Ozone Exposure and Potential for Vegetation Injury within the Atlanta, Georgia Metropolitan Area

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Ozone-induced vegetation injury may be prevalent within metropolitan areas in the southeastern United States. The purpose of this study is to explore the relationship between ozone exposure and potential foliar injury within the Atlanta, Georgia metropolitan statistical area (MSA). The main methods involve calculating seasonal ozone exposure at 11 monitoring stations in the Atlanta MSA for 2000–2005 and measuring ozone-induced visible foliar injury in the eastern portion of the MSA in August 2004. Ozone exposure within the Atlanta MSA probably was high enough to injure only highly sensitive species, and the 2004 survey did reveal foliar injury to highly sensitive species.

KEY WORDS: ozone, foliar injury, Atlanta

INTRODUCTION

High concentrations of ground-level ozone exist throughout the interior portion of the southeastern United States. Ground-level ozone is formed by photochemical reactions involving volatile organic compounds (VOCs) and nitrogen oxides (NO_x) (Haagen-Smit 1952; Crutzen 1979). The interior Southeast has high ozone concentrations during the summer because of (1) the predominance of high-pressure systems and associated atmospheric conditions (i.e. high solar radiation, high temperatures, and poor ventilation) (Vukovich et al. 1977; Vukovich 1994); (2) abundant biogenic VOCs (BVOCs) (Chameides et al. 1988; Geron et al. 1994; Geron et al. 1995); and (3) large emissions of NO_x from motor vehicles and from coal-fired power plants throughout the region (US EPA 2006a; Ryerson et al. 2001). Ozone nonattainment areas (i.e. areas exceeding the federal ozone standard) in the southeastern United States include the following metropolitan statistical areas (MSAs): Atlanta, Birmingham, Charlotte-Gastonia-Rock Hill, Chattanooga, Clarksville-Hopkinsville, Fayetteville, Greensboro-Winston Salem-High Point, Greenville-Spartanburg-Anderson, Hickory-Morganton-Lenoir, Johnson City-Kingsport-Bristol, Knoxville, Macon, Nashville, Raleigh-Durham-Chapel Hill, and Rocky Mount, (US EPA 2006b) (Figure 1).

Many plant species native to the southeastern United States may be sensitive to ozone. At least 20 species in Great Smoky Mountains National Park (GSMNP), part of which is located in the eastern portion of the Knoxville, Tennessee MSA (Figure 1), have been confirmed in Neufeld et al. (1992) as being sensitive to ozone, and those species include American sycamore (*Platanus occidentalis* L.), black cherry (*Prunus serotina* Ehrh.), blackeyed Susan (*Rudbeckia hirta* L.), cutleaf coneflower

(*Rudbeckia laciniata* L.), eastern redbud (*Cercis canadensis* L.), flowering dogwood (*Cornus florida* L.), Great Smoky Mountain mannagrass (*Glyceria nubigena* W.A. Anderson), New York ironweed (*Vernonia noveboracensis* (L.) Michx.), poke milkweed (*Asclepias exalta* L.), red maple (*Acer rubrum* L.), Rugel's Indianplantain (*Cacalia rugelia* Shuttlw. ex Chapman), sassafras (*Sassafras albidum* (Nutt.) Nees), smooth blackberry (*Rubus canadensis* L.), sweetgum (*Liquidambar styraciflua* L.), Table Mountain pine (*Pinus pungens* Lamb.), whorled wood aster (*Aster acuminatus* Michx.), winged sumac (*Rhus copallinum* L.), yellow buckeye (*Aesculus flava* Ait.), yellow crownbeard (*Verbesina occidentalis* (L.) Walt.), and yellow-poplar (*Liriodendron tulipifera* L.). The highly sensitive species are American sycamore, black cherry, blackeyed Susan, cutleaf coneflower, poke milkweed, red maple, sassafras, Table Mountain pine, winged sumac, and yellow crownbeard (Neufeld et al. 1992). Loblolly pine (*Pinus taeda* L.), a prevalent species in the Southeast, also may be sensitive to ozone. Kuehler and Flagler (1999) and Manning et al. (2003) note that seedlings of a half-sib family, S6PT2, are sensitive to ozone.

