Pergamon

Atmospheric Environment Vol. 31, No. 11, pp. 1695-1708, 1997
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1352-2310/97 $17.00 + 0.00

PII: S1352-2310(96)00258-0

EFFECT OF SURFACE OZONE EXPOSURES ON VEGETATION GROWN IN THE SOUTHERN APPALACHIAN MOUNTAINS: IDENTIFICATION OF POSSIBLE AREAS OF CONCERN

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(*First* ***received 28 May 1996 and*** *in final form* ***7 August 1996. Published March 1997)***

Abstract-The results described in this paper are derived from an analysis, for the 8-yr period 1983-1990, that combined experimental exposure-response effects data for deciduous and coniferous seedlings and/or trees with characterized O_3 ambient exposure data for a local area and soil moisture to identify areas that may be at risk in the Southern Appalachian Mountains. Results from seedling and tree experiments operated in open-top chambers were used to characterize O_3 exposure regimes that resulted in growth loss under controlled conditions. Available O_3 monitoring data were characterized for the states of Alabama, Georgia, South Carolina, North Carolina, West Virginia, Tennessee, Kentucky, and Virginia, using the W126 biologically based cumulative exposure index. As a part of the analysis, both the occurrences of hourly average O_3 concentrations $\geqslant$ 0.10 ppm and the soil moisture conditions in the geographic area were considered. Combining exposure information with moisture availability and experimental exposure-response data, the extreme northern and southern portions of the Southern Appalachian area were identified as having the greatest potential for possible vegetation effects. The study was based mostly on results from individual tree seedlings grown in chambers and pots and additional research is needed to identify what differences in effects might be observed if exposures were similar to those experienced in forests. Furthermore, we recommend future investigations to verify the location and presence of specific vegetation species and amounts and whether actual growth losses occurred in those areas of concern that have been identified in this study. © 1997 Elsevier Science Ltd. All rights reserved.

Key ***word index:*** Ozone exposure, W126 cumulative exposure index, Palmer hydrologic index, kriging, vegetation, seedlings, trees, sensitive species.

INTRODUCTION

Ozone (O_3) is a naturally occurring chemical in both the upper atmosphere and at surface levels. Ozone is considered the pollutant of greatest concern with respect to the potential regional impacts to trees in North America (U.S. EPA, 1986, 1996; National Acid Precipitation Assessment Program, 1991a). The effects of 0, on individual plants and factors that modify plant response to O_3 are complex and vary with species, environmental conditions, and soil and nutrient conditions. Factors, such as genetic susceptibility, light, temperature, relative humidity, soil nutrients, and soil moisture influence the uptake of O_3. Evidence indicates that drought stress may reduce the impact of O_3 on plants, but the protective benefits are offset by growth and productivity loss which occurs from drought (U.S. EPA, 1986, 1996). There is some evidence that O_3 exposures > 0.04 ppm may interact with low soil moisture and high air temperatures to reduce short-term rates of stem expansion in loblolly pine trees (*Pinus taeda* L.) (McLaughlin and Downing, 1995a). Reams et al. (1995) have questioned this conclusion and McLaughlin and Downing (1995b) have responded and believe their hypothesis is correct.

Ozone is an omnipresent air pollutant that has caused foliar injury and growth losses to agricultural crops and trees (U.S. EPA, 1986; Chevone and Linzon, 1988; Krupa and Manning, 1988; Pye, 1988; Swank and Vose, 1991; Chappelka and Chevone, 1992). For trees located in the southern United States, several surveys have noted O_3 foliar injury on sensitive plant species (Winner ***et al.,*** 1989; Chevone et al., 1985; Anderson et al., 1986, 1988; Renfro, 1989; Jackson et al., 1992; Brantley and Tweed, 1992; Hildebrand et al., 1996). Besides identifying O_3 injury to vegetation in the southern United States, investigators, using exclusion chambers (Duchelle ***et al.,*** 1982) and artificial fumigation experiments (Neufeld et al., 1995) have observed growth reduction to trees.

For characterizing the specific doses responsible for affecting trees, there has to be a linkage between exposure and actual dose. Because (1) insufficient information is available to quantify the links between exposure and dosage and (2) routine monitoring for O_3 is summarized as hourly average concentrations (i.e. potential exposure), investigators have used concentration and exposure to assess possible effects of O_3 on vegetation (U.S. EPA, 1986, 1992, 1996).

Air pollution specialists have used exposure indices as surrogates for dose (Oshima, 1975; Lefohn and Benedict, 1982; U.S. EPA, 1986, 1992; Lefohn et al., 1988; Lee et al., 1988, 1991; Hogsett et al., 1988; Lefohn, 1992a). For the purposes of this analysis, we have used exposure indices that account for the higher hourly average concentration exposures and include the mid- and lower-level values (Lefohn and Runeckles, 1987). However, as reported in the literature) (Lefohn and Foley, 1992; Lefohn, 1992b), many of the exposure indices currently used do not always relate well with the occurrences of elevated hourly average concentrations (i.e. hourly values $\geqslant$ 0.10 ppm). These indices have difficulty in characterizing the high end of the hourly average distribution curve for ambient monitoring sites when large numbers of hourly average concentrations occur in the range of 0.0660.10 ppm. For these types of exposures, the magnitude of the cumulative exposure index is mostly associated with the occurrences of the hourly average concentrations in this range and the infrequent occurrences of hourly values $\geqslant$ 0.10 ppm have little effect on the magnitude of the index. This problem frequently occurs for sites both located in high-elevation forested locations, as well as for some low-elevation forested and agricultural areas. At these locations, the magnitude of the cumulative exposure indices is high (Lefohn, 1992).

Alternatively, it has been noted that some experimental vegetation studies have numerous occurrences of hourly average values $\geqslant$ 0.10 ppm, which result also in large magnitudes for the cumulative indices. Thus, it is difficult to differentiate between two exposure regimes, both experiencing high magnitudes for the cumulative indices, but different occurrences of hourly average concentrations $\geqslant$ 0.10 ppm. In order to adequately describe the exposure regimes (i.e. the occurrences of high, mid-, and low-level hourly average concentrations) that occurred under experimental and ambient conditions, in our study, we have identified both the magnitude of the cumulative exposure index and the number of hourly values $\geqslant$ 0.10 ppm. This paper describes an approach for combining experimental exposure-response effects data for deciduous and coniferous seedlings and/or trees with (1) characterized O_3 ambient exposure data for the local area and (2) soil moisture to identify species and areas that may be at risk. The Southern Appalachian Mountain area was selected for a case study.

APPROACH

In this study, we follow the conclusions of Musselman et al. (1994) that all hourly average concentrations have the potential for impacting vegetation, but that the higher values should be given a greater weighting than the mid- and low-levels. At this time, the cumulative-type exposure index has been shown to perform adequately in relating growth reduction to vegetation and O_3 exposures occurring with single experiments (U.S. EPA, 1992, 1996; Lee et al., 1991; Lefohn, 1992a). However, when attempting to relate a particular set of exposureeresponse results to ambient conditions or other experimental results, single-parameter cumulative indices should be combined with some measure of the high hourly average values, which occurred in many of the open-top experiments (Lefohn and Foley, 1992, 1993; Lefohn et al., 1992a).

