv. Pros, no interactions occurred with regard to growth effects.

5.4.6.4 Hydrogen Fluoride and Other Gaseous Pollutants

The adverse effects of HF released from the aluminum smelting process and superphosphate fertilizer manufacture are well documented, but information about possible HF/O_3 interactions are limited to a single study. MacLean (1990) reported that exposures of corn plants on alternate days to 4 h at $1\mu g/m^3$ fluorine as HF or 0.06 ppm O_3 showed reduced rates of senescence, compared with plants exposed only to O_3.

5.4.6.5 Acid Deposition

Any impact that acid deposition has on crops or natural ecosystems occurs either through direct effects on foliage or indirectly through the soil. Soil effects may result from a change in pH or to the deposition of sulfate or nitrate onto the soil. The effects of acidic deposition have been reviewed extensively by Shriner et al. (1991). Although concerns over the possible role of exposures to acid rain or acid fog and O_3 in the forest-decline syndrome led to several studies with forest tree species, studies also have been conducted on crops. Of over 80 recent reports of studies on over 30 species, more than 75% of the reports indicated no significant interactions between O_3 and acidity of simulated acid rain (SAR) or acid fog. The reports are summarized in Table 5-10. In 63 studies, there was either no effect of one or other of the pollutants (usually acid rain) or the effects of both pollutant stresses were simply additive.

However, in other studies, statistically significant interactions have been reported for several species, as also shown in Table 5-11. For example, although a large number of studies of loblolly pine revealed no interaction, Qiu et al. (1992) reported significant interactions on foliar and stem and root biomass with seedling trees of an O_3-sensitive family. However, because the study failed to show a significant main effect of acidity of the SAR, the authors question whether the interaction is meaningful.

With Norway spruce, antagonistic interactions were noted on stomatal conductance (Barnes et al., 1990a) and dark respiration (Barnes et al., 1990b). In contrast, Eamus and Murray (1991) reported greater than additive effects of O_3 and acid mist on photosynthetic rates. However, no interactions were noted in nine other investigations (Table 5-11).

Kohut et al. (1990) observed significant interactions on needle and shoot growth of red spruce. In both cases the inhibition caused by O_3 and SAR at pH 5.1 was reversed by more acidic rain at pH 3.1. However, there were unexplained inconsistencies in the trends because the combination of intermediate O_3 levels and low pH resulted in the greatest reductions in dry matter. Percy et al. (1992), also working with red spruce, observed an unexplained statistically significant interaction on the thickness of the needle epidermal cell cuticular membrane: at intermediate O_3 exposures, increased acidity led to reduced membrane thickness, whereas lower or higher O_3 levels led to thicker membranes.

Shelburne et al. (1993) reported that, in two growing seasons, needle biomass of shortleaf pine (*Pinus echinata*) was reduced significantly in tree seedlings receiving the

Table 5-11. References to Reports of Interaction or No Interaction Between Ozone and Acid Rain or Acid Fog

Species	No.	Interaction References	No.	No Interaction References
Tree Species				
CONIFERS				
Jeffrey pine	0	—	1	62
Loblolly pine	1	41	13	1, 10, 16-21, 26, 32, 43, 47, 49, 55
Ponderosa pine	0	—	2	65, 66
Shortleaf pine	1	52	1	8
Slash pine	2	9, 13	0	—
White pine	1	47	3	44, 46, 56
Douglas fir	0	—	1	25
Norway spruce	1	3, 4	9	2, 5-7, 15, 24, 30, 36, 50
Red spruce	2	31, 39	5	33, 34, 38, 40, 62
Sequoia	1	63	0	—
Totals	9		35	
HARDWOODS				
Green ash	0	—	1	23
White ash	0	—	1	23
European beech	1	14	1	35
Paper birch	1	29	0	—
Sugar maple	0	—	2	44, 45
Red oak	0		2	44, 45
Yellow poplar	3	11, 12, 27	1	48
Totals	5		8	
Crop Species				
FORAGES AND FIELD CROPS				
Alfalfa	1	59	4	42, 53, 59, 64
Sorghum	1	51	0	—
Soybean	1	67	4	28, 37, 53, 57
Wheat	0	—	1	53
Totals	2		5	
HORTICULTURAL CROPS				
Snap bean	0	—	1	53
Celery	0	—	1	60
Corn	0	—	1	60
Pepper	0	—	2	58, 60

Species	No.	Interaction References	No.	No Interaction References
HORTICULTURAL CROPS (cont'd)				
Strawberry	0	—	2	60, 61
Tomato	0	—	2	53, 60
Avocado	1	22	0	—
Citrus	1	22	0	—
Totals	2		9	
Others				
Ivy	0	—	1	30
Lichen (Lobaria)	0	—	1	54
Totals	0		2	
TOTALS	19		63	

References:
1. Adams and O'Neill (1991). 2. Barnes and Brown (1990). 3. Barnes et al. (1990a). 4. Barnes et al. (1990b). 5. Blank et al. (1990a). 6. Blank et al. (1990b). 7. Blaschke and Weiss (1990). 8. Boutton and Flagler (1990). 9. Byres et al. (1992a,b). 10. Carter et al. (1992). 11. Chappelka et al. (1985). 12. Chappelka et al. (1988b). 13. Dean and Johnson (1992). 14. Eamus and Murray (1991). 15. Ebel et al. (1990). 16. Edwards and Kelly (1992). 17. Edwards et al. (1990b). 18. Edwards et al. (1991). 19. Edwards et al. (1992a). 20. Edwards et al. (1992b). 21. Edwards et al. (1992c). 22. Eissenstat et al. (1991b). 23. Elliott et al. (1987). 24. Führer et al. (1990). 25. Gorissen et al. (1991b). 26. Hanson et al. (1988). 27. Jensen and Patton (1990). 28. Johnston and Shriner (1986). 29. Keane and Manning (1988). 30. Kerfourn and Garrec (1992). 31. Kohut et al. (1990). 32. Kress et al. (1988). 33. Laurence et al. (1989). 34. Lee et al. (1990b). 35. Leonardi and Langebartels (1990). 36. Magel et al. (1990). 37. Norby et al. (1986). 38. Patton et al. (1991). 39. Percy et al. (1992). 40. Pier et al. (1992). 41. Qiu et al. (1992). 42. Rebbeck and Brennan (1984). 43. Reddy et al. (1991a,b). 44. Reich and Amundson (1985). 45. Reich et al. (1986b). 46. Reich et al. (1987). 47. Reich et al. (1988). 48. Roberts (1990). 49. Sasek et al. (1991). 50. Senser (1990). 51. Shafer (1988). 52. Shelburne et al. (1993). 53. Shriner and Johnson (1987). 54. Sigal and Johnston (1986). 55. Somerville et al. (1992). 56. Stroo et al. (1988). 57. Takemoto et al. (1987). 58. Takemoto et al. (1988a). 59. Takemoto et al. (1988b). 60. Takemoto et al. (1988c). 61. Takemoto et al. (1989). 62. Taylor et al. (1986). 63. Temple (1988). 64. Temple et al. (1987). 65. Temple et al. (1992). 66. Temple et al. (1993). 67. Troiano et al. (1983).

highest O_3 exposures ($2.5 \times$ ambient) and SAR at pH 3.3. However, there were no effects at lower O_3 exposure levels or at higher pHs.

A 3-year study of slash pine revealed a significant interaction on stem volume increment in each year (Dean and Johnson, 1992). This was attributed to a high rate of increase observed with increasing acidity in trees exposed to an intermediate O_3 level ($2 \times$ ambient). In contrast, at higher or lower O_3 exposures, acidity of the SAR applied had little effect. Although another study with slash pine indicated a significant interaction on photosynthetic rates, no information was provided about its nature (Byres et al., 1992b).

The mineral status (potassium, calcium, and manganese) of white pine showed antagonistic interactions between O_3 and SAR (Reich et al., 1988). Increased acidity nullified

the increase in foliar potassium and the decreases in root calcium caused by O_3, whereas increased O_3 nullified the increase in root manganese that resulted from increased acidity.

Temple (1988) reported a synergistic response to O_3 and SAR of root growth of giant sequoia. Yellow poplar showed no interactions in one study (Table 5-11), but a greater than additive response of root growth was observed by Chappelka et al. (1985). Chappelka et al. (1988b) found that, although neither O_3 nor the pH of SAR caused any significant effects on growth, at intermediate O_3 levels, increased acidity caused significant decreases in stem and leaf biomass. Jensen and Patton (1990), on the other hand, reported significant antagonistic interactions on yellow poplar leaf and shoot growth. Based on estimates from growth models derived from experimental data, increased acidity (pH 5.5 to 3.0) of SAR reduced the decreases caused by O_3 by almost 50%.

Adverse effects of O_3 on the leaf area and shoot, leaf, and root biomass of paper birch (*Betula papyrifera*) were reversed by increased acidity of SAR (Keane and Manning, 1988). Similarly, in both avocado and lemon (*Citrus volkameriana*) trees, Eissentstat et al. (1991b) found that increased acidity offset the negative effects of O_3 on leaf growth.

Although there are four reports of no interactions on alfalfa, Takemoto et al. (1988b) observed significant interactions on leaf drop. In charcoal-filtered air, leaf drop increased by a factor of 6 as the pH of the fog treatment changed from 7.24 to an extremely acid pH 1.68, the lowest level recorded in the field in Southern California. In unfiltered air, in contrast, leaf drop increased only 20%.

Several studies with soybean revealed no significant interactions. However, Troiano et al. (1983) reported a 42% reduction in seed yield between CF and unfiltered air with SAR at pH 2.8 versus a 6% reduction at pH 4.0. Increased acidity thus multiplied the effect of O_3, due largely to a stimulation of seed yield caused by increased acidity. Shafer (1988) observed a stimulation of shoot growth of sorghum at pH 2.5 of SAR over growth at pH 5.5, as a result of which, greater growth occurred at low O_3 exposure levels, although there was no effect of acidity at the highest O_3 level (0.3 ppm).

In summary, although the majority of studies have not demonstrated the existence of interactions between O_3 and SAR, where statistically significant interactions on growth or physiology have been reported, the interactions were mostly antagonistic. The only synergistic interactions reported are in two studies of yellow poplar and single studies of sequoia and shortleaf and slash pines. In most cases where significant interactions were noted, the authors have had difficulty in providing any mechanistic explanation. It appears that, although the effects may have passed normally accepted tests of statistical significance, they may nevertheless have been spurious findings. Overall, it appears that exposure to acidic precipitation is unlikely to result in significant enhancement of the adverse effects of O_3 in most species. In the few cases of antagonistic interactions, the suggestion was made that these may have reflected a beneficial fertilizer effect due to the nitrate and sulfate present in the SAR applied.

The preceding review has focused on interactive effects of O_3 and wet hydrogen ion deposition. With regard to the anionic constituents of acid deposition, studies with SAR have tended to use dilute mixtures of nitric and sulfuric acids, together with other anions and cations, to achieve the desired pH levels. However, no studies appear to have been undertaken to separate any interactive effects of the individual cations (nitrates or sulfates) from those involving hydrogen ions. However, given the limited and variable information on interactive responses of O_3 and nitrogen and sulfur as soil nutrients, it is not possible to

predict the nature of any possible interactions of O_3 with the wet deposition of these elements.

5.4.6.6 Heavy Metals

Interactions of O_3 with several heavy metal pollutants were reviewed in the previous criteria document (U.S. Environmental Protection Agency, 1986). The limited data for pollutants such as cadmium, nickel, and zinc almost invariably showed that they enhanced the adverse effects of O_3, usually additively, but occasionally more than additively. To the results with cadmium, nickel, and zinc on garden cress (*Lepidium sativum*), lettuce (*Lactuca sativa*), pea, tomato, and aspen, reviewed at that time, should be added similar findings with zinc on pinto bean (McIlveen et al., 1975); increased zinc results in significantly increased foliar injury and decreased mycorrhizal infection. However, in a study of the effects of O_3, nickel, and copper on tomato, Prokipcak and Ormrod (1986) found that, as the levels of both O_3 and nickel increased, the interaction changed from additive to less than additive. Complex interactions were observed when the treatments included both nickel and copper.

No information appears to be available about possible interactions with lead. Although qualitatively heavy metals appear to increase plant sensitivity to O_3, the limited information available precludes defining any quantitative relationships.

5.4.6.7 Mixtures of Ozone with Two or More Pollutants

Pollutant-pollutant interactions are not limited to mixtures or sequences of two pollutants. Several studies have been made of interactions of O_3 with various combinations of SO_2, NO_2, and acid rain. However, in some of these investigations, no treatment with O_3 was included in the experimental design, and, therefore, no information was obtained on effects in response to O_3. Some studies using only repeated daily exposures to high levels (>0.3 ppm) of one or more pollutants are excluded from this review.

Adaros et al. (1991b), in a field study of spring rape using open-top chambers, found no significant interactions between O_3 and NO_2 (sequential exposures) and SO_2 (continuous exposures). In a 2-year study on spring barley and spring wheat, some statistically significant interactions were noted, but they were scattered through the different growth measurements, cultivars, and years with no consistent pattern (Adaros et al., 1991c). Additive effects with no interactions were observed in studies of shore juniper (*Juniperus conferta*) (Fravel et al., 1984), radish (Reinert and Gray, 1981), and azalea (*Rhododendron* spp.) (Sanders and Reinert, 1982). Yang et al. (1982) reported a less than additive interaction on injury to white pine.

No significant three-way interactions were found in studies of soybean (Norby et al., 1985), yellow poplar (Chappelka et al., 1985, 1988b), or any other hardwood species (Davis and Skelly, 1992a; Jensen and Dochinger, 1989; Reich et al., 1985) exposed to O_3, SO_2, and SAR.

No information was collected on interactions in the few published studies involving O_3, SO_2, NO_2, and SAR.

The limited data make it difficult to draw any firm conclusions, but, in general, the consequences of such exposures appear to be dictated largely by the dominant individual two-way interaction.

5.4.7 Interactions with Agricultural Chemicals

Agricultural chemicals are used for the control of insect pests, diseases, and weeds and for the control of growth in specialized situations, such as the selective thinning of fruit on orchard trees. The potential for some agricultural chemicals to modify plant response to O_3, first noted with certain fungicides on pinto beans (Kendrick et al., 1954), led to numerous field and laboratory studies. As noted in the previous criteria document (U.S. Environmental Protection Agency, 1986), protection against O_3 injury was found to be conferred by applications of numerous commercial fungicides, herbicides, and growth regulators.

The available information is derived from studies involving a number of different commercial chemicals and species. No comprehensive and systematic studies have been reported, but the weight of evidence indicates that certain fungicides are consistent in providing protection. In particular, there have numerous reports of protection conferred by applications of benomyl (benlate; methyl-1-[butylcarbamoyl]-2-benzimidazolecarbamate). In addition to the studies reviewed in the previous criteria document (U.S. Environmental Protection Agency, 1986), benomyl protection of grape (Musselman and Taschenberg, 1985) and bean cultivars (Pell, 1976; Pellisier et al., 1972) also has been reported. It is of interest to note that, although several nematocides were found to increase sensitivity of tobacco and pinto bean to O_3, applications of benomyl overcame this response and conferred resistance (Miller et al., 1976). However, benomyl was found to increase the injury caused by PAN (Pell and Gardner, 1979). It also should be noted that many of the effective fungicides are carbamates and have been used as antioxidants in other applications, such as rubber formulations.

The need to distinguish between protective action against O_3 injury and fungicidal activity per se is shown by a study of fentin hydroxide (Du-Ter; tetraphenyltin hydroxide) on potato (Holley et al., 1985). The fungicide reduced foliar injury in the field and also the colonization of injured leaf tissue by the early blight fungus, *Alternaria solani*. However, yield increases appeared to result from the reduction of disease rather than from diminished O_3 injury.

The triazoles are a family of compounds with both fungicidal and plant growth regulating properties. Fletcher and Hofstra (1985) reported on the protective action of triadimefon [1-(4-chlorophenoxy)-3,3-dimethyl-1-(1H-1,2,4-triazo-1-yl)-2-butanone], and Musselman and Taschenberg (1985) found that triadimefon and the triazole, etaconazole (1-[(2,4-dichlorophenyl)-4-ethyl-1,3-dioxolan-2-yl]methyl-1H-1,2,4-triazole), were as effective as benomyl in protecting grape from oxidant injury; cultivar differences were noted, with the fungicides being more effective on Concord than on Ives foliage. Seed treatment with triazole S-3307 ([E]-1-[4-chlorophenoxy]-3,3-dimethyl-2-[1,2,4-triazol-1-yl]- 1-penten-3-ol) resulted in a 50% reduction in the size of wheat plants but provided complete protection from an excessive exposure to 0.5 ppm O_3 for 6 h that resulted in severe necrosis on the leaves of untreated plants (Mackay et al., 1987).

A range of commercial plant growth regulating compounds was studied by Cathey and Heggestad (1972). The plant growth retardants, CBBP (Phosfon-D; 2,4-dichloro-benzyltributyl phosphonium chloride) and SADH (Alar®; succinic acid, 2,2-dimethyl-hydrazide) and several of its analogs, were found to be more effective than benomyl in reducing O_3 injury on petunia.

Conflicting reports of the effects of herbicide-O_3 interactions were reviewed in the previous criteria document (U.S. Environmental Protection Agency, 1986). Recent studies of

metolachlor (2-chloro-*N*-[2-ethyl-6-methlphenyl]-*N*-[2-methoxy-1-methylethyl] acetamide) (Mersie et al., 1989) and atrazine (2-chloro-4-ethylamino-6-isopropylamino-*s*-triazine) (Mersie et al., 1990) revealed species-dependent effects: metolachlor sensitized corn to O_3 but offered protection to bean and soybean. The effects of atrazine on corn were additive to those induced by exposure to 0.2 ppm O_3 for 6 h/day, twice weekly, for three weeks, but antagonistic to exposures to 0.3 ppm. Mersie et al. (1990) also observed a protective action of the commercial antioxidant, *n*-propyl gallate, on corn.

In spite of reports to the contrary (Teso et al., 1979), Rebbeck and Brennan (1984) found that the insecticide, diazinon (O,O-diethyl-O-[2-isopropyl-4-methyl-6-pyrimidinyl] phosphorothioate), did not protect alfalfa from O_3 injury in a greenhouse study.

The knowledge of the interactions of these different types of agricultural chemicals with O_3 is still too fragmentary to enable any general conclusions to be drawn, other than to note the general efficacy of the carbamate fungicides. As noted in the previous criteria document (U.S. Environmental Protection Agency, 1986), it is premature to recommend their use specifically for protecting crops from the adverse effects of O_3, rather than for their primary purpose.

5.4.8 Factors Associated with Global Climate Change

This section focuses solely on the ways in which features of global climate change may be expected to affect the impact of oxidants on vegetation. It is not intended to provide a comprehensive review of the issues and components of climate change per se.

The magnitudes and causes of some of the changes in features of the global climate that have been observed or are predicted to occur are currently the subject of controversy. However, there is clear evidence of increases in mean CO_2 levels (Keeling et al., 1989), which, together with other anthropogenic emissions of radiatively active gases, may contribute to the upward trend in mean surface-level temperatures observed over the past century (Jones, 1989) and to changes in precipitation patterns throughout the world (Diaz et al., 1989). In addition, depletion of the stratospheric O_3 layer in the polar regions, caused by halofluorocarbons, results in increased penetration of the atmosphere by solar ultraviolet-B (UV-B) radiation (280- to 320-nm wavelengths). However, the intensity of UV-B radiation reaching the earth's surface may be attenuated by O_3-pollution in the lower troposphere (Brühl and Crutzen, 1989). Differences in the degree of this attenuation probably contribute to the discrepancies between recently observed trends in surface-level UV-B intensities (Scotto et al., 1988; Blumenthaler and Ambach, 1990).