Despite the presence of ozone-sensitive species and potentially high ozone exposure in southeastern MSAs, no published studies have examined both ground-level ozone and its effect on vegetation in MSAs other than the eastern portion of the Knoxville MSA. Therefore, the purpose of this study is to explore the relationship between ozone exposure and potential foliar injury in a southeastern metropolitan area. It is well beyond the scope of the study to examine the actual ozone dose (i.e. amount of ozone absorbed into the plant over time), because of the multitude of factors affecting ozone dose (e.g., Musselman et al. 2006).

STUDY AREA

The 28-county Atlanta, Georgia MSA is an ideal area in which to examine ozone exposure and visible foliar injury (Figure 1). Atlanta, with a population exceeding four million persons, is the largest MSA in the southeastern United States (US Census Bureau 2006). Since 2000, ozone has been measured continuously at 12 monitoring stations located through the MSA. Within a rectangular zone encompassing 11 stations (i.e. the "ozone-analysis region") (Figure 1), the spatial-sampling interval of ozone is ~28 km (Figure 1). This value is substantially smaller than the mean sampling interval of ~70 km for 41 ozone-mapping studies as reported in Diem (2003); therefore, the Atlanta MSA has an unusually dense ozone-monitoring network. Finally, in the eastern portion of the Atlanta MSA is Stone Mountain, a monadnock well suited for an ozone-related vegetation survey (Figures 1 and 2) for the following reasons: (1) earlier Stone Mountain cruise surveys by the authors revealed the presence of loblolly pine along with three species, black cherry, sand blackberry (*Rubus cuneifolius* Pursh) (e.g., Barbo et al. 1998), and winged sumac, that are highly sensitive to ozone; and (2) in contrast to a typical mature loblolly pine, which does not have easily accessible whorls, most loblolly-pine individuals on Stone Mountain are short, thereby facilitating efficient examination of needles for ozone injury.