In this analysis, a 24 h sigmoidally weighted exposure index, W126, was used (Lefohn and Runeckles, 1987) for assessing growth losses. Alternatively, a 24 h SUM06 (the sum of all hourly average concentrations $\geqslant$ 0.06 ppm) exposure index could have been used. Both the W126 and the SUM06 are highly correlated and provide similar exposure-response results in modeling efforts (U.S. EPA, 1996); however, the W126 was selected because it does not use a subjectively determined threshold of 0.06 ppm, which cannot at this time be biologically substantiated. Although the index provides differentially greater weight to the higher hourly average concentrations, the W126 does include the lower, less biologically effective concentrations. At hourly average values below 0.04 ppm, the weighting is almost zero. We have integrated the W126 cumulative index over a 24 h period.

Limited research has addressed the problem of determining vegetation sensitivity as a function of time of day or growth season. Although there is a general pattern of increase in the morning and decline in the evening, the path of photosynthesis (and conductance) are quite different among days. Some plants keep their stomata open all night. Results reported by Winner et al. (1989) also indicate that plants can be sensitive to O_3 at night. Matyssek et al. (1995) reported that nighttime exposures to O_3 reduced the whole-plant production in one birch clone. It is difficult to generalize across all plant species and thus, the inherent variability in stomata1 opening makes using a set time period of O_3 exposure problematic.

For estimating the O_3 exposure regimes that relate to growth reduction of various deciduous and coniferous species grown in the Southern Appalachian region, we characterized 0, exposures from biological experiments. Experimental studies were included in our effort if the hourly averaged data were available and the investigators attempted to apply experimental exposures that mimicked actual conditions.

Using these criteria, Table 1 lists the O_3 vegetation experiments considered for developing exposure threshold values for the following nine species: black

Table 1. Listing of ozone exposure studies considered to develop the exposure threshold values

Common name	Species	Reference
Black cherry	*Prunus serotina* Ehrh.	Lee (personal comm.)
		Samuelson (1994)
Slash pine	*Pinus elliotti* Engelm.	Hogsett et al. (1985)
Yellow-poplar	*Liriodendron tulipijera* L.	Lee (personal comm.)
Eastern white pine	*Pinus strobus* L.	Lee (personal comm.)
Sugar maple	*Acer saccharum* Marsh.	Lee (personal comm.)
Red oak	*Quercus rubra* L.	Samuelson and Edwards (1993)
		Edwards *et al.* (1994)
		Samuelson *et al.* (1996)
Virginia pine	*Pinus viryiniana* Mill.	Lee (persona1 comm.)
Loblolly pine	*Pinus taeda* L.	Lefohn *et al.* (1992a)
		Shafer and Hkagle (1989)
		Kress (persona1 comm.)
Red maple	*Acer rubrum* L.	Lee (persona1 comm.)
		Samuelson (1994)

cherry (*Prunus serotina* Ehrh.); yellow-poplar (*Liriodendron tulipifera* L.); Virginia pine (*Pinus virginiana* Mill.); red maple (*Acer rubrum* L.); sugar maple (*Acer saccharum* Marsh.); eastern white pine (*Pinus strobus* L.); slash pine (*Pinus elliotti* Englem.); loblolly pine (*Pinus taeda* L.); and red oak (*Quercus rubra* L.). Ozone exposure data from these studies were obtained either from the papers or from the authors of the study, and the SUM06, W126, and number of hours $\geqslant$ 0.10 ppm were determined from the hourly averaged concentration data. Although the SUM06 index was not used in our investigations because of high correlation with the W126 index, the SUM06 values are provided for future reference. It was important that the hourly data were monitored over a 24 h period, not just during the fumigation period. If ambient data were collected over a 24 h period and the treatment data were not, the ambient data were used to fill in the missing information.

Table 2 summarizes the exposure regimes associated with growth reduction effects that were either (1) estimated at the 10% level (Lee, personal communication) or (2) reported by the investigators in their papers. The same growth reduction parameters are not universally measured by all investigators. For example, Neufeld et *al.* (1995) used reduced height growth, total, leaf, root, and shoot + root biomass as indicators of growth changes. Lee (personal communication) used biomass (i.e. foliage, stem, and root growth) as an indicator of growth changes. Samuelson and Edwards (1993) used leaf dry weight. Although no uniform measures of growth reduction are measured by the investigators which allow comparisons across species, we have noted when growth reduction was observed by each investigator listed in Table 2. In some cases, no effects were reported by the investigators, but the exposure regimes were noted because of the high exposures used in the experiments.

Lee (personal communication) provided the hourly O_3 data for several studies listed in Table 1 and provided the exposureeresponse equations that related total biomass with SUM06 and W126 exposures, using a 24 h period of exposures. Lee (personal communication) provided the 10% 24 h, 92 day adjusted SUM06 and W126 estimates for growth losses. In order to identify the exposure regimes that most closely matched the exposures estimated at the 10% yield loss with the actual exposure regimes used in the experiments, the 92 days SUM06 and W126 adjustments were readjusted for the actual exposure period. The readjusted SUM06 and W126 values that estimated 10% loss were then compared to the SUM06 and W126 values experienced in each of the experimental treatments to identify the estimated number of hourly average concentrations $\geqslant$ 0.10 ppm. Our concern was that if ambient data were used to predict growth losses using exposure-response relationships derived from experimental data that contained numerous occurrence $\geqslant$ 0.10 ppm, the result would possibly be overestimated. Although no formal analysis was performed by Lee (personal communication) to determine the combined levels for the multiple exposure indices associated with biomass response, the identification of the experimental treatment closest to the SUM06 or W126 exposure value predicted by Lee at the 10% growth loss level allowed for an estimate of the number of hourly average concentrations $\geqslant$ 0.10 ppm. The procedure was described by Lefohn and Foley (1992) in their analysis of National Crop Loss Assessment Network data.

For the studies where only effects were noted and not predicted, the regime used was the one that matched the level for the treatment at which growth effects were identified by the authors. In some cases, the treatments used in the experiments were charcoal-filtered (CF), non-filtered (NF), or two times ambient (NF x 2.0). If only the NF x 2.0 treatment exhibited an effect, the regime associated with that treatment was characterized and used in the study. It is possible that a level lower than that of the NF x 2.0 treatment may have exhibited an identified growth loss; however, given the design of the experiment, it