Independent of any effects of ambient temperature, CO_2 level affects plant-water relations through effects on stomatal aperture and conductance, leading to effects on leaf and canopy temperature and the uptake of gaseous pollutants. The effects of UV-B on numerous growth processes have been reviewed by Tevini and Teramura (1989) and Runeckles and Krupa (1994). Individual interactive effects of O_3 and several effects of global climate change have been reviewed in the previous sections. However, it is important to recognize that, because of the interactions among the different components of climate change themselves, a holistic approach is essential, which includes the potential of interactions for modifying plant response to oxidants. Overall reviews of the interactions involving the factors of climate change and O_3 have been presented by Krupa and Kickert (1989) and Ashmore and Bell (1991).

The effect of increased CO_2 in stimulating photosynthetic rates also may lead to increased leaf area, biomass, and yield (Allen, 1990). Increased CO_2 also leads to stomatal closure. However, with regard to water use, the result of decreased stomatal conductance in reducing transpiration is offset partly by the increase in leaf and canopy temperature, resulting from reduced evaporative cooling, and the increase in leaf area. The net result is that increased CO_2 may lead to only slight increases in water-use efficiency, which are attributable more to increased photosynthetic activity than to reduced transpiration (Allen, 1990). On the other hand, because the primary route of entry into the leaf of a gaseous pollutant such as O_3 is through the stomata, increased CO_2 levels would be expected to decrease the impact of O_3 by reducing uptake as a consequence of reduced stomatal conductance. The effects of increasing CO_2 levels discussed above relate to plants with the C_3 pathway of carbon fixation. These include the following major broad-leaved crops: wheat, rice (*Oryza sativa*), legumes, potato, and cole crops. Plants with the C_4 pathway tend to have greater water-use efficiencies (WUEs) than C_3 plants, but show less response to increased CO_2 levels. Major C_4 crops are corn and sorghum. However, no studies appear to have been conducted on O_3/CO_2 interactions in C_4 species.

Allen (1990) provides a simulation of the effect of doubling the average ambient CO_2 level from 340 to 680 ppm on soybean yield, based on the Weibull response model to O_3 and SO_2 of Heagle et al. (1983b) and the model of stomatal conductance developed for soybean by Rogers et al. (1983):

$$g_s = 0.0485 - 7.00 \times 10^{-5}[CO_2] + 3.40 \times 10^{-8}[CO_2]^2,$$

where g_s is stomatal conductance (in meters per second), and $[CO_2]$ is CO_2 concentration (in parts per million). According to this model, a doubling of the CO_2 level would reduce g_s by a factor of 0.69, effectively reducing the O_3 and SO_2 concentrations to 0.038 and 0.018 ppm, respectively. At the current 340 ppm CO_2 level, the Weibull model predicts a yield of 340.5 g/m of row. Reduced pollutant entry at 680 ppm CO_2 gives a predicted yield of 390.6 g/m of row, an increase of 14.7%. This is a conservative estimate because it ignores the direct effect of the increased CO_2 level on soybean growth.

Although the calculation makes numerous assumptions, it is supported qualitatively by evidence from the few studies published to date on CO_2/O_3 interactions. Barnes and Pfirrmann (1992) reported that an increased CO_2 level of 765 ppm countered the adverse effects of O_3 on photosynthesis, shoot growth rate, leaf area, and water-use efficiency of radish. Protection against the adverse effects of O_3 on soybean by elevated CO_2 also was reported by Kramer et al. (1991). The yield loss due to O_3 at ambient CO_2 was 11.9%, whereas, in the presence of ambient + 150 ppm CO_2, the loss was only 6.7%.

Although these studies support the prediction of Allen (1990), they were conducted in growth chambers (Barnes and Pfirrmann, 1992) or OTCs (Kramer et al., 1991; Mulchi et al., 1992), as were the studies on which Allen's model was based. Hence, the plants would not have been subjected to the environmental conditions typical of the open field, particularly with respect to wind speed and its effects on transpiration and temperature. Nevertheless, these studies support the view that increased CO_2 levels will reduce adverse effects of O_3 on crops.

It is unclear as to whether such CO_2-induced reductions of the impact of O_3 also apply to the long-term growth of trees, and it is equally unclear as to how increased CO_2 will affect the impact of O_3 on ecosystems. These uncertainties arise because of the numerous

compensatory feedback mechanisms that play important roles in both long-term perennial growth and in the behavior of ecosystems. Such feedback includes changing demands for nutrients, increased leaf area and potential water loss, and changes in litter quality and quantity. For example, in terms of the effects of increased CO_2 alone, long-term studies of several species suggest that, although photosynthesis may be demonstrably stimulated, there may be little or no net response at the ecosystem level (Bazzaz, 1990).

The consequences of global warming as a feature of climate change are difficult to assess because, as discussed in Section 5.4.4, the information on the effects of temperature on O_3-response is conflicting. However, as Ashmore and Bell (1991) point out, concerns over the effects of O_3 on sensitivity to freezing temperatures will become increasing unimportant as warming occurs.

Various models of climate change scenarios have indicated that changed precipitation patterns will lead to increased drought in some mid-latitude regions of the world. The bulk of the evidence reviewed in Section 5.4.4 suggests that this would reduce the impact of O_3. However, because of the major direct impact of drought per se, such protection would be of little practical significance.

Greater certainty surrounds the likelihood that global warming will increase the incidence and severity of losses caused by pests and diseases. Concurrent increases also may favor the competitiveness of many weed species. At present, it is not possible to quantify such changes or to determine how they would influence the interactions discussed in Section 5.4.3.

With regard to possible interactions of O_3 and UV-B, Runeckles and Krupa (1994) point out that, because of the episodic nature of O_3 pollution, including its typical diurnal pattern, surface-level exposures to UV-B also will be episodic. They have described various possible O_3/UV-B scenarios that need to be considered. With low surface-O_3 levels and increased UV-B irradiation due to stratospheric O_3 depletion, effects of UV-B will predominate. On the other hand, elevated surface-O_3 levels will cause increased attenuation of UV-B resulting in reduced surface intensities. With no stratospheric O_3 depletion, this condition implies that surface effects of O_3 will predominate over the effects of UV-B; with stratospheric O_3 depletion, the resulting surface level irradiation will be dependent on the concentration and thickness of the surface O_3 layer, and both O_3 and UV-B effects may occur.

To date, there have been no experiments conducted specifically to simulate these different scenarios. However, Miller et al. (1994) exposed soybean in field OTCs, within which lamps were suspended to provide increased intensities of UV-B. The O_3 treatments were ambient and $1.5 \times$ ambient. No significant O_3/UV-B interactions were noted; the effects on growth were solely attributable to the O_3 exposure. However, increased UV-B irradiation resulted in increases in the foliar content of UV-absorbing constituents. In contrast, Miller and Pursley (1990) reported that a preliminary experiment revealed a less than additive interaction of O_3 and UV-B on soybean growth.

It is clear overall that the effects of O_3 on vegetation will be modified to some degree by various components of the complex mix of factors that constitute climate change. Considerably more research will need to be undertaken before quantitative assessments of the magnitudes of the changes will be possible.

5.4.9 Summary—Environmental Factors

Since the previous criteria document (U.S. Environmental Protection Agency, 1986), additional studies have been published on a wide range of biological, physical, and chemical factors in the environment that interact with plant response to O_3.

Biological components of the environment of individual plants include pests, pathogens, and plants of the same or other species in competition. With regard to insect pests, although only a very limited number of plant-insect systems have been studied, there is a general trend in the observations that suggests that some pests have a preference for and grow better when feeding on plants that have been impacted by O_3. Unfortunately, because there is no knowledge of how the vast majority of plant-insect systems will be affected by O_3, it is not possible to offer any quantitative overall assessment of the consequences of such interactions on the growth of crops and natural vegetation. At best, there is a reasonable likelihood that some insect pest problems will increase as a result of increased ambient O_3 levels, but there is no evidence to suggest that O_3 may trigger pest outbreaks.

Plant-pathogen systems also are affected by O_3, but, here too, the available evidence is far from representative of the wide spectrum of plant diseases. Nevertheless, the suggestion of Dowding (1988) that diseases caused by obligate pathogens tend to be diminished by O_3, whereas those caused by facultative pathogens tend to be favored, generally is supported by the limited evidence available. In terms of its broader implications, this suggests that continued exposure to O_3 may lead to a change in the overall pattern of the incidence and severity of specific plant diseases affecting crops and forest trees. However, it is not possible, with the limited evidence currently available, to predict whether the net consequences of O_3 exposure would be more or less harmful.

A major level of uncertainty concerns the effects of O_3 at the population and community levels within natural ecosystems. Very few studies have been conducted on multi-species systems, and Woodward (1992) has pointed out the hazards of attempting to extrapolate from responses of the individual plant to responses of a population of such plants. This is borne out by the observations of Evans and Ashmore (1992) who showed that the behavior to O_3-exposure of a species growing in mixture with other species is not predictable from its behavior when grown in isolation. This has serious implications with regard to complex natural ecosystems and identifies a serious gap in the knowledge of the effects of O_3 that can be filled only by a substantial research effort.

With regard to the physical environment, the combination of light, temperature, air turbulence, and water availability largely determines the success of plant growth because of the influence of these factors on the processes of photosynthesis, respiration, and transpiration. Air turbulence plays an important role in O_3 uptake because it determines the amount of O_3 to which a plant is exposed, as well as when exposure will occur. For agricultural crops, perhaps the most important of these potential interactions with O_3 concerns water availability and use. There is consistent evidence that drought conditions tend to reduce the direct adverse effects of O_3 on growth and yield. Conversely, the ready availability of soil water tends to increase the susceptibility of plants to O_3 injury. However, a lack of water should not be viewed as a potentially protective condition, because of the adverse effects of drought per se. The combination of drought conditions and exposure to O_3 is likely to result in adverse effects on growth and yield that are largely the result of lack of water. However, with perennial trees, there is evidence that prolonged exposures to O_3 may lead to greater water use efficiency, which would enable such trees to be better able to survive drought conditions.

In contrast with crop species, with tree species, the relative roles of light, temperature, and water are shifted somewhat because of the differences in plant form. In particular, the photosynthetic function of the leaves is carried out by a much smaller proportion of the plant's biomass. Conversely, a larger demand is placed on temperature-dependent respiratory processes to maintain and support the tissues of the stem and root systems. In addition, in temperate regions, the perennial habit brings with it the requirement for storage of carbohydrates and other reserves, in order to permit survival during the winter season and to facilitate renewed spring growth. Hence, with tree species it becomes important to distinguish between the immediate effects of exposure to O_3 and the longer term consequences of these effects.

Of particular importance in northern latitudes and at higher elevations is the demonstrated role of O_3 in adversely affecting cold hardiness by reducing carbohydrate storage. Independent of effects on winter hardiness, there is also evidence to indicate that adverse effects on storage also may be a component of changes in growth occurring in subsequent seasons (Hogsett et al., 1989; Andersen et al., 1991; Sasek et al., 1991). However, it is not yet possible to assemble these observations into a general quantitative model.

The plant's environment also contains numerous chemical components, ranging from soil nutrients and other air pollutants to agricultural chemicals used for pest, disease, and weed control. With regards to plant nutrients and their influence on plant response to O_3, the available evidence is highly fragmentary and frequently contradictory and, hence, does not permit the drawing of any general conclusions. A large number of studies have been conducted on the effects of O_3 in conjunction with other gaseous air pollutants such as SO_2 and NO_2, although the information obtained in several of the studies is of no more than academic interest because of the unrealistic exposure conditions used. Although there is clear evidence to show that O_3 and SO_2 may act synergistically in increasing foliar injury in some species, the available evidence indicates that this type of response is not universal. Several empirical models of the O_3-SO_2 interaction have been developed, but they have little in common and are highly specific to the crop and exposure conditions used. Furthermore, the frequently observed lack of interaction implies that in many cases the impact of O_3 is probably best assessed on its own. The same is true of the situation with regard to combinations of O_3 and acid rain or acid fog and of O_3 and NO_2.

Numerous agricultural chemicals have been found to influence the responses of plants to O_3. In particular, several fungicides have been shown to provide protection against visible injury, although none has been adopted for commercial application for this purpose. On the other hand, the experimental chemical EDU has been found consistently to provide protection of a wide range of species, both in the laboratory and in the field.

Because increased tropospheric O_3 is a component of global climate change, results from studies on the interactions of O_3 with increased levels of CO_2 and UV-B radiation are beginning to appear. Initial work with CO_2 suggests that increased CO_2 levels may ameliorate the effects of O_3. However, it is too soon to be able to generalize on the outcome of this interaction. At the present time, no investigations of the compound interactions involving O_3, CO_2, UV-B, increased temperature, and changed soil-moisture status have been reported.

In conclusion, in spite of the amount of work carried out on the interactions of O_3 with environmental factors, there exists only a very fragmented understanding from which to draw conclusions. This is probably inevitable in view of the vast scope of the possible

interactions between O_3 and all the other environmental variables. It is also a result of the fact that most of the published work consists of studies resulting from personal interests of the investigators, rather than from coordinated programs of research that focus on systematic investigations. The consequence is that, although information has been reported about magnitudes of many interactions of O_3 with environmental variables (or the lack thereof), the fragmented and nonsystematic nature of the information prevents the drawing of general conclusions and of defensible estimates of the uncertainties associated with these interactions.

5.5 Effects-Based Air Quality Exposure Indices
5.5.1 Introduction
5.5.1.1 Biological Support for Identifying Relevant Exposure Indices

The effects of O_3 on individual plants and the factors that modify plant response to O_3 are complex and vary with species, environmental conditions, and soil and nutrient conditions. Because of the complex effect of O_3 and its interactions with physical and genetic factors that influence response, the development of exposure indices to characterize plant exposure and to quantify the relationship between O_3 exposure and ensuing plant response has been, and continues to be, a major problem. At best, experimental evidence of the effect of O_3 on biomass production can refine the knowledge of those factors of O_3 exposure that affect the ability to predict plant response using exposure indices. The impacts of measured O_3 concentrations on plant response are discussed and evaluated to determine the key factors of exposure that account for the variations in plant response and, if possible, to develop measures of pollutant exposure that relate well with plant response.

Considerable evidence of the primary mode of action of O_3 on plants (e.g., injury to proteins and membranes, reduction in photosynthesis, changes in allocation of carbohydrate, early senescence), which eventually impacts biomass production, identifies O_3 uptake as the measurement of plant exposure (Section 5.3). Ozone uptake is controlled by canopy and stomatal conductance and by ambient O_3 outside the leaf (see Figure 5-3). Any factor that will affect stomatal conductance (e.g., light, temperature, humidity, soil and atmospheric chemistry, air turbulence, nutrients, time of day, phenology, biological agents) will affect O_3 uptake and, consequently, plant response (i.e., yield or biomass). Biochemical mechanisms 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 ultimately lead to reductions in biomass production. In most cases, increasing the duration of exposure increases the effect of O_3 on plant response. Peak concentrations, when they occur during daylight (when stomatal conductance is high), can have more influence in determining the impact of O_3 on plant response than lower concentrations or night concentrations because of a greater likelihood of intracellular impairment.

From a toxicological perspective, duration and peak concentrations above some level have value in determining plant response but interact with other factors such as respite time, temporal variation, phenology, canopy structure, physiological processes, environmental conditions, and soil and nutrient conditions in different fashions, depending on species. Effects occur on vegetation when the amount of pollutant absorbed exceeds the ability of the plant to detoxify O_3 or to repair the initial impact (Tingey and Taylor, 1982).

Although O_3 uptake integrates the above factors with atmospheric conditions and relates well with plant response, it is difficult to measure. Several empirical models to predict stomatal conductance have been developed for particular species (Lösch and Tenhunen, 1981) but have not been used to estimate O_3 uptake or to develop exposure indices. Based on atmospheric measurements 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,b) proposed an ambient O_3 exposure potential for characterizing O_3 uptake and related it to the damaged-leaf area (DLA) of leaf No. 4 of Bel W3 tobacco (Grünhage et al., 1993a,b).

5.5.1.2 Historical Perspective on Developing Exposure Indices

For almost 70 years, air pollution specialists have explored alternative mathematical approaches for summarizing ambient air quality information in biologically meaningful forms that can serve as surrogates for dose for vegetation effects purposes. Some of the indices introduced have attempted to incorporate some of the factors (directly or indirectly) described above. Recognizing the importance of duration and peak concentrations in conjunction with stomatal conductance, the optimum exposure index can be written as

$$\text{Index} = \sum_{i=1}^{n} w_i \times f(C_i), \tag{5-1}$$

where C_i is the hourly mean concentration, $f(C_i)$ is some function of C_i, and w_i is some weighting scheme that relates ambient condition and internal O_3 flux. The optimal weights are difficult to develop because of the complex relationship among exposure, environmental condition, and species.

Equation 5-1 represents a taxonomy of exposure indices that have been proposed as surrogates of dose in the literature. The exposure indices differ in the ways in which the values are assigned to w_i. Based on the weighting function, the exposure indices can be arranged into the categories described below (description from Lee et al., 1989).

· One Event: $w_i = 0$ for all C_i, except for the few concentrations where $w_i = 1$. Examples of such indices are the second highest daily maximum 1-h concentration (2HDM), the maximum of 7-h (P7) and 1-h (P1) maximum daily averages, and the 90th or higher percentiles of hourly distribution.

· Mean: $w_i = 0$ for all C_i outside the period of interest (P) and $w_i = v_i/\Sigma_{i=1}^{n} v_i$ for all C_i inside the period P, where v_i is a function of C_i or some environmental variable. Examples are the seasonal mean of 7-h daily means (M7) (Heagle et al., 1979b); the effective mean (m_e), where m_e^v is the index in Equation 5-1 with $f(C_i) = C_i^{-1/v}$ and $w_i = 1$ for some parameter v (Larsen and Heck, 1984); the solar-weighted mean where v_i is the hourly solar radiation value (Rawlings et al., 1988b).

· Cumulative: $w_i = 1$ for all C_i. An example is the seasonal sum of all hourly concentrations (i.e., total exposure, denoted as SUM00).

· Concentration Weighting: $w_i = g(C_i)$ where $g()$ is a monotonically nondecreasing function. Examples are the seasonal sum of hourly concentrations at or above a threshold level such as 0.06 ppm (SUM06) or 0.08 ppm (SUM08); the seasonal sum of the difference between an hourly concentration above a threshold level, less the threshold value, such as 0.08 ppm (AOT08); the total impact with $w_i = C_i^{(-1-1/v)}$ for some v (Larsen et al.,

1983); the index with the allometric function, $g(C_i) = C_i^a$, $a > 0$; the index with sigmoidal weighting function, $g(C_i) = 1/[1 + M \times \exp(-AxC_i)]$, where $M = 4{,}403$ and $A = 126$, denoted as W126 by Lefohn et al. (1988a), and $M = 500$ and $A = 100$, denoted SIGMOID by Lee et al. (1989); total hours with concentrations at or above a threshold level, such as 0.08 ppm (HRS08), $g(C_i) = 0$ for $C_i < 0.08$ ppm and $w_i = 1/C_i$ for $C_i \geq 0.08$ ppm.

· Multicomponent: $w_i = g(C_i, i)$. Examples are indices that incorporate several characteristics of exposure and crop development stage, including the phenologically weighted cumulative impact indices (Lee et al., 1987).

