OZONE EXPOSURES AND IMPLICATIONS FOR VEGETATION IN RURAL AREAS OF THE CENTRAL APPALACHIAN MOUNTAINS, U.S.A.

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Abstract. The United States is making the transition from the 1979 1 hr maximum ozone standard to the newly adopted 8 hr ozone standard (3 yr average of the 4th highest maximum 8 hr ozone concentration). Consequently, we analyzed and compared ozone concentrations under both standards from a variety of monitoring sites throughout the central Appalachian region of Kentucky (KY), West Virginia (WV), and Virginia (VA). Data from 1988–1999 were used to determine how ozone exposure between the two metrics compared for remote sites. Most sites exceeded the 1 hr standard in 1988–1990 due to the 3 yr averaging and multiple high ozone concentrations that occurred over the region in 1988. All sites were in compliance with the 1 hr standard every year after 1991. It was much more common for the ozone exposure to exceed the 8 hr standard, particularly from 1997–1999. Many sites showed exceedences beginning in 1995; Big Meadows (VA) exceeded the 8 hr standard all years except 1994 and 1996. Response of vegetation to ozone in these areas was determined using the combination of W126 values (sigmoidally weighted exposure index), the number of hours that average concentrations $\geq$0.10 ppm (N100), and the presence of moderate or more extreme droughts. In general, W126 and N100 values suggested that negative vegetation growth responses over most of the 12 yr would have been minimal for most sites, even for those exceeding ozone standards. Drought-induced stomatal closures would have overridden more extreme negative growth responses at all but the Big Meadows site in 1988.

Keywords: air pollution, compliance, drought, forest health, Ozone standards

1. Introduction

Ozone often is cited as the air pollutant of greatest direct threat to vegetation in the eastern United States (U.S. Environmental Protection Agency, 1996). The USDA Forest Service seeks to understand how ambient ozone exposures might affect vegetation on public lands it manages, to comment appropriately on regulation changes that might affect air quality on National Forests. The Forest Service also is mandated by Congress to review Prevention of Significant Deterioration (PSD) draft permits prepared by state air permitting authorities for industries that want to increase or initiate pollution emissions which might affect Class 1 Wilderness 'air quality related values' (Clean Air Act 42 U.S.C. 7401 *et seq.*). The central Appalachian Mountains contain 4 Class 1 areas: Dolly Sods, Otter

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Creek, and James River Face Wildernesses, and Shenandoah National Park. Several ozone-monitoring sites within the region provide useful data for the federal land manager's permit review and final comments regarding elevated pollution emissions.

The United States is making the transition from the 1979 1 hr maximum ozone standard to the newly adopted 8 hr standard. Toward this end, in this paper we summarize ozone data collected during the past decade from 9 rural monitoring sites in the Kentucky/West Virginia/Virginia portion of the central Appalachians in relation to the 1 and 8 hr ozone standards. Exposure-response relationships also are examined to estimate the biological response of trees during those years. The 1 hr standard is a maximum 1 hr average of 0.12 ppm. Nonattainment occurs when the annual number of hourly ozone concentrations >0.12 ppm averaged over 3 consecutive years exceeds 1.0 (U.S. Environmental Protection Agency, 1979, 1997a). The 3 yr average is determined from the average of the current year's and 2 previous years' number of exceedences (U.S. Environmental Protection Agency, 2002a). Nonattainment under the 8 hr standard occurs when the 3 yr average (again, using the current and previous 2 yr) of the 4th highest daily maximum 8 hr ozone concentration is >0.08 ppm (U.S. Environmental Protection Agency, 1997b).

Primary and secondary ozone standards exist for both the 1 and 8 hr concentrations. The primary standard is set to protect human health; the secondary standard is to protect welfare, which includes protecting vegetation (U.S. Environmental Protection Agency, 1997c). Our interests and discussion here involve vegetation responses, so focus is on the secondary standards. However, since the primary and secondary standards for both ozone standards are set at the same levels (U.S. Environmental Protection Agency, 2002b), the distinction between primary and secondary standards is somewhat academic.

Note that while we discuss results in terms of exceeding or not exceeding the standards, we have not used the same quality assurance procedures nor limited data to those obtained only from sites in the United States Environmental Protection Agency (U.S. EPA) Ambient Air Monitoring Program. Consequently, our interpretations of ozone exposures in relationship to the national ambient air quality standards are not entirely comparable to those of states or U.S. EPA. Also, additional monitoring sites outside of the state monitoring networks have been included in this analysis to assess potential impacts to vegetation in forested areas.

