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Temporal Patterns of Ozone Pollution in West Virginia: Implications for High-Elevation Hardwood Forests

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ABSTRACT

Hourly ozone (O_3) data from one rural and four urban sites throughout West Virginia were analyzed for a three-year period (1987-1989) focusing on seasonal and diurnal patterns of O_3 concentrations. Based on maximum hourly O_3 concentrations (highest 1-hr maximum value per month), there were definite seasonal patterns with highest values from May to August and lowest values from December to February for all years and sites. High O_3 exposures (defined in this study as concentrations $\geq$0.080 ppm) for the study period were greater in Greenbrier County (a distinctly rural region) and Wood County (an industrialized area). Of these two sites, O_3 concentrations remained high with little diurnal variation in June and July (1988) in the rural area; in contrast, there was large diurnal fluctuation in the urban area. Considering the high O_3 concentrations found at our rural site, the seasonal coincidence of high O_3 with the growing season, and a low diurnal fluctuation of high summer O_3 concentrations at the rural high-elevation site, tropospheric O_3 pollution could represent a distinct threat to the high-elevation hardwood forests of West Virginia. Ozone concentrations presented in this study are well within the range of values which were found by studies in the literature to be damaging to physiological processes and growth parameters in trees.

INTRODUCTION

Relative to other forms of air pollution, such as trace metal and acidic deposition, ozone (O_3) has been cited as perhaps the most profound in its effects on forests of the United States, especially those of the eastern U.S. Ozone has been demonstrated to reduce photosynthesis and growth and alter carbon allocation in several ecologically and commercially important tree species.[1] Furthermore, O_3 has been shown to increase susceptibility of trees to pest and microbial pathogen activity.[1,2]

Tropospheric O_3 production generally follows patterns of urban activity and is often associated with high pressure systems, accompanied by warm temperatures, light winds, and regional stagnation.[3,4] However, urban emissions (O_3 precursors and O_3) can be transported great distances downwind to rural locations, resulting in elevated rural O_3 concentrations[4] and creating the potential for forest and crop damage, especially in the eastern U.S. Indeed, the National Acid Precipitation Assessment Program (NAPAP)[5] has shown that rural O_3 levels are generally quite elevated for most of the eastern U.S. south of Pennsylvania.

Gilliam et al.[6] showed that O_3 concentrations can increase in high elevation hardwood forests throughout the early growing season when deciduous forest canopies are developing most rapidly. They suggested that the seasonal increase might represent a threat of forest exposure to O_3 since it is at this time that leaves are most sensitive to O_3 damage, which reduces photosynthetic rates and potentially decreases forest productivity.[7] Lefohn and Shadwick[4] discovered an increasing trend in O_3 for 20% of the sampling sites throughout forested areas of the mid-Atlantic region over a five-year period and found that 50% of the sites in the Appalachian agricultural region showed another increasing O_3 trend over a ten-year period. These patterns further suggest a potential problem of long-term O_3 damage to forests of these regions.

Notably absent from Lefohn and Shadwick[4] were data from West Virginia, a state supporting large areas of forested land. Approximately 79% of the land is forested and 64% of the state is classified as rural.[8,9] More recently, Edwards et al.[10] reported on O_3 concentrations at low and high elevation rural sites in West Virginia. The objective of our study was to examine the seasonal patterns of O_3 pollution at several sites throughout the state of West Virginia, with an emphasis on the potential significance of these patterns for high-elevation hardwood forests in the rest of the state.

Temporal patterns of O_3 are important in assessing potential problems for eastern hardwood forests. As already

IMPLICATIONS

Seasonal patterns of tropospheric ozone (O_3) concentrations throughout a five-county network in West Virginia have significant implications for the higher elevation hardwood forests which dominate the rural areas of the site. High O_3 concentrations begin early in the growing season, a time when deciduous leaves may be more sensitive to ozone exposure, and continue to increase throughout it. O_3 levels found in this study, especially those for the highest elevation rural site, are well within the range considered potentially harmful to sensitive species, such as black cherry, yellow poplar, and white ash, all of which are economically and ecologically quite important to this region.