Oshima (1975) and Oshima et al. (1976) proposed an exposure index, where the difference between the value above 0.10 and 0.10 ppm was summed. This is referred to as the AOT10 exposure index with $f(C_i) = C_i - 0.10$ and $w_i = 0$ for $C_i < 0.10$ ppm and $w_i = 1$ for $C_i \geq 0.10$ ppm in Equation 5-1. Alternatively, Lefohn and Benedict (1982) introduced an exposure index based on the hypothesis that, if the higher O_3 concentrations had greater value in predicting adverse effects on agricultural crops than did the lower values, then the higher hourly mean concentrations should be given more weight than the lower values. This index summed all hourly concentrations equal to and above a 0.10-ppm threshold level. This index is referred to as the SUM10 exposure index, with $f(C_i) = C_i$ and $w_i = 0$ for $C_i < 0.10$ ppm and $w_i = 1$ for $C_i \geq 0.10$ ppm. The SUM indices are not concentration weighting but threshold weighting, in that all concentrations at or above a threshold level have equal weight rather than increasing weight to higher concentrations.

A 6-h, long-term, seasonal mean, O_3 exposure index was used by Heagle et al. (1974). Also, Heagle et al. (1979b) reported the use of a 7-h experimental period mean. The 7-h (0900 to 1559 hours) mean, calculated over an experimental period, was adopted as the statistic of choice by the U.S. Environmental Protection Agency's (EPA's) NCLAN program (Heck et al., 1982). The 7-h daily daylight period was selected by NCLAN because the index was believed to correspond to the period of greatest plant susceptibility to O_3 pollution. In addition, the 7-h period of each day (0900 to 1559 hours) was assumed to correspond to the time that the highest hourly O_3 concentrations would occur. However, not all monitoring sites in the United States experience their highest O_3 exposures within the 0900 to 1559 hours 7-h time period (Lefohn and Jones, 1986; Lefohn and Irving, 1988; Logan, 1989). Toward the end of the program, NCLAN redesigned its experimental protocol and applied proportional additions of O_3 to its crops for 12-h periods. The expanded 12-h window reflected NCLAN's desire to capture more of the daily O_3 exposure. In the published literature, the majority of NCLAN's experiments were summarized using the 7-h experimental-period average.

Based on the concept that higher concentrations of O_3 should be given more weight than lower concentrations (summarized in U.S. Environmental Protection Agency, 1986), concerns about the use of a long-term average to summarize exposures of O_3 began appearing in the literature (Lefohn and Benedict, 1982; Tingey, 1984; Lefohn, 1984; Lefohn and Tingey, 1985; Smith et al., 1987). Specific concerns were focused on the fact that the use of a long-term average failed to consider the impact of peak concentrations. The 7-h seasonal mean contained all hourly concentrations between 0900 to 1559 hours; this long-term average treated all concentrations within the fixed window in a similar manner. A large number of hourly distributions within the 0900- to 1559-hours window could be used to generate the same 7-h seasonal mean, ranging from those containing many peaks to those containing none. Larsen and Heck (1984) pointed out that it was possible for two air

sampling sites with the same daytime arithmetic mean O_3 concentration to experience different estimated crop reductions.

In the late 1980s, the focus of attention turned from the use of long-term seasonal means to cumulative indices (i.e., exposure indices that sum the products of concentrations multiplied by time over an exposure period). As indicated previously, the cumulative index parameters proposed by Oshima (1975) and Lefohn and Benedict (1982) were similar. Both parameters gave equal weight to the higher hourly concentrations but ignored the concentrations below a subjectively defined minimum threshold (e.g., 0.10 ppm). Besides the cumulative indices proposed by Oshima (1975), Oshima et al. (1976), and Lefohn and Benedict (1982), other cumulative indices were suggested, including the number of occurrences of daily maximum hourly averaged concentrations greater than a threshold level (Ashmore, 1984) and the use of exponential functions (Nouchi and Aoki, 1979; Larsen and Heck, 1984) to assign unequal weighting to O_3 concentrations.

A possible disadvantage of applying an integrated exposure index, as defined by Oshima (1975) and Lefohn and Benedict (1982), is that the use of an artificial threshold concentration as a cutoff point eliminates any possible contribution of the lower concentrations to vegetation effects. Although this disadvantage may not be important when considering O_3 exposures that occur in the California South Coast Air Basin, where repeated high concentrations are experienced from day to day, and there are relatively short periods between episodes, it is important when assessing the typical exposures experienced in other parts of the United States.

Recognizing the disadvantage, Lefohn and Runeckles (1987) suggested a modification to the Lefohn and Benedict (1982) exposure index by weighting individual hourly mean concentrations of O_3 and summing over time. Lefohn and Runeckles (1987) proposed a sigmoidal weighting function that was used in developing a cumulative integrated exposure index. The index included the lower concentrations in the integrated exposure summation.

None of the exposure indices mentioned above fully characterize the potential for plant uptake of O_3 because the indices, being measures of ambient condition, ignore the biological processes controlling the transfer of O_3 from the atmosphere through the leaf and into the leaf interior (U.S. Environmental Protection Agency, 1986, 1992). Early studies with beans and tobacco, reviewed in the previous criteria document (U.S. Environmental Protection Agency, 1986), showed that short-term, higher peak exposures induced more visible injury than longer term, lower peak exposures of the same total exposure, indicating that concentration has more value than exposure duration in eliciting a response, at least for short-lived species. Other studies with soybean, tobacco, and bean, conducted prior to 1983 and described in U.S. Environmental Protection Agency (1986), showed that the foliar injury response to subsequent peak exposures varies with temporal pattern. Predisposition to low levels of O_3 for a few days increases plant sensitivity to subsequent peaks (Johnston and Heagle, 1982; Heagle and Heck, 1974; Runeckles and Rosen, 1977). Tobacco plants exposed to 2 consecutive days of peak exposures showed greater injury on the first day (Mukammal, 1965). Plants exposed to a series of successive short exposures suffered more injury than did those plants that received a continuous uniform exposure, with all plants receiving equal total exposure (Stan and Schicker, 1982).

When yield or growth are considered, "not only are concentration and time important, but the dynamics of the O_3 exposure are also important" (U.S. Environmental Protection Agency, 1986). Musselman et al. (1983) were the first to demonstrate that plants

exposed to variable concentrations showed greater effect on plant growth than those exposed to a fixed or daily peak concentration of equal total exposure but lower peak concentrations. The Hogsett et al. (1985b) study also reported a greater effect on plant growth of variable concentrations; however, no plant response data is presented in the paper. Musselman et al. (1986b), in a subsequent experiment, exposed kidney bean plants to either a simulated ambient or a uniform concentration that had equal total exposure and peak concentration (at two levels of 0.30 and 0.40 ppm) and found that the effects of the two distributions did not differ significantly. Consequently, when peak concentrations and total exposures are equal, the diurnal distribution of concentrations appears to be unimportant.

More recent studies with bean (Kohut et al., 1988b), soybean (Heagle et al., 1986b), and tobacco (Heagle et al., 1987b) (reviewed in U.S. Environmental Protection Agency, 1992) showed conflicting evidence of no significant differences in response to different exposure patterns of equal total exposure but varying peak concentrations. The value of peak concentrations in influencing response was inconclusive. For the study with beans, plants exposed to peak exposures showed significant impairment in the early harvests, but, at the final harvest, O_3 effects on growth and yield were not statistically significant. For the NCLAN studies with soybean and tobacco, differences in yield between the constant and proportional 7-h O_3-addition exposures were not significant, even though the proportional-addition treatments had greater peak concentrations. In reanalysis of the soybean and tobacco studies, Rawlings et al. (1988b) stated that the differences between the constant and proportional O_3 additions were relatively small, thus limiting the power of the comparison test. However, 12-h exposures caused greater effects than 7-h exposures, but the decrease in yield loss was not directly proportional to the increased length of exposure (Rawlings et al., 1988b).

Considerable research since the publication of the previous criteria document (U.S. Environmental Protection Agency, 1986) has been directed at developing measures of exposure that were consistent with then-current knowledge of the mode of action of O_3 on plants, as well as on factors such as concentration, duration, and temporal dynamics of exposure influencing response. A number of retrospective studies of existing data to evaluate and compare exposure indices based on statistical fit (Rawlings et al., 1988b; Adomait et al., 1987; Cure et al., 1986; McCool et al., 1986, 1987; Smith et al., 1987; Lee et al., 1987, 1988; Lefohn et al., 1988a; Tingey et al., 1989; Musselman et al., 1988) have been summarized in the literature between 1986 and 1988 and reviewed by the U.S. Environmental Protection Agency (1992). Studies using O_3 exposures in chambers suggest the following conclusions: O_3 effects are cumulative, peak concentrations may be more important than lower concentrations in eliciting a response, and plant sensitivity to O_3 varies with time of day and crop development stage. Exposure indices that cumulate the exposure and preferentially weight the peaks yield better statistical fits to response than do the mean and peak indices.

Because the mean exposure index treats all concentrations equally and does not specifically include an exposure duration component, the use of a mean exposure index for characterizing plant exposures appears to be inappropriate for relating exposure with vegetation effects (U.S. Environmental Protection Agency, 1992). In particular, the weighting of the hourly O_3 concentrations of the mean is inconsistent with the weighting function of plant exposure to O_3 in Equation 5-1, which attempts to relate O_3 flux to ambient condition. The total exposure index includes an exposure duration component but does not adequately relate pollutant exposure with plant response because the index weights all concentrations equally and focuses on the lower concentrations.

Evidence supporting the use of peak-weighted, cumulative indices in relating O_3 exposure and plant response is based on statistical reanalyses of NCLAN data. However, it is unlikely that the empirical modeling of plant response will determine the optimal weighting function of hourly O_3 concentrations for use in characterizing plant exposure, which varies with environmental factors and species. The development and comparison of exposure indices based on statistical fits is difficult because only a limited number of experiments have been designed specifically to test and evaluate the various exposure indices.

Although much research has been conducted on O_3 effects on crops and trees since 1988, the overall understanding of the mode of action of O_3 on plants and factors that modify plant response remains unchanged since the previous criteria document (U.S. Environmental Protection Agency, 1986) and its supplement (U.S. Environmental Protection Agency, 1992). Additional studies further support the value of concentration, duration, and temporal pattern of exposure in describing plant exposure and its relation to plant response. Studies that applied two or more different exposure patterns of equal exposure but possibly different peak concentrations are reviewed in Section 5.5.2.2 to substantiate the value of exposure structure in influencing the magnitude of plant response. Recent papers that report results from replicate studies over time and space are summarized in Section 5.5.2.3 to test the value of duration and its relation to plant response. In addition, a few recent studies that provide additional insight to those factors that modify plant response are reviewed in Sections 5.5.2.4 and 5.5.2.5.

5.5.2 Developing Exposure Indices
5.5.2.1 Experimental Design and Statistical Analysis
Controlled and field exposure-response studies, where extraneous factors influencing response are controlled or monitored, allow the study of concentration, duration, respite time, and temporal fluctuations at various stages of crop development in influencing response. These studies provide insight on the efficacy of exposure indices in explaining variation of response. A small number of experiments have been designed specifically to study the components of exposure and have applied two or more different patterns of exposure that measure the same SUM00 values. These designs provide the best evidence to determine whether plants respond differentially to temporal variations in O_3 concentrations; however, they may have limited application in developing a statistical relationship between O_3 exposure and plant response. Other design considerations, including the number, kind, and levels of O_3 exposure; the patterns of randomization; the number of replicates used in the experiment; and experimental protocol, determine the strength of the statistical analysis that is applied to the treatment mean comparison tests and the range of ambient and environmental conditions over which generalizations may be made. These designs have been used successfully to test the value of components of exposure, particularly concentration, in influencing response (Musselman et al., 1983, 1986b, 1994; Hogsett et al., 1985b). Different approaches that include either a mean separation procedure or a regression procedure have been used to identify those important components of exposure that influence response.

To identify the importance of exposure in contributing to variation of plant response, the majority of pollutant effects studies use regression-based designs that apply a single pattern of exposure at varying concentration levels. However, if these designs are used, the application of the results is limited; plant response (i.e., plant yield) with respect to exposure is unchanged with different measures of exposure. The relative position and spacing

between exposure levels is a function of how the exposure index weights the hourly O_3 concentrations and governs the statistical fit to response. The regression approach has been used to compare and evaluate various exposure indices, but the ability to discriminate among indices is low for these studies. By their nature, those studies that have used regression-based designs that utilize data from single patterns of exposure cannot distinguish between mean exposure indices and sums constructed from means (i.e., mean × duration) and, consequently, cannot be used to test the value of duration in explaining the variation of response.

Evidence to substantiate the value of duration in explaining the experimental variation of plant response may be obtained when combining data from replicate studies of the same species and cultivar over time and space. Pooling of data from replicate studies of the same species to evaluate duration effects and to compare various exposure indices assumes that the primary cause of biological response is pollutant exposure. This assumption may or may not be valid, particularly when plants from replicate studies are grown under varying environmental, edaphic, and agronomic conditions that tend to mask the treatment effects during the growth of the plant (Section 5.3). Hence, it is more difficult to substantiate the importance of exposure-dynamic factors from retrospective analyses of combined data from replicate studies of the same species than from experiments designed specifically to address the components of exposure. The comparison of environmental conditions, as well as the yields of plants exposed to CF air over replicate studies, is a simple check of interaction but does not ensure that O_3 effects on response can be isolated. In addition, when the main effect of O_3 is insignificant, the data may be limited for determining the value of duration or other components of exposure in predicting response. Nonetheless, if an air pollutant is the primary source of variability in plant response, the relationship between exposure and response should be consistent when data sets for the same crop are combined over several years or locations.

Sets of replicate studies of equal and varying duration are readily available in the published literature, but only a few reports have combined the data to test specifically the value of duration in explaining variation of plant response or to evaluate exposure indices based on statistical fit. Lefohn et al. (1988a) were the first to fit a common response model to combined data from two replicate studies of varying duration using various exposure indices. Greater yield losses occurred when plants were exposed for the longer duration, indicating that the duration component of exposure was important in influencing response, and that a cumulative-type index was able to describe adequately the relationship between exposure and yield. More recent papers have reported results of the 2 years of replicate studies, and a few papers have used the regression approach, with and without variance components for sites and years, to evaluate various exposure indices based on the adequacy of fit of a common response model.

A number of the papers relevant to the study of components of exposure influencing plant response report only the mean and total exposure (SUM00) indices. Because exposure indices weight hourly O_3 concentrations differently, it is almost impossible to convert one index to another. The original data, which in many cases are not available, would be necessary to generate alternative exposure indices. Therefore, unless adequate information is given to allow calculation of exposure indices, the analysis of reported results from individual and combined data to evaluate different exposure indices is not possible, although it may be possible to perform retrospective evaluation of the structure of exposure in altering plant response.

Another concern relates to the experimental design, particularly the number, kind, and levels of exposure used in the study. Generalization of experimental results is largely dependent on the degree to which atmospheric and biospheric conditions mimic those of the target population when growing under ambient conditions. However desirable the need to mimic the real world, understanding the relationship between exposure and the ensuing response (i.e., plant yield) and identifying those components of exposure that influence response may require the use of exposure regimes with temporal pattern, concentration, or structure that are not observed in nature. Such data requires the comparison of exposure levels between CF and near-NF conditions, but the mathematician who attempts to model an experiment requires higher than NF levels of O_3 to better determine the nature of plant response to O_3. A discussion of the advantages and disadvantages of OTCs and the types of NCLAN exposures is discussed in the section on methodologies (Section 5.2.1.1). The O_3 exposures utilized by the NCLAN program have been described as producing artificial regimes that do not mimic actual conditions.

In addition to the CF concentration regimes, Lefohn et al. (1988a) have reported that the highest treatments have a tendency to display bimodal distributions that are unrealistic (Figure 5-9). At this time, there is no evidence to suggest whether or not these higher NF exposures provide realistic information on the impact of O_3 on plant response.

Studies that utilize exposures with peak concentrations above 0.40 ppm may not provide realistic evidence of O_3 impact on plant response in the United States. These studies provide limited evidence for substantiating the value of peak concentrations in influencing response. Consequently, these studies are not included in this section.

5.5.2.2 Studies with Two or More Different Patterns of Exposure

Experiments using chambers that focused on the structure of exposure have shown that plant response is differential to temporal patterns of O_3 exposure. For crop species, there is evidence to suggest that plant response is influenced more by higher concentrations than by lower concentrations or exposure duration. Greater response to concentration occurred when plants were predisposed to low concentrations for a few days or when peaks occurred just prior to or at maximum leaf expansion (U.S. Environmental Protection Agency, 1978, 1986). Plants exposed to two (or more) different exposure patterns of equal exposure (i.e., same SUM00 value) showed greater foliar injury response to:

   (1)   the short-term, high-concentration exposure than to the longer term exposure with lower peak concentrations (Heck et al., 1966; Heck and Tingey, 1971; Bennett, 1979; Nouchi and Aoki, 1979; Amiro et al., 1984; Ashmore, 1984; Tonneijck, 1984); and

   (2)   the exposure that predisposes plants to low O_3 concentrations for a few days prior to a high O_3 concentration than to exposures that have a set diurnal pattern of O_3 concentrations or less than 2 days of respite time between high concentrations (Heck and Dunning, 1967; Johnston and Heagle, 1982; Heagle
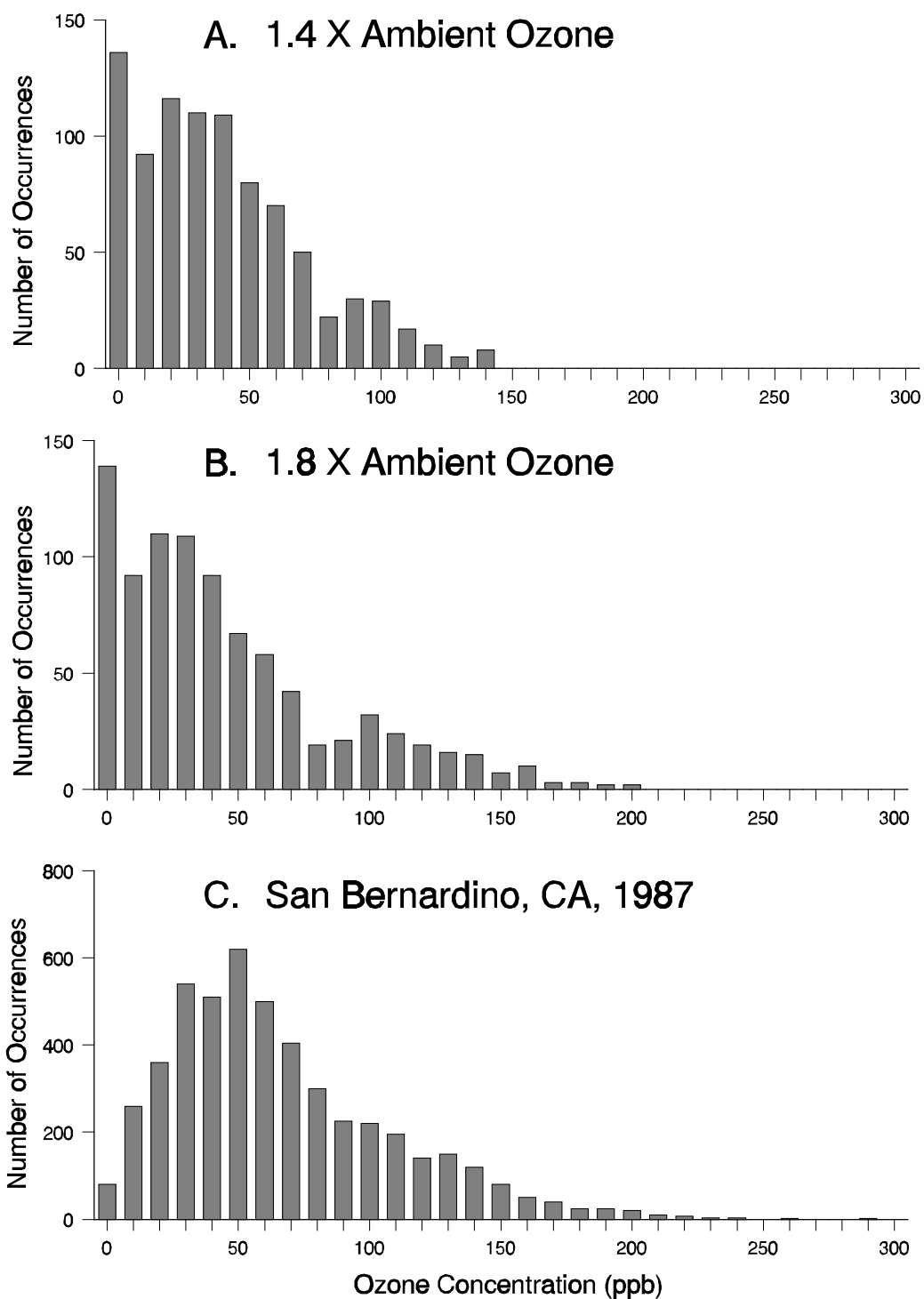
Figure 5-9. *Distribution pattern showing the number of ozone concentrations within specified ranges for the 1983 winter wheat proportional-addition experiment for the (A) 1.4 × ambient air and (B) 1.8 × ambient air treatments and for (C) San Bernardino, CA, in 1987.*

and Heck, 1974; Runeckles and Rosen, 1977; Mukammal, 1965; Stan and Schicker, 1982).