Table 2. Summary of range of exposure for vegetation

Species	Year	≥ 0.10 ppm	SUM06 (ppm h)	W126 (ppm h)	Reference
Black cherry	1989	**10**	**8.2**	7.4	Lee (personal comm.)
Black cherry	1992	**6**	**6.5**	5.9	Lee (personal comm.)
Black cherry	1993	**616**	**131.7**	122.5	Samuelson (1994)
Slash pine			**67.8**	55.2	Hogsett et al. (1985)
Yellow-poplar	1990	51	**26.0**	23.8	Lee (personal comm.)
Eastern white pine	1990	67	**29.8**		Lee (personal comm.)
Eastern white pine	1990	84		30.2	Lee (personal comm.)
Sugar maple	1990	84	41.2	44.7	Lee (personal comm.)[a]
Red oak					
Seedlings	**1992**	**298**	**100.5**	**89.2**	**Samuelson and Edward (1993)**
Trees	**1992**	**135**	**79.1**	**66.6**	**Samuel son and Edwards (1993)**
Seedlings	**1991**	**399**	**133.9**	**116.4**	**Edward et *al.* (1994)**
Trees	**1991**	**410**	**135.6**	**119.2**	**Edwards et al. (1994)**
Seedlings	**1992**	**298**	**100.5**	**89.2**	**Samuelson *et* al. (1996)**
Trees	**1992**	**212**	**84.6**	**72.2**	**Samuelson et *al.* (1996)**
Seedling	**1992**	**655**	**138.2**	**129.1**	**Samuelson *et al.* (1996)**
Trees	**1993**	**514**	**124.1**	**113.6**	**Samuelson *et al.* (1996)**
Seedlings	**1994**	**330**	**101.0**	**89.6**	**Samuelson et al. (1996)**
Trees	**1994**	**480**	**120.0**	**109.2**	**Samuelson et *al.* (1996)**
Virginia pine	**1992**	146[b]	**266.3**	**266.3**	Lee (personal comm.)[a]
Loblolly pine	**1988**	**1042**	**196.2**	**189.5**	Lefohn et al. (1992a)
Loblolly pine	**1989**	**1430**	**257.8**	**247.3**	Lefohn *et al.* (1992a)
Loblolly pine	**1985**	**252**	**75.3**	**67.4**	Shafer and Heagle (1989)
Loblolly pine	**1986**	**292**	**94.0**	**84.2**	Shafer and Heagle (1989)
Loblolly pine	**1987**	**466**	**117.3**	**107.0**	Shafer and Heagle (1989)’
Loblolly pine	**1988**	**867**	**176.3**	**164.7**	Kress (personal comm.)[d]
Loblolly pine	**1989**	**819**	**170.0**	**158.8**	Kress (personal comm.)[d]
Loblolly pine	**1990**	**1164**	**217.4**	**206.8**	Kress (personal comm.)[d]
Red maple	**1988**	**645**	**89.5**	**78.4**	Lee (personal comm.)
Red maple	**1993**	**655**	**135.2**	**126.7**	**Samuelson (1994)**

[a] Lee (personal communication) estimated 10% growth loss.
[b] Underestimate: No treatment levels were used that approximated the listed SUM06 or W126 values
‘Estimates derived from data described by Shafer and Heagle (1989).
[d] Estimates derived from data obtained from Kress and his colleagues.
Bold: No or minimal effect observed

was not possible to predict that level. It is important to note that we know of no studies where O_3 fumigations were conducted on mature trees within a forest. Therefore, there is uncertainty when extrapolating the O_3 fumigated seedling data or open-top mature red oak tree data to the forest level.

Those works that contributed an important part to our study for estimating the exposures that resulted in growth effects are summarized in Table 2. As indicated in the Introduction, we were concerned that if the experimental exposure protocols resulted in large number of hourly average concentrations ≥ 0.10 ppm, but ambient monitoring data indicated infrequent occurrences above this level, it would be difficult to apply experimental exposure-response relationships with ambient data for predictive purposes because, although the cumulative value might be similar, the exposure regimes (frequency of hourly average concentrations) were different in the two cases. The data summarized in Table 2 indicate that many of the experimental studies used in our analysis experienced far more numerous occurrences of hourly average concentrations ≥ 0.10 ppm than occur under ambient conditions. Unlike the experimental vegetation data used in our study, the 0.10 ppm level is infrequently exceeded at most ambient monitoring sites in the United States; at these ambient sites, the magnitude of the W126 exposure index, as well as the SUM06 index, is mostly influenced by the number of hourly average concentrations < 0.10 ppm. Thus, we focused on the 0.10 ppm level as a way to differentiate two different types of exposure regimes; one that experienced a large cumulative value with large numbers of occurrences ≥ 0.10 ppm and a second that also experienced a large cumulative value but with infrequent occurrences ≥ 0.10 ppm.

Some of the information provided by Lee (personal communication) that was used in our analysis was derived from work described by Karnosky et *al.* (1995), Neufeld et ***al.*** (1995), and Neufeld and Renfro (1993). Results reported by Samuelson (1994), Hogsett et ***a/.*** (1985), Lefohn et ***al.*** (1992a), Shafer and Heagle (1989), Kress (personal communication), Samuelson and Edwards (1993), Edwards et al. (1994), and

Table 3. Ozone exposure levels as a function of tree response category

Tree response category	W126 (ppm h)		Exposure hours ≥ 0.10 ppm
Minimal	≥ 0	and	≥ 0
Level 1 (only high sensitive species affected) (e.g. black cherry)	≥ 5.9	and	≥ 6
Level 2 (moderately sensitive species affected) (e.g. yellow-poplar)	≥ 23.8	and	≥ 51
Level 3 (resistant species affected) (e.g. red oak)	≥ 66.6	and	≥ 135

Samuelson et al. (1996) contributed an important part in estimating the exposures that resulted in growth effects.

We decided to organize the experiments into three groupings after examining the W 126 and hourly average O_3 concentrations ≥ 0.10 (Table 2). The species (black cherry and slash pine) with the greatest sensitivity were classified as Level 1. The second grouping, Level 2, included the moderately sensitive species of yellow-poplar, white pine, and sugar maple. The third grouping, Level 3, included red oak, Virginia pine, loblolly pine, and red maple. Using these experimental results, four broad sensitivity categories (i.e. minimal, Levels l-3) were defined to relate ambient O_3 exposures measured in the field to the experimental studies examining growth impacts. Table 3 describes the O_3 exposure ranges for each sensitivity category based upon the experimental results that had the lowest W126 and/or average hourly O_3 concentrations ≥ 0.10 ppm. The Level 1 category was based on the black cherry study identified by Lee (persona1 communication); the Level 2 category was based on the yellow-poplar study identified by Lee (persona1 communication); the Level 3 category was based on the open-top red oak tree study described by Samuelson and Edwards (1993). The miminal category was used to identify areas where there was a low likelihood for growth losses due to 0, because (1) the exposures were low, or (2) as discussed later in the paper, the soil moisture was so low that the stomata were likely to be closed and O_3 penetration may have been minimal into the leaf.

Linking the identified experimental exposure regimes with ambient data resulted in the characterization of hourly average O_3 monitoring data. Hourly average O_3 concentration data were gathered from the U.S. Environmental Protection Agency (EPA) Aerometric Information Retrieval System (AIRS) database and from the data in the National Dry Deposition Network program for the period 198331990. The monitoring sites included those found in Alabama, Georgia, Indiana, Illinois, Mississippi, Missouri, Arkansas, South Carolina, North Carolina, Tennessee, Kentucky, Virginia, West Virginia, Maryland, Pennsylvania, and Ohio. The W 126 cumulative exposure index was characterized for the 24 h period for April through October.