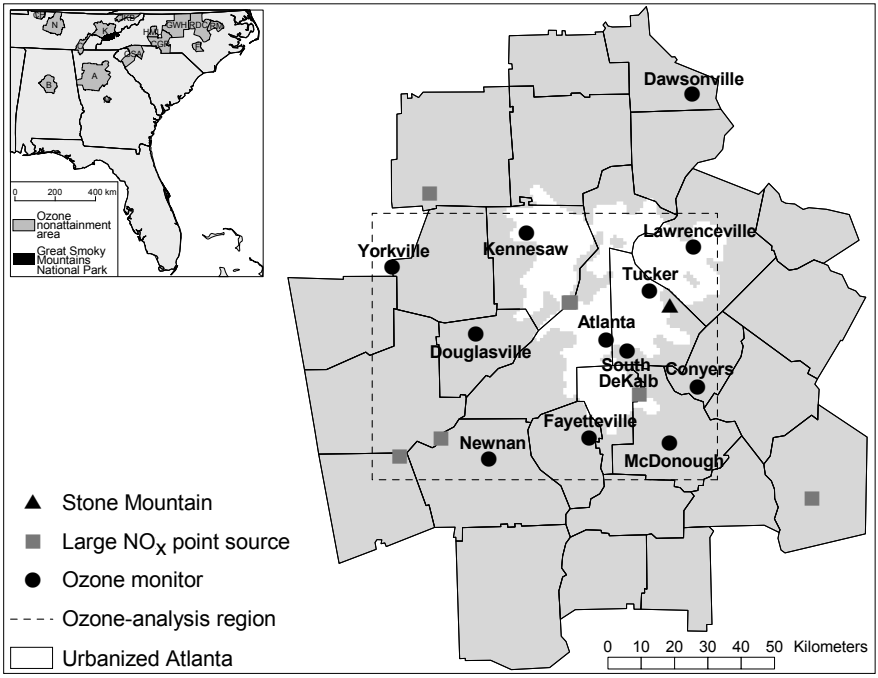

Figure 1. Ozone nonattainment areas (including Great Smoky Mountains National Park) in the southeastern United States along with the 28-county Atlanta, Georgia metropolitan statistical area (MSA). Abbreviations for the nonattainment areas are as follows: A = Atlanta, B = Birmingham, C = Chattanooga, CGR = Charlotte-Gastonia-Rock Hill, CH = Clarksville-Hopkinsville, F = Fayetteville, GSA = Greenville-Spartanburg-Anderson, GWH = Greensboro-Winston Salem-High Point, HML = Hickory-Morganton-Lenoir, JKB = Johnson City-Kingsport-Bristol, K = Knoxville, M = Macon, N = Nashville, R = Rocky Mount, and RDC = Raleigh-Durham-Chapel Hill. Located on the Atlanta MSA map are the following: Stone Mountain, ozone monitors, major point sources of nitrogen oxides (NO_x), and urbanized Atlanta within the MSA. NO_x-emissions estimates from point sources for 1999 were obtained from the U.S. Environmental Protection Agency, and only those facilities emitting < 4 Gg NO_x yr^{-1} were labeled as "large" sources (US EPA 2006a). Urbanized Atlanta was determined from a 1997 land-cover database of the Atlanta region (Yang and Lo 2002). The gridded database was converted into a binary image (i.e. urban and non-urban), before being coarsened to 1-km resolution using a majority filter and nearest-neighbor resampling.

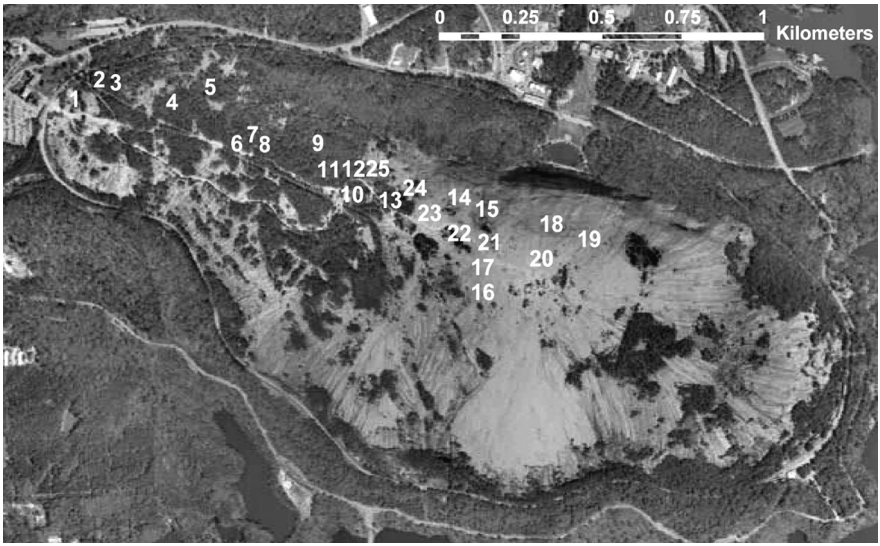

Figure 2. Locations of the 25 sampling sites on Stone Mountain. The sites are displayed on a 23 April 2002 high-resolution orthoimage acquired from the U.S. Geological Survey.

METHODOLOGY

Ozone exposure was calculated at 11 ozone-monitoring stations in the Atlanta MSA. Raw hourly ozone concentrations were acquired from the U.S. Environmental Protection Agency for the 2000–2005 ozone seasons (i.e. March–October). Only 3.3 percent of the hours for the Atlanta-MSA stations had missing values. Linear-regression models were used to produce predicted ozone concentrations at a particular station; the predictor variable was ozone at a highly correlated station. Three regression models were developed for each station; missing values at a station in question were replaced first using the highest correlated station and then the remaining missing values were replaced using the other two stations. All remaining missing values were replaced with values using a temporal inverse-distance-weighting scheme. The resulting serially complete databases were amenable to the calculation of the following ozone-exposure indices: AOT40, W126, and N100. AOT40 is calculated as the sum of the differences between the hourly ozone concentrations and the threshold value of 40 ppb during daylight hours. W126 is a sigmoidally weighted index (Lefohn and Runeckles 1987). N100 is the number of hours with ozone concentrations $\geq$ 100 ppb (Lefohn et al. 1997). W126 and N100 have been tied to ozone damage in parts of the southeastern United States (Lefohn et al. 1997).

