Ground-Level Ozone

Question 5:

What impact does ground-level ozone have on forests?

Ozone is a naturally occurring chemical in both the upper atmosphere and at ground level. Although they can be higher, the majority of hourly average concentration levels of ozone near the ground are usually less than 0.04 parts per million (ppm) at pristine sites in the world (Lefohn and others 1990). Hourly average concentrations above 0.05 ppm are frequently recorded at monitoring stations in the eastern United States (Lefohn and Jones 1986). Ozone exposures above 0.05 ppm are of greatest concern to scientists, resource managers, and the public. Ozone is potentially the most significant pollutant affecting forests in North America (Barnard and others 1991).

Numerous surveys have been conducted within the Southern Appalachian mountains where symptoms found on the leaves of known sensitive species resemble the pattern of ozone injury found under controlled experiments. Renfro (1989) reported ozone symptoms on 21 trees, 15 herbs, 9 shrubs, 3 vines, 1 fern, and 1 grass species in Great Smoky Mountains National Park. Ozone symptoms have also been reported consistently for several species for numerous years at wildernesses designated as Class I areas under the Clean Air Act (CAA) Amendments of 1977 (Brantley and Tweed 1994). Surveys in Shenandoah and Great Smoky Mountains National Parks found a relationship between the amount of injury to foliage and elevational trends in monthly average ozone exposures (Winner and others 1989, Chappelka and others 1992). Other researchers, such as those noted by Dowsett and others (1992), have also reported ozone injury within the Southern Appalachians, and symptoms of ozone injury can be found in many areas in any year.

Several factors affect the uptake of ozone by a plant. Primarily, the genetic code of a plant influences how a plant will respond to ozone. Among plant species there are differences in sensitivity when exposed to the same ozone levels. Variation in sensitivity to ozone within a species can also occur. During field surveys it is possible to see one plant with severe ozone symptoms, while another individual of the same species, growing adjacent to and experiencing similar environmental conditions as the first individual, has no ozone symptoms. In another example, it appears that a portion of the most ozone-sensitive eastern white pines (*Pinus strobus* L.) have been removed from the population due to ozone exposures (U.S. Environmental Protection Agency 1986). Other factors, such as light, temperature, relative humidity, soil nutrients, and soil moisture also influence the uptake of ozone. The U.S. Environmental Protection Agency (EPA 1986) has presented evidence which indicates that drought stress may reduce the impact of ozone on plants, but the protective benefits may be masked by the growth and productivity losses which occur from the drought.

Monitored concentrations in the atmosphere recorded as hourly average values in ppm in the database represent exposure. The exposure is defined as the amount of ozone which contacts the outside of the leaf; whereas the dose is the amount of ozone which actually enters the leaf. Estimates of dose are difficult to predict without detailed modeling of the relationship between exposure and dose. Exposure is used as a surrogate for dose, and exposures are used by researchers and policy makers to assess the possible effects of ozone on vegetation.

Ozone enters a leaf through openings called stomata. Once inside the leaf the ozone is either destroyed by biochemical processes, or the ozone kills the cells found just below the upper leaf surface and between the veins of the leaf. Cells which are killed lose their green pigmentation and usually turn reddish or black, in a process called stippling. The symptoms of ozone injury cannot be observed until a large number of cells are dead. People who conduct field surveys have a checklist of characteristics which identify plants with ozone symptoms. The symptoms indicate that the plant has had a physiological response to the ozone dose, resulting in injury. Damage results when the ozone dose was large enough to reduce the intended human use or the value of the plant or ecosystem (Tingey and others 1991). This report uses the term damage to mean a growth loss is predicted, even though forested lands in the Southern Appalachians are used for many purposes other than commercial timber production. Furthermore, it is believed that ozone symptoms, as indication of injury, can be found on sensitive species in the Southern Appalachians (Dowsett and others 1992). Thus, the remainder of this report will focus on the possible extent and frequency of damage from ozone to forest trees within the Southern Appalachians.

Ozone Assessment Techniques

Ozone formation is strongly influenced by meteorological conditions and the amount of ozone precursors present in the atmosphere (National Research Council 1992). For example, 1988 was a hot and dry year during which large sections of the eastern United States had high ozone exposures; by comparison, 1989 was cool and moist, and the ozone exposures were low. The range in yearly ozone exposures required that more than one year be examined to describe the current condition for the study area. The years selected for the analysis were 1983 through 1990.