Cumulative indices from hourly average O_3 data are almost always computed with data sets that do not have 100% of all possible monitoring hours represented. Currently, there is no statistically justified method for correcting cumulative indices to reflect 100% data capture. However, for this analysis, several criteria were applied to correct the seasonal W126 index. Lefohn *et al.* (1992b) have described the correction algorithm used.

Once the W126 cumulative exposure index was calculated for each monitoring site, the 7-month (April–October) W126 exposure index value was kriged for each $\frac{1}{2}$ by $\frac{1}{2}^\circ$ cell in Alabama, Georgia, South Carolina, North Carolina, West Virginia, Tennessee, Kentucky, and Virginia for each year from 1983 to 1990. Lefohn et *al.* (1987, 1992b) have discussed the approach used for kriging 0,.

Each $\frac{1}{2}$ by $\frac{1}{2}^\circ$ grid cell in the Southern Appalachian area was assigned one of the four categories listed in Table 3. Because the criteria listed in Table 3 require that both the W 126 and number of hours ≥ 0.10 ppm be met, it was necessary to predict the number of occurrences of high hourly average concentrations. There is a paucity of air quality monitoring data which makes it difficult, at this time, to spatially predict the number of hourly average concentrations ≥ 0.10 ppm accurately. However, we found that it was possible to separate the area into broad exposure categories due to the occurrences of hourly average concentrations ≥ 0.10 ppm during "high" and "low" O_3 exposure years. For example, in 198331986 and 1989-1990, the number of hourly average concentrations ≥ 0.10 ppm at all sites in the geographic area was less than 51, which is below the Level 2 sensitivity category. In 1987, there was only one site that experienced greater than 51 occurrences ≥ 0.10 ppm. In 1988, the high exposure year, 11 of 15 monitoring sites experienced 51 or more hourly occurrences ≥ 0.10 ppm. Subjectively, it was decided that grids which had two or more O_3 monitors were classified using the highest value; cells which did not have an O_3 monitor were classified by examining the pattern from O_3 monitors surrounding the cell and selecting a site whose value was the second highest number of hours ≥ 0.10 ppm. The final classification of a grid cell was defined by the highest level achieved in Table 3. Note that if a grid is rated at Level 2, the O_3 exposure may be high enough to cause growth reductions for species with Level 2 sensitivities, as well as for those species which have Level 1 sensitivities.

The above initial approach assumes that the (1) environmental conditions were favourable for O_3 to enter the leaf and (2) total cumulative exposure would

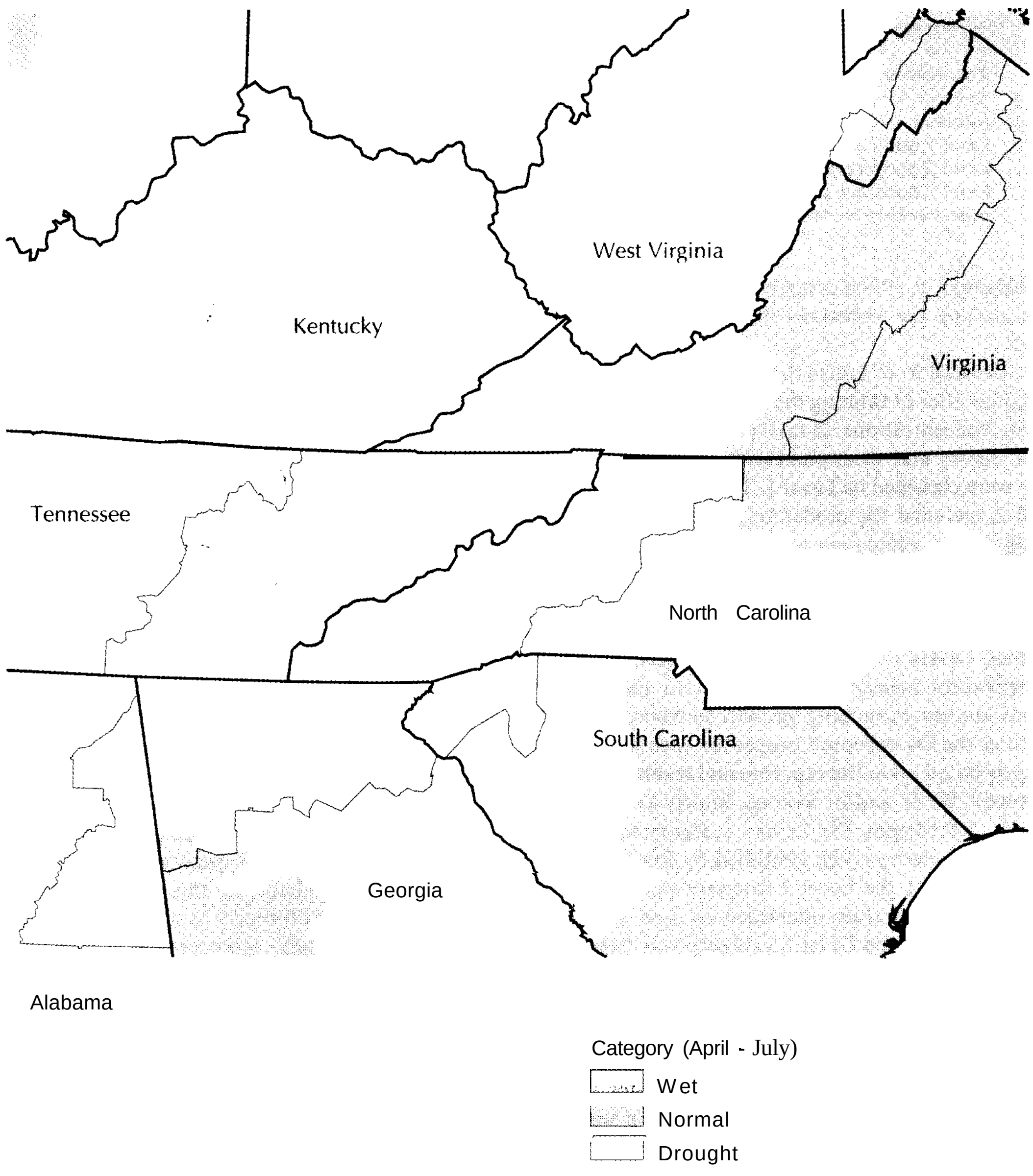

Fig. 1. Palmer hydrologic drought index for 1988.

result in a growth loss. However, as mentioned in the Introduction, it is necessary to consider conditions that affect a plant's sensitivity. The experimental studies listed in Table 1 used seedling and tree species which were grown under optimum conditions (e.g. adequate moisture and nutrients). Showman (1991), Jackson et al. (1992) and Kouterick (1995) have observed significantly fewer O_3 symptoms on sensitive species during periods of drought than during years when the growing season had adequate rainfall. Unfortunately, at this time, little experimental information is available relating O_3 exposure, drought conditions, and tree growth reduction.