Cumulative ozone exposure for each season was used initially to determine if vegetation could have been injured by ozone. The initial ozone-exposure critical level was based on the AOT40 value, while

Table 1. List of the 11 ozone-monitoring stations in the Atlanta Metropolitan Statistical Area followed by four ozone-monitoring stations in Great Smoky Mountains National Park.

ID	Name	Latitude (°)	Longitude (°)	Elevation (m)	% Missing
130670003	Kennesaw	34.01	−84.61	317	1.0
130770002	Newnan	33.40	−84.75	262	6.0
130890002	South DeKalb	33.69	−84.30	244	4.5
130893001	Tucker	33.85	−84.21	329	7.3
130970004	Douglasville	33.74	−84.78	375	1.8
131130001	Fayetteville	33.46	−84.42	256	1.5
131210055	Atlanta	33.72	−84.36	311	1.4
131350002	Lawrenceville	33.96	−84.07	290	7.1
131510002	McDonough	33.43	−84.16	256	1.9
132230003	Yorkville	33.93	−85.05	396	2.5
132470001	Conyers	33.59	−84.07	220	1.6
370870036	Purchase Knob	35.59	−83.08	1550	6.7
470090101	Look Rock	35.63	−83.94	793	2.2
471550101	Cove Mountain	35.70	−83.61	1243	2.7
471550102	Clingmans Dome	35.56	−83.50	2021	4.5

"ID" is the U.S. Environmental Protection Agency identification number for the station. Elevation is in height above sea level. "% Missing" is the percentage of hours that did not have valid ozone concentrations.

additional critical levels were based on values of W126 and N100. The AOT40 critical level has been defined as 10 ppm h over the April-September period, and it is based on the biomass response of European beech (*Fagus sylvatical*) to AOT40 (in Fuhrer et al. 1997). The additional critical levels, which are termed Levels 1, 2, and 3, are based on responses of black cherry, yellow-poplar, and red oak (Quercus rubra L.) in the southeastern United States to combinations of W126 and N100 over the April-October period (Lefohn et al. 1997). Level 1 indicated injury to only highly-sensitive species (e.g., black cherry) and its respective W126 and N100 values were 5.9 ppm h and 6 h. Level 2 indicates injury not only to highly-sensitive species but also to moderately-sensitive species (e.g., yellow-poplar), and its respective W126 and N100 values were 23.8 ppm h and 51 h. Level 3 indicates injury not only to highly-sensitive and moderately-sensitive speices but also to resistant species (e.g., red oak), and its respective W126 and N100 values were 66.6 ppm h and 135 h.

Ozone exposure in the Atlanta MSA was compared directly with ozone exposure in GSMNP, because ozone-induced foliar injury has been found proximate to four ozone-monitoring stations in the park. Injury to cutleaf coneflower has been found at Clingmans Dome and Purchase Knob (Chappelka et al. 2003). Injury to black cherry and yellow-poplar has been found at Cove Mountain, while injury to black cherry, sassafras, and yellow-poplar has been found at Look Rock (Chappelka