Initially, many researchers used long-term average concentrations to describe ozone exposures when assessing vegetation effects (Heck and others 1992). The EPA (1989) examined the peer-reviewed literature and concluded that long-term averages are not adequate indicators for relating ozone exposure to plant response. Furthermore, EPA (1986 and 1992) concluded that greater effects to vegetation occur when the exposures include short-term, high concentrations rather than long-term, low concentrations. The W126 statistic is a mathematical index, which places emphasis on the high concentrations, but does not ignore the potential effects that can occur from the mid- and lower-level concentrations. Each hourly average ozone concentration is used in the calculation, and all of the W126 values are added together over the growing season. Although the W126 exposure index includes all hourly average concentrations, it focuses on concentrations from 0.04 ppm and higher; the inflection point of the sigmoidal weighting is near 0.066 ppm. At approximately 0.10 ppm and above, a maximum weighting of 1 is provided (Lefohn and Runeckles 1987). Results obtained from the W126 calculations or any other cumulative exposure index can result in high values, but high hourly average concentrations equal to or above 0.10 ppm may not occur. Consequently, the recommendation of Lefohn and Foley (1992) has been followed, and the number of hours greater than or equal to 0.10 ppm are also included in the analysis.

For this assessment, data in EPA's Aerometric Information Retrieval System (AIRS) database and from the National Dry Deposition Network program were used. The monitoring sites included those in the states of Alabama, Georgia, Indiana, Illinois, Mississippi, Missouri, Arkansas, South Carolina, North Carolina, Tennessee, Kentucky, Virginia, West Virginia, Maryland, Pennsylvania, and Ohio. The monitoring sites selected from these states had 75 percent or greater data capture for each particular year. Numerous statistics were calculated using the 24-hour period over the growing season, defined as the months of April through October. The statistics used for this assessment are the W126 (Lefohn and Runeckles 1987) and the number of hours with ozone concentrations greater than or equal to 0.10 for the months of April through October.

Ozone Sensitivity Levels

Numerous studies have been conducted to examine the relationship between ozone exposures and tree response. A listing of the studies considered for this assessment are found in table 6.1. These particular studies were selected because the hourly ozone values were available for each of the experimental treatments. Both pieces of information were necessary to determine levels at which ozone exposures are likely to cause damage to plants of varying ozone sensitivity. Ozone exposure data were used to calculate the W126 value and number of hours greater than or equal to 0.10 ppm for each study. These values, along with the information on associated growth loss to individual species, were used to identify four sensitivity categories of forest-tree response to ozone exposure. The categories are described below and again in table 6.2. Note that as ozone exposure increases in intensity, more species can be affected.

Minimal - This ozone exposure is so low that little or no growth loss is predicted to occur for any species. Ozone symptoms may have been present even though the exposures were low.

Level 1 - The ozone exposure at this level is high enough to cause growth reductions in species considered highly sensitive to ozone, such as black cherry.

Level 2 - The ozone exposure at this level is high enough to cause growth reductions in species with moderate sensitivity to ozone, such as tulip poplar, in addition to those species which are included in Level 1.

Level 3 - The ozone exposure at this level is high enough to cause growth loss in many species, even those normally considered resistant to ozone exposures, such as red oak, in addition to these species in Level 1 and Level 2.

Ozone Impacts to Trees Across the SAA

The next step in the analysis was to stratify the landscape by these categories to show areas where ozone exposures may have been great enough to cause growth reductions to tree species of various ozone sensitivities. To accomplish this task, it was necessary to extrapolate the ozone-monitoring data beyond the monitoring sites. Extrapolations of the W126 values across the SAA were accomplished using a statistical technique described in a report by Lefohn and others (1995). The W126 estimates were made for grid cells of 0.5 degrees latitude by 0.5 degrees longitude across the Southern Appalachian region.

Table 6.1 Listing of ozone exposure studies considered to identify the exposure effects levels for selected Southern Appalachian trees.