2. Approach

2.1. Monitoring sites and data collection

Ozone concentrations from 9 broadly located sites in the Appalachian Mountain region of West Virginia (WV), Virginia (VA), and Kentucky (KY) were used (Figure 1). Six of these sites were part of U.S. EPA's Clean Air Status and Trends

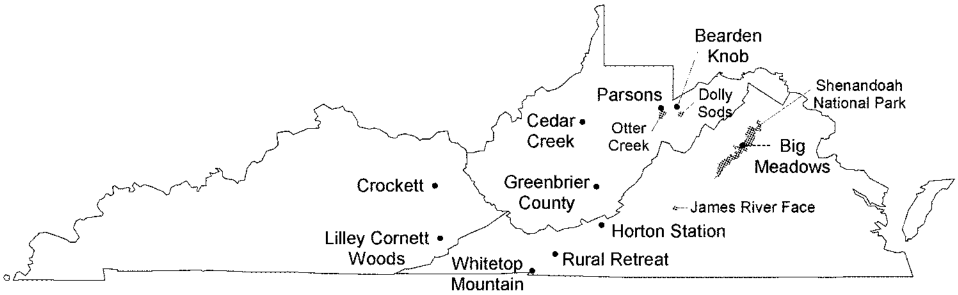

Figure 1. Locations of the ozone monitoring sites (solid black dots) and Class 1 Wildernesses (grey shaded areas).

Network (CASTNet), formerly the National Dry Deposition Network (Table I). The Bearden Knob site is operated by the Forest Service, while the Rural Retreat and Greenbrier County sites are operated by VA and WV, respectively (Table I). The latter sites are part of the State and Local Air Monitoring Stations (SLAMS) program (U.S. Environmental Protection Agency, 1994). The Lilley Cornett Woods site was operated from 1988–1993. In 1993, monitoring was discontinued at this site and initiated at the Crockett site, which is approximately 100 km north of Lilley Cornett Woods. The Parsons and Bearden Knob sites are only about 20 air km apart, but Parsons is at a low elevation and Bearden Knob is at a high elevation (Table I).

Measuring and data handling protocols for all CASTNet sites were identical (Environmental Science and Engineering, 1999). Ozone concentrations were measured continuously year-round from ambient air at 10 m above ground using Thermo Electron Model 49 ozone analyzers. Instrument operation was checked every Tuesday and Friday. Internal zero, precision and span calibration checks were performed automatically and reviewed every week. Manual calibration was performed quarterly by the U.S. EPA contractor. Data were recorded as 5 min averages then averaged hourly on an Odessa 3260 data logger. Data were transmitted to the U.S. EPA contractor responsible for installation, calibration, and maintenance of CASTNet sites and then to the U.S. EPA's Atmospheric Research Exposure Assessment Laboratory at Research Triangle Park, North Carolina for validation and verification. Following validation, a final data set of daily hourly averages was developed.

Although not operated by CASTNet, Bearden Knob used the same instrumentation and housing, and essentially followed CASTNet monitoring protocols except that site visits were only on Tuesdays and quarterly calibrations of the Bearden Knob site were performed by Forest Service personnel. A U.S. EPA audit of the Bearden Knob site in 1999 indicated satisfactory calibration. Bearden Knob data were verified by Forest Service personnel, who developed the final average hourly data set.

TABLE I
Characteristics of ozone monitoring sites

Site	Years	Latitude (°N)	Longitude (°W)	Elevation (m)	Land use	Network
West Virginia						
Parsons	1988–1999	39.0906	79.6614	510	Forest	CASTNet[a]
Bearden Knob	1993–1999	39.1050	79.4258	1175	Forest	FS research[c]
Cedar Creek	1988–1999	38.8794	80.8478	234	Forest	CASTNet
Greenbrier County	1995–1999	37.9083	80.6328	756	Agricultural	SLAMS[b]
Virginia						
Big Meadows	1988–1999	38.5231	78.4347	1073	Forest	CASTNet
Rural Retreat	1988–1999	36.8931	81.2550	835	Agricultural	SLAMS
Horton Station	1987–1999	37.3300	80.5573	920	Agricultural	CASTNet
Whitetop Mountain	1993–1999	36.6386	81.6053	1686	Forest	EPA research[c]
Kentucky						
Crockett	1994–1999	37.9211	83.0658	455	Agricultural	CASTNet
Lilley Cornett Woods	1988–1993	37.1300	82.9900	335	Agricultural	CASTNet
'Low O_3' comparison						
Glacier Nat. Park, MT	1989–1999	48.5103	113.9956	976	Forest	CASTNet
'High O_3' comparison						
Joshua Tree Nat. Mon., CA	1995–1999	34.0714	116.3906	1244	Desert	CASTNet

[a] CASTNet: U.S. EPA Clean Air Status and Trends Network.
[b] SLAMS: U.S. EPA State and Local Air Monitoring Stations Program.
[c] Research sites operated by USDA Forest Service and U.S. EPA.