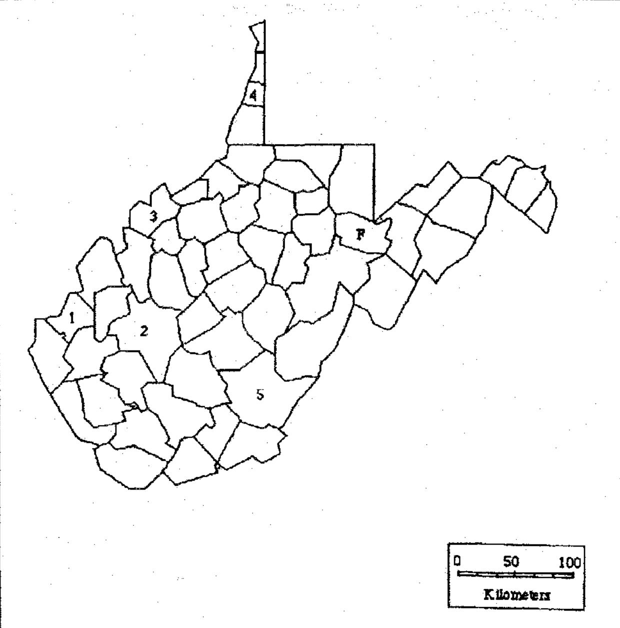

Figure 1. Locations of O_3 monitoring sites: 1) Cabell County, 2) Kanawha County, 3) Wood County, 4) Ohio County, and 5) Greenbrier County. "F" represents location of Fernow Experimental Forest, Tucker County, West Virginia.

discussed, the seasonal coincidence of springtime increases in O_3 concentrations and the development of the hardwood canopy can increase susceptibility of several species to damage.[6,7] However, the coincidence of diurnal patterns of O_3 concentrations (i.e., daytime increases and nighttime decreases) with the metabolic activity of the forest can also be of significance. Whereas the diurnal patterns of O_3 in areas of lower elevation (as well as urban areas) often exhibit distinct curves with a maximum in the middle of the day, O_3 in higher elevation rural areas often exhibits flatter patterns, the result of less scavenging of O_3 by pollutant precursors at such sites.[11] Accordingly, this study compared diurnal patterns of O_3 between an urban and a rural site in West Virginia.

MATERIALS AND METHODS

Study Site

West Virginia is a mid-Atlantic state with warm, humid summers, cold, humid winters, and abundant rainfall. Elevation ranges from 73 m to 1,483 m with an approximate mean elevation of 458 m. This range of climatic and topographic characteristics has given rise to three divisions of forest types (moving west to east): central hardwood, northern forest, and oak-pine forest.[12] Oak-hickory is the dominant forest type throughout much of the state, with mixed hardwoods also being quite prevalent.[8]

Chemical and allied products are the leading manufacturing industries in West Virginia.[13] The state has also been one of the leading producers of bituminous coal since 1931.[13] According to the 1980 census, West Virginia ranked 34th in the United States with a total population of 1.90 million, but tenth in per capita energy consumption.[9]

For our study sites, Kanawha County ranked first in both industrialization and population, followed in descending order by Cabell, Wood, and Ohio Counties. The dominant industries included coal mining, chemical and allied products, and petroleum refining and related industries.[13] Greenbrier County was lowest in manufacturing establishments (coal mining) and population. Thus, Greenbrier is classified as a rural county, with the other four counties classified as urban.[13]