Forest Tree Response Category[1]	Common Name	Genus and Species	Reference
Level 1	black cherry	*Prunus serotina*	Neufeld and others 1995
			Samuelson 1994
	slash pine	*Pinus elliotti*	Hogsett and others 1985
Level 2	green ash	*Fraxinus pennsylvanica*	Kress and Skelly 1982
	sycamore	*Plantus occidentalis*	Kress and Skelly 1982
	tulip poplar	*Liriodendron tulipifera*	Lee 1995
			Kress and Skelly 1982
			Chappelka and others 1988
			Cannon and others 1993
	white ash	*Fraxinus americana*	Kress and Skelly 1982
	white pine	*Pinus strobus*	Lee 1995
			Reich and others 1988
Level 3	American beech	*Fagus grandifolia*	Jensen and Dochinger 1982
	loblolly pine	*Pinus taeda*	Lefohn and others 1992
			Shafer and Heagle 1989
			Kress 1995
			Kress and Skelly 1982
	pitch pine	*Pinus rigida*	Kress and Skelly 1982
	red maple	*Acer rubrum*	Lee 1995
			Samuelson 1994
	red oak	*Quercus rubra*	Samuelson and Edwards 1993
			Edwards and others 1994
			Samuelson and others 1995
	shagbark hickory	*Carya ovata*	Jensen and Dochinger 1989
	Virginia Pine	*Pinus virginiana*	Lee 1995
			Kress and Skelly 1982
	white oak	*Quercus alba*	Jensen and Dochinger 1989

[1]Classification based upon listed research studies, and frequency and magnitude of ozone symptoms observed during field surveys.