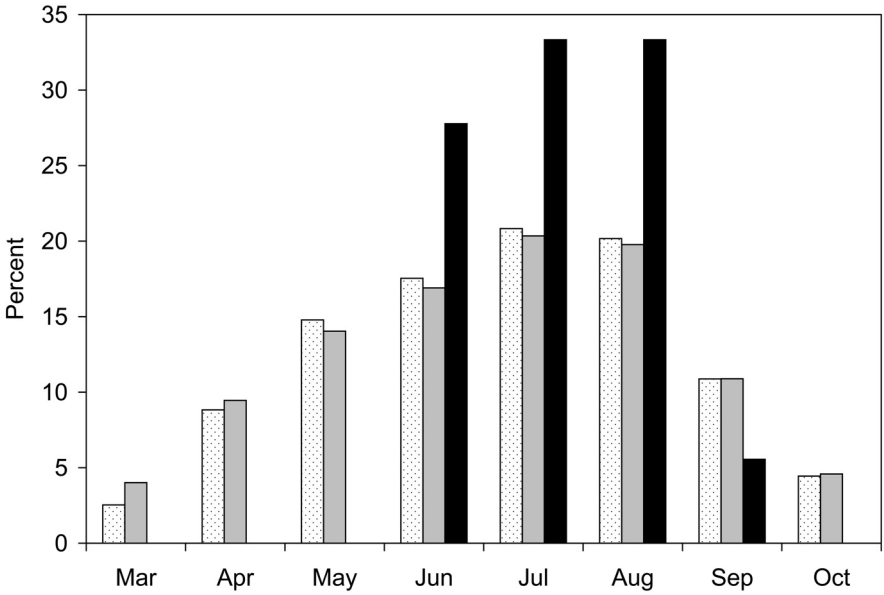

Figure 3. Typical monthly percentage of seasonal ozone exposure for the Atlanta metropolitan area. AOT40, W126, and N100 are the stippled, grey, and black bars, respectively.

et al. 1999a, b). Hourly data for Clingmans Dome, Cove Mountain, Look Rock, and Purchase Knob were acquired from the U.S. Environmental Protection for the May-September period from 2000–2005 (Table 1). Seasonal ozone exposure was calculated initially with the raw hourly data and subsequently was adjusted upwards by multiplying the seasonal value by the ratio of all seasonal hours to seasonal hours with valid data. The Mann-Whitney *U* test was employed to determine if seasonal ozone exposure at the GSMNP stations was significantly higher than seasonal ozone exposure at Atlanta-MSA stations. The one-tailed significance level was 0.05.

A survey of visible foliar injury to black cherry, loblolly pine, sand blackberry, and winged sumac was conducted on Stone Mountain in August 2004. Twenty-five vegetated sampling sites with an approximate ten-meter diameter were randomly selected along a west-east transect that corresponded with the only trail that leads to the top of the mountain (Figure 2). The sites were located predominantly on the western side of the mountain; thus, most sites had good exposure to urbanized Atlanta. Foliar injury was evaluated through an incidence survey and was quantified using a ranking system following criteria adapted from the Forest Inventory and Analysis (FIA) National Program guidelines (US Forest Service 2006). Purple stippling, purple-red scorching, and brown stippling were the indicators for black cherry, sand blackberry, and winged sumac, respectively (Neufeld et al. 1992). Chlorotic mottling was the indicator of foliar injury to loblolly pine (Kuehler and Flagler 1999; Manning et al. 2003).