The Greenbrier County and Rural Retreat SLAMS sites operated by protocols described in U.S. Environmental Protection Agency (1994). Specific brands of instrumentation for monitoring, downloading, and data handling were not set forth within the protocols, but they required continuous analysis, set minimum requirements for instrument precision and accuracy, concentration response checks, and calibration checks. They also provided specifications for siting equipment (such as ozone probe heights located 3–15 m above ground), network design, and quality

TABLE II

Tree-response categories as a result of combined W126 and N100 values, assuming adequate moisture and nutrition (after Lefohn *et al*., 1997)

Tree response category	W126		N100
Minimal	≥0	and	≥0
Only highly sensitive species affected	≥5.9	and	≥6
Moderately and highly sensitive species affected	≥23.8	and	≥51
Resistant, moderately, and highly sensitive species affected	≥66.6	and	≥135

assurance (QA) programs. Annual QA reports were reviewed by U.S. EPA. The SLAMS sites included in this paper monitored ozone only from April through October.

2.2. Data handling and analyses

U.S. EPA protocols were used for data calculations. Only data from April through October were used because these months have climatic conditions most conducive to formation of high ozone concentrations and the 2 SLAMS sites collected data only from April through October. Hourly averages were calculated as 0000–0059 EST, 0100–0159 EST, etc. For both the 1 and 8 hr standards, ozone concentrations are reported as parts per million (ppm) to 3 decimal places (U.S. Environmental Protection Agency, 1979, 1998). Insignificant digits to the right of the decimal (4th place and higher digits) are truncated and are not used to round the third significant digit. Concentrations for both the 1 and 8 hr standards are determined using only 2 significant digits, so the retained third significant digit is used for rounding. A concentration is rounded up when the third significant digit is ≥5 (U.S. Environmental Protection Agency, 1999). For example, a reading of 0.065 ppm would be rounded to 0.07 ppm and a reading of 0.114 ppm would be rounded to 0.11 ppm. Thus, a computed 3 yr average ozone concentration of 0.085 ppm is the smallest that would exceed the 8 hr standard (U.S. Environmental Protection Agency, 1999). A computed concentration of 0.125 ppm is the smallest concentration that would be counted toward exceeding the 1 hr standard (Jones and Adler, 1995).

The 3 yr average number of occurrences >0.12 ppm to determine exceedence of the 1 hr standard was calculated by tabulating the number of annual 0.12 ppm exceedences using a SAS (SAS Institute, 1988) program and then manually calculating the 3 yr average number of exceedences. The 3 yr average of the 4th highest daily maximum 8 hr ozone standard was calculated using a SAS program provided by the National Park Service (8hrnaaqsfinal.sas revision dated 23 November, 1998, David Joseph, USDI National Park Service, Air Resources Division).

TABLE III

Palmer drought indices and corresponding wetness/dryness categories

Palmer Drought Index Value Range	Wetness/dryness category
≤–4.0	Extreme drought
–3.0 to –3.9	Severe drought
–2.0 to –2.9	Moderate drought
–1.9 to +1.9	Near normal
+2.0 to +2.9	Moderately moist
+3.0 to +3.9	Very moist
≥+4.0	Extremely moist

W126 and N100 values were determined using the Ozone Calculator program (William Jackson, Region 8, USDA Forest Service; http://webcam.srs.fs.fed.us/calculator/calculator.htm) to evaluate ozone effects on vegetation. The W126 metric is a 24 hr sigmoidally weighted exposure index (Lefohn and Runeckles, 1987). All average hourly ozone concentrations are considered to have the potential for impacting vegetation, but progressively higher concentrations are given greater weighting (Mussleman *et al*., 1994). All concentrations ≥0.10 ppm are given a weighting of 1 (Lefohn and Runeckles, 1987). The N100 metric is the number of hours (April–October) for which hourly average ozone concentrations ≥0.10 ppm. Both metrics have been used to develop exposure threshold levels and tree response categories (Table II) for several eastern forest tree species based on ozone exposure response studies on seedlings (Lefohn *et al*., 1997; SAMAB, 1996).

While several studies have reported tree response based only on W126, we used W126 and N100 values together to categorize exposure threshold levels, as was done in Lefohn *et al*. (1997), because growth reductions are not always associated with high W126 values alone. Rather, some minimal number of associated peak concentrations ≥0.10 ppm generally is needed for growth reductions to occur (Lefohn and Foley, 1992).

Exposure responses typically become more severe and more apparent at higher ozone concentrations, but exposure responses occur only under conditions of adequate moisture and nutrition (SAMAB, 1996). Under drought conditions, stomatal resistance increases, minimizing the amount of ozone that enters the leaf. Therefore, drought conditions tend to reduce the negative effects that otherwise would occur (Peñuelas *et al*., 1999). Consequently, in this analysis exposure responses are evaluated in conjunction with the Palmer drought index (Palmer, 1965, 1967) for the year and area in which each ozone monitor is/was located. Monthly drought data by state division (for KY, VA, and WV) were obtained for 1988–1999 from the National Oceanic and Atmospheric Administration's (NOAA) National Climatic Data Center. A mean Palmer index value was calculated from the April through October data for each year. The averages were categorized into wetness and dryness categories using NOAA's delineations (Table III). When the Palmer drought index value was ≤–2, signifying occurrence of moderate, severe, or extreme drought (Table III), tree responses to ozone were assigned a minimal rating; in such cases, the designation of a tree response category by the W126 and N100 metrics were overridden by the presence of drought. If Palmer drought index values were >–2, signifying near normal or wet conditions (Table III), W126 and N100 metrics determined the appropriate tree-response category from those in Table II (Lefohn *et al.*, 1997).