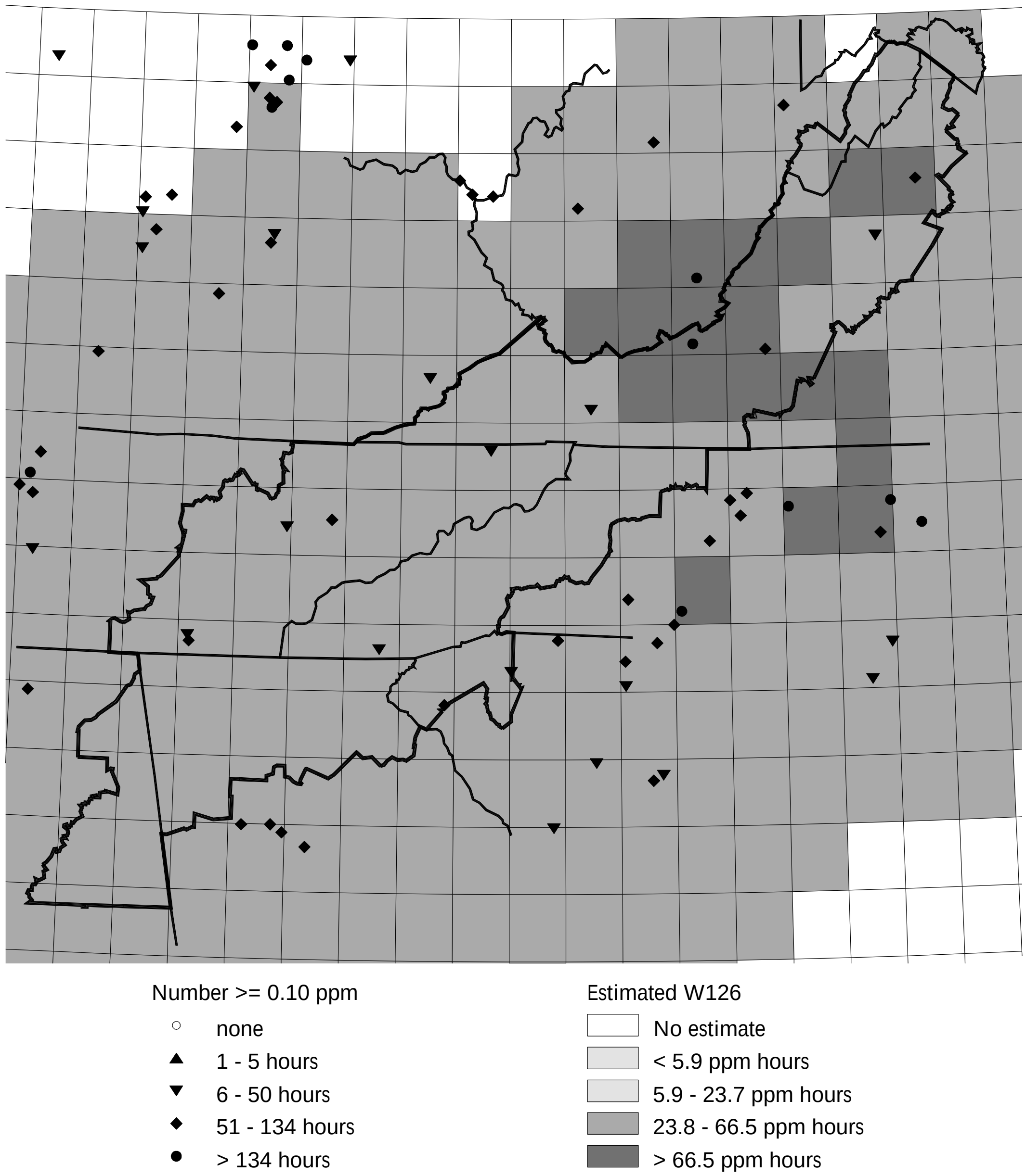

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Figure 6.1 Results for the W126, and the number of hours with ozone concentrations greater than or equal to 0.10 ppm at ozone monitoring sites – 1988.

For each grid cell, a W126 value was assigned to one of the W126 ranges listed in table 6.2. The criteria listed in table 6.2 required consistency with both the W126 and the number of hours with concentrations greater than or equal to 0.10 ppm. Because the number of hours greater than or equal to 0.10 ppm could not be statistically extrapolated across the study area, it was necessary to finish the classification by visually examining the monitored values for the number of hours greater than or equal to 0.10 ppm. Grids which had one or more ozone monitors present were classified using the results from the ozone monitors, but cells which did not have an ozone monitor were classified by examining the pattern from ozone monitors surrounding the cell to be classified (fig. 6.1). Cells which met the W126 criteria for a particular category and not the number of hours greater than or equal to 0.10 ppm for the same category were assigned the category which matched the number of occurrences greater than or equal to 0.10 ppm. For example, some cells in northern Virginia

Table 6.2 Ozone exposure levels associated with forest tree response.

	Effects Range[2]	
Forest Tree Response Category[1]	W126	Hours > = 0.10 ppm
Minimal	< 5.9	< 6
Level 1 (only highly sensitive species affected, e.g. black cherry)	> = 5.9	> = 6
Level 2 (moderately sensitive species affected, e.g. tulip poplar)	> = 23.8	> = 51
Level 3 (all species affected, even those normally resistant, e.g. red oak)	> = 66.6	> = 135

[1]Level 2 includes Level 1 species and Level 3 includes species included within Levels 1 and 2.

[2]Ozone effects ranges were selected for four response categories based upon the studies listed in table 6.1 The levels are reached when the seasonal ozone exposure is equal to or greater than the number of hours under the 0.10 ppm column and when W126 value falls within the range listed in the column for a particular response category.

were rated as Level 3 in 1988 for the W126 value (fig. 6.1), but were reduced to Level 2 because the number of hours greater than or equal to 0.10 ppm was less than 135 hours and more than 50 hours during the growing season (fig. 6.2). Each cell was assigned a value in the database once the final category was decided. Cell classification of “minimal” received a zero; Level 1 received a one; Level 2 received a two; and Level 3 received a three.

The experimental studies listed in table 6.1 used plants which were grown under optimum conditions of adequate soil moisture and nutrients. The picture presented in figure 6.2 assumes that the environmental conditions were favorable for ozone to enter the leaf and that the cumulative exposure would result in a growth loss. However, it is necessary to consider environmental conditions that affect a plant’s sensitivity to ozone, especially drought. Showman (1991) and Jackson and others (1992) have both observed fewer ozone symptoms on sensitive species during periods of drought than in seasons with adequate rainfall, even though ozone exposures were high in the drought. Soil moisture is considered to be an important variable which influences the uptake of ozone by a plant (EPA 1986). The Palmer Hydrologic Index was chosen as a surrogate measurement of soil moisture. The index, a monthly value computed for climatic division, indicates the severity of a wet or dry spell (fig. 6.3). A Palmer Hydrologic Index of less than a minus two was considered to indicate low soil moisture conditions (Briffa and others 1994), and it was hypothesized that ozone would not damage the plants. Values above a minus two indicated adequate soil moisture, when ozone therefore could potentially penetrate the leaves and damage the plants. The average Palmer Hydrologic Index for the months of April through July was calculated for each climatic division and used in the assessment.