Data Analysis

Data were gathered from the West Virginia Air Pollution Control Commission and the United States Environmental Protection Agency Storage and Retrieval of Aerometric Data system for five O_3 monitoring stations in West Virginia located in Cabell, Greenbrier, Kanawha, Ohio, and Wood Counties (Figure 1) for the years 1987, 1988, and 1989. The maximum hourly values per month (i.e., highest one-hour maximum value per month) for all sites were used to construct seasonal O_3 profiles for each year of the study period. All maximum hourly values equal to or exceeding 0.080 ppm were counted for each month to show the frequency of high O_3 levels for each year. The selection of this value (0.080 ppm) was based on a study by Davis and Skelly,[14] who found that several eastern hardwood species showed a reduction in a variety of growth parameters at 0.080 ppm. All maximum hourly concentrations equal to or exceeding 0.080 ppm were then arranged by site to compare conditions of O_3 pollution within the state. Finally, mean hourly O_3 concentrations were determined for the months of June and July 1988 for Greenbrier and Wood Counties to compare diurnal O_3 patterns between a rural high-elevation site (Greenbrier) and an industrialized low-elevation site (Wood).

RESULTS AND DISCUSSION

Three-year mean and yearly maximum O_3 concentrations (Table 1), indicate that while annual maximum values varied substantially between sites, annual means exhibit only slight differences between sites. Although this may indicate

Table 1. Mean and maximum O_3 concentrations (based on daily maximum values) for five West Virginia sites for the years 1987-1989.

Site	1987		1988		1989	
	mean	*max*	*mean*	*max*	*mean*	*max*
	ppm					
Cabell	0.052	0.140	0.051	0.154	0.043	0.153
Greenbrier	0.051	0.123	0.058	0.135	0.045	0.121
Kanawha	0.048	0.118	0.051	0.174	0.042	0.119
Ohio	0.042	0.138	0.043	0.124	0.041	0.110
Wood	0.050	0.172	0.050	0.220	0.047	0.125