3. Mid-Appalachian Site Results

3.1. Comparisons of 1 and 8 hr Standards

Ozone data are summarized in Table IV and are compared to the 1 and 8 hr standards. Years in which the standards were exceeded are shaded in gray. The numbers of annual exceedences >0.12 ppm for the 1 hr standard for available years of data are given in Table V. Although 3 yr of data are needed for the 1 hr standard, exceedences for initial years for some sites could be established simply because of the high number of values >0.12 ppm during the first year of monitoring. For example, exceedences for 1988 and 1989 at Parsons could be established because the 13 concentrations >0.12 ppm in 1988 were sufficient to guarantee nonattainment using 3 yr averaging. Even under the best-case scenario of 0 occurrences >0.12 ppm in 1986 and 1987, the 3 yr average number of exceedences for 1988 would equal 4.3 (i.e., [0 + 0 + 13]/3), which is >1.0 permitted under the 1 hr standard. Exceedences determined using this estimation method are presented as values with ≥ designations in Table IV.

Parsons, Cedar Creek, Big Meadows, and Horton Station exceeded the 1 hr standard during 1988–1990 (Table IV). In all cases, this was due solely to ozone concentrations in 1988 (Table V). Only 4 individual maximum hourly average concentrations >0.12 ppm were observed outside of 1988 – 1 observation each for Bearden Knob (1997), Crockett (1994), Big Meadows (1998), and Whitetop Mountain (1994). The extreme numbers of >0.12 ppm concentrations in 1988 compared to other years were attributed largely to intense solar radiation and air stagnation that occurred during a drought in 1988 (Edwards *et al.*, 1991).

The 8 hr standard has been exceeded much more frequently (Table IV). Ozone exceeded the 8 hr standard for all years for which calculations were possible for Bearden Knob and for all but 2 of 10 yr for Big Meadows. The Greenbrier County site exceeded the standard for 2 of 3 yr. At Parsons, Cedar Creek, Rural Retreat, and Horton Station the 8 hr standard was exceeded only in the early 1990's. Crockett and Lilley Cornett Woods represent 2 different sites and sampling periods in eastern KY. Lilley Cornett Woods, located in southeastern KY, did not exceed the 8 hr

TABLE IV

Results for the 8 and 1 hr ozone standards. Table values for the 8 hr standard are 3 yr average of the 4th highest maximum 8 hr ozone concentrations; table values for the 1 hr standard are number of observations >0.12 ppm averaged over 3 yr. Cells shaded in grey exceed the corresponding standard for that year

Site	Standard	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
West Virginia													
Parsons	8-hr	-	-	0.092	0.084	0.079	0.080	0.079	0.083	0.079	0.078	0.079	0.082
	1-hr	≥4.3	≥4.3	4.3	0	0	0	0	0	0	0	0	0
Bearden Knob	8-hr	-	-	-	-	-	-	-	0.085	0.087	0.089	0.092	0.090
	1-hr	-	-	-	-	-	-	-	0	0	0.33	0.33	0.33
Cedar Creek	8-hr	-	-	0.088	0.084	0.080	0.079	0.077	0.079	0.078	0.077	0.082	0.084
	1-hr	≥1.7	≥1.7	1.7	0	0	0	0	0	0	0	0	0
Greenbrier Co.	8-hr	-	-	-	-	-	-	-	-	-	0.083	0.089	0.090
	1-hr	-	-	-	-	-	-	-	-	-	0	0	0
Virginia													
Big Meadows	8-hr	-	-	0.094	0.088	0.086	0.086	0.084	0.086	0.083	0.085	0.092	0.096
	1-hr	≥6	≥6	6	0	0	0	0	0	0	0	0.33	0.33
Rural Retreat	8-hr	-	0.084	0.085	0.078	0.077	0.077	0.077	0.080	0.078	0.078	0.081	0.084
	1-hr	-	0	0	0	0	0	0	0	0	0	0	0
Horton Station	8-hr	-	0.096	0.093	0.085	0.082	0.082	0.082	0.084	0.080	0.079	0.084	0.083
	1-hr	≥5	5	4.7	0	0	0	0	0	0	0	0	0
Whitetop Mtn.	8-hr	-	-	-	-	-	-	-	0.083	0.082	0.083	0.089	0.094
	1-hr	-	-	-	-	-	-	-	0.33	0.33	0	0	0
Kentucky													
Crockett	8-hr	-	-	-	-	-	-	-	-	0.094	0.087	0.088	0.082
	1-hr	-	-	-	-	-	-	-	-	0.33	0	0	0
Lilley Cornett	8-hr	-	-	0.080	0.071	0.069	0.070	-	-	-	-	-	-
Woods	1-hr	-	-	0.33	0	0	0	-	-	-	-	-	-
Glacier Nat. Park	8-hr	-	-	-	0.047	0.042	0.040	0.041	0.045	0.051	0.053	0.056	0.056
"Low O_3"	1-hr	-	-	-	0	0	0	0	0	0	0	0	0
Joshua Tree Nat. Mon.	8-hr	-	-	-	-	-	-	-	-	-	0.109	0.112	0.109
"High O_3"	1-hr	-	-	-	-	-	-	-	≥2	≥5.33	11.33	15	13.67