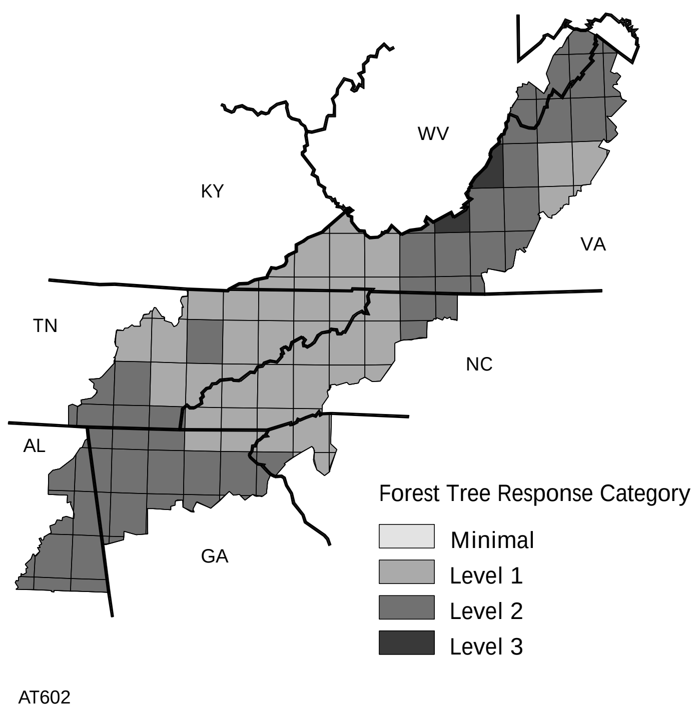

Figure 6.2 Results after combining the W126 and number of hours with ozone concentrations greater than or equal to 0.10 ppm – 1988.

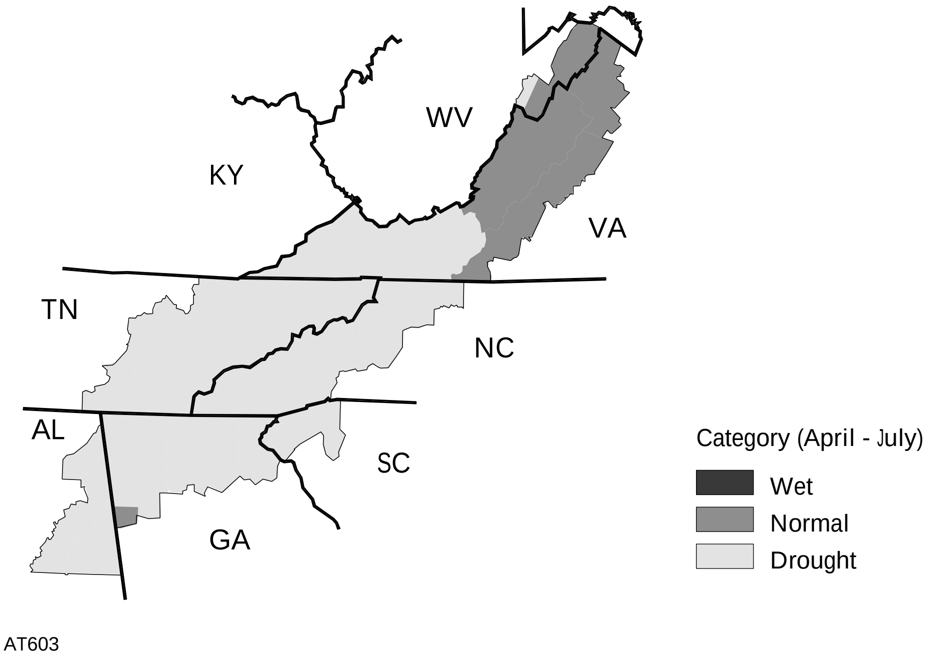

Figure 6.3 Palmer Hydrologic Drought Index result – 1988.

Combining the results from the Palmer Hydrologic Index (fig. 6.3) and ozone exposure (fig. 6.2) provides an indication of (1) soil moisture adequacy and (2) ozone exposures severe enough to cause growth losses. Areas which were classified as experiencing a drought were assigned the category as "minimal" effect from ozone; otherwise the sensitivity category value remained the same after applying the criteria in table 6.2 (fig. 6.4).

The final step in the analysis was to combine the results for all years to determine which areas had the greatest frequency of potential for growth loss. The values, zero through three, assigned to each of the forest-tree response categories were added together for the years 1983 through 1990.