Based on observations in the field and in experiments, soil moisture is an important variable which influences the uptake of O_3 by a plant (U.S. EPA, 1986, 1996). To take these potential effects into consideration in our study, the Palmer hydrologic index was selected as an indicator of soil moisture (Palmer, 1965, 1967). Because Palmer hydrologic index data were available for the period 198331990, the study was limited to this time frame. The index is a monthly value, computed for a climatic division, which indicates the severity of a wet or dry spell. Figures 1 and 2 show a comparison of a dry (1988) and wet (1989) year for the Palmer hydrologic index. The index has been used widely to study the nature of drought over the contiguous United States and has been used to study the interactive effects of ambient O_3 and climate on tree growth (McLaughlin and Downing, 1995a; Brooks, 1994); only recently has it been applied in

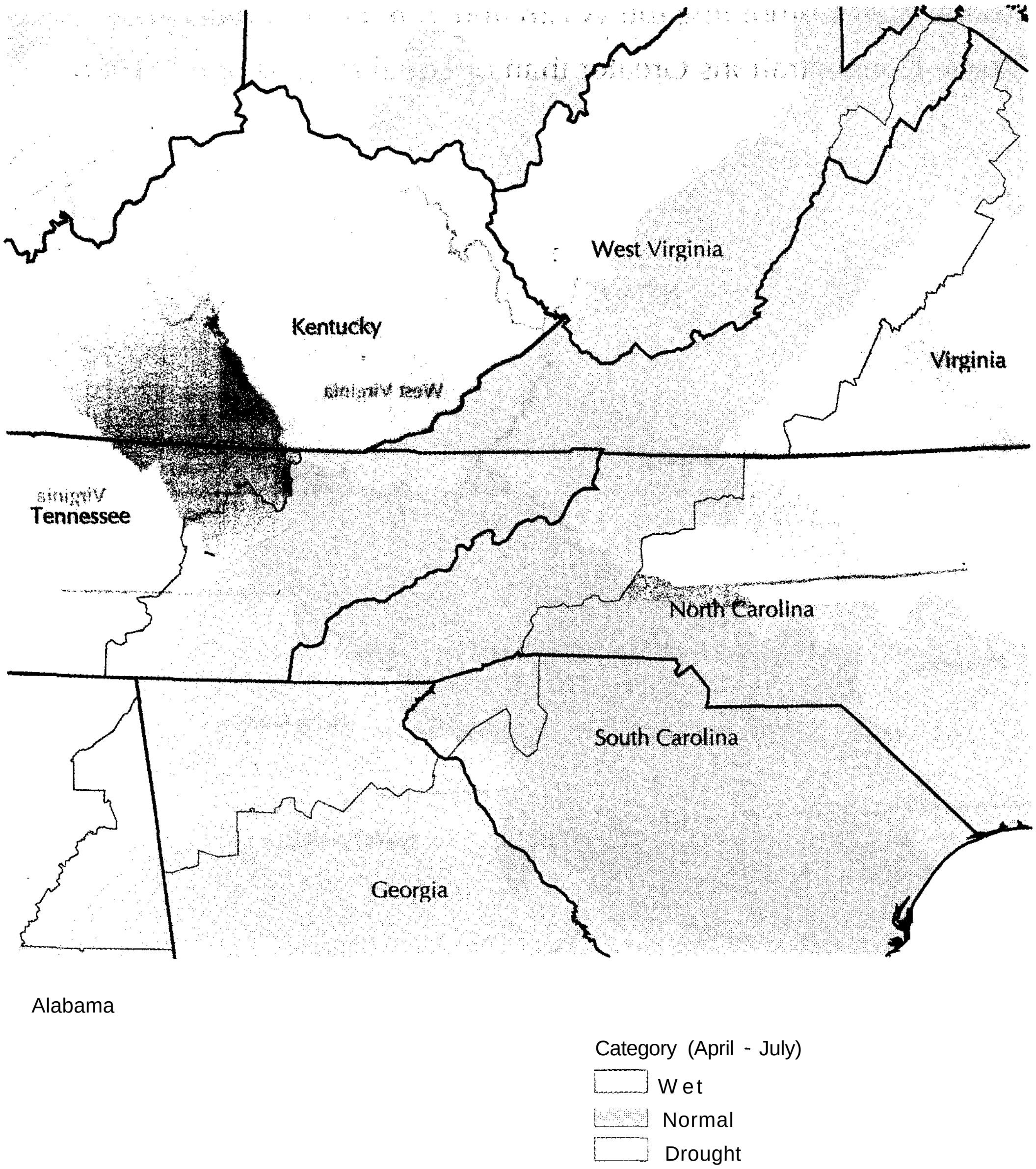

Fig. 2. Palmer hydrologic drought index for 1989.

Europe (Briffa *et al.*, *1994)*. A Palmer hydrologic index of less than − 2 was assumed in our analysis to be drought conditions (Briffa *et al.*, 1994), with the implication that O_3 might not damage the plants. Values above − 2 were considered to have adequate soil moisture. The average Palmer hydrologic index was restricted to the months of April through July (Vose and Swank, 1993), based upon the observation of growth patterns during years of drought. The investigators observed that most growth during drought occurred in spring and early summer, in contrast to a wet year, where growth was more uniform throughout the entire spring and summer. In our study, the average Palmer hydrologic index was calculated for each regional climatic division.

Combining the Palmer hydrologic index and O_3 exposure allowed us to identify those areas within the region where (1) soil moisture may have been adequate in the area and (2) ambient O_3 exposure regimes closely matched those experiments where growth losses were observed. Areas which were classified as experiencing a drought were assigned the minimal category; otherwise, the sensitivity category value remained the same after applying the critieria in Table 3.

RESULTS

For the years 1983-1990, the O_3 exposure kriging estimates resulted in most of the grid cells falling in

Results After Combining the W126 and Number of Hours with
Ozone Concentrations Greater than or Equal to 0.10 ppm - 1988