TABLE V

Number of 1 hr maximum ozone concentrations >0.12 ppm

Site	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
West Virginia												
Parsons	13	0	0	0	0	0	0	0	0	0	0	0
Bearden Knob	–	–	–	–	–	0	0	0	0	1	0	0
Cedar Creek	5	0	0	0	0	0	0	0	0	0	0	0
Greenbrier Co.	–	–	–	–	–	–	–	0	0	0	0	0
Virginia												
Big Meadows	18	0	0	0	0	0	0	0	0	0	1	0
Rural Retreat	0	0	0	0	0	0	0	0	0	0	0	0
Horton Station	14	0	0	0	0	0	0	0	0	0	0	0
Whitetop Mtn.	–	–	–	–	–	0	1	0	0	0	0	0
Kentucky												
Crockett	–	–	–	–	–	–	1	0	0	0	0	0
Lilley Cornett Woods	1	0	0	0	0	0	–	–	–	–	–	–
Glacier Nat. Park	–	0	0	0	0	0	0	0	0	0	0	0
Joshua Tree Nat. Mon.	–	–	–	–	–	–	–	6	10	18	17	6

standard in any year that it was monitored (Table IV), and the ozone values were consistently the lowest of each year for all the sites. By contrast, concentrations for Crockett were among the highest for individual years (Table IV) and exceeded the 8 hr standard 3 of 4 yr.

For the period of overlapping record at the high-elevation Bearden Knob site and the nearby low-elevation Parsons site neither exceeded the 1 hr standard. Since 1995, both sites had ozone levels below the 1 hr standard (Table IV). Only one exceedence >0.12 ppm was observed at Bearden during all years (Table V), and while this observation was the highest 1 hr average concentration recorded at either site, a single exceedence could not result in a value of 1.0 using 3 yr averaging. Results differed for the 8 hr standard. Parsons has had ozone levels below the 8 hr standard since 1995, while levels at Bearden Knob have exceeded the 8 hr standard all years since 1995 (Table IV). Further, the concentration defining the 8 hr standard value generally has increased over time, suggesting worsening air quality.

To put these regional concentrations in perspective, we also compared the KY, WV, and VA sites to concentrations from 2 rural sites – Glacier National Park, Montana and Joshua Tree National Monument, California – with consistently very low and very high ozone concentrations, respectively (Table I). Glacier National Park always had ozone levels below the 1 hr and 8 hr standards (Table IV). It had no average hourly ozone concentrations >0.12 ppm from 1989 to 1999, and the concentrations calculated for the 8 hr standard were half to two-thirds of those in WV, KY, or VA (Table IV). Joshua Tree National Monument consistently exceeded both standards (Table IV). The annual number of average concentrations >0.12 ppm ranged from 6–18 (Table V), resulting in 3 yr average numbers of exceedences of the 1 hr standard from ≥ 2 to nearly 14, with the highest numbers occurring in the most recent 3 yr (Table IV). By contrast, only concentrations from the earliest years (1988–1990) from the WV, KY, and VA sites were similar to the 2 lower values (≥ 2 and ≥ 5.33) for Joshua Tree. The 8 hr standard values for Joshua Tree were at least a third greater than the highest values for the Appalachian sites. While the rounding rules for ozone calculations were important in determining exceedence of standards for some Appalachian sites/years, average concentrations at Joshua Tree were much higher so rounding did not affect the exceedence of standards.