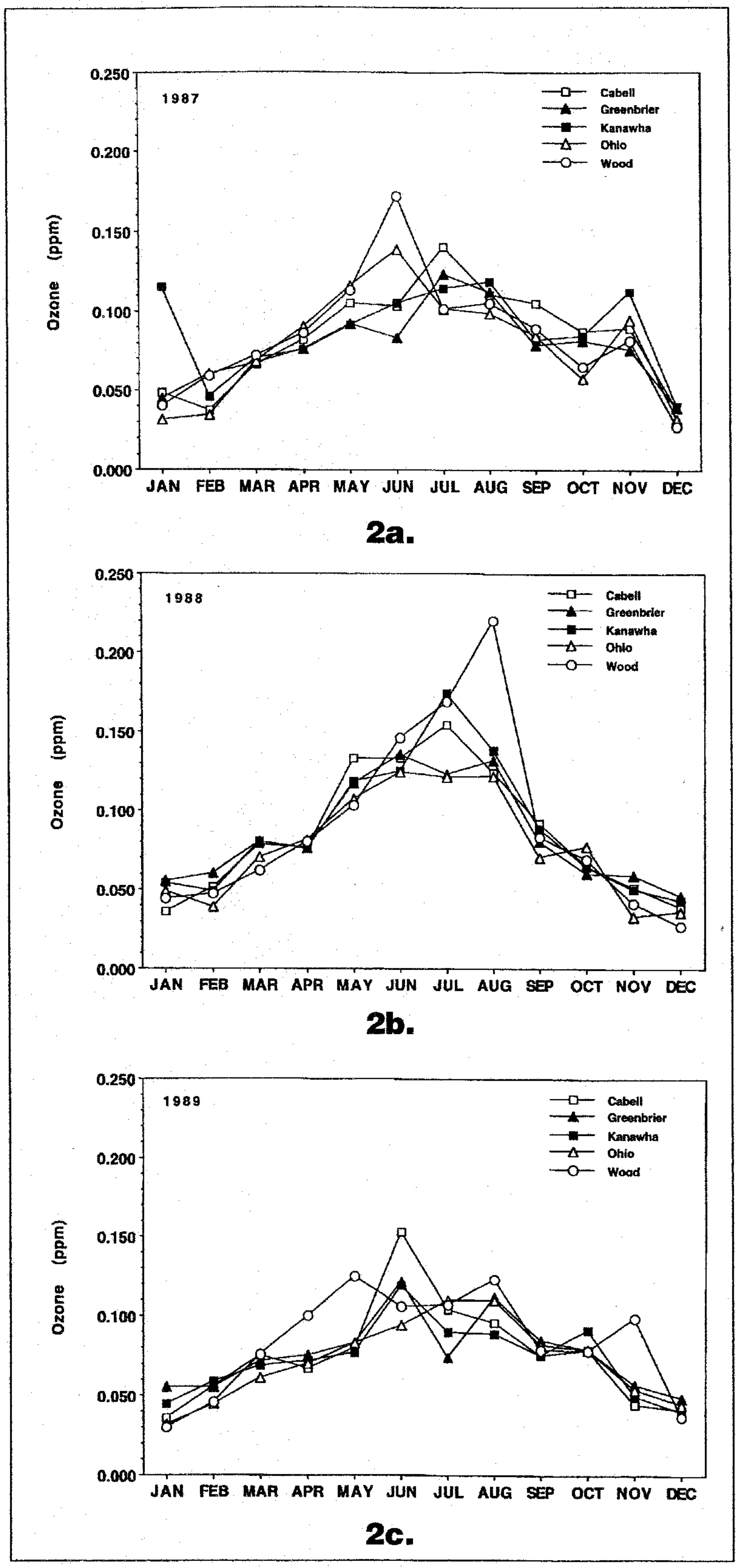

Figure 2. Maximum hourly O_3 concentrations for five West Virginia counties by month: a) 1987, b) 1988, and c) 1989.

that there is little variation in O_3 conditions throughout the state, most likely it suggests that annual means are not indicative of the considerable variations in ambient O_3 exposure experienced within a region.[15]

There were distinct seasonal patterns in O_3 concentrations, with highest values occurring from May to August (Figure 2), presumably the result of summertime meteorological conditions conducive to O_3 production.[3] This pattern was consistent across all sites and years. Indeed, there was little difference between sites in terms of seasonal O_3 trends, regardless of year (Figure 2). The seasonal pattern of high summertime O_3 concentrations was most prominent for 1988 (Figure 2), a year with high O_3 pollution conditions throughout most of the eastern U.S.[4]

Important in the context of potential damage for forests is the duration and frequency of high O_3 concentrations.[3] In 1987 and 1988 (Figures 3a and 3b, respectively), the greatest frequency of high O_3 levels occurred in June and July, respectively. In 1989 (Figure 3c), the greatest frequency was in August. By far, 1988 had the highest levels of O_3 pollution in the study period (Figure 3b). In this year, June had the greatest frequency of high O_3 levels followed very closely by July; the rural Greenbrier site had the greatest number of high hourly values for the year (Figure 3b, Table 2). These West Virginia data are in agreement with the high O_3 concentrations reported for several regions of the United States (including forest and agricultural areas of the mid-Atlantic region) during the hot, dry summer of 1988.[4,16,17] In contrast to 1988, one of the highest exposure years in the ten-year study of Lefohn and Shadwick,[4] indications are that 1989 O_3 levels were regionally much lower than those experienced in 1988,[17] underscoring the importance of meteorological factors in influencing O_3 levels on a regional scale. Data presented here for 1989 support this pattern (Figure 3c).

Table 2 summarizes the number of maximum hourly O_3 concentrations $\geq$ 0.080 ppm (and the EPA standard of 0.120 ppm) by year and by site. Again, 1988 exhibited extremely high levels of O_3 pollution for the study period, with over 83% of the EPA standard exceedences for the three-year study period. Based on the total frequencies of O_3 $\geq$ 0.080 ppm, Greenbrier County had by far the highest level of O_3 pollution, followed by Wood County. Using the number of EPA exceedences, Wood County had the highest levels of O_3 pollution.

Levels of O_3 pollution found in the rural areas of Greenbrier County and the similarity that existed between the Greenbrier and Wood County data support conclusions of Meagher et al.[14] that rural O_3 concentrations may equal and even exceed urban concentrations. Data also suggest that long range transport of O_3 from urban to rural areas is occurring.