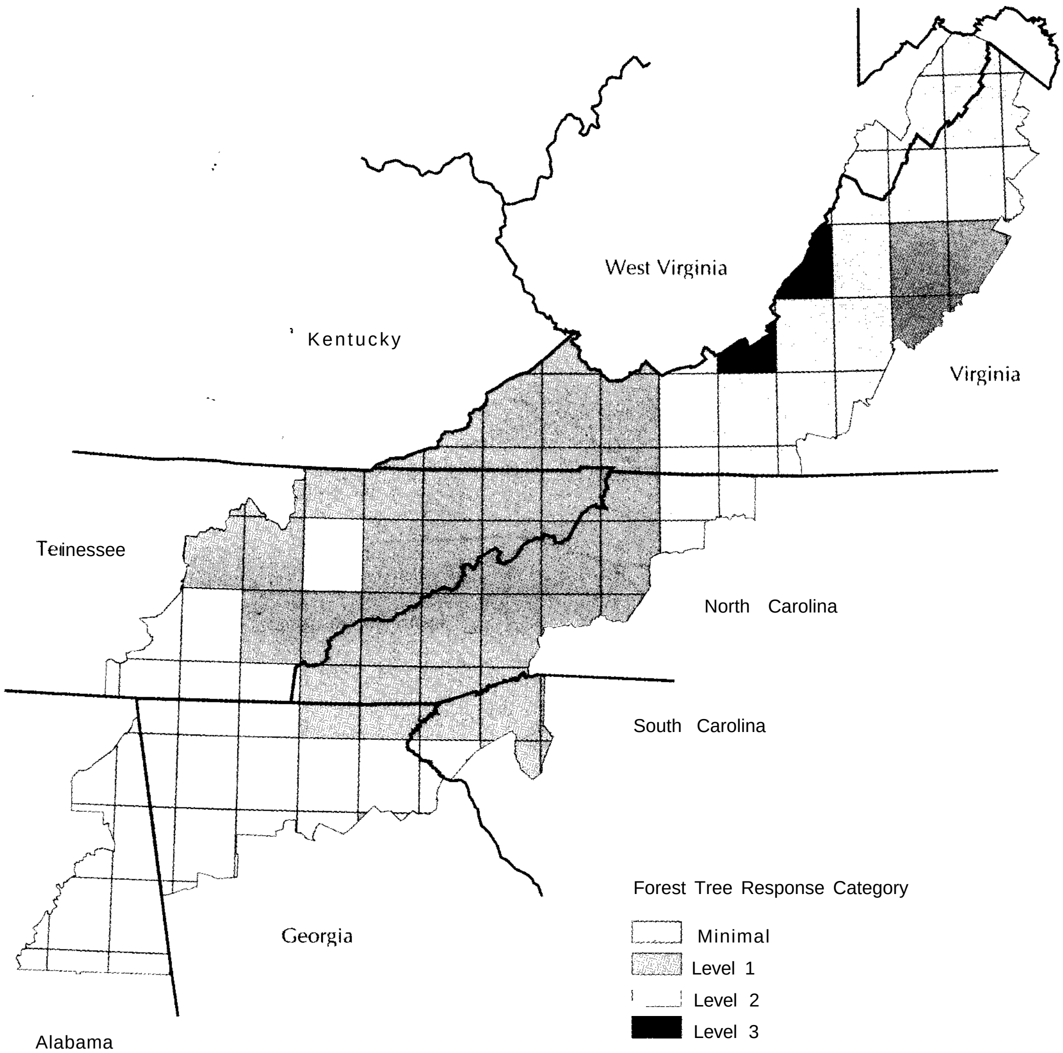

Fig. 3. The combination of the W126 ozone exposure index and the number of hours with ozone concentrations greater than or equal to 0.10 ppm for 1988.

the range of W126 values of 23.8-66.5 ppmh. In 1988, 11 of the 120 cells had W126 estimates greater than 66.5 ppm h. Three cells in 1986 and 1989, and one cell in 1990, had a W126 estimate of 5.9-23.7 ppm h. No cells were classified as having less than 5.9 ppmh. Usually, within the Southern Appalachian area boundary, the O_3 monitors experienced fewer than 40 h in which the hourly average O_3 concentration was $\geqslant$ 0.10 ppm. The only year that deviated from this pattern was 1988; 11 of the 15 O_3 monitors in the area had greater than 50 h in which the hourly average O_3 concentration was $\geqslant$ 0.10 ppm. Figures 3 and 4 summarize geographically, by forecast tree response category, the results after combining the W126 exposure index with the number of hourly concentrations $\geqslant$0.10 ppm for 1988 and 1989. Note the exposure difference between the two years. Table 4 summarizes the number of hectares (by sensitivity levels) exposed to O_3 levels that may be of concern.

As indicated above, it is important to consider drought conditions. For the period 1983–1990, the Palmer hydrologic index showed that for the some of the Appalachian area, normal or wet moisture conditions occurred in every year. A large number of

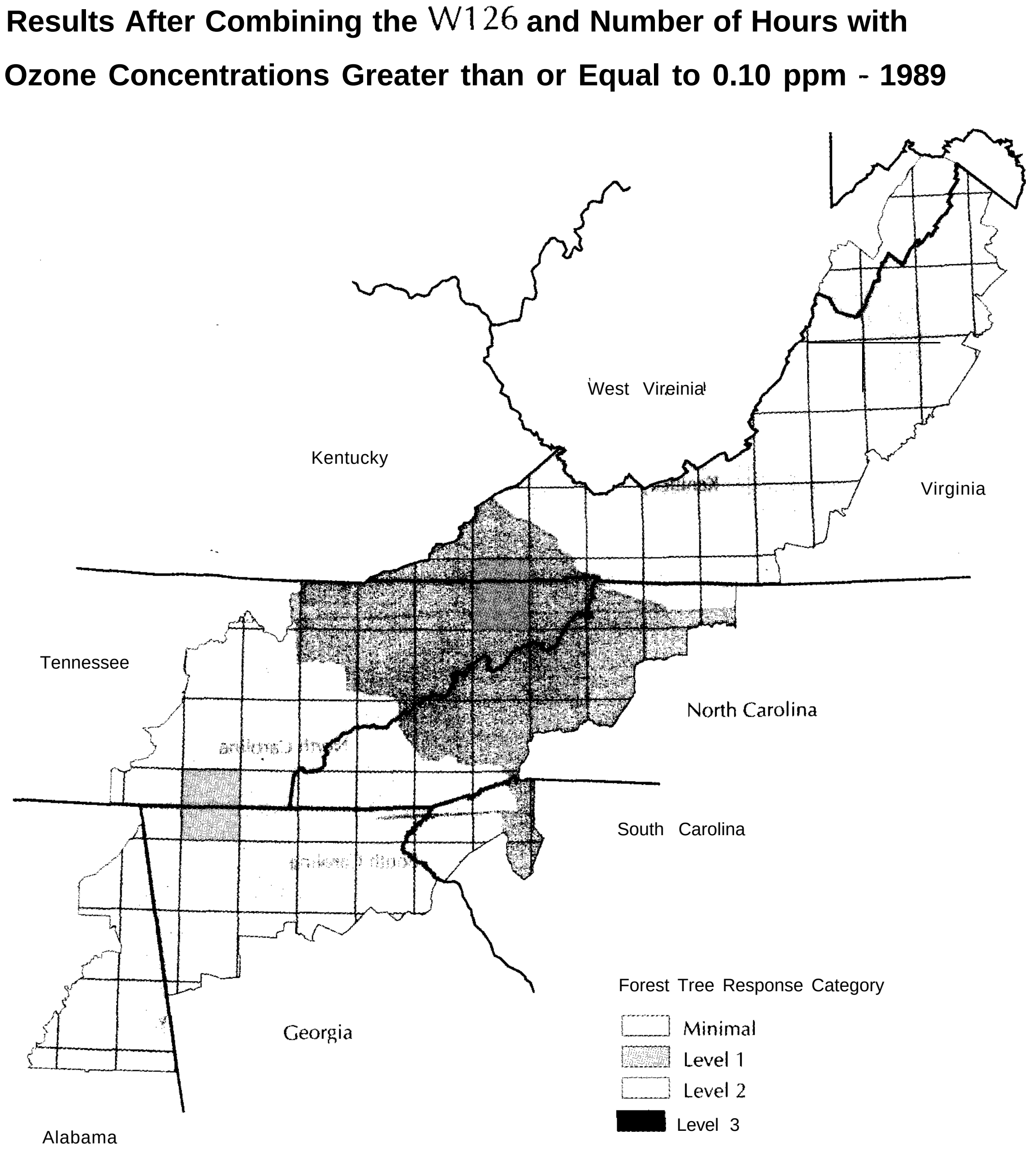

Fig. 4. The combination of the W126 ozone exposure index and the number of hours with ozone concentrations greater than or equal to 0.10 ppm for 1989.