3.2. Vegetation Responses

For most years across most of the central Appalachian sites, the combination of W126 and N100 values suggests minimal ozone effects, or effects to only highly sensitive tree species (Tables II and VI). W126 and N100 values indicate that moderately sensitive and/or resistant tree species could have experienced growth reductions due to ozone in 1988 at Parsons, Cedar Creek, Big Meadows, and Horton Station and in 1998 at Big Meadows (Table VI). However, average Palmer index conditions (Figure 2) for 1988 indicated moderate and severe droughts for all the central Appalachian sites except Big Meadows. As a result, high stomatal

TABLE VI

W126 and N100 values for April–October. Cell color indicates predicted tree response category (refer to Table II): white = minimal, grey = only highly sensitive species affected, tan=moderately and highly sensitive species affected, purple = most species affected. Designations apply to the categories for simultaneous W126 and N100 values without considering any effects of drought conditions

Site	Metric	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
West Virginia													
Parsons	W126	54.70	29.35	30.77	39.25	17.72	36.36	29.90	34.25	32.35	27.94	42.82	45.28
	N100	103	4	6	0	0	7	4	4	1	2	11	7
Bearden Knob	W126	-	-	-	-	-	63.94	55.90	69.90	60.80	61.40	81.94	79.08
	N100	-	-	-	-	-	2	2	6	6	13	26	7
Cedar Creek	W126	49.95	20.73	25.16	34.39	14.87	28.27	26.53	21.69	18.45	22.00	31.35	50.95
	N100	81	1	9	13	0	11	4	0	6	5	14	44
Greenbrier Co.	W126	-	-	-	-	-	-	-	65.94	41.96	62.42	70.66	47.90
	N100	-	-	-	-	-	-	-	5	0	5	37	1
Virginia													
Big Meadows	W126	60.25	77.21	72.44	82.81	41.45	78.87	56.87	75.61	62.77	65.46	118.57	99.50
	N100	85	0	1	3	0	2	1	1	0	4	67	11
Rural Retreat	W126	45.84	24.69	33.59	29.28	21.61	48.46	28.19	35.31	29.71	41.18	49.28	52.90
	N100	22	1	1	0	0	1	1	1	0	0	0	2
Horton Station	W126	128.04	69.30	73.82	72.16	45.40	72.42	61.52	55.27	20.84	68.22	98.27	101.14
	N100	189	0	0	3	0	0	0	0	1	2	10	3
Whitetop Mtn.	W126	-	-	-	-	-	22.86	55.88	68.50	42.48	65.51	107.51	93.80
	N100	-	-	-	-	-	0	3	0	4	4	42	12
Kentucky													
Crockett	W126	-	-	-	-	-	7.78	55.50	60.62	33.80	43.01	72.72	89.93
	N100	-	-	-	-	-	0	31	20	19	0	10	16
Lilley Cornett Woods	W126	44.34	17.75	13.07	13.39	8.92	12.73	-	-	-	-	-	-
	N100	45	0	0	0	1	0	-	-	-	-	-	-
Glacier Nat. Park "Low O_3"	W126	-	5.62	3.97	5.07	3.94	2.22	5.16	2.96	5.43	2.27	5.60	5.39
	N100	-	0	0	0	0	0	0	0	0	0	0	0
Joshua Tree Nat. Mon. "High O_3"	W126	-	-	-	-	-	-	-	101.97	143.29	133.46	86.31	118.40
	N100	-	-	-	-	-	-	-	122	228	217	66	69