The studies that applied the same exposure but used different patterns of exposure have been reviewed in previous criteria documents (U.S. Environmental Protection Agency, 1978, 1986, 1992) and substantiate the role of concentration, temporal dynamics, respite time, and predisposition in influencing the magnitude of plant response to O_3.

Musselman et al. (1983) and Hogsett et al. (1985b) were among the first to demonstrate that variable concentrations produced greater effect on plant growth than did fixed or set diurnal patterns of exposure of equal total exposure but with lower peak concentrations (Table 5-12). Musselman et al. (1986a), in a subsequent experiment, exposed kidney bean plants to either a variable or a uniform concentration of equal total exposure and equal peaks (at two levels of 0.30 and 0.40 ppm) and found that the effects of the two distributions were not significantly different (Table 5-12). Musselman et al. (1994), in a third experiment, exposed kidney bean plants to four different patterns of equal total exposure and, like Musselman et al. (1983), found that patterns with higher peak concentrations or longer duration of high concentrations (>0.16 ppm) produced significantly greater effect on top dry weight than the square wave pattern. Cumulative, peak-weighted exposure indices with an allometric weighting parameter between 2 and 3.5 gave the best fit for dry weight, necrosis, and number of pods. These results provide evidence that: total exposure (i.e., SUM00), being unable to differentiate among the exposure patterns, is a poor predictor of plant response; the peak concentrations or sequence of peak concentrations (>0.16 ppm) are important in determining plant response; and greater weight should be given to higher concentrations when describing exposure. Consequently, when peak concentration and total exposure are equal, the diurnal distribution of concentrations (e.g., sequence of peak concentrations >0.16 ppm) *may be* an important factor.

One recent study exposed bean plants to two consecutive exposures of 0.30 ppm for 3 h/day in the rapid vegetative growth stage and showed greater reductions in total dry weight when exposures were 3 to 6 days apart (McCool et al., 1988) (Table 5-12); this finding is consistent with earlier results on the role of predisposition in influencing response (e.g., Hogsett et al., 1988). Predisposition to a high concentration above the level that causes visible injury may increase plant sensitivity over time (Mukammal, 1965). As a result, the subsequent response to a high concentration following recovery may be greater than experienced in prior exposures. In future modeling efforts, this phenomenon may have to be taken into consideration, by the weighting of hourly concentrations, for properly characterizing plant exposure.

Sensitivity of plants to O_3 is a function of stomatal conductance and varies with the cultivar, time of day, and phenology. To test the role of phenology, Heagle et al. (1991b) applied 16 patterns of exposure in combinations of either CF or NF air for each quarter of the experimental period (31 days/quarter) (Table 5-12). The authors concluded that the phenological stage of development played a role in plant response, and that exposures during mid- to late-growth stages caused greater yield losses than did exposures during earlier developmental stages. For crops, foliage appears to be most sensitive to O_3 just prior to or during maximum leaf expansion (U.S. Environmental Protection Agency, 1978). These results are consistent with earlier studies (Lee et al., 1987) that reported better statistical fits to response using exposure indices that preferentially weighted hourly O_3 concentrations during the period of anthesis to seed fill.

Species	Facility[b]	Total Number of Chambers	Exposure Patterns[c]	Exposure Duration	Concentration (ppm)/Exposure[d] (ppm-h)	Variable	Effect[e]	Reference
Glycine max L. Merrill cv. Davis, Forrest, Bragg, and Ransom	OTC in pots	24	16 combinations of CF or NF + over 4 quarters (31-days/quarter)	124 days	M7 (ppm): CF range from 0.016 to 0.038 over the 4 quarters, NF+range from 0.096 to 0.098 over the 4 quarters	Total seed weight	Forrest: greater effect in Q3 than in other quarters. Davis: no consistent effect Q1, significant but similar effects for Q2, Q3, and Q4. Ransom: no significant O_3 effects in Q1 or Q2, and equal responses in Q1, Q3, and Q4. Bragg: no significant O_3 effects in Q1 or Q2, significant decreases in Q3 and Q4.	Heagle et al. (1991b)
Medicago sativa L.	OTC in pots	8	E, DP	133 days	Equal SUM07 (ppm-h): DPH=113, DPL=63, EH=117, EL=72 Equal SUM00 (ppm-h): DPH=183, DPL=140, EH=193, EL=145 M7 (ppm): DPH=0.099, DPL=0.074, EH=0.084, EL=0.064	Shoot dry weight	91 and 67% reductions for EH and DPH. Significant difference between E and DP regimes. Treatment means are ordered CF<DPL<EL<DPH<EH.	Hogsett et al. (1985b)
Phaseolus vulgaris L. cv. Calif. Dark Red Kidney Bean	GC in pots	8	U, V	3 weeks (1 day/ week)	Equal SUM00 (ppm-h/day): UL=VL=0.69; UH=VH=0.92 Equal Max concentration (ppm): UL=VL=0.30, UH=VH=0.40	Pod and seed dry weights	6% less yield when exposed to variable (NS). Response to O_3 same in reproductive and vegetative growth stages.	Musselman et al. (1986b)
Phaseolus vulgaris L. cv. Calif. Dark Red Kidney Bean	GC in pots	8	U, V	3 weeks (1 day/ week)	Equal SUM00 (ppm-h/day): UL=VL=1.20; UH=VH=1.68 Max concentration. (ppm): UL=0.20, VL=0.50,UH=0.28, VH=0.715	Pod and seed dry weights	38% less yield when exposed to variable. No significant difference between low and high. Beans in reproductive growth stage when exposed.	Musselman et al. (1983)
Phaseolus vulgaris L. cv. Calif. Dark Red Kidney Bean	GC in pots	8	Square wave (SW), Triangular (T), Flattened triangular (FT), Rhomboid (R)	7 weeks (3 days/ week)	Equal SUM00 (ppm-h/day): SW=T=FT=R=0.60. Max concentration (ppm): SW=0.12, T=0.36, FT=R=0.24.	Top dry weight	SW had significantly higher yield than other three patterns. Treatment means are ordered R=T<FT<SW	Musselman et al. (1994)
Phaseolus vulgaris L. cv. Calif. Dark Red Kidney Bean	GC in pots	10	Initial exposure of 0.3 ppm for 3-h and second exposure of 0.3 ppm at 2-6 (or 1-5) days after initial exposure	2-6 days in 1984 and 1-5 days in 1985	Equal maximum concentration of 0.30 ppm.	Total dry weight	Reductions due to the second exposure were significant when exposures were 3-6 days apart in 1984 and 5 days apart in 1985.	McCool et al. (1988)

[a]See Appendix A for abbreviations and acronyms.

[b]GC = Controlled environmental growth chamber, or CSTR; OTC = Open-top chamber.

[c]CA = Constant addition, PA = Proportional addition, CF = Charcoal-filtered, NF = Nonfiltered, NF+ = Nonfiltered plus ozone, E = Episodic, DP = Daily peak, U = Uniform, V = Variable, HE = High elevation.

[d]H = High, L = low.

[e]Significant at the 0.05 level, NS = not significant.

There is very limited information on the effect of O_3 on mature trees. Most of the information available deals with the nature of seedling response to O_3 (see Section 5.6.4); however, much less is known about the role of exposure-dynamic factors (e.g., concentration, duration, respite time, temporal variation) in influencing biomass response in long-lived species.

When yield is considered, a number of exposure-dynamic factors, including concentration, temporal pattern, predisposition, and respite times, as well as phenological stage of plant development, have been shown to influence the impact of O_3 on plant response. Evidence from studies of kidney bean (Musselman et al., 1983, 1994), alfalfa (Hogsett et al., 1985b), tobacco (Heagle et al., 1987b), soybean (Heagle et al., 1986b), ponderosa pine, and aspen suggests that concentration and temporal variation of exposure are important factors in influencing biomass production and, consequently, become considerations in measures of exposure. Because the SUM00 index weights all concentrations equally, the SUM00 is inadequate for characterizing plant exposure to O_3 (Lefohn et al., 1989). Other factors, including predisposition time (McCool et al., 1988) and crop development stage (Heagle et al., 1991b), contribute to variations in biological response, which suggests the need for weighting O_3 concentrations to account for predisposition time and phenology. However, the roles of predisposition and phenology in influencing plant response vary with species and environmental conditions and are not understood well enough to allow specification of a weighting function for use in characterizing plant exposure.

5.5.2.3 Combinations of Years, Sites, or Species: Comparisons of Yield Losses with Different Exposure Durations

Duration has not been a focus in experimental designs of studies that applied two or more exposure regimes over the growing season. Several lines of evidence suggest that the ultimate yield depends on the cumulative impact of repeated peak concentrations (U.S. Environmental Protection Agency, 1986, 1992), and that O_3-induced reductions in growth are linked to reduced photosynthesis, which is impaired by the cumulative O_3 exposure (Reich and Amundsen, 1985; Reich, 1987; Pye, 1988). In EPA reviews of the literature (U.S. Environmental Protection Agency, 1986, 1992), EPA concluded that "When plant yield is considered, the ultimate impact of an air pollutant on yield depends on the integrated impact of the pollutant exposures during the growth of the plant." As a measure of plant exposure, the appropriate index should differentiate between exposures of the same concentration but of different duration. For example, a mean index calculated over an unspecified time cannot accomplish this (Lefohn et al., 1988a; Hogsett et al., 1988; Tingey et al., 1989, 1991; U.S. Environmental Protection Agency, 1986, 1992).

The paper by Lefohn et al. (1988a), reviewed previously in U.S. Environmental Protection Agency (1992), along with published criticisms and responses, was the first to fit a common response model to combined data from two replicate studies of unequal duration (71 and 36 days for the 1982 and 1983 wheat studies, respectively, conducted at Ithaca, NY) to test specifically for the importance of duration in influencing plant response. Greater yield losses occurred in 1982, which can be attributed partially to the longer duration. Because the mean index ignores the length of the exposure period, the year-to-year variation in plant response was minimized by the use of several cumulative indices rather than the mean. Lefohn (1988) and Lefohn et al. (1988b) concluded that duration has value in explaining variation in plant response, and that a cumulative-type index was preferred over a mean or peak index based on statistical fit.

When O_3 effects are the primary cause of variation in plant response, plants from replicate studies of varying duration showed greater reductions in yield or growth when exposed for the longer duration (Lee et al., 1991; Olszyk et al., 1993; Adaros et al., 1991a) (Table 5-13, Part A). Using NCLAN data for wheat, cotton, kidney bean, and potato from replicate studies with markedly different exposure durations, Lee et al. (1991) showed that year-to-year variations in the magnitude of relative yield loss were minimized by the use of exposure indices that are cumulative and weight peak concentrations more than low concentrations, indicating that O_3 effects are cumulative (Figure 5-10). Olszyk et al. (1993), using the two NCLAN cotton studies summarized by Temple et al. (1985) and Lee et al. (1991), in addition to cotton studies replicated at four sites in California's San Joaquin Valley over 2 years, tested and compared various exposure indices (SIGMOID, SUM06, M7, and 2HDM) based on statistical fit of a common response model. A Weibull response model with variance components was fit to the combined data and used to test for a common response (Gumpertz and Rawlings, 1991, 1992; Gumpertz and Pantula, 1992). The likelihood ratio test of parallel exposure-response curves was statistically significant for M7 and 2HDM for at least one set of cotton data, indicating significant differences in the magnitude of response across years or sites. On the other hand, the SIGMOID and SUM06 indices resulted in consistent patterns of response for both sets of cotton data, as well as between sets of cotton data (Figure 5-11). The authors concluded that the peak-weighted, cumulative indices minimized the temporal and spatial variations in crop yield and better predicted cotton yield responses than the M7 or 2HDM indices. The mean and peak indices did not differentiate between exposure seasons of differing duration and could not account for year-to-year differences in response.

The results of European studies with wheat (Adaros et al., 1991a,c), spring rape (Adaros et al., 1991b), barley (Adaros et al., 1991c), and kidney beans (Bender et al., 1990), using data from replicate studies with varying duration, are less conclusive as to the role of duration in determining plant response (Table 5-13, Part A). Exposures are reported using a mean index. Adaros et al. (1991a) showed a greater reduction in above-ground dry weight when exposed for the longer duration for the wheat cultivar Star but not for the cultivar Turbo (Figure 5-12). Adaros et al. (1991c), in another 2-year study with barley (cv. Arena and Alexis) and wheat (cv. Star and Turbo), involving mixtures of O_3, SO_2, and NO_2, showed greater reductions in yield when exposed for the longer duration for all species and cultivars except barley cv. Alexis (Table 5-13, Part A). Ozone effects were insignificant in both years for barley cv. Alexis. The authors did not attribute the differential response in growth and yield to any single factor, but the data suggested that O_3 effects are cumulative. When O_3 exposure is the primary source of response, the mean exposure index of unspecified duration could not account for the year-to-year variation in response.

The role of duration in influencing growth or yield is unclear for the other studies because of the following limitations in the data:

   (1) Treatment levels were below the levels necessary to induce injury or damage to kidney bean plants in 2 of the 3 years. None of the years produced a significant O_3 effect at or below 70 ppb concentration (Bender et al., 1990). Similarly, the study with barley showed no significant O_3 effects.

Table 5-13. A Summary of Studies Reporting the Effects of Ozone on the Growth, Productivity, or Yield of Plants for Two or More Replicate Studies Having Equal Total Exposures and Either Varying Durations (Part A) or Similar Durations (Part B)[a]

Species	Facility[b]	Total No. of Plots	Duration [dates and (days)]	Concentration (ppm)/ Exposure (ppm-h)[c]	Variable	Effect[d]	Reference
PART A							
Brassica napus L. var. Napus cv. Callypso	OTC in pots	1987: 18 1988: 24 1989: 16	1987: 05-13 to 08-10 (89) 1988: 05-02 to 08-24 (113) 1989: 05-08 to 08-01 (84)	1987: M24 (M8) in ppb range from 5 (9) to 16 (43). 1988: M24 (M8) in ppb range from 3 (5) to 16 (48). 1989: M24 (M8) in ppb range from 6 (5) to 22 (62).	Seed dry weight	1987: 27% reduction at M8 = 43 ppb (***). 1988: 18% reduction at M8 = 48 ppb (***). 1989: 11% reduction at M8 = 62 ppb (***).	Adaros et al. (1991b)
Gossypium hirsutum L. cv. Acala SJ2	OTC	1981: 12 1982: 12	1981: 07-06 to 09-15 (72) 1982: 06-04 to 09-09 (98)	1981: M7 (SUM06) range from 18 ppb (0 ppm-h) to 138 (68). 1982: M7 (SUM06) range from 12 ppb (0 ppm-h) to 111 (71).	Lint dry weight	45 and 66% reductions at M7 = 111 ppb. 57 and 60% reductions at SUM06 = 68 ppm-h.	Lee et al. (1991), Olszyk et al. (1993)
Hordeum vulgare L. cf. Arena and Alexis	OTC in pots	1988: 24 1989: 16	1988: 04-29 to 08-15 (108) 1989: 05-08 to 08-15 (99)	1988: M8 (max 8-h mean) in ppb range from 5 (15) to 48 (89). 1989: M8 (max 8-h mean) in ppb range from 11 (27) to 62 (101).	Seed dry weight	Arena: 14% (*) and 6% (NS) reductions at M8 = 48 ppb. Alexis: No reductions at M8 = 48 ppb (NS).	Adaros et al. (1991c)
Phaseoulus vulgaris L. cv. Calif. Dark Red Kidney Bean	OTC	1980: 20 1982: 20	1980: 08-20 to 09-10 (22) 1982: 08-11 to 10-06 (57)	1980: M7 (SUM06) range from 24 ppb (0 ppm-h) to 139 (19). 1982: M7 (SUM06) range from 19 ppb (0 ppm-h) to 110 (40).	Seed dry weight	13 and 59% reductions at M7 = 110 ppb. 28 and 8% reductions at SUM06 = 19 ppm-h.	Lee et al. (1991)
Phaseolus vulgaris L. cf. Rintintin	OTC in pots	1988 I: 4 1988 II: 6 1989 III: 8	1988 I: 06-15 to 08-04 (51) 1988 II: 07-24 to 08-29 (37) 1989 III: 06-04 to 07-25 (52)	I. M8 (max) in ppb range from 3 (19) to 48 (70). II. M8 (max) in ppb range from 2 (19) to 50 (105). III. M8 (max) in ppb range from 6 (26) to 109 (159).	Pod dry weight	I. 2% reduction at M8 = 48 ppb (NS). II. 0% reduction at M8 = 50 ppb (NS). III. 0% (NS) and 47% (*) reductions at M8 = 50 and 109 ppb.	Bender et al. (1990)
Solanum tuberosum L. cv. Norchip	OTC	1985: 15 1986: 39	1985: 06-14 to 08-22 (70) 1986: 06-20 to 08-20 (62)	1985: M7 (SUM06) range from 22 ppb (0 ppm-h) to 85 (47). 1986: M7 (SUM06) range from 24 ppb (0 ppm-h) to 88 (38).	Tuber weight	42 and 25% reductions at M7 = 85 ppb. 32 and 27% reductions at 12-h SUM06 = 38 ppm-h.	Lee et al. (1991)
Triticum aestivum L. cv. Vona	OTC	1982: 20 1983: 12	1982: 05-18 to 07-17 (61) 1983: 06-12 to 07-17 (36)	1982: M7 (SUM06) range from 21 ppb (0 ppm-h) to 95 (41). 1983: M7 (SUM06) range from 26 ppb (0 ppm-h) to 96 (22).	Seed dry weight	74 and 49% reductions at M7 = 95 ppb. 49 and 62% reductions at SUM08 = 21 ppm-h. 55 and 60% reductions at 7-h SUM06 = 22 ppm-h.	Lefohn et al. (1988a), Lee et al. (1991)