Table 4. Number of hectares exposed to O_3 levels that are of concern by sensitivity level

Year	Minimal	Level 1	Level 2	Level 3
1983		15,143,160		
1984	6,653,386	8,489,774		
1985	5,179,678	9,963,482		
1986	8,002,438	7,140,722		
1987	1,870,230	13,022,809	205,121	
1988		6,993,216	7,906,006	243,938
1989	14,641,415	501,745		
1990	9.773,653	5,369,507		

hectares experienced drought conditions in 1985-1988, with the largest area, 14,640,687 hectares, being affected in 1986 (Table 5).

The combination of the Palmer hydrologic index and the O_3 exposure results takes into consideration soil moisture conditions that may possibly ameliorate 0, exposure (Table 6 and Figs 5 and 6). By comparing Tables 4 and 6, it can be concluded that drought in 1985-1988 has reduced the number of hectares that may be of concern regarding possible O_3 effects, relative to considering O_3 alone (cf. Tables 4 and 6 and Figs 3 and 5). Based on the above analyses, by

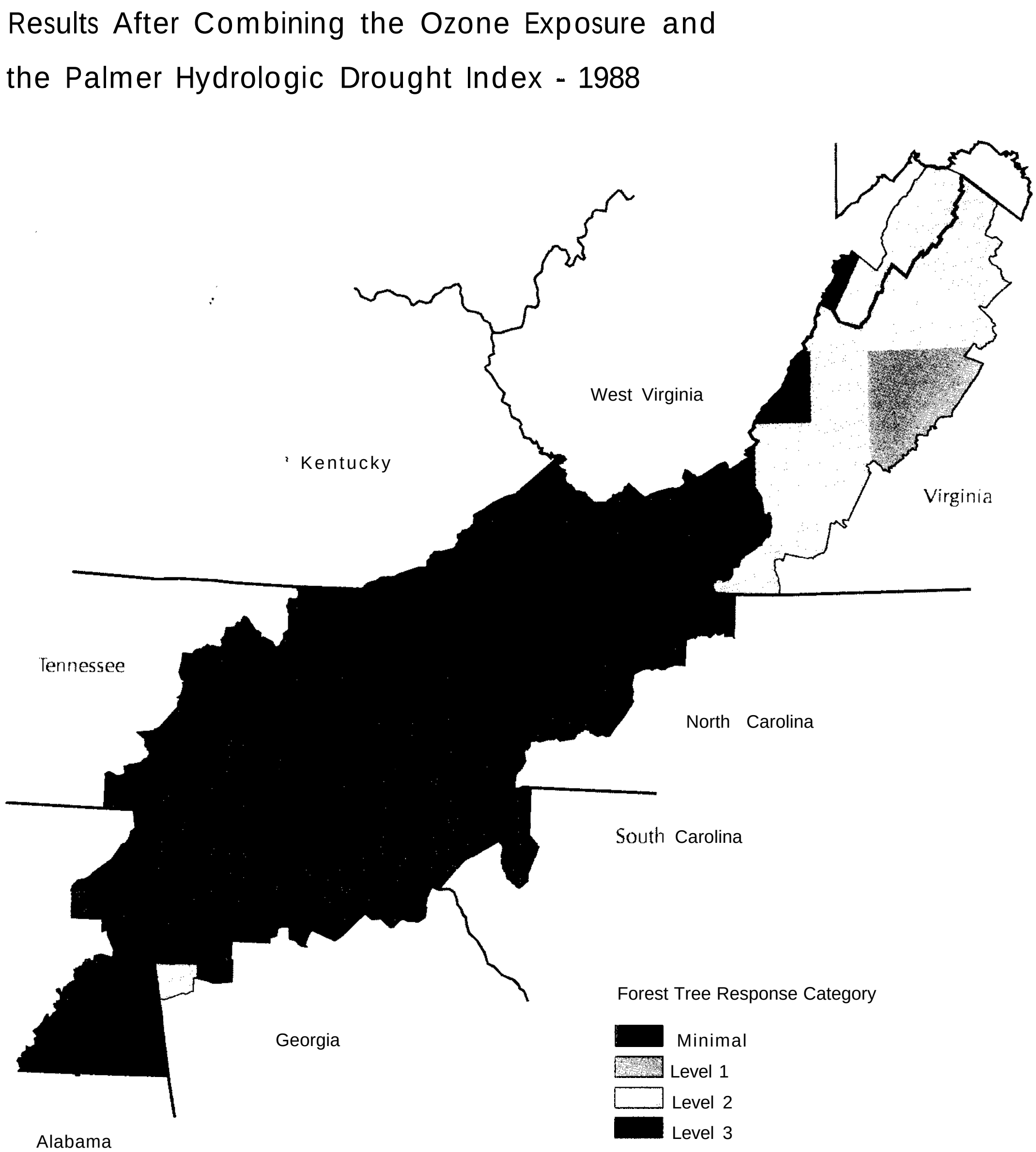

Fig. 5. The combination of the W126 ozone exposure index and the Palmer hydrologic drought index for 1988.

Table 5. Number of hectares in each moisture index category

Year	Average (April&July) Palmer hydrologic index		
	Drought	Normal	Wet
1983		12,010,770	3,132,390
1984		5104,709	10,038,451
1985	11,182,273	3,960,887	
1986	14,640,687	502,473	
1987	4,683,119	8,522,399	1,937,642
1988	11,802,449	3,340,711	
1989		12,860,859	2,282,301
1990		4,638,304	10,504,856

Table 6. Number of hectares exposed to O_3 levels that are of concern by sensitivity levels combined with adequate moisture conditions

Year	Minimal	Level 1	Level 2	Level 3
1983		15,143,160		
1984	6,653,386	8,489,774		
1985	13,000,521	2,142,639		
1986	15,143,160			
1987	6,052,083	9,091,077		
1988	11,802,449	574,965	2,596,896	168,850
1989	14,641,415	501,745		
1990	9,773,653	5,369,507		