Other studies have shown that long range transport is a major source of O_3 in rural areas,[18,19] resulting from slow movement of urban plumes in association with high pressure systems.[19]

Diurnal O_3 Patterns and Implications for Hardwood Forests

Diurnal O_3 patterns were determined for Greenbrier and Wood Counties for the months of June and July of 1988. These hourly O_3 values (Figure 4) represent the 24-hr mean of 30 or 31 (June or July, respectively) O_3 concentrations. Both sites were similar in having generally higher O_3 concentrations in June than in July of 1988. Also, both had maximum mean hourly O_3 values of > 0.100 ppm (Figure 4). The two sites contrasted quite sharply, however, with respect to degree of diurnal fluctuation. The Greenbrier site had a minimum-maximum O_3 range of about 0.030 ppm, whereas the Wood site had a range of around 0.060 ppm. Although O_3 concentrations attained high levels at both sites, the Greenbrier site experienced these high O_3 concentrations for a greater duration during a typical 24-hr period (Figure 4). Thus, the total exposure to O_3 at the rural site was greater than that at the urban site.

Such differences between sites are likely due both to differences in elevation (190 m versus 829 m for the Wood and Greenbrier sites, respectively) and to site-specific processes of O_3 production and scavenging.[11,15] The diurnal pattern of Wood County is indicative of a low-elevation urban area where O_3 concentrations rise during the morning hours from interactions of hydrocarbons, NO_2, and sunlight. Ozone levels peak during the early afternoon hours and then steadily decrease during the evening and night hours, as O_3 is consumed by reactions with NO to form NO_2 and O_2 in the absence of light. The lack of a pronounced nocturnal depletion of O_3 at high-elevation sites, especially those which are rural, such as Greenbrier, results from less scavenging of O_3; e.g., lower concentrations of NO are present to facilitate this reaction.[11,15] The early morning decrease in O_3 concentration for Greenbrier may have been caused by dry deposition of O_3 due to the development of inversion layers.[6,20]