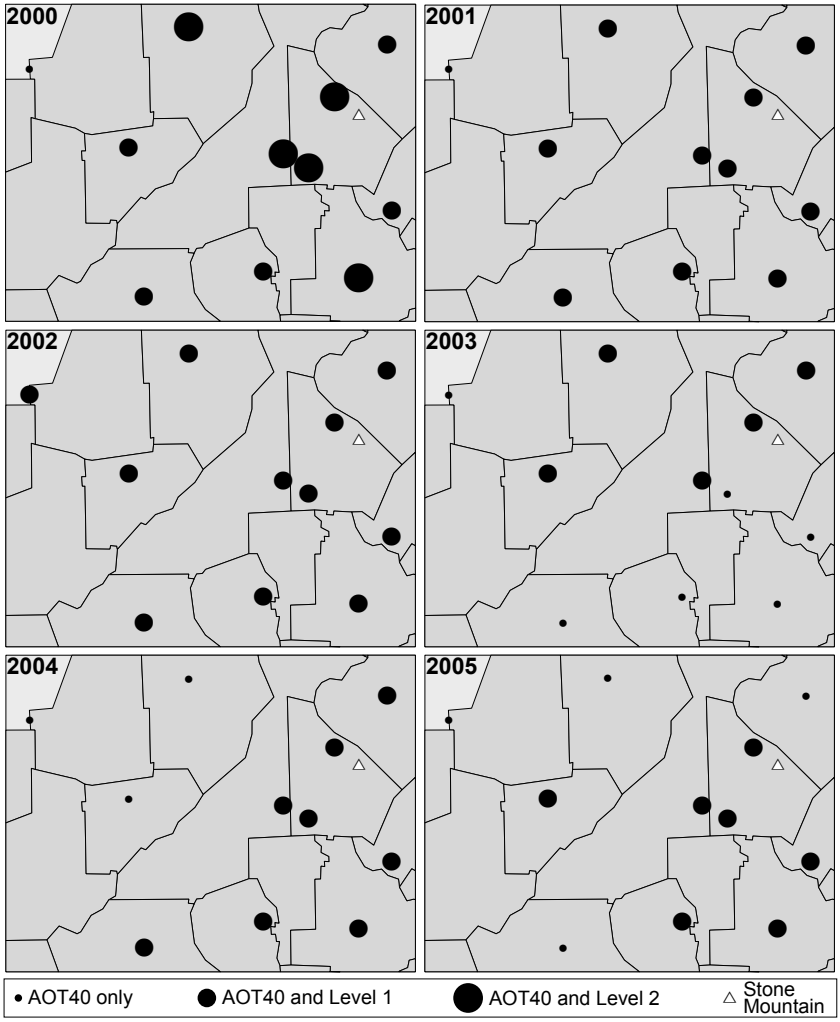

Figure 4. Exceedances of ozone-exposure critical levels within the Atlanta MSA from 2000 to 2005.

Only foliage within reach of the examiner was evaluated.

RESULTS AND DISCUSSION

Based solely on ozone exposure, which peaked in June, July, and August (Figure 3), ozone-induced injury to vegetation was possible throughout the metropolitan area from 2000–2005 (Figure 4); however, it probably was limited to highly sensitive species. All stations exceeded the AOT40 critical level in each year. Level 1 ozone exposure was achieved at multiple stations in each year; however, ozone exposure at only two stations, Atlanta and Tucker,

Table 2. Significant differences in seasonal ozone exposure from 2000–2005 between monitoring stations in the Atlanta Metropolitan Statistical Area (MSA) and Great Smoky Mountains National Park (GSMNP).

	Clingmans Dome	Cove Mountain	Look Rock	Purchase Knob
Atlanta	A,W	W	W,***N***	N
Conyers	A,W	W	A,W	W,***N***
Douglasville	W	W	W	W,***N***
Fayetteville	A,W	A,W	A,W	W
Kennesaw	A,W	W	W	W,***N***
Lawrenceville	A,W	W	W	W,***N***
McDonough	A,W	W	A,W	W,***N***
Newnan	A,W	A,W	A,W	W
South DeKalb	A,W	A,W	A,W	W,***N***
Tucker	A,W	W	W	W,***N***
Yorkville	A,W	W	W	W

"A," "W," and "N" refer to AOT40, W126, and N100, respectively. Bold, italicized characters indicate that an Atlanta-MSA station had significantly higher exposure, while normal characters indicate a GSMNP monitor had significantly higher exposure.

reached or exceeded Level 1 in all six years. Level 2 ozone exposure was achieved only in 2000, with the few Level 2 stations located predominantly in the eastern portion of the MSA.

Ozone exposure within the Atlanta MSA typically was less than ozone exposure at GSMNP locations where foliar injury has been documented (Table 2). Ozone exposure at Clingmans Dome, Cove Mountain, and Look Rock was significantly higher than exposure throughout the Atlanta MSA. Therefore, ozone exposure in the Atlanta MSA was not as high as ozone exposure at GSMNP locales where injury to a moderately sensitive species, tulip poplar, has been observed (Chappelka et al. 1999a, b). Nevertheless, ozone exposure at all 11 Atlanta-MSA stations may have been equivalent to exposure at Purchase Knob, where injury to a highly sensitive species, cutleaf coneflower, has been observed (Chappelka et al. 2003).