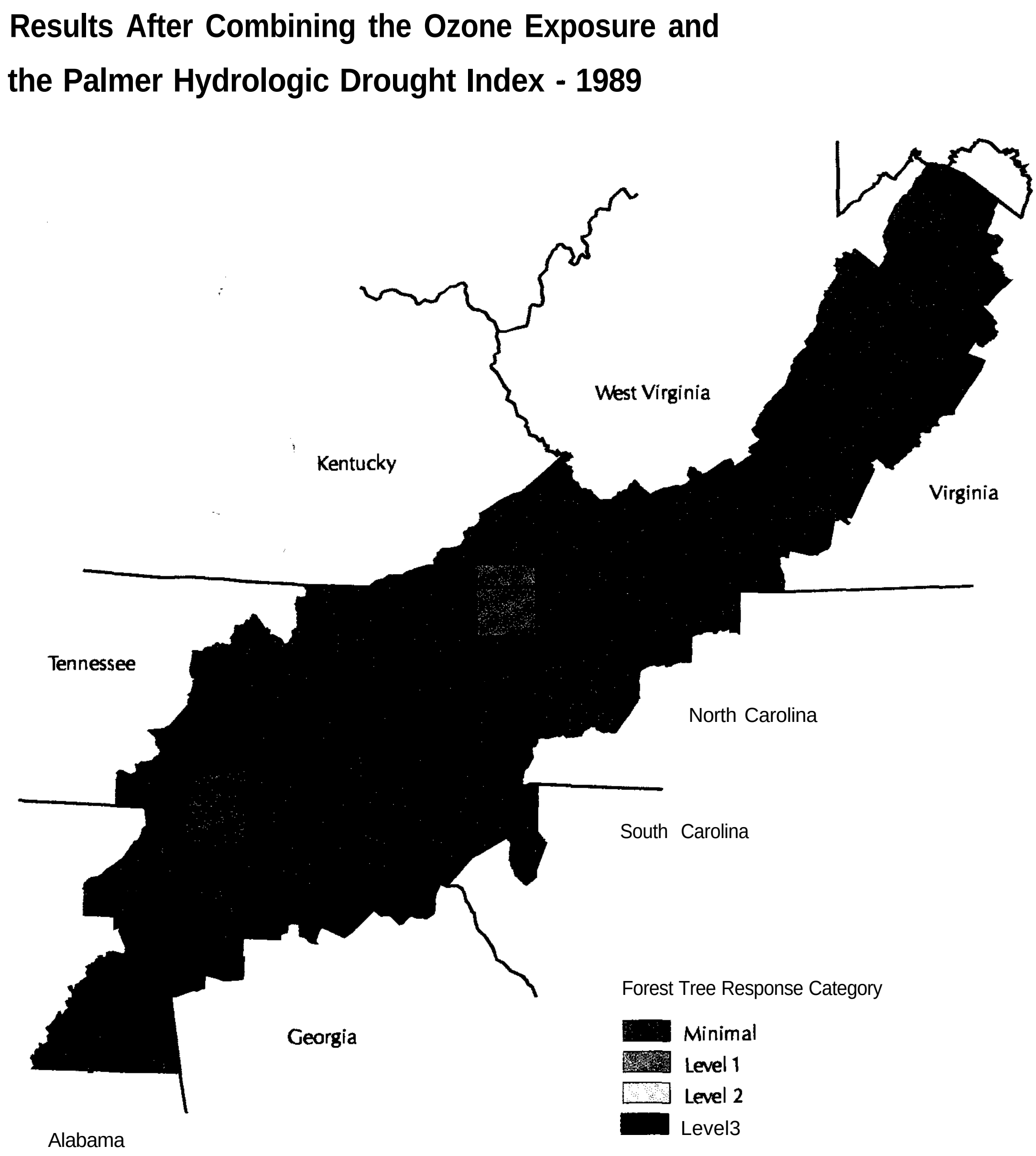

Fig. 6. The combination of the W126 ozone exposure index and the Palmer hydrologic drought index for 1989.

combining exposure information with moisture availability and experimental exposure-response data, the extreme northern and southern portions of the Southern Appalachian area were identified as having the greatest potential for possible vegetation effects. However, the following caveats are important:

1. The W126 exposure index value was accumulated over the April-October period. Most of the experimental data used in the open-top chamber experiments in this analysis were collected over a 3- to 4-month period. Thus, by using a 7-month period to accumulate the W126 value, we may have *overestimated* the likelihood of vegetation effects that have been experienced.

2. The Palmer hydrologic index does not consider the soil moisture holding capacity and low values do not necessarily indicate that the plant is drought stressed. Individual areas 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 915 m) 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 (National Acid Precipitation Assessment Program, 1991b).

3. The study was mostly based on results from individual seedlings in chambers and pots and it is unclear what differences in effects might be observed if similar exposures were experienced in actual forests.

4. Response of large trees to O_3 may be different than when tree seedlings are exposed. Competition among species, as well as closed vs more open canopy conditions may alter the responses of O_3 exposure (U.S. EPA, 1996).

5. Response to a specific tree species may not translate to forest effects given the competitive nature of forests. Thus, if one species is affected by growth losses due to ozone, another species, more resistant to ozone, may increase its growth.

DISCUSSION AND CONCLUSIONS

As an ameliorating effect from O_3 exposures on vegetation, we have considered soil moisture. An additional effect has been described by Lefohn *et al.* (1990). Given the same ppm value experienced at both high- and low-elevation sites, the absolute concentrations (i.e. micrograms per cubic meter), at two elevations are different. Therefore, if we assume that the sensitivity of a plant is nearly identical at both low and high elevations, some adjustment to the exposure-response relationship may be necessary when attempting to link experimental data obtained at low-elevation sites with air quality data monitored at high-elevation stations.

Using available O_3 monitoring data for 1983-1990 and exposure-response data based on seedlings and trees, we identified geographic regions within the area that may have experienced O_3 exposures, which include high cumulative values as well as the presence of sufficient numbers of high concentrations, coupled with suffcient soil moisture, that have the potential for inhibiting vegetation growth. Our results indicate that in a small number of areas within the region, O_3 exposures and soil moisture availability might be sufficient to cause growth losses to some sensitive species. The number of hectares where vegetation may be affected by O_3 exposures may represent an overestimate due to the optimum growth conditions experienced in the experimental open-top chambers and the manner in which we characterized the ambient O_3 data (i.e. over a 7-month period). In addition, two other items are important: (1) the growing range of each species and amounts of species in each cell were not used in our analysis; and (2) the resolution of the Palmer hydrologic index is at the climatic division for each month and, depending upon the variability of soils in the climatic area, the index may provide less than optimum predictions. In our study, we have identified areas where 0, exposure and some environmental conditions may have been favourable for some unknown amounts of growth loss to occur. However, we caution that verification of actual growth losses must occur in the identified areas before one can link O_3 exposure and predicted vegetation losses.

Acknowledgements—Dr Lefohn wishes to acknowledge the Tennessee Valley Authority and the USDA Forest Service, Asheville, NC for supporting his research. The authors wish to thank the U.S. Environmental Protection Agency, Corvallis Oregon and Dr E. Henry Lee, Dynamac Corporation, Corvallis, Oregon, for providing us with the exposure–response data for several of the seedling and tree species used in our analysis. We are pleased to acknowledge Drs Allan Heagle and Lisa Samuelson for providing us with air quality data that were associated with their biological experiments. We acknowledge Dr Lance Kress for giving us permission to use the hourly average O_3 data that were associated with his biological experiments. We wish to acknowledge Mr Karl Hermann, National Biological Service of Department of Interior, for his analytical support with the geographic information systems and Dr Pat Brewer, Tennessee Valley Authority, for her helpful comments.

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