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Ozone Injury to Forests Across the Northeast and North Central United States, 1994 - 2010

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Abstract

Ozone is a highly toxic air contaminant that has been shown to decrease tree growth and cause significant disturbance to forested ecosystems. Ozone also causes distinct foliar injury symptoms to certain species (bioindicator plants) that can be used to detect and monitor ozone stress (biomonitoring) in the forest environment. In the early 1990s, the U.S. Forest Service, in partnership with the U.S. Environmental Protection Agency, developed and implemented a suite of forest health indicators to respond to emerging demands for a comprehensive assessment of the health of U.S. forests. This report focuses on the states in the Northern Research Station-Forest Inventory and Analysis region, which has the longest record of ozone biomonitoring in the country, from 1994 through 2010. The results of 17 years of ozone injury detection provide indisputable evidence that ozone-induced foliar injury symptoms occur routinely on ozone-sensitive bioindicator plants across much of the forested landscape and in areas previously thought to be relatively ozone free. This report provides state-level information on where ozone stress occurs and whether ozone stress is increasing or decreasing over time. It also provides state-level estimates of the acres of forest land and volume of ozone-susceptible species at risk of ozone impact.

Cover Photos

Ozone injury, clockwise from top left:

Maple, photo by Robert L. Anderson, U.S. Forest Service, bugwood.org
Yellow-poplar, photo by U.S. Forest Service, Region 8, bugwood.org
Black cherry, photo by Tim Tigner, Virginia Department of Forestry, bugwood.org
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INTRODUCTION

In the early 1990s, the U.S. Forest Service (USFS), in partnership with the U.S. Environmental Protection Agency (EPA), developed and implemented a suite of forest health indicators to respond to emerging demands for a comprehensive assessment of the health of U.S. forests (Anonymous 1995). The ozone (O_3) indicator was developed by the USFS Forest Health Monitoring (FHM) program to address specific concerns about the negative effects of O_3 pollution on forest health and productivity. Ozone is a highly toxic air contaminant that has been shown to decrease tree growth and cause significant disturbance to forested ecosystems (Bytnerowicz et al. 2008, Karnosky et al. 2007, Krupa and Legge 1995, Laurence and Anderson 2003, Percy et al. 2003)[1]. Ozone also causes distinct foliar injury symptoms to certain species (bioindicator plants) that can be used to detect and monitor O_3 stress (biomonitoring) in the forest environment (Smith et al. 2003, 2008).

Ozone detection with bioindicator plants does not identify specific levels of O_3 present in ambient air but does identify if conditions are favorable for O_3 injury to occur. Favorable conditions are dependent on plant susceptibility to O_3, the concentration and duration of exposure to O_3, and the external environment in which the plant is growing (Kohut 2005, Krupa et al. 2001, Schaub et al. 2003). Of the many environmental conditions that influence plant-pollutant interactions, soil moisture status is often considered the most critical because stomatal closure during periods of drought or low soil moisture can severely limit O_3 uptake. With few exceptions, field-based studies have shown that increases in both O_3 uptake and foliar injury correlate with increased availability of soil water in the forest environment (Chappelka and Samuelson 1998, McLaughlin et al. 2007, Showman 1991). However, the controlling influence of soil moisture on O_3 uptake may depend on the severity of water stress as well as other plant-based factors that influence the balance between moisture input (precipitation) and moisture output (evapotranspiration) for individual plants or sites (Zhang et al. 2010). Generally, O_3 concentrations in excess of 60 ppb O_3 for several hours will cause injury to ozone-sensitive plants provided there are no external growth conditions (e.g., low soil moisture) that cause stomates to close (Mansfield 1998, U.S. EPA 2007). For certain genotypes of otherwise sensitive O_3 species, injury may also be reduced by a plant's inherent ability to construct and maintain internal defense and repair mechanisms following O_3 uptake.

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A useful bioindicator plant may be a tree, woody shrub, or herb species as long as the species responds to ambient levels of O_3 pollution with distinct visible foliar symptoms that are easy to diagnose (Chappelka and Samuelson 1998). Field studies and controlled fumigation experiments were used to identify ozone-sensitive species and characterize the specific foliar response for each species used in the

[1]An earlier document provides detail on O_3 formation, sources, and transport and a comprehensive review of O_3 impacts on trees. The rationale for O_3 biomonitoring is discussed along with procedures for data collection and quality control and detailed information on the sampling and estimation techniques used to summarize data and interpret findings (Smith et al. 2008).