Species	Facility[b]	Total No. of Plots	Duration [dates and (days)]	Concentration (ppm)/ Exposure (ppm-h)[c]	Variable	Effect[d]	Reference
PART A (cont'd)							
Triticum aestivum L. cv. Star and Turbo	OTC in pots	1988: 6 1989: 10	1988: 04-27 to 08-23 (118) 1989: 05-09 to 08-15 (98)	1988: M8 (max,SUM06) in ppb range from 4 (58,0) to 51 (106,8.2). 1989: M8 (max,SUM06) in ppb range from 10 (34,0) to 113 (162,87).	Seed dry weight	Star: 20% (*) and 9% (NS) reductions at M8 = 51 ppb. Turbo: 25% (*) and 31% (*) reductions at M8 = 51 ppb.	Adaros et al. (1991a)
Triticum aestivum L., cv. Star and Turbo	OTC in pots	1988: 24 1989: 16	1988: 04-29 to 08-15 (108) 1989: 05-08 to 08-15 (99)	1988: M8 (max 8-h mean) in ppb range from 5 (15) to 48 (89). 1989: M8 (max 8-h mean) in ppb range from 11 (27) to 62 (101).	Seed dry weight	Star: 26% (*) and 12% (*) reductions at M8 = 48 ppb. Turbo: 34% (*) and 17% (*) reductions at M8 = 48 ppb.	Adaros et al. (1991c)
PART B							
Glycine max L. Merr. cv. Davis	OTC in pots	1977: 8 1978: 8	1977: 06-17 to 10-10 (116) 1978: 06-28 to 10-21 (116)	1977: M7 (max) in ppb range from 27 (78) to 154 (277). 1978: M7 (max) in ppb range from 28 (84) to 131 (241).	Seed dry weight	47 and 37% reductions at M7 = 131 ppb.	Cure et al. (1986), Heagle et al. (1983a)
Glycine max L. Merr. cv. Williams	OTC	1981: 31 1982: 31 1983: 31	1981: 07-20 to 09-22 (65) 1982: 07-14 to 09-22 (71) 1983: 07-23 to 09-23 (63)	1981: M7 in ppb range from 15 to 64. 1982: M7 in ppb range from 17 to 99. 1983: M7 in ppb range from 19 to 132.	Bean dry weight	28, 20, and 32% reductions at M7 = 64 ppb. 43 and 41% reductions at M7 = 99 ppb in 1982 and 1983	Heggestad and Lesser (1990), Heggestad et al. (1988)
Medicago sativa L. cv. WL-514	OTC	1984: 30 1985: 30	1984: 03-16 to 10-10 (209) 1985: 03-23 to 10-09 (201)	1984: M12 in ppb range from 16 to 109. 1985: M12 in ppb range from 10 to 94.	Top dry weight	29% (*) and 25% (*) reductions at M12 = 94 ppb.	Temple et al. (1988a)
Pinus rigida Mill.	OTC in pots	Exp. 1: 4 Exp. 2: 4	Exp. 1: 13 weeks Exp. 2: 13 weeks	1: M8 in ppb range from 0 to 200 (U). 2: M8 in ppb range from 0 to 200 (U).	Total dry weight	49 and 46% reductions at M8 = 200 ppb.	Schier et al. (1990)
Pinus taeda L.	GC in pots	1986: 15 1987: 15	1986: 09-15 to 12-04 (81) 1987: 07-27 to 10-15 (81)	1986: SUM00 in ppm-h range from 0 to 99 (U). 1987: SUM00 in ppm-h range from 0 to 99 (U).	Total dry weight	43 and 28% reductions at SUM00 = 99 ppm-h averaged across all families. Individual families show similar reductions (e.g., 35 and 33% reductions at SUM00 = 99 ppm-h for family 5.56, 14 and 12% reductions at SUM00 = 99 ppm-h for family 1.68).	Shafer et al. (1993)

Table 5-13 (cont'd). A Summary of Studies Reporting the Effects of Ozone on the Growth, Productivity, or Yield Of Plants for Two or More Replicate Studies Having Equal Total Exposures and Either Varying Durations (Part A) or Similar Durations (Part B)[a]

Species	Facility[b]	Total No. of Plots	Duration [dates and days]	Concentration (ppm)/ Exposure (ppm-h)[c]	Variable	Effect[d]	Reference
PART B (cont'd)							
Picea rubens Sarg.	OTC in pots	1987: 12 1988: 12	1987: 05-30 to 12-15 (199) 1988: 06-01 to 12-01 (184)	1987: SUM00 in ppm-h are 32, 61, 91, and 119. 1987: SUM00 in ppm-h are 36, 70, 101, and 135.	Total dry weight	0% (NS) reduction in biomass after first year, 8% (*) reduction at SUM00 = 135 ppm-h after second year of exposure.	Alscher et al. (1989) Amundson et al. (1991)
Pisum sativum L. cv. Puget	ZAPS	1986: 14 1987: 14	1986: last 58 days 1986: last 52 days	M12 and D25 (numbers of days with 1-h concentrations >25 ppb) used in simple linear regression.	Pea fresh weight	0% reductions at M12 = 100 ppb based on linear regression models.	Runeckles et al. (1990)
Populus tremuloides Michx clones	OTC in pots	1988: 18 1989: 18	1988: 07-19 to 09-27 (71) 1989: 07-20 to 09-20 (64)	1988: SUM00 in ppm-h are 5.0, 10.0, and 19.4 (U). 1989: SUM00 in ppm-h are 7.7, 15.4, and 26.4 (U).	Stem and leaf dry weights	36% (*) and 40% (*) reductions at SUM00 = 19.4 ppm-h.	Karnosky et al. (1992b)
Triticum aestivum L. cv. Albis	OTC	1986: 12 1987: 16 1988: 16	1986: 05-06 to 07-31 (86) 1987: 04-27 to 08-10 (92) 1988: 05-04 to 08-01 (89)	1986: M24 (max) in ppb range from 12 (61) to 47 (181). 1987: M24 (max) in ppb range from 12 (54) to 45 (175). 1988: M24 (max) in ppb range from 17 (65) to 45 (148).	Seed dry weight	1986: 61% reduction at M24 = 47 ppb. 1987: 27% reduction at M24 = 45 ppb. 1988: 65% reduction at M24 = 45 ppb.	Fuhrer et al. (1989)
Triticum aestivum L. cv. Albis	OTC	1989: 24 1990: 24	1989: 05-16 to 08-14 (91) 1990: 05-14 to 08-09 (88)	1989: M7 (SUM06) range from 18 ppb (0 ppm-h) to 62 (3.8). 1990: M7 (SUM06) range from 17 ppb (0 ppm-h) to 71 (5.6).	Seed dry weight	29 and 22% reduction at M7 = 62 ppb. 29 and 17% reduction at SUM06 = 3.8 ppm-h.	Fuhrer et al. (1992)
Triticum aestivum L. cv. Severn, Potomac, Oasis, MD5518308	OTC	1984: 20 1985: 20	1984: 05-14 to 06-22 (40) 1985: 05-06 to 06-15 (41)	1984: M4 (AOT03) in ppb (ppb-h) range from 32 (0) to 93 (10). 1985: M4 (AOT03) in ppb (ppb-h) range from 30 (0) to 86 (9).	Seed dry weight	31% (*) and 9% (NS) reductions at M4 = 86 ppb.	Slaughter et al. (1989)

[a]See Appendix A for abbreviations and acronyms.
[b]GC = Controlled environmental growth chamber, or CSTR; OTC = open-top chamber; ZAPS = zonal air pollution system.
[c]U = Uniform.
[d]* = Significant at the 0.05 level; NS = not significant.
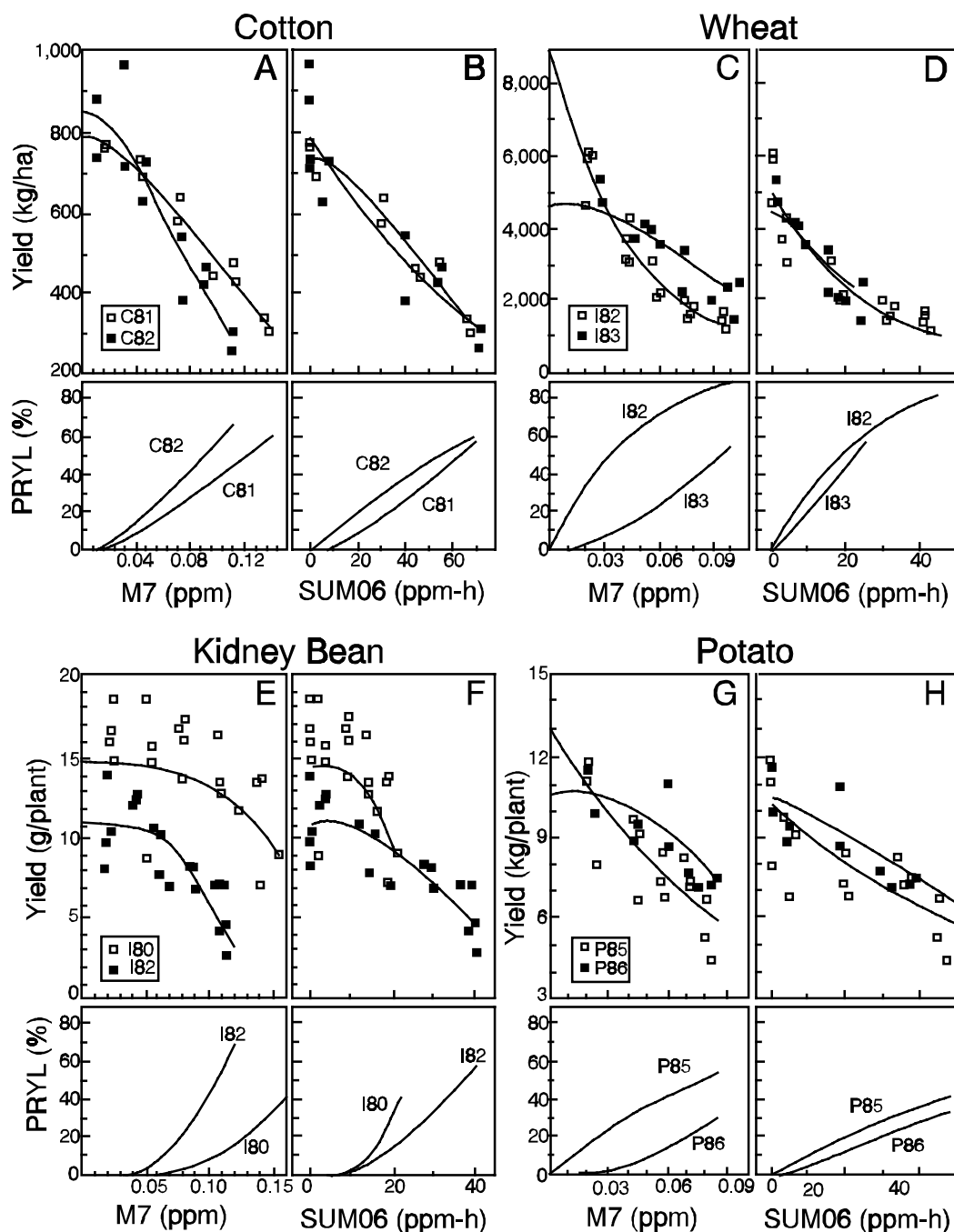
Figure 5-10.

Comparison of the Weibull exposure-response functions and its predicted relative yield loss (PRYL) curves (relative to 0 ozone) using M7 and daytime SUM06 for replicate years of National Crop Loss Assessment Network Program's data for (A) and (B) cotton (var. Acala SJ-2), (C) and (D) wheat (var. Vona), (E) and (F) kidney bean (var. California light red), and (G) and (H) potato (var. Norchip), respectively. Mean dry weights and the Weibull exposure-response functions for replicate studies are given in the top portion of the graphs (Lee et al., 1991).
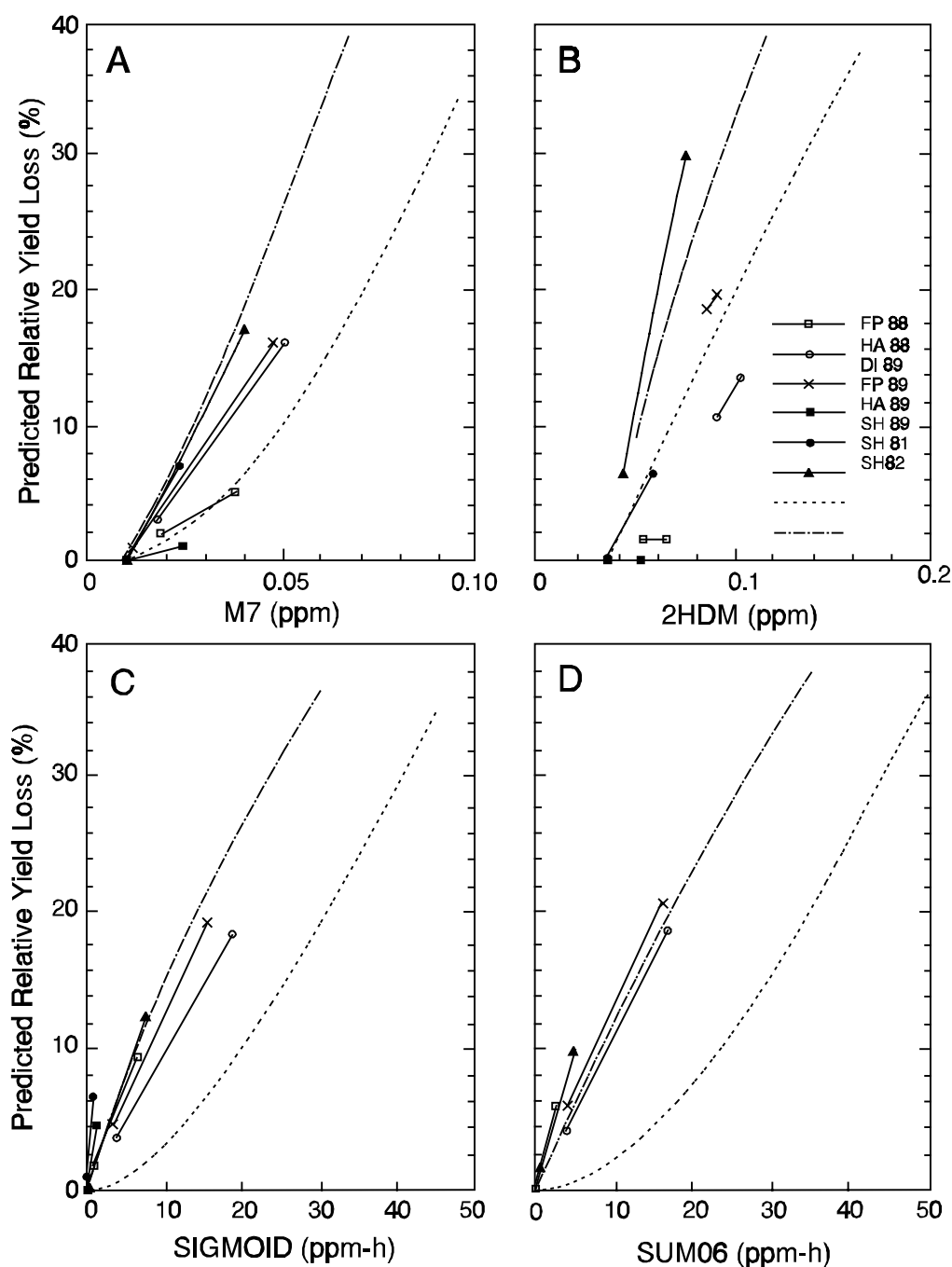
Figure 5-11. **Predicted relative yield losses (lint weight) for Acala SJ-2 cotton for four sites and multiple years (1981, 1982, 1988, and 1989) relative to 0.01 ppm for M7, 0.035 ppm for 2HDM, 0 ppm-h for SIGMOID, and 0 ppm-h for SUM06, which correspond to typical levels in the charcoal-filtered chambers. Predicted losses are based on M7 (A), 2HDM (B), SIGMOID (C), and SUM06 (D) exposure indices. Abbreviations: DI = Dinuba, FP = Five Point, HA = Hanford, and SH = Shafter (Olszyk et al., 1993).**

Figure 5-12. *Relative effect of ozone on growth and yield of spring wheat cultivars (var. Star and Turbo) from two growing seasons (Adaros et al., 1991a).*

(2) Differences in growing conditions and varying kinds of interactions among O_3, SO_2, and NO_2 resulted in different sizes of control plants of spring rape over y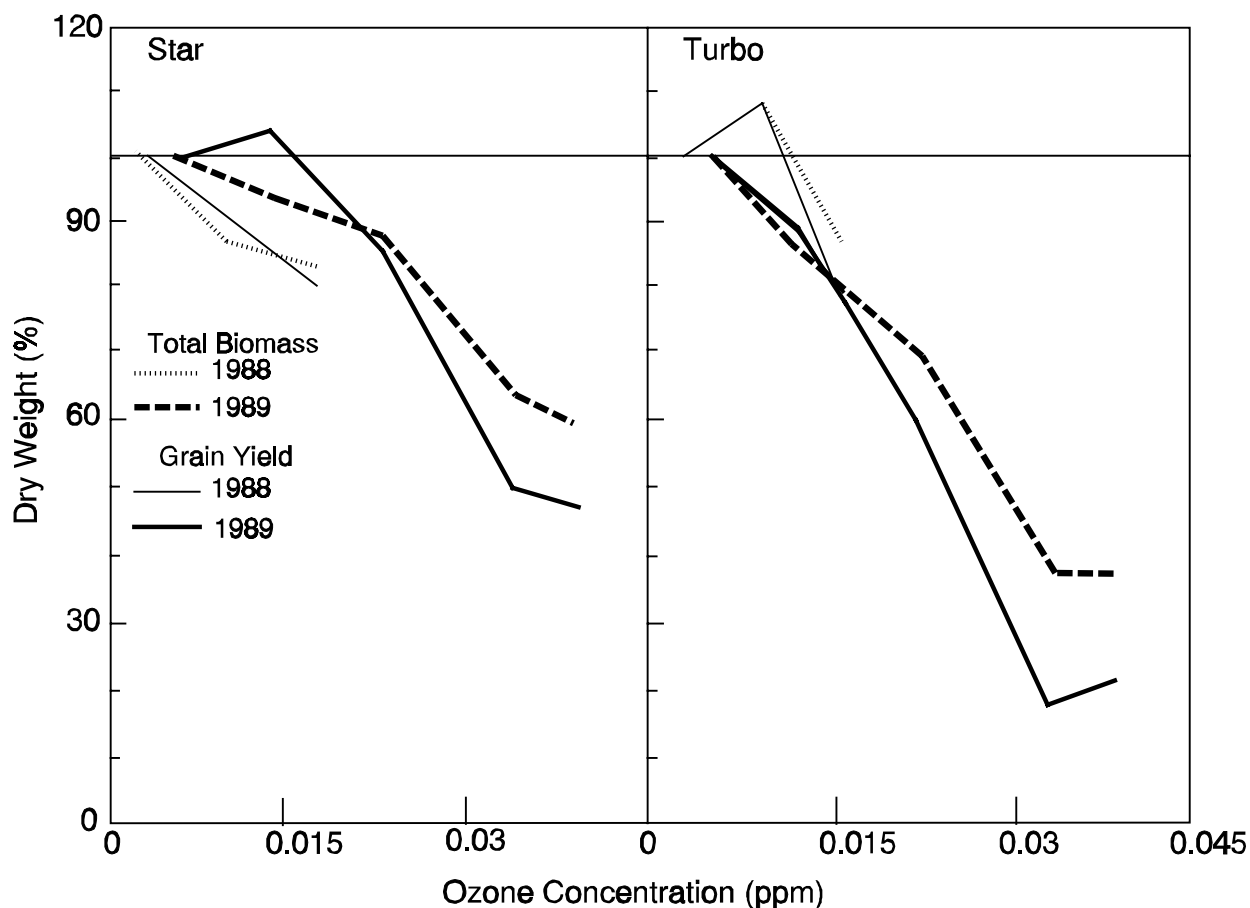ears and affected the magnitude of response to O_3. Compared to 1987, yield of control plants increased by 32% in 1988 and by 94% in 1989 (Adaros et al., 1991b). Consequently, the evidence of duration as the primary cause of differences in response over years was difficult to substantiate.