Table 6.3 Number of acres where ozone exposures may have been large enough to cause growth reductions.

Year	Minimal	Level 1	Level 2	Level 3
1983		37,419,416		
1984	16,440,810	20,978,606		
1985	12,799,214	24,620,202		
1986	19,774,377	17,645,039		
1987	4,621,422	32,179,934	618,060	
1988		17,280,546	19,536,088	602,782
1989	36,179,580	1,239,836		
1990	24,151,128	13,268,288		

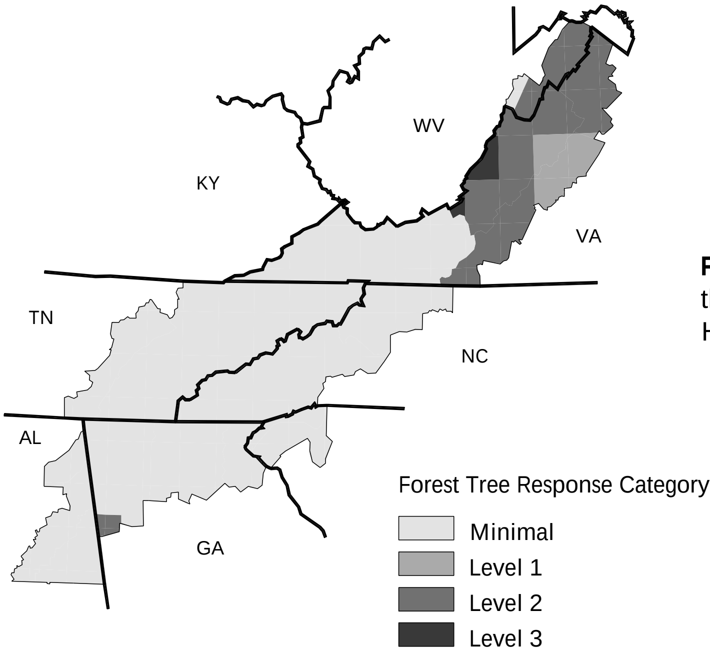

Figure 6.4 Results after combining the ozone exposure and the Palmer Hydrologic Drought Index – 1988.

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Ozone – Current and Future

Current Ozone Impacts to the Southern Appalachian Forests

The results from statistical estimates placed almost all of the cells into W126 units of 23.8 - 66.5 ppm-hours for the years 1983 through 1990. In 1988, 11 of the 120 cells had W126 estimates of greater than 66.5 ppm-hours. Three cells in 1986 and 1989 and one cell in 1990 had a W126 estimate of 5.9 23.7 ppm-hours. No cells were classified as having less than 5.9 ppm-hours. These data indicate that Level 2 and Level 1 species may have had growth losses for the 8 years. However, because hourly average ozone concentrations were seldom greater than or equal to 0.10 ppm, such losses were not actually anticipated and the cells were reduced to a lower category. Southern Appalachian ozone monitors usually measured less than 40 hours when the hourly average ozone concentration was greater than or equal to 0.10 ppm. Only one year deviated from this pattern: in 1988, 5 of the 10 ozone monitors in the study area recorded greater than 50 hours in which the hourly average ozone concentration exceeded or equaled 0.10 ppm (fig. 6.1).

Considering only ozone exposures, table 6.3 lists the number of acres estimated in each of the sensitivity categories. Overall, the ozone exposures are such that somewhere in the Southern Appalachians, Level 1 species could have growth loss in almost every year. In 1989, there was a lack of ozone concentrations which equaled or exceeded 0.10 ppm, and there was a high probability that minimal growth loss was caused by ozone exposures. In 1988, on 52 percent of SAA acres, Level 2 species could be damaged, and on 2 percent, Level 3 species may have had sufficient ozone exposures for growth loss. It is important to note that the W126 exposure index value was accumulated over the April to October period. Most of the experimental data used in this assessment were collected over a 3- to 4-month period. Thus, using a 7-month period to accumulate the W126 value may overestimate the likelihood of experiencing growth losses.

Although ozone exposures may have been large enough to cause growth reductions, losses also require environmental conditions to be favorable for uptake of the pollutant by the vegetation. This assessment focused on soil moisture potential by examining the Palmer Hydrologic Index values for a climatic division. Portions of the Southern Appalachians were normal or wet in every year, but large areas

Table 6.4 Number of acres in each moisture index category.