Concerning potential spatial variations in vegetation responses to ozone, foliar injury should be more likely in the eastern portion rather than the western portion of the Atlanta MSA. Ozone production in the Atlanta region during the summer months is NO_x-sensitive, and this is most likely due to the heavy emission of BVOCs (Sillman et al. 1995; Saylor et al. 2002). With the direction of lower-troposphere winds during the peak months of the ozone season being approximately southwesterly/westerly (Diem and Mote 2005), NO_x emitted in the urbanized area and from large point sources west of the urbanized area were transported primarily to the eastern portion of the metropolitan area (Figure 1). Consequently, the highest N100 levels

Table 3. Species present at and location information for the 25 sampling sites on Stone Mountain.

Site	Species	Easting (m)	Northing (m)	Elevation (m)
1	RUCU (12)	762761	3744732	305
2	RUCU (5)	762837	3744792	314
3	RHCO (4)	762888	3744782	317
4	PITA (40)	763062	3744723	335
5	RHCO (5)	763181	3744769	354
6	PRSE (4)	763263	3744597	354
7	PRSE (7)	763324	3744624	366
8	RHCO (14), RUCU (14)	763350	3744594	366
9	RHCO (7), RUCU (7)	763514	3744598	387
10	RHCO (5)	763600	3744568	396
11	RHCO (31)	763643	3744518	402
12	RHCO (16)	763793	3744520	424
13	PRSE (4)	763881	3744424	454
14	RHCO (11)	763931	3744433	466
15	PITA (29)	764017	3744398	485
16	RHCO (28)	764005	3744319	476
17	PITA (49)	763992	3744351	476
18	RHCO (4)	764217	3744352	512
19	PITA (22)	764342	3744308	503
20	PITA (6)	764186	3744248	500
21	PITA (52)	764001	3744277	470
22	PITA (12)	763931	3744324	463
23	PITA (17)	763833	3744410	436
24	RHCO (15)	763785	3744461	424
25	RHCO (23)	763681	3744522	405

"PITA," "PRSE," "RHCO," and "RUCU" refer to *Pinus taeda* L. (loblolly pine), *Prunus serotina* Ehrh. (black cherry), *Rhus copallinum* L. (winged sumac), and *Rubus cuneifolius* Pursh (sand blackberry), respectively. Values in parentheses are the number of individuals examined in each plot. Easting and northing correspond to the Universal Transverse Mercatur (zone 16N) projection.

typically occurred within or approximately east of urbanized Atlanta.

Results from the vegetation survey on Stone Mountain validate results from the ozone-exposure analyses. Highly-sensitive species showed symptoms of ozone injury in August 2004. Among the 163 winged-sumac, 38 sand-blackberry, and 15 black-cherry individuals, 73, 25, and four individuals, respectively, displayed ozone-injury symptoms. Therefore, approximately 25 percent of individuals of highly-sensitive species were injured by ozone. Of the 226 loblolly-pine individuals present at eight sampling sites (Table 3), none of the individuals had chlorotic mottling.

CONCLUSIONS

The results from this research suggest that ozone exposure within the Atlanta MSA during 2000–2005 probably was high enough to injure only highly sensitive species. Results from a 2004 vegetation survey at Stone Mountain support published ozone-exposure critical levels for several ozone-exposure indices: highly sensitive species, such as black cherry, sand blackberry, and winged sumac, were injured, and this was expected based on cumulative values of AOT40, W126, and N100. Ozone exposure throughout the Atlanta MSA was significantly lower than ozone exposure at several GSMNP stations, where multiple species, including a moderately sensitive species, have exhibited foliar injury. Future ozone-exposure research in the Atlanta MSA or in other southeastern MSAs should involve spatially extensive examinations of foliage of highly sensitive, moderately sensitive, and resistant species over several years.

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