When durations were nearly equal, plant response to O_3 were similar for 2- or 3-year studies with alfalfa (Temple et al., 1988a), pea (Runeckles et al., 1990), soybean (Heagle et al., 1983a; Heggestad and Lesser, 1990; Cure et al., 1986), wheat (Fuhrer et al., 1989, 1992), aspen clones (Karnosky et al., 1992b), loblolly pine (Shafer et al., 1993), and pitch pine (Schier et al., 1990) (Table 5-13, Part B). For example, year-to-year variations in wheat yield response to O_3 were small for the 3 years having durations between 86 and 92 days, allowing pooling of the data to fit a common Weibull model using Rawling's solar-radiation-weighted mean index (Fuhrer et al., 1989) (Figure 5-13). Different growing conditions were reported in studies of Shafer et al. (1993), Fuhrer et al. (1989), but no
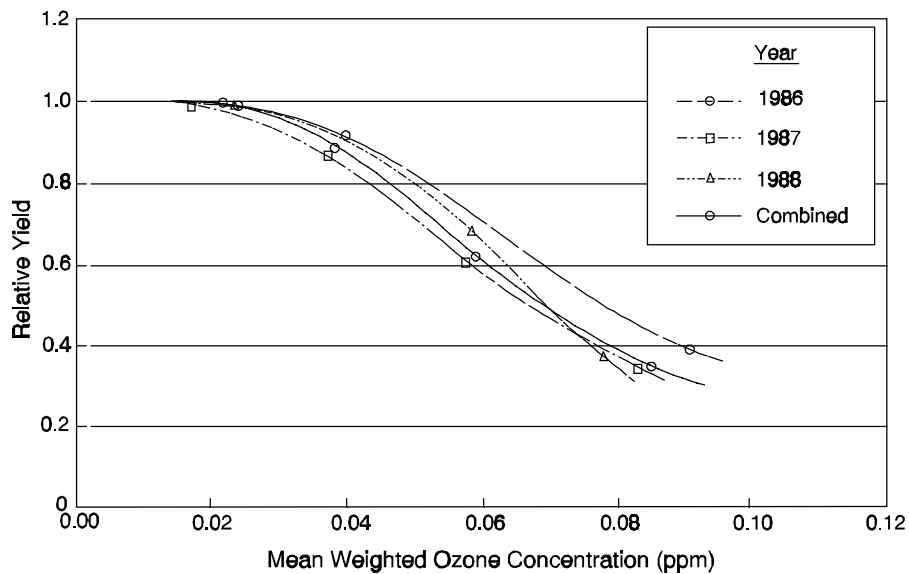
Figure 5-13.

Weibull exposure-response curves for the relative effect of ozone on grain yield of spring wheat for 3 years, individually and combined (Fuhrer et al., 1989).

interaction between O_3 and climatic effects was found. On the other hand, Slaughter et al. (1989) reported reductions in wheat grain yield of 69 and 9% in a 2-year study having equal exposure durations, which the authors attribute to differences in rainfall and temperature. Environmental conditions in 1985 favored greater photosynthate partitioning for grain development rather than for vegetative growth, resulting in larger plants in 1985. Air pollution effects may not have been the primary source of variation in response, and, consequently, the data do not substantiate the role of duration in influencing response.

These studies report plant response as a function of a mean exposure index and do not evaluate or compare various exposure indices, based on statistical fit. In a series of papers that examined the response of spring wheat to O_3 at higher elevations, Grandjean Grimm and Fuhrer (1992a,b) and Fuhrer et al. (1992) conducted a 2-year study in which the flux of O_3 was determined in OTCs. Plants were exposed to O_3 for periods lasting 44 and 50 days in 1989 and 1990, respectively, and flux measurements were taken repeatedly over the experimental period. In addition to O_3 flux, exposures were characterized using M7, M24, SUM06, and the solar-radiation-weighted mean index (Rawlings et al., 1988b). The quadratic response curves relating the various indices with grain yield showed that year-to-year variations were minimized using the mean O_3 flux index (Figure 5-14). The other three exposure indices showed slightly greater yield losses in 1989 than in 1990, in contrast with longer exposure in 1990 and drier conditions in 1989. The authors concluded that the O_3 flux related well with yield because the mean flux incorporated environmental factors, canopy structure, and physiological processes, which affected the uptake of O_3 from the air to the leaf interior. The measurements of pollutant concentrations ignored these factors and,

consequently, were unable to account for all of the year-to-year variability in wheat response. The authors suggested that O_3 flux was a surrogate of Fowler and Cape's
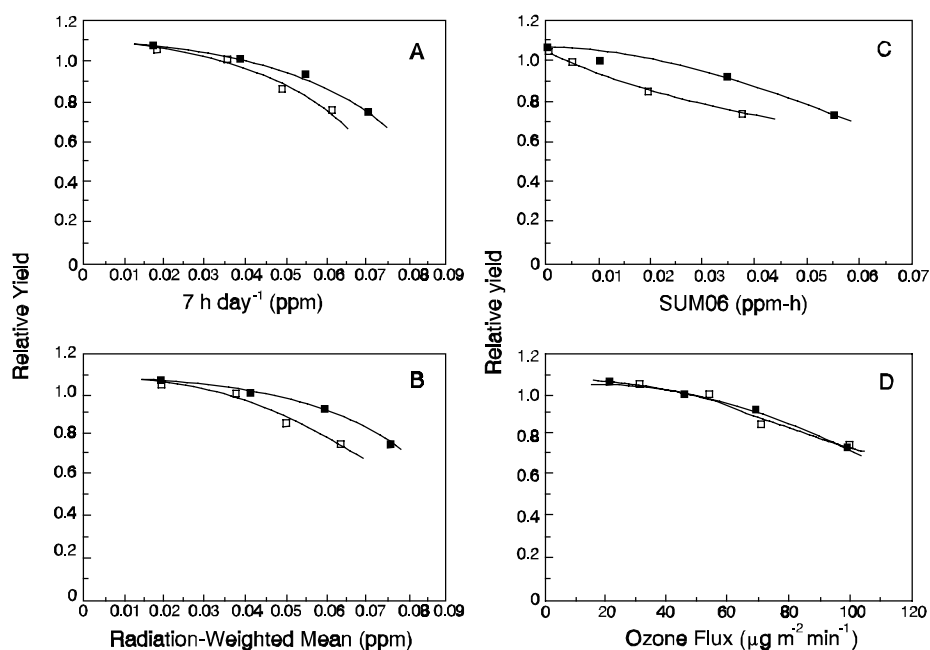
Figure 5-14.

Quadratic exposure-response curves for the relative effect of ozone on grain yield of spring wheat in 1989 and 1990, using four different exposure indices (A through D).

Source: Modified from Fuhrer et al. (1992).

(1982) "pollutant absorbed dose" and appeared to be the relevant measure for use in relating exposure and plant response.

Alscher et al. (1989) and Amundson et al. (1991) report on the impact of O_3 on growth, injury, and biomass response of 2-year-old red spruce seedlings after 1 and 2 years of exposure, respectively. Exposures were characterized using the M12 (or M7), M24, and SUM00 indices. No significant O_3 effects on biomass were detected in 1987 (Alscher et al., 1989) because stomatal conductances in red spruce are inherently low and, consequently, result in low rates of pollutant uptake (Seiler and Cazell, 1990). However, in the second year, O_3 reduced leaf and root starch, increased foliar antioxidant content, and reduced biomass of 1988 fixed-growth foliage. However, O_3 effects on biomass were slight in the second year. The authors concluded O_3 effects are cumulative because the onset of damage occurred in the second year rather than the first year of exposure.

Plant response is influenced by exposure duration and O_3 concentration. Regardless of whether concentrations are above or below levels at which injury has been observed, plant responses are determined by the cumulative effects of the number of times exposures have occurred. The results of these studies are in general agreement that O_3 effects are cumulative, and the ultimate impact of long-term exposures to O_3 on crops and seedling biomass response depends on the integration of repeated peak concentrations during the growth of the plant. Consequently, the mean or peak indices are inappropriate because the length of exposure is unspecified, and these indices cannot differentiate among exposures of

the same concentration but of various durations. These results support the conclusion that an appropriate O_3 index should cumulate all hourly concentrations in some fashion to reflect the nature of O_3 on plant response. Fuhrer et al. (1992) suggested that the weighting function should reflect the relationship between ambient pollutant concentration and internal O_3 flux, consistent with the mode of action of O_3 on plants and with earlier findings that peak-weighted, cumulative indices give better predictions of plant response than mean or peak indices.

5.5.2.4 Comparisons of Measures of Exposure Based on Reanalysis of Single-Year, Single-Species Studies

Studies cited in previous sections focused on the role of the structure of exposure in influencing plant response but do not identify specifically the weighting function for use in characterizing plant exposure to O_3. In addition to these types of studies, other studies have focused on comparison of measures of exposure based on reanalysis of single-year, single-species studies. The variety of statistical approaches used to relate exposure and plant response range from informal description of the distributions of O_3 concentrations associated with response to more formal regression-based procedures.

The regression approach is designed to select those exposure indices that properly order and space the treatment means along the horizontal axis to optimize the fit of a linear or curvilinear model. However, because the experimental designs are not intended to evaluate various indices, the power of the regression approach to identify the important exposure-dynamic factors influencing plant response is less desirable (Lefohn et al., 1992a). Consequently, these retrospective studies provide less substantiating evidence of the role of exposure-dynamic factors (e.g., concentration, duration, temporal pattern, respite time) than do those studies with experimental designs and analyses that focus on specific components of exposure.

Most of the early retrospective studies reporting regression results using data from the NCLAN program or from Corvallis, OR (Lee et al., 1987, 1988; Lefohn et al., 1988a; Tingey et al., 1989), or using data collected by Oshima (U.S. Environmental Protection Agency, 1986; Musselman et al., 1988) were in general agreement and consistently favored the use of cumulative peak-weighted exposure indices. These studies have been reviewed previously by EPA (U.S. Environmental Protection Agency, 1992). Lee et al. (1987) suggested that exposure indices that included all the data (24 h) performed better than those that used only 7 h of data; this is consistent with the conclusions of Heagle et al. (1987b) that plants receiving exposures for an additional 5 h/day showed 10% greater yield loss than those exposed for 7-h/day. In a subsequent analysis using more of the NCLAN data, Lee et al. (1988) found the "best" exposure index was a general phenologically weighted, cumulative-impact index, with sigmoid weighting on concentration and a gamma weighting function as surrogate of time of increased plant sensitivity to O_3. For most cases, Lee et al. (1987) computed their exposure indices based on the daylight exposure periods used by the NCLAN investigators. The exposure indices with minimum residual sum of squares were those indices that cumulated hourly O_3 concentrations over the growth of the plant, gave preferential weighting to peak concentrations, and phenologically weighted the exposures to emphasize concentrations during the plant growth stage. The paper by Tingey et al. (1989) is a summarization of the results in Lee et al. (1988) and shows the limitations of the mean index.

Lefohn and Foley (1992) characterized the NCLAN exposures that had a SUM06 level closest to those that predicted a 20% yield loss, using the exposure-response equations as reported in Lee et al. (1991) and Tingey et al. (1991). Lefohn and Foley (1992) characterized the hourly average concentrations using percentiles, HRS06, HRS10, SUM06, and W126 for each of 22 NCLAN studies. The authors noted that the frequent occurrence, in many cases, of high hourly concentrations ($\geq$0.10 ppm) may have been partly responsible for the 20% yield loss. The number of hourly average concentrations ranged from 0 to 515 with only one of the 22 NCLAN experiments experiencing no hourly average concentrations $\geq$0.10 ppm, whereas the remaining experiments experienced multiple occurrences $\geq$0.10 ppm. The repeated occurrences of high hourly average concentrations were a result of the NCLAN protocol (Table 5-14). As a result of their analysis, Lefohn and Foley (1992) and Lefohn et al. (1992b) stressed that, because the NCLAN experiments contained peak hourly average concentrations, it is important that any index selected to characterize those regimes responsible for growth reduction adequately capture the presence of these peak concentrations when attempting to predict biological responses using actual ambient air quality data.

For example, Tingey et al. (1991), using mostly NCLAN data, identified 24.4 ppm-h as the SUM06 value, calculated over a 3-mo period, that would protect 50% of the NCLAN crops analyzed at the 10% yield reduction level. These predicted relative yield loss (PRYL) calculations assume that the crops being protected will be grown using NCLAN protocol. There are monitoring sites in the United States that experience 3-mo cumulative SUM06 values greater than 24.4 ppm-h, but do not experience frequent occurrences of hourly average concentrations >0.10 ppm. For example, 24% (1987), 10% (1988), 30% (1989), 25% (1990), and 31% (1991) of the rural agricultural sites listed in the EPA Aerometric Information Retrieval System (AIRS) database experienced 3-mo cumulative SUM06 values greater than 24.4 ppm-h but experienced fewer than 11 hourly average concentrations equal to or greater than 0.10 ppm. Lefohn and Foley (1992) noted that agricultural crops grown at a site experiencing a 3-mo cumulative SUM06 value greater than 24.4 ppm-h, but with infrequent high hourly average concentrations (e.g., $\geq$0.10 ppm), might experience less yield reduction than predicted using NCLAN experimental results. For rural forest sites, 21% (1987), 23% (1988), 54% (1989), 50% (1990), and 52% (1991) of the sites exhibited 3-mo cumulative SUM06 values greater than 24.4 ppm-h, but fewer than 11 hourly average concentrations equal to or greater than 0.10 ppm. Tables 5-15 and 5-16 illustrate that sites that experience 3-mo SUM06 values $\geq$24.4 ppm do not necessarily have peaks, whereas sites that experience values <24.4 ppm-h do have peaks.

Reich (1987) reviewed 44 studies on 45 species to study the effects of O_3 on net photosynthesis (Pn) and growth of crops and tree species. Plants responded differently to equivalent total exposures (i.e., SUM00), when peak concentrations differed widely, with greater loss of Pn for increasing concentrations (Figure 5-15). Short-term, high concentrations above 0.40 ppm (e.g., 0.50 ppm for 8 h) caused rapid and significant reduction in Pn. Longer term exposures (for weeks) to lower concentrations had a significant effect on Pn; the observed reductions were less severe than at the higher concentrations. Based on short-term, high concentration studies, SUM00 alone was an inadequate descriptor of exposure for predicting response. However, for assessing the effects of long-term, low concentrations typical of ambient condition, SUM00 may be adequate, because the response of field-grown plants to SUM00 was roughly linear. SUM00 explained much, although not all, of the variation in Pn and the growth of conifers, hardwood trees, and agricultural crops (Figures 5-16 through 5-18). Unexplained variation can be attributed to biological variation, inherent experimental error, experimental conditions, and differences

Table 5-14. Summary of Ozone Exposures That Are Closest to Those Predicted for 20% Yield Reduction per SUM06 Exposure Response Models Used by Lee et al. (1991) in Selected National Crop Loss Assessment Network Experiments[a] (Concentrations are in parts per million.)

Experiment[b]	Chamber	Min.	10	30	50	70	90	95	99	Max	Number of Obs.	≥0.06	≥0.08	≥0.10	SUM 06 (ppm-h)	08 (ppm-h)	W126 (ppm-h)
SOYBEAN																	
A80S0 - Corsoy	NF+0.03-1	0.000	0.000	0.011	0.026	0.045	0.077	0.090	0.111	0.123	1,344	263	113	35	21.1	10.7	17.7
A83SO - Amsoy	NF+0.03-1	0.000	0.001	0.014	0.028	0.049	0.083	0.098	0.123	0.168	1,992	467	223	90	39.1	22.1	33.2
A83SO - Corsoy	NF+0.03-1	0.000	0.001	0.014	0.028	0.049	0.083	0.098	0.123	0.168	1,992	467	223	90	39.1	22.1	33.2
A85SO - Corsoy-79 D	NF×2.00-1D	0.000	0.000	0.008	0.023	0.051	0.110	0.129	0.160	0.194	2,352	657	495	319	67.5	56.2	63.0
A85SO - Corsoy-79 W	NF×2.00-1W	0.000	0.000	0.011	0.026	0.063	0.114	0.134	0.162	0.199	2,352	729	547	358	75.1	62.5	70.0
A86SO - Corsoy-79 D	NF×2.5-1D	0.000	0.002	0.016	0.035	0.085	0.137	0.161	0.207	0.279	2,040	784	654	515	92.1	83.2	88.6
A86SO - Corsoy-79 W	NF×2.0-1W	0.000	0.002	0.015	0.033	0.065	0.105	0.124	0.161	0.242	2,040	719	510	271	69.6	55.1	63.7
B83SO - Corsoy-79 D	NF-1D	0.000	0.002	0.006	0.018	0.037	0.063	0.074	0.087	0.111	1,512	184	51	5	13.5	4.4	10.6
B83SO - Corsoy-79 W	NF+0.03-1W	0.000	0.002	0.006	0.019	0.049	0.084	0.097	0.118	0.135	1,512	359	198	70	30.1	18.9	25.8
B83SO - Williams D	NF+0.03-1D	0.000	0.002	0.006	0.019	0.049	0.084	0.098	0.118	0.137	1,512	364	204	66	30.5	19.5	26.0
B83SO - Williams W	NF+0.03-1W	0.000	0.002	0.006	0.019	0.049	0.084	0.097	0.118	0.135	1,512	359	198	70	30.1	18.9	25.8
I81SO - Hodgson	NF+0.06-1	0.000	0.004	0.007	0.015	0.031	0.083	0.090	0.105	0.132	1,680	323	191	29	26.7	17.4	22.9
R81SO - Davis	NF-1	0.000	0.003	0.015	0.026	0.043	0.066	0.075	0.088	0.145	2,664	421	79	6	30.2	7.0	22.6
R82SO - Davis	NF+0.02-1	0.000	0.001	0.013	0.026	0.047	0.080	0.091	0.123	0.203	2,160	471	218	56	39.0	21.4	33.1
R83SO - Davis Dry	NF+0.02-1D	0.000	0.002	0.015	0.030	0.055	0.089	0.104	0.126	0.155	2,640	721	378	163	61.6	37.7	53.1
R83SO - Davis Wet	NF+0.02-1W	0.000	0.002	0.015	0.030	0.054	0.087	0.101	0.119	0.138	2,640	698	359	140	58.7	35.0	50.7
R84SO - Davis Dry	NF+0.015-1D	0.000	0.006	0.018	0.030	0.047	0.077	0.089	0.113	0.140	2,496	512	208	59	41.2	19.9	34.8
R84SO - Davis Wet	NF+0.015-1W	0.000	0.006	0.018	0.029	0.046	0.075	0.089	0.110	0.159	2,496	486	193	62	38.9	18.6	32.6
R86SO - Young Dry	NF×1.3-1D	0.000	0.003	0.013	0.024	0.047	0.089	0.107	0.137	0.206	2,568	597	345	175	53.7	36.2	47.7
R86SO - Young Wet	NF×1.3-1W	0.000	0.003	0.013	0.023	0.046	0.087	0.101	0.129	0.198	2,568	573	323	136	50.2	32.8	44.1
SORGHUM																	
A82SG - Dekalb	NF+0.10-1	0.000	0.001	0.010	0.023	0.055	0.145	0.160	0.185	0.223	2,040	599	557	516	79.1	76.3	78.2
WHEAT																	
A82WH - Abe	NF+0.03-1	0.000	0.002	0.015	0.027	0.047	0.079	0.094	0.113	0.149	1,344	300	130	43	24.1	12.5	19.8
A82WH - Arthur-71	NF+0.06-1	0.000	0.002	0.015	0.027	0.053	0.109	0.121	0.144	0.170	1,344	373	293	186	37.4	31.8	35.3
A83WH - Abe	NF+0.06-1	0.000	0.004	0.019	0.032	0.054	0.108	0.123	0.159	0.186	1,296	365	295	186	37.4	32.5	35.6
A83WH - Arthur-71	NF+0.06-1	0.000	0.004	0.019	0.032	0.054	0.108	0.123	0.159	0.186	1,296	365	295	186	37.4	32.5	35.6
BTI82WH - VONA	NF-1	0.000	0.011	0.025	0.034	0.042	0.057	0.064	0.072	0.098	1,464	114	2	0	7.6	0.2	6.2
BTI83WH - VONA	NF-1	0.000	0.006	0.021	0.036	0.049	0.071	0.083	0.097	0.116	864	165	51	4	12.4	4.7	9.8

Table 5-14 (cont'd). Summary of Ozone Exposures That Are Closest to Those Predicted for 20% Yield Reduction per SUM06 Exposure Response Models Used by Lee et al. (1991) in Selected National Crop Loss Assessment Network Experiments[a] (Concentrations are in parts per million.)