Year	Average (April-July) Palmer Hydrologic Index Drought	Normal	Wet
1983		29,679,142	7,740,274
1984		12,613,961	24,805,455
1985	27,631,889	9,787,527	
1986	36,177,782	1,241,634	
1987	11,572,194	21,059,223	4,787,999
1988	29,164,372	8,255,044	
1989		31,779,750	5,639,666
1990		11,461,453	25,957,963

experienced drought conditions in 1985 through 1988, with the largest amount (36,177,782 acres) being affected in 1986 (table 6.4). Consequently, the lack of soil moisture in portions of the region may have reduced uptake of ozone by vegetation, and ozone exposures had little effect on growth.

The combination of the Palmer Hydrologic Index results and the ozone exposure results are shown in table 6.5. The drought present in 1985 through 1988 significantly reduced the area that might have been adversely affected by ozone. Nevertheless, growth losses were probably occurring to the Level 1 (highly sensitive) species somewhere in the Southern Appalachians almost every year. In 1988, some areas may have had growth losses occurring to Level 2 and Level 3 species (see table 6.1). Figure 6.5 presents the areas with the greatest frequency of potential damage from ozone exposures. The range of possible values was between 0 and 24, but the results for this study show a range between 1 and 6 (table 6.6). Thus, ozone damage may have occurred to sensitive

Figure 6.5 Areas with the greatest frequency of potential ozone damage, 1983-1990.

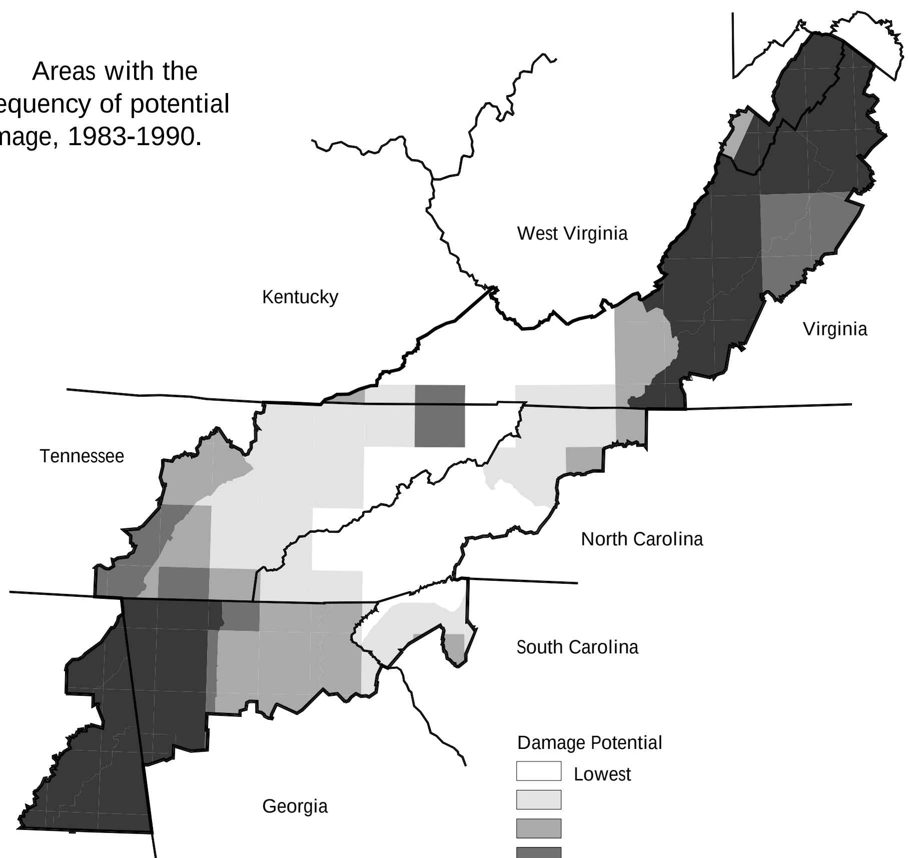

Table 6.5 Number of acres when ozone exposures and Palmer Hydrologic Index were favorable for growth loss.