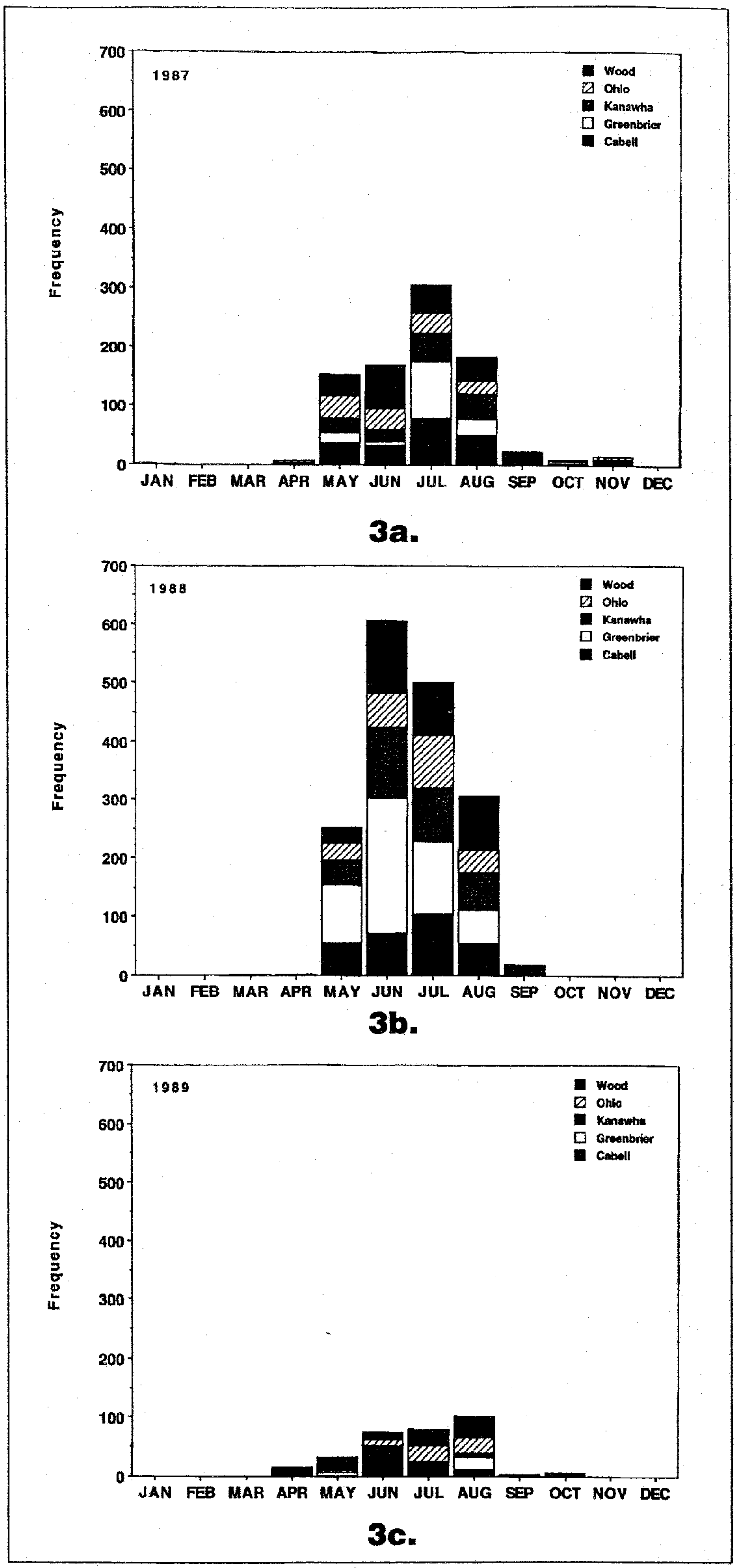

Figure 3. Frequency of high O_3 concentrations for five West Virginia counties by month: a) 1987, b) 1988, and c) 1989. Frequencies are based on all hourly values ≥0.080 ppm.

The patterns of O_3 concentrations presented here for the state of West Virginia have important implications for the high-elevation hardwood forests which dominate the rural areas of the state. Seasonal patterns indicate that high O_3 levels begin to appear early in the growing season and continue to increase throughout it (Figures 2 and 3). This seasonal pattern has been found by other studies.[6,20,21] Gilliam et al.[6] and Gilliam[22] suggested that this is a critical period for O_3 exposure, since it is a time when growing hardwood leaves

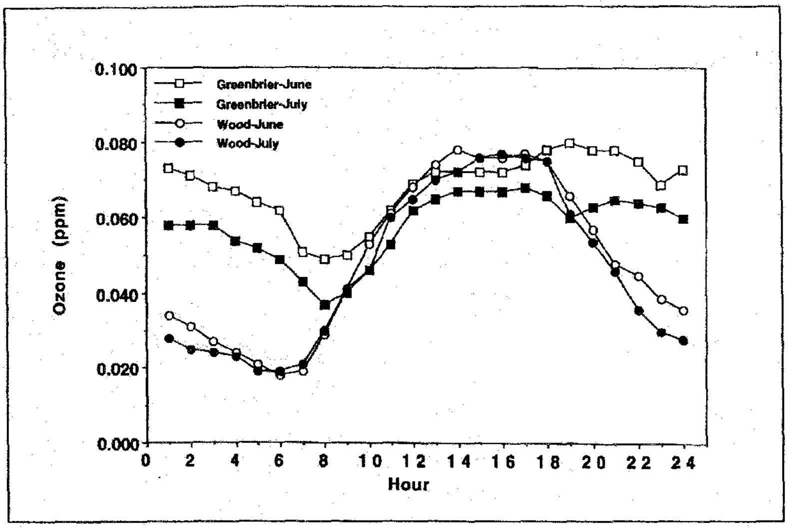

Figure 4. Diurnal patterns of O_3 concentrations at a low-elevation urban site (Wood County) and a high-elevation site (Greenbrier County) in West Virginia for the months of June and July, 1988. Data shown are means of all hourly values.