Experiment[b]	Chamber	Min.	10	30	50	70	90	95	99	Max	Number of Obs.	≥0.06	≥0.08	≥0.10	SUM 06 (ppm-h)	08 (ppm-h)	W126 (ppm-h)
CORN																	
A81MA - PAG 397	NF+0.06-2	0.000	0.000	0.008	0.020	0.052	0.111	0.126	0.150	0.187	1,968	552	461	306	57.5	51.0	55.1
A81MA - Pioneer	NF+0.06-2	0.000	0.000	0.008	0.020	0.052	0.111	0.126	0.150	0.187	1,968	552	461	306	57.5	51.0	55.1
COTTON																	
R82CO - Stoneville	NF-1	0.000	0.003	0.018	0.029	0.044	0.065	0.074	0.087	0.152	2,856	390	64	7	28.2	5.8	22.7
R85CO - McNair Dry	NF×1.99-1D	0.000	0.003	0.012	0.024	0.052	0.117	0.154	0.221	0.291	3,000	810	609	407	92.9	78.9	88.2
R85CO - McNair Wet	NF×1.33-1W	0.000	0.003	0.012	0.024	0.041	0.073	0.091	0.129	0.166	3,000	487	226	118	41.4	23.5	35.9
PEANUT																	
R80PN - NC-6	NF+0.015-1	0.000	0.004	0.017	0.029	0.043	0.066	0.076	0.091	0.112	2,688	369	101	5	27.2	8.8	22.0
TOBACCO																	
R83TO - McNair 944	NF+0.020-1	0.000	0.003	0.018	0.037	0.061	0.089	0.104	0.121	0.155	1,968	611	288	117	50.7	28.4	42.6

[a]See Appendix A for abbreviations and acronyms.
[b]Separate analyses were performed for each water stress level, dry (D) and well-watered (W).

Table 5-15. Summary of Percentiles for Ozone Monitoring Sites in 1989 (April through October) with a Maximum Three-Month SUM06 Value <24.4 ppm-h but with a Second Hourly Maximum Concentration ≥0.125 ppm

AIRS Site	Name	Min.	10	30	50	Percentiles 70	90	95	99	Max	Maximum Uncorrected SUM06 (ppm-h)	Number of Observ. Over 7-mo Period
060010003	Livermore, CA	0.000	0.000	0.010	0.030	0.040	0.050	0.060	0.090	0.140	17.0	5,067
060371301	Lynwood, CA	0.000	0.000	0.010	0.020	0.030	0.050	0.070	0.100	0.140	18.1	4,793
060374002	Long Beach, CA	0.000	0.010	0.020	0.020	0.030	0.050	0.060	0.080	0.160	13.6	4,876
060375001	Hawthorne, CA	0.000	0.000	0.020	0.030	0.040	0.060	0.060	0.080	0.190	18.1	4,894
060830008	Santa Barbara, CA	0.000	0.010	0.020	0.030	0.040	0.050	0.060	0.080	0.190	17.1	4,823
060830010	Santa Barbara, CA	0.000	0.010	0.020	0.030	0.040	0.050	0.060	0.080	0.220	13.3	4,663
060833001	Santa Barbara County, CA	0.000	0.010	0.020	0.030	0.040	0.050	0.060	0.080	0.140	12.3	5,077
090010113	Bridgeport, CT	0.000	0.002	0.011	0.022	0.033	0.048	0.059	0.091	0.156	16.5	4,865
090091123	New Haven, CT	0.000	0.003	0.010	0.019	0.029	0.045	0.056	0.091	0.156	12.9	4,502
220191003	Westlake, LA	0.000	0.003	0.013	0.022	0.033	0.052	0.061	0.082	0.137	12.2	4,811
220330003	Baton Rouge, LA	0.000	0.001	0.009	0.021	0.034	0.059	0.069	0.094	0.168	17.4	4,964
220330004	Baton Rouge, LA	0.000	0.002	0.008	0.016	0.028	0.047	0.057	0.078	0.138	8.4	4,791
220331001	East Baton Rouge, LA	0.000	0.003	0.012	0.022	0.034	0.056	0.066	0.092	0.171	14.4	4,890
220470002	Iberville Parish, LA	0.000	0.005	0.014	0.023	0.034	0.057	0.068	0.093	0.149	15.9	5,040
220770001	New Roads, LA	0.000	0.001	0.011	0.021	0.033	0.052	0.062	0.083	0.141	12.0	4,964
230052003	Cape Elizabeth, ME	0.001	0.017	0.027	0.034	0.042	0.055	0.064	0.093	0.146	16.7	4,627
471630009	Kingsport, TN	0.001	0.001	0.005	0.017	0.032	0.054	0.062	0.078	0.125	13.4	4,252
481410027	El Paso, TX	0.000	0.010	0.020	0.030	0.040	0.050	0.060	0.080	0.260	14.9	4,484
481990002	Kountze, TX	0.000	0.000	0.010	0.020	0.030	0.050	0.060	0.080	0.130	10.6	4,630
482010024	Harris County, TX	0.000	0.000	0.010	0.020	0.030	0.060	0.070	0.110	0.230	19.2	4,728
482010062	Houston, TX	0.000	0.000	0.010	0.020	0.030	0.050	0.070	0.110	0.170	16.8	4,600
482011034	Houston, TX	0.000	0.000	0.010	0.010	0.030	0.050	0.060	0.100	0.220	14.0	4,595
482011037	Houston, TX	0.000	0.000	0.010	0.010	0.030	0.050	0.060	0.110	0.250	16.3	4,729
490350003	Salt Lake County, UT	0.000	0.001	0.008	0.029	0.042	0.056	0.062	0.083	0.125	17.4	4,585
490353001	Salt Lake City, UT	0.000	0.002	0.014	0.029	0.041	0.053	0.061	0.079	0.140	13.0	4,544

Table 5-16. Summary of Percentiles for Ozone Monitoring Sites in 1989
(April Through October) with a Maximum Three-Month SUM06 Value ≥ 24.4 ppm-h
but with a Second Hourly Maximum Concentration <0.125 ppm

| AIRS Site	Name	Min.	Percentiles 10	30	50	70	90	95	99	Max	Maximum Uncorrected SUM06 (ppm-h)	Number of Observ. Over 7-mo Period
040132004	Scottsdale, AZ	0.000	0.006	0.018	0.031	0.045	0.062	0.071	0.084	0.107	31.7	5,070
060070002	Chico, CA	0.000	0.010	0.020	0.030	0.040	0.060	0.070	0.080	0.100	33.5	4,690
060170009	South Lake Tahoe, CA	0.000	0.020	0.030	0.040	0.050	0.060	0.070	0.080	0.100	44.8	4,768
060430004	Yosemite National Park, CA	0.000	0.008	0.022	0.035	0.049	0.065	0.072	0.083	0.111	37.6	4,853
060710006	San Bernardino County, CA	0.000	0.020	0.040	0.050	0.060	0.070	0.080	0.090	0.100	70.5	4,856
061011002	Yuba City, CA	0.000	0.000	0.020	0.030	0.040	0.060	0.070	0.080	0.100	29.0	4,623
120094001	Cocoa Beach, FL	0.002	0.017	0.024	0.032	0.042	0.059	0.068	0.077	0.094	28.7	5,012
170190004	Champaign, IL	0.000	0.008	0.020	0.029	0.039	0.065	0.072	0.078	0.088	32.0	5,091
170491001	Effingham County, IL	0.000	0.009	0.023	0.036	0.046	0.063	0.070	0.081	0.104	25.3	4,600
180970042	Indianapolis, IN	0.001	0.006	0.021	0.034	0.046	0.063	0.072	0.085	0.103	25.4	4,592
240030014	Anne Arundel, MD	0.000	0.006	0.021	0.032	0.045	0.064	0.073	0.090	0.120	25.5	4,360
240053001	Essex, MD	0.000	0.002	0.010	0.024	0.038	0.059	0.069	0.089	0.121	25.2	5,028
310550032	Omaha, NE	0.002	0.021	0.030	0.037	0.047	0.062	0.067	0.075	0.098	24.9	4,160
350431001	Sandoval County, NM	0.000	0.010	0.020	0.030	0.040	0.060	0.060	0.070	0.090	25.1	5,059
360310002	Essex County, NY	0.016	0.033	0.042	0.050	0.056	0.067	0.073	0.086	0.106	45.6	4,070
370270003	Lenoir, NC	0.000	0.007	0.019	0.032	0.045	0.062	0.067	0.078	0.092	25.8	4,806
370810011	Guilford County, NC	0.004	0.010	0.023	0.034	0.046	0.063	0.070	0.083	0.113	27.7	4,853
371470099	Farmville, NC	0.000	0.010	0.023	0.034	0.044	0.062	0.070	0.083	0.100	26.4	4,833
390030002	Allen County, OH	0.000	0.007	0.022	0.032	0.043	0.060	0.068	0.086	0.107	24.5	4,854
391510016	Canton, OH	0.000	0.008	0.019	0.030	0.042	0.060	0.070	0.088	0.110	26.3	4,875
420070003	New Brighton, PA	0.000	0.008	0.021	0.032	0.043	0.062	0.070	0.087	0.102	29.4	5,055
420770004	Allentown, PA	0.000	0.003	0.016	0.028	0.039	0.060	0.070	0.087	0.102	25.1	5,040
470090101	Smoky Mountain National Park, TN	0.000	0.025	0.036	0.044	0.053	0.065	0.070	0.081	0.098	35.9	4,764
510130020	Arlington County, VA	0.000	0.001	0.010	0.023	0.037	0.059	0.071	0.088	0.116	25.7	5,029
510610002	Fauquier County, VA	0.000	0.009	0.021	0.033	0.045	0.061	0.069	0.084	0.122	24.6	5,050
511870002	Shenandoah National Park (Dickey Ridge), VA	0.004	0.027	0.037	0.045	0.054	0.065	0.071	0.082	0.100	59.0	4,454
550270001	Horicon, WI	0.002	0.019	0.029	0.037	0.047	0.062	0.070	0.088	0.111	24.6	4,142
551390007	Oshkosh, WI	0.002	0.016	0.028	0.038	0.048	0.063	0.070	0.084	0.121	27.9	4,206
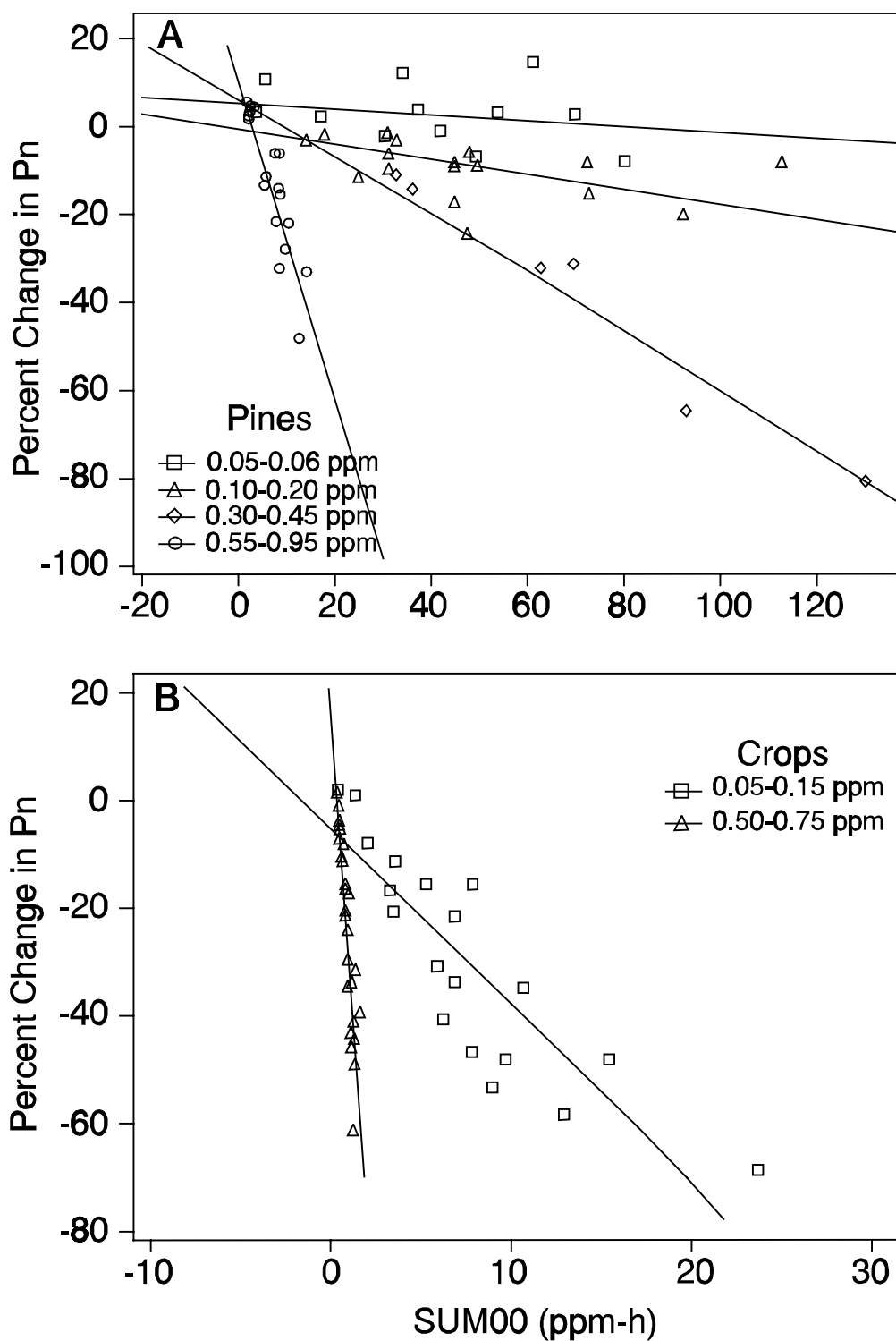
Figure 5-15. *Percent reduction in net photosynthesis (Pn) of (A) pines (including one point for red spruce) and (B) agricultural crops in relation to total ozone exposure (SUM00), for several ranges of peak concentrations (Reich, 1987).*
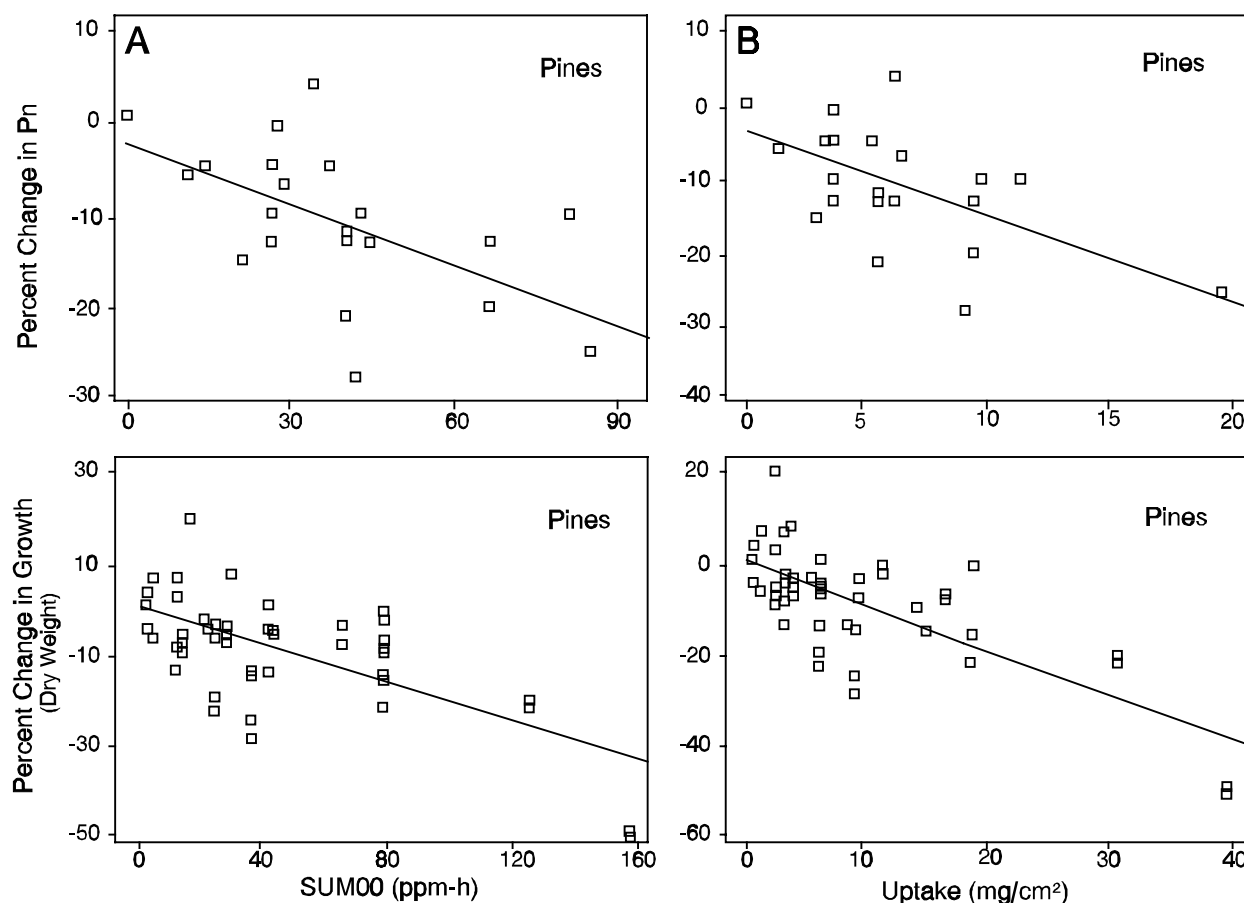
***Figure 5-16. Percent reduction in net photosynthesis (Pn) and biomass growth of
coniferous species in relation to (A) total exposure (SUM00) and
(B) estimated total ozone uptake (Reich, 1987).***

in O_3 uptake. Imputed O_3 uptake calculated as the product of SUM00 and mean diffusive
conductance (ks) for each species better correlated with Pn and growth than did SUM00.