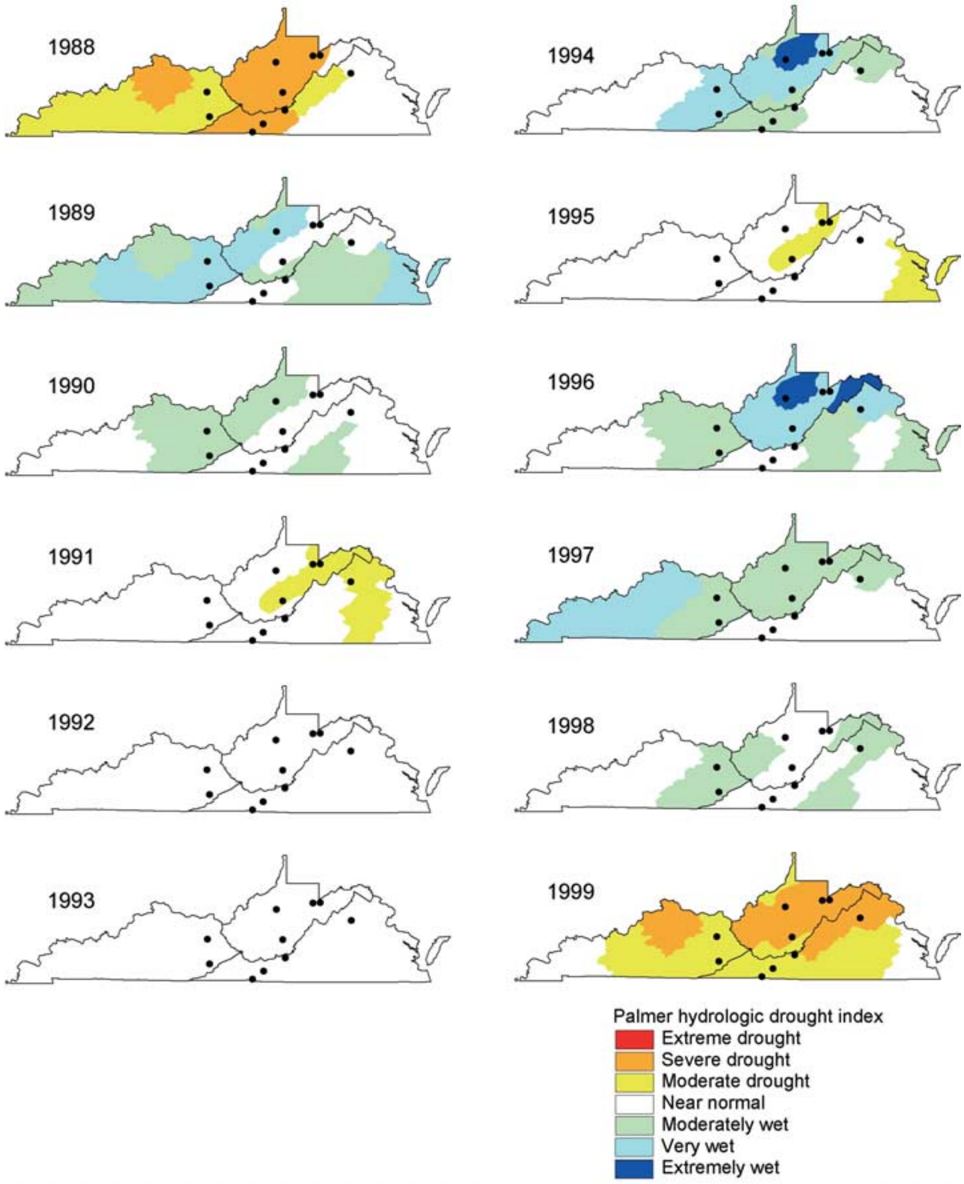

Figure 2. Palmer drought index maps for growing seasons (April – October) from 1988–1999. The solid black dots indicate the ozone monitoring sites.

resistance would have been common, so moderate and severe ozone damage would have been unlikely. Otter Creek and Dolly Sods Wildernesses in West Virginia were evaluated for ozone injury during this drought period. Ozone damage symptoms in 1988 under severe drought were less than those observed in 1989–1990 under near normal conditions (Jackson *et al.*, 1992), supporting the idea that stomatal closure did moderate high ozone concentrations. Big Meadows experienced moderately wet conditions during the 1998 growing season (Figure 2), so drought probably would not have offset ozone effects to moderately and highly sensitive tree species that year at that site. However, there were no vegetation surveys in that area during that period to document ozone injury levels.

The widespread drought conditions of 1999 were not important in tempering ozone effects because all of the central Appalachian sites were projected to have experienced only minimal negative growth responses or ozone would have affected only the most highly sensitive tree species (Table VI). During the other 2 yr of localized droughts, 1991 and 1995, only Bearden Knob, Cedar Creek, and Crockett had W126 and N100 data that suggested ozone responses would have been more than minimal.

4. Discussion

Our analysis indicates that ozone levels frequently exceed the 8 hr standard in rural areas of the central Appalachians. Only Parsons, Cedar Creek, Horton Station, and Rural Retreat have had ozone levels below the 8 hr standard for most of the previous decade (Table IV).

Monitoring station elevation frequently is cited as a primary factor influencing local ozone concentrations. High-elevation sites typically have higher ozone concentrations than nearby lower elevation sites, and high-elevation sites lack large diel responses (Baumgardner and Edgerton, 1998; Lefohn *et al.*, 1990), allowing elevated concentrations for more hours each day and each growing season. Our analysis showed that on a regional basis, elevation was not consistently a strong factor influencing whether the 8 hr standard was exceeded, though exceedences of the 8 hr standard for the high elevation sites generally were distributed fairly evenly over a much broader portion of the day (1000–0100 hr) compared to low elevation sites which experienced more than 50% of their exceedences between 1000–1200 hr.

Bearden Knob always had ozone levels above the 8 hr standard for the years of available data (1995–1999), and Big Meadows exceeded the standard in 8 of 10 yr. The elevation at each of these sites is located above 1000 m. By contrast, Whitetop Mountain has the highest elevation (1686 m) but ozone levels were below the 8 hr standard from 1995–1997. Levels exceeded the standard in 1998–1999. In addition, the low elevation Crockett site (455 m) exceeded the 8 hr standard in all years except 1999. The sites most frequently below the 8 hr standard also were not always at low elevation; Parsons, Cedar Creek, Rural Retreat, and high elevation Horton Station have been below the standard since at least 1992 (Table IV).

Greenbrier County and Rural Retreat had contrasting results even though both are agriculture sites with similar elevations (Table I) and are relatively close to each other (Figure 1). Dissimilar results between fairly close pairs of CASTNet and SLAMS sites were described elsewhere by Sickles *et al.* (2000) and the presence of systematic differences between the 2 types of site have been cited as a reason for increased ozone monitoring in rural areas for decisions of attainment (Sickles *et al.*, 2000; Baumgardner and Edgerton, 1998). Where terrain is particularly complex, local ozone monitoring is needed to adequately understand ozone exposures (Baumgardner and Edgerton, 1998).