are most sensitive to O_3 injury.[23] Certainly, O_3 levels found in our study are within the range considered potentially harmful to sensitive hardwood species, such as black cherry, yellow poplar, and white ash,[7,14,24] all of which are of great ecological significance and commercial value for the region. Davis and Skelly[14] found that ozone concentrations of 0.080 ppm caused a reduction in at least three of 13 measured growth parameters (e.g., height, diameter, leaf production) for all species they studied: black cherry, red maple, northern red oak, and yellow poplar. Furthermore, Edwards et al.[25] found reductions in several physiological parameters (including photosynthesis, stomatal conductance, intercellular CO_2, respiration, and transpiration) of mature northern red oak trees using concentrations of O_3 within the range of values presented in this study. They further concluded that mature northern red oak trees were actually more sensitive to elevated O_3 effects than were seedlings.[25]

Our data support previous observations that high O_3 conditions are not necessarily only associated with major urban centers. Greenbrier, our only rural site, had some of the highest O_3 pollution of our five sites, with the highest frequencies of ≥ 0.080 ppm values of all sites for 1988 (Table 2), which was a high O_3 year for most of the eastern U.S.[4,17] The similarities between our data and those of Edwards et al.[10] for another remote site (Fernow Experimental Forest, Tucker County, WV; see "F" in Figure 1) may mean that O_3 conditions found at Greenbrier are typical of those experienced by West Virginia forests. Lefohn et al.[26] reported O_3 values for several rural sites throughout West Virginia and Virginia and found concentrations for 1988 similar to those in our study. Furthermore, using a variety of O_3 exposure indices, their results indicated that O_3 conditions at Greenbrier were similar to other sites in West Virginia, such as Wood County, which were more closely associated with production of O_3 precursors (Figure 1).

Perhaps of greatest significance to high-elevation hardwood forests are the typical diurnal patterns of O_3 and how they change with elevation.[27] Data for the high-elevation Greenbrier site in 1988 indicate that high O_3 exposures were of a long duration, compared to a low-elevation urban site (Figure 4). It could be argued that chronically high levels of O_3 during the growing season do not represent a threat to forest trees during hot, dry summers, such as that of 1988, since stomatal closure would result from temperature and water stress.[28,29] However, over a 24-hr period, stomates of leaves of high-elevation hardwood trees would no doubt be open during early dawn when temperatures are lower and humidity is higher. Indeed, trees predictably open their stomates during pre-dawn and dawn periods, regardless of moisture status.[30] Using a dawn "window" of 6:00 to 10:00 a.m. during which stomates of tree leaves would invariably be open,[30] frequencies of O_3 concentrations ≥ 0.080 ppm for this time period were determined for both sites in Figure 4. When these were compared there was no appreciable difference (i.e., 12 and 6 versus 11 and 11, for June and July, Wood versus Greenbrier Counties, respectively). Regardless of similarities or differences between urban and rural sites, data from this study do suggest that O_3 concentrations at high elevations would remain high during these times of stomatal opening.

Table 2. Number of hourly O_3 concentrations ≥ 0.080 ppm by site. Number of hourly EPA exceedances (EPA standard = 0.120 ppm) in parentheses.

Site	*1987*	*Year* *1988*	*1989*	*Total*
Greenbrier	148 (1)	510 (14)	29 (1)	687 (16)
Wood	203 (10)	340 (48)	117 (5)	660 (63)
Cabell	237 (4)	295 (27)	67 (5)	599 (36)
Kanawha	157 (0)	329 (36)	37 (0)	523 (36)
Ohio	134 (6)	215 (5)	67 (0)	416 (5)
Total	879 (21)	1689 (130)	317 (11)	2885 (156)

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