        Kickert and Krupa (1991) criticized Reich's (1987) findings on the basis of
insufficient reporting of statistical model parameters, possible nonnormality of Pn and growth
variables, exclusion of ks terms for imputing O_3 uptake for each species, and the absence of
implication for any individual plant species. However, Reich's synthesis of Pn and growth,
using the SUM00 index, would not necessarily be invalidated by nonnormality of the
variables. Reich's use of a mean diffusive conductance to impute O_3 uptake is questionable
because leaf diffusive conductance measurements vary with time of day, season, and
environmental condition. In addition, the timing of an O_3 exposure and stomatal conductance
is of utmost importance because they determine whether a plant will respond to O_3 exposure
or not.   Consequently, numerous measurements of conductance are required to weight hourly
O_3 concentrations to calculate O_3 uptake over the growth of a plant.

        Pye (1988) reviewed 15 studies on 26 seedling species and found reductions in
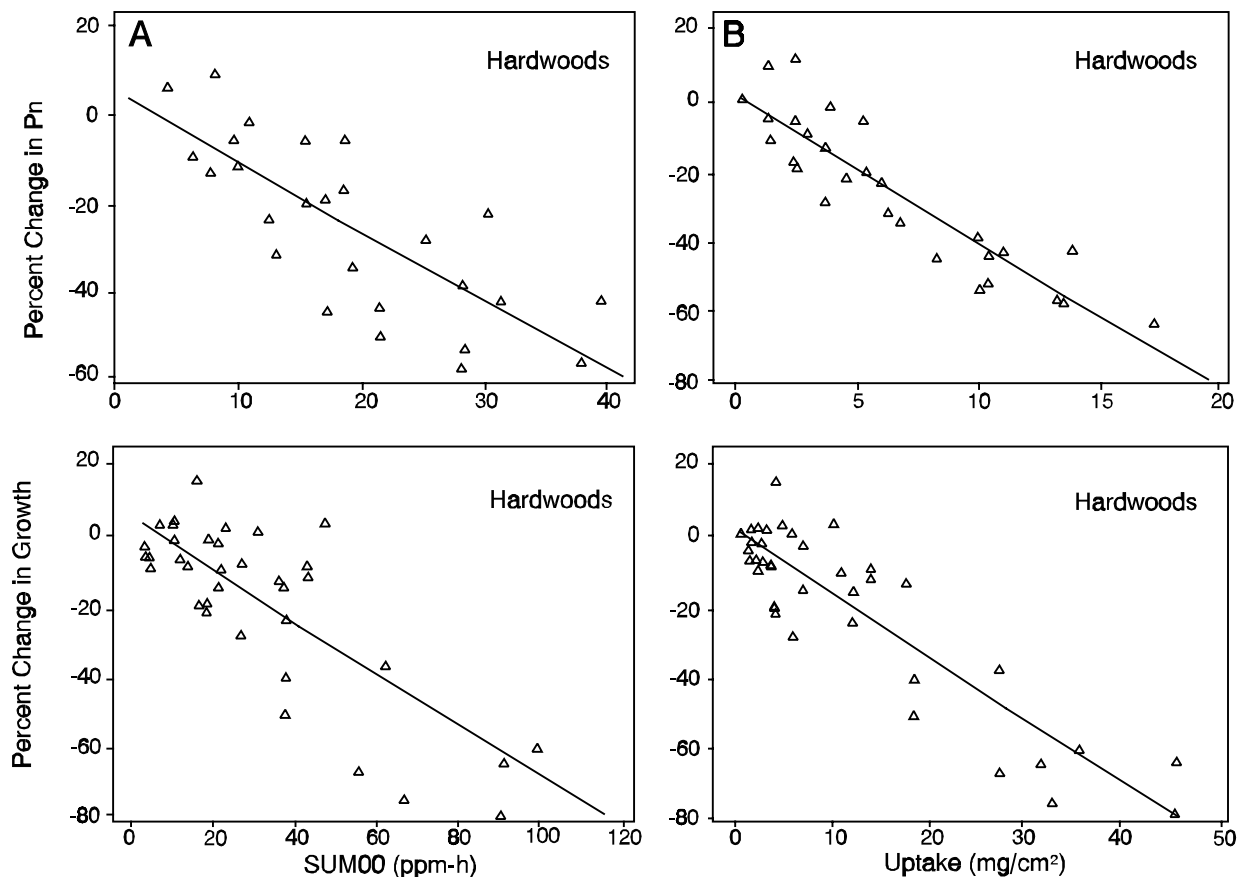biomass response increased with SUM00 (Figure 5-19). Seasonal sum of hourly

Figure 5-17.

Percent reduction in net photosynthesis (Pn) and biomass growth of hardwood species in relation to (A) total exposure (SUM00) and (B) estimated total ozone uptake (Reich, 1987).

concentrations values ranged from 4 to 297 ppm-h. However, there was substantial variation in response. Pines, poplars, sycamore (*Platanus occidentalis*), ash, and maple (*Acer saccharum*) are all relatively sensitive. Both concentration and duration are important factors governing impact on growth and photosynthesis, but they probably are not equally important. The biomass data suggest a nonlinear response to fumigation, and the presence of convexity of response implies that for similar mean O_3 exposures, damage will be greater when O_3 concentrations are more variable.

There is limited information for assessing the relative performance of exposure indices for relating to vegetation effects. Lefohn et al. (1992a) reported that it was not possible to differentiate among the SUM00, SUM06, SUM08, and W126 exposure indices because the indices were highly correlated with one another in the experiment (Figure 5-20). However, results based on biological experiments, reported by Musselman et al. (1983, 1994) and Hogsett et al. (1985b) have shown that different exposure regimes with similar SUM00

values resulted in those exposures experiencing peak concentrations exhibiting the greater effects. The authors demonstrated that plants exposed to variable O_3 concentrations
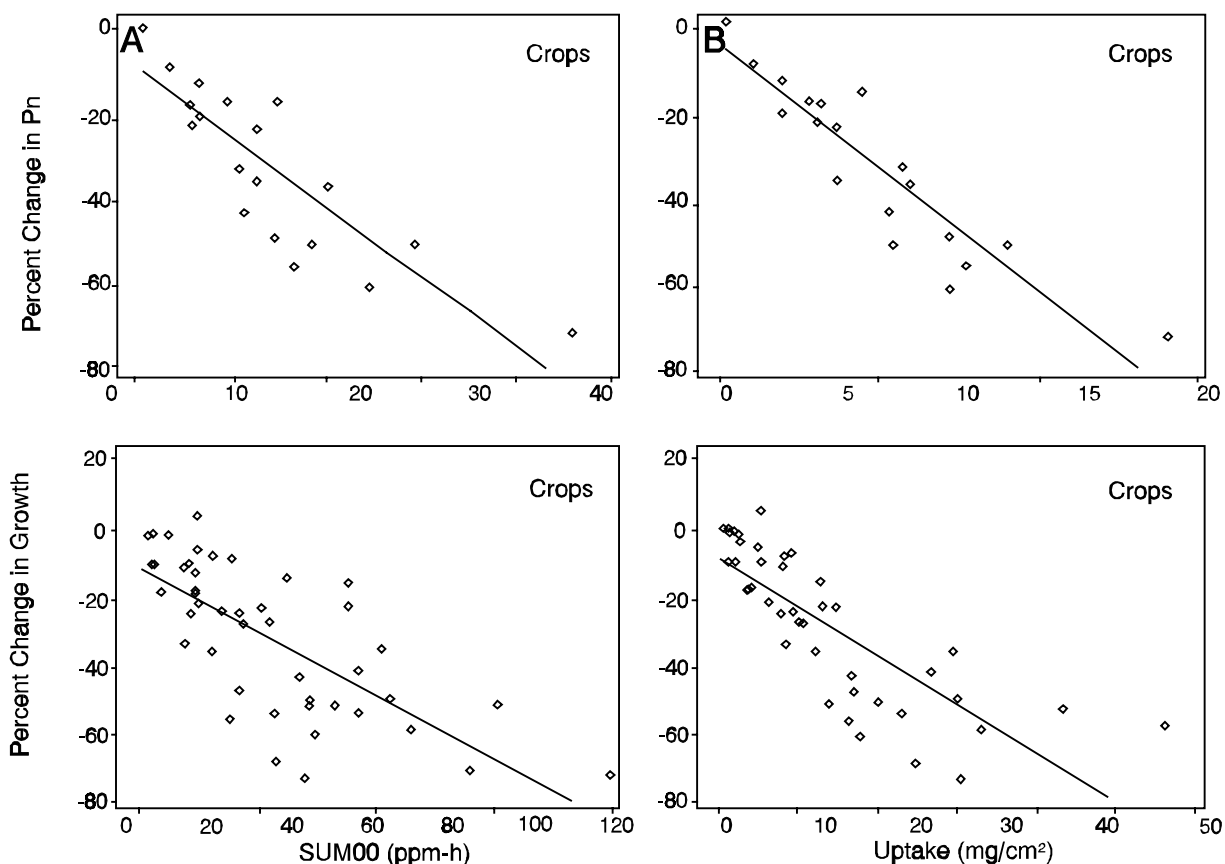
Figure 5-18. Percent reduction in net photosynthesis (Pn) and biomass growth of agricultural crops in relation to (A) total exposure (SUM00) and (B) estimated total ozone uptake (Reich, 1987).

in chambers showed greater effect on plant growth than did those exposed to a fixed or daily peak concentration of equal SUM00, but with lower peak concentrations.

Building on the above cited results of chamber studies that indicated a greater biological response to the higher hourly average concentrations, Lefohn et al. (1989) concluded that the SUM00 index did not appear to perform adequately. Using air quality data, Lefohn et al. (1989) showed that the magnitude of the SUM00 exposure index was largely determined by the lower hourly average concentrations (Figure 5-21). Figure 5-21 illustrates that the slope of the curve that described the cumulative frequency for the SUM00 index (referred to as TOTDOSE) was greater than the slope of the curve for the W126 index until approximately 0.06 ppm; thereafter, the reverse was true. This occurred because the W126 index weighted the higher concentrations more heavily than the lower ones, whereas the TOTDOSE index did not.

Supplementing the results in Lefohn et al. (1989), Lefohn et al. (1992a), using loblolly pine data exposed at Auburn, AL, to varying levels of O_3 over 555 days (Lefohn et al., 1992a) reported that the magnitude of the SUM00 values in the CF chamber, although
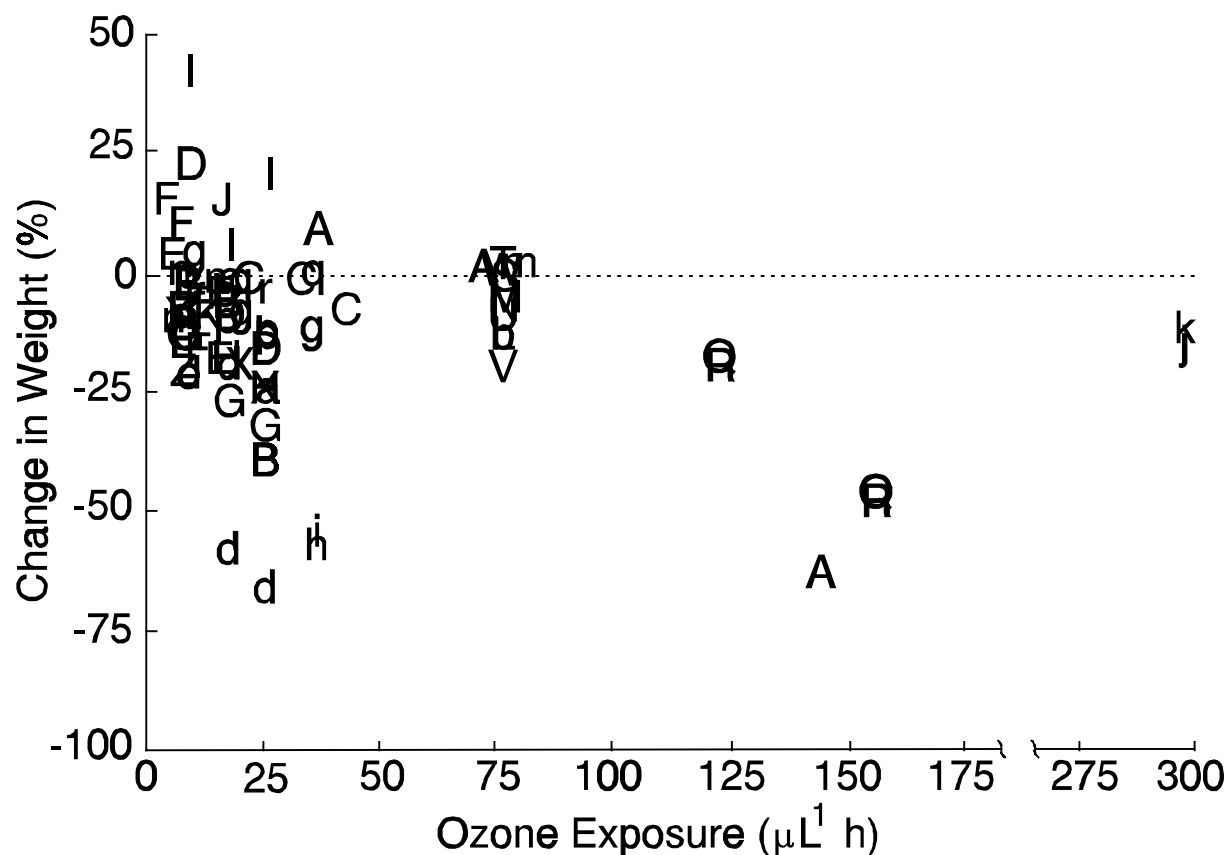
Figure 5-19.

Percent reduction in biomass growth of tree seedlings in relation to total exposure (Pye, 1988).

experiencing hourly average values greater than those at the South Pole or Pt. Barrow, AK, was about 50% less than the SUM00 values experienced at the South Pole and Pt. Barrow.

In a similar analysis using ambient data, Lefohn et al. (1992a) identified a separate set of ambient sites that experienced SUM00 values similar to those of the ambient treatments at Auburn; these ambient sites experienced fewer hourly concentrations above 0.07 ppm than did the ambient chambers. Similar to the results cited above, the authors noted that the magnitude of the SUM00 index was unable to capture the occurrence of the higher hourly average concentrations in the ambient treatments. The authors indicated that the SUM00 index was inadequate because of the observed inconsistencies of the SUM00 value between chambers and selected monitoring sites.

When taken by themselves, the importance of these findings may be debatable because the clean sites are not representative of loblolly growing regions, and there is no substantiating evidence of differing effects at these levels. However, the coupling of the air quality considerations, as described by Lefohn et al. (1989, 1992a), with the biological findings reported by Musselman et al. (1983, 1994) and Hogsett et al. (1985b), builds a consistent picture that the SUM00 index does not describe properly the occurrence of the higher hourly average concentrations.
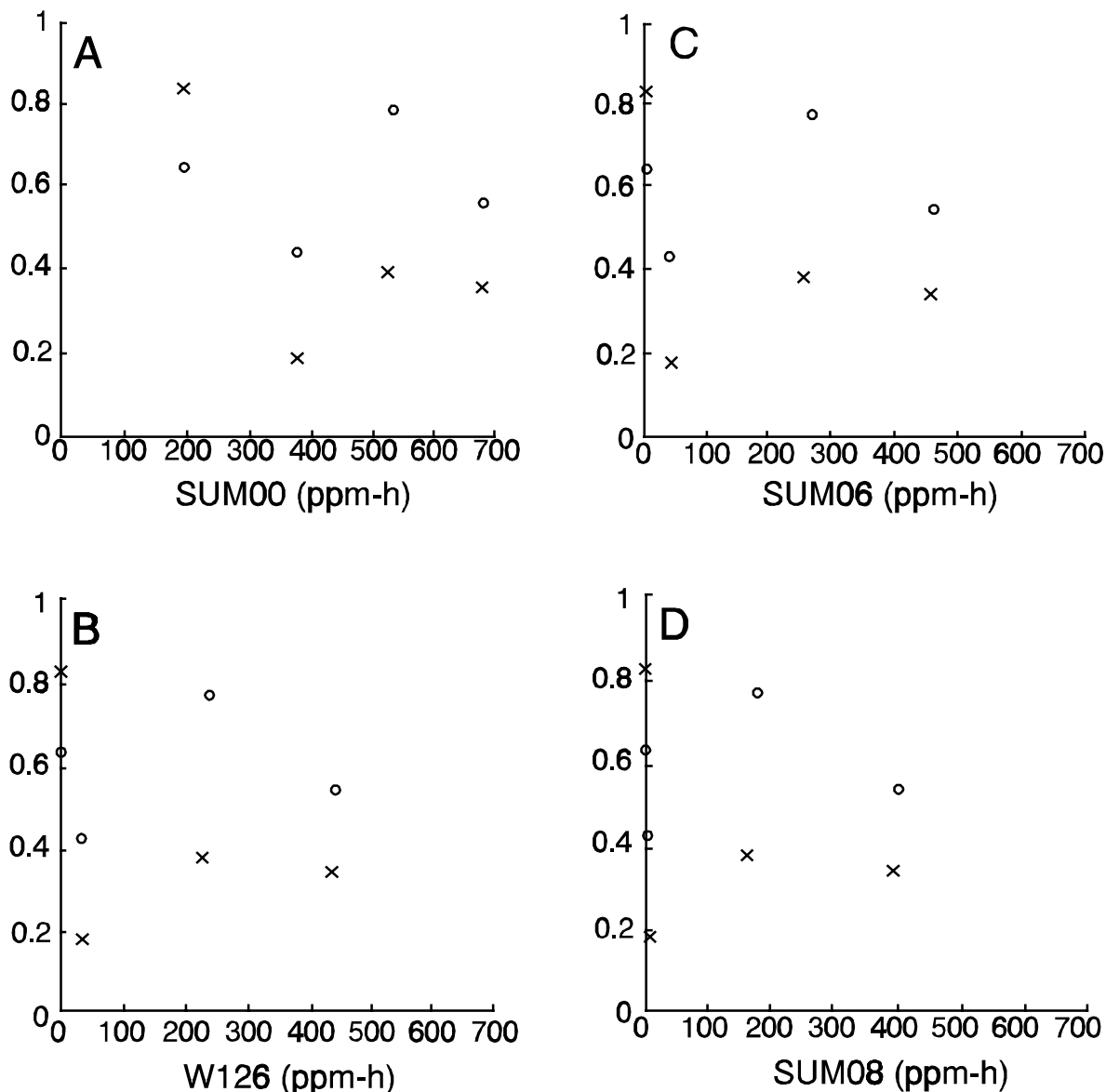
Figure 5-20.

Reduction in volume production of loblolly pine seedlings (family 91) in relation to four exposure indices (A through D) (Lefohn et al., 1992a).

As noted earlier in this section (see also Section 5.4), the sensitivity of vegetation at time of exposure varies with species and is a function of several factors (e.g., soil moisture, light conditions, humidity, air turbulence). Assuming all factors are held constant (a condition not found in the ambient atmosphere), the results reported by Musselman et al. (1983, 1994), and Hogsett et al. (1985b), imply that, given any distribution of hourly average concentrations, higher hourly average concentrations should be given greater weight than lower hourly average concentrations. This statement provides only guidance concerning the potential of each hourly average concentration to affect one type of vegetation relative to