Year	Minimal	Level 1	Level 2	Level 3
1983		37,419,416		
1984	16,440,810	20,978,606		
1985	32,124,860	5,294,556		
1986	37,419,416			
1987	14,954,963	22,464,453		
1988	29,164,372	1,420,764	6,417,044	417,236
1989	36,179,580	1,239,836		
1990	24,151,128	13,268,288		

species throughout the Southern Appalachians at least one year, but damage from ozone exposures did not occur at all locations every year. Northern Virginia and the SAA area in West Virginia, and the southern portion of the SAA located in Alabama and northern Georgia are the regions most frequently affected by ozone exposures (fig. 6.5).

Caution should be used in interpreting these findings since localized areas within the Southern Appalachians may have had adequate soil moisture, even though the climatic division was classified as drought. For example, it is known that high-elevation sites above 3,000 feet receive a significant amount of precipitation from cloud moisture. Furthermore, it has been reported that the western and central portions of the Appalachian mountains may receive more rainfall than the eastern portion (Hicks and others 1991). Thus, these areas may receive adequate moisture for the uptake of ozone through the stomates.

Lefohn and others (1990) have described another important aspect of the exposure question. Gaseous pollutant concentrations have been reported in ppm. This unit is a molecular fraction and is not affected by temperature and pressure. However, if exposures at low-elevation sites are compared with those experienced at high-elevation sites, where temperature and pressure are less, the variation of concentration (in units of micrograms per cubic meter [ug/m^3]) as a function of altitude is significant. Given the same ppm value experienced at both high- and low-elevation sites, the absolute concentrations (i.e., ug/m^3), at two elevations are different. Therefore, assuming that the sensitivity of a plant is nearly identical at both low and high elevations, some adjustment should be necessary when attempting to link experimental data obtained at low-elevation sites with air-quality data monitored at high-elevation stations. Lefohn and others (1990) have reported that pressure adjustments can be large for specific cumulative index values. There are some indications that vegetation sensitivity may not be similar as a function of elevation. Winner and others (1989) report that visible injury to foliage increased with elevation. However, the number of elevated hourly occurrences of high values did not increase, thus leading the authors to speculate that sensitivities may have differed as a function of elevation.

Future Trends in Southern Appalachian Ozone Exposures

Current efforts by state, local, and federal air pollution agencies provide evidence that ozone exposures in rural forests could possibly be reduced in the future. For example, there could be a lowering of ozone exposures in the Southern Appalachians as soon as ozone nonattainment areas outside the study area implement control strategies that bring the region back into compliance with federal law. Furthermore, a revision of the National Ambient Air Quality Secondary standard from the current form could also benefit the Southern Appalachian mountains. Currently, Whitetop Mountain in Virginia is the only area

Table 6.6 Number of acres for each damage category when all years are combined.

Damage Potential	Category	Acres
Lowest	1	8,078,321
	2	7,877,033
	3	6,040,146
	4	3,495,672
	5	11,026,331
Highest	6	901,910

designated as non-attainment for ozone because the 0.12 ppm standard was exceeded. A secondary standard, which included both cumulative ozone exposure, such as the W126, and peak concentration, such as the number of hours greater than or equal to 0.10 ppm, would assist in focusing efforts to reduce damage to vegetation in the Southern Appalachians.

Ozone exposures in the study area result from the chemical reaction of nitrogen oxides and volatile organic compounds. The volatile organic compounds are known to be abundant, and it appears that nitrogen oxides may be the limiting factor in ozone formation (Chameides and Cowling 1995). Regional strategies which reduce nitrogen oxides may result in lower ozone exposures for the Southern Appalachians. The current efforts of the Southern Appalachian Mountain Initiative (SAMI) could provide reasonable pollution control strategies that lead to reduced ozone exposures. Although SAMI is focusing on numerous Class I areas found in the Southern Appalachians, there should be benefits to all of the area if pollution control programs are implemented which reduce ozone exposures in the Class I areas.

Key Findings

1. **Current ozone exposures are causing visible symptoms on the foliage of sensitive species. The injury can be found in numerous locations throughout the Southern Appalachians.**

2. **Ozone exposures, when soil moisture is adequate, may be sufficient to cause growth losses to the most sensitive species in the Southern Appalachians.**

3. **Low moisture availability occurred throughout the Southern Appalachians in 1985 through 1988. Growth losses to vegetation probably occurred, but the reductions should be attributed primarily to drought.**

4. **Between 1983 and 1990, conditions in the northern and southern portions of the Southern Appalachians were most conducive to growth reductions from ozone exposures.**