Although there is some degree of consistency between high 8 hr ozone standard values (Table IV) and estimates of growth effects to vegetation from exposure responses (Table VI), the 2 metrics are not interchangeable. For some of our sites, some years had ozone exposures above the 8 hr standard, while estimated vegetation responses were minimal. In these situations, N100 values were very low and reduced the degree of ozone responses. In other instances, exposures were below the 8 hr standard but vegetation responses were indicated only for the highly sensitive species. Where moderately sensitive or resistant tree species were projected to have growth reductions, ozone concentrations always exceeded the 8 hr standard.

Over approximately the past decade, most ozone exposure responses suggested that growth reductions would have been minor, so drought rarely played an important role in reducing ozone damage. Only the 1988 drought may have played an important role in tempering negative effects on tree growth. Parsons, Cedar Creek, Big Meadows, and Horton Station each were projected to have growth reductions of moderate and/or resistant tree species, but moderate to severe drought probably reduced the extent of those reductions at all but the Big Meadows site.

As Lefohn *et al.* (1997) pointed out, growth response estimates using any metrics are only estimates of potential reductions. They listed the following caveats with respect to applying growth responses from W126 and N100 metrics to forests: W126 exposure values are obtained from seasonal responses while those obtained from open-top chamber studies typically are of shorter duration; the Palmer drought index does not consider soil-moisture conditions or the presence of local differences in precipitation; responses of trees within a forest may differ from those of individual trees in a growth chamber; and seedlings do not necessarily respond like larger trees. However, Hanson *et al.* (1994) found that if ozone uptake differences between mature and seedling-size trees are accounted for, reductions in photosynthesis due to ozone are similar and growth reductions can be projected.

Translating growth reductions of individual trees to the stand or forest scale is difficult because so many processes and stresses occur in the forest, and many are interrelated (Chappelka and Samuelson, 1998). Different and sometimes contrasting modeled projections have been made. For example, the Southern Appalachian Mountains Initiative (2002) analyzed ozone exposure data from many sites throughout the Southeast and projected tree growth responses for various Class 1 areas and specific forest types. Their simulation modeling predicted that shifts in species competition will be the principal effect from ozone pollution, but changes to basal area are expected to be small. Weinstein *et al.* (2001) projected reductions of 10% for yellow-poplar over 100 yr in the Great Smoky Mountains National Park, with smaller changes in relative abundances of red maple, black cherry, and basswood (*Tilia americana*). An analysis using the same modeling approach as Weinstein and others was done for the Shenandoah National Park (USDI National Park Service 2003). At current ozone levels, they predicted no growth responses for most modeled species and an approximately 1% growth decrease for white ash (*Fraxinus americana*) over the 3 yr simulation period. Flagler *et al.* (1992) extrapolated the results of open topped chamber studies of southern pines to the forest level and projected an 8% decrease in foliage biomass and a 2% decrease in stem biomass. Ollinger *et al.* (1996) used PnET-II to predict forest responses to ozone for northeastern United States. They predicted reductions in net primary productivity due to ozone that translated to wood production decreases of 3–22% during 1987–1992.

Much research still needs to be done to understand the variables that control individual tree and stand sensitivity to ozone. Many physiological variables, such as tree developmental stage (Kelly *et al.*, 1995), leaf structural characteristics (Bennett *et al.*, 1992), compensatory increases in foliar production and photosynthesis (Coleman *et al.*, 1995; Pell *et al.*, 1994), and genotype variation (Berrang *et al.*, 1986), as well as environmental factors such as soil moisture and nutrition (Tingey and Hogsett, 1985), carbon dioxide levels (Soinit *et al.*, 1985), ozone concentration and exposure length, and shade exposure (Tjoelker *et al.*, 1993), all affect the extent to which a tree or stand is sensitive to ozone stress. The interactions among the many variables at play make understanding and predicting vegetative changes due to ozone a substantial challenge.

5. Conclusion

Ozone data from 1988–1999 from rural sites in the central Appalachian region of KY, WV, and VA were examined to determine how exposures compared to the 1 and 8 hr standards, and how vegetation may have been affected. While few rural sites are included in the U.S. EPA's Ambient Air Monitoring Program to determine ozone attainment, the sites we used indicate that ozone exposures in rural and forested areas often exceed the existing ozone standards. Ozone exposures often exceeded the 8 hr standard, but this did not necessarily translate to predictions of substantial negative effects to forests, at least in the short term. During most years at most sites, only highly sensitive trees typically would have been affected by ozone. Ozone damage surveys at Otter Creek Wilderness support the idea that drought tempered negative ozone effects to vegetation via stomatal closure during

1988, the year when growth reductions attributable to high ozone concentrations and exposures would have been at their worst.

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