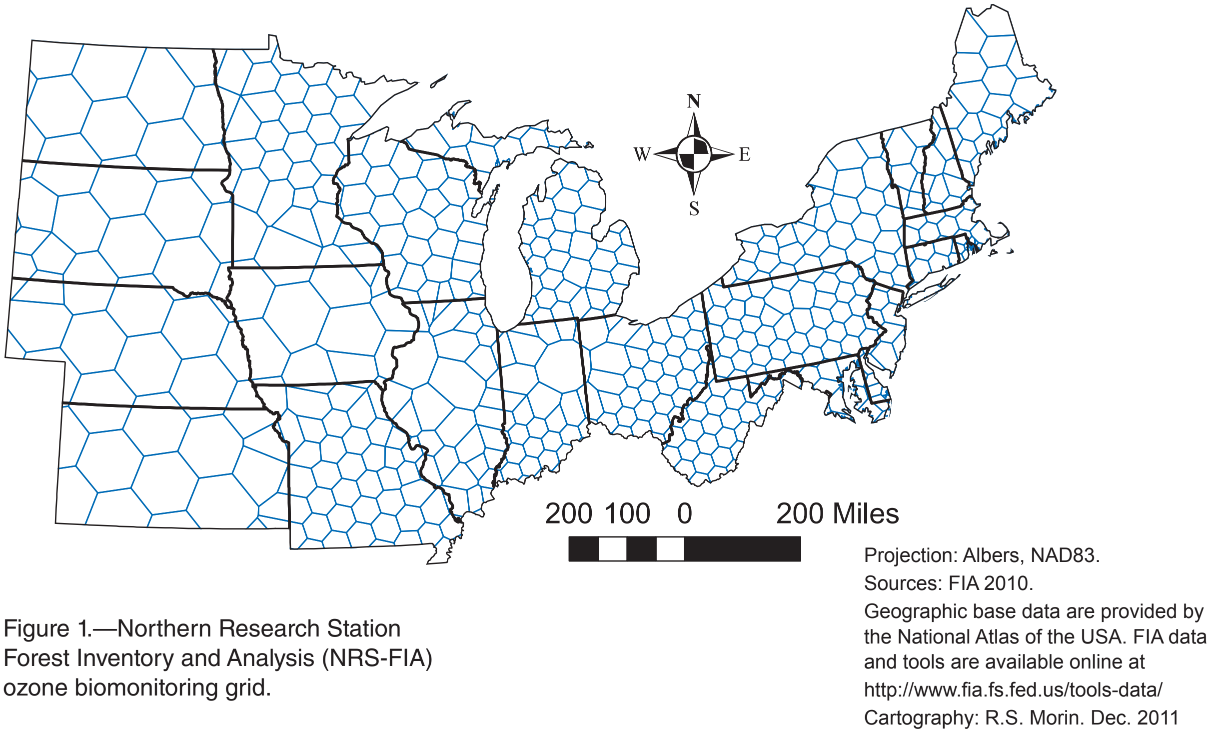

Figure 1.—Northern Research Station Forest Inventory and Analysis (NRS-FIA) ozone biomonitoring grid.

USFS biomonitoring program (Brace et al. 1999, Davis et al. 1982, Krupa and Manning 1988). Many of these species show a highly variable response to O_3 under field conditions because of intraspecific genetic variation in O_3 sensitivity and variable site or microsite factors. Still, acknowledging the complexity and variability inherent to any field-based study, ozone-induced foliar injury symptoms occur routinely on sensitive bioindicator species during the growing season and detection of foliar injury is diagnostic for the presence of phytotoxic O_3 concentrations in U.S. forests (Eckert et al. 1999, Kohut 2007, Krupa et al. 1998, Manning 2003).

Across the country, O_3 surveys are managed by the USFS Forest Inventory and Analysis (FIA) program and implemented in three of the four regional units covered by the Northern, Southern, and Pacific Northwest Research Stations (http://fia.fs.fed.us/regional-offices/).[2] Currently, the national grid consists of more than 1,005 field sites in 40 states. At every site, the amount and severity of injury to the foliage of sensitive plants is used to formulate a plot-level injury index referred to as the ozone biosite index or BI (Smith et al. 2007). Plot data provide detection-level information on where O_3 stress is occurring across a state or region and whether stress is increasing or decreasing over time.

The USFS biomonitoring survey includes a standardized protocol for sampling and site selection designed to maximize the opportunity for O_3 injury detection during the growing season (U.S. Forest Service 2006). Sampling occurs on a unique national grid that consists of a single panel of O_3 biomonitoring sites that are measured every year. A map of the portion of the O_3 grid covered by the Northern Research Station, Forest Inventory and Analysis region (NRS-FIA) is shown in Figure 1. Before 2002, biosite locations were co-located with forested ground plots[3] and, as a result, were restricted to the best possible opening or open canopy area in a wooded area (Fig. 2). These less than optimal areas for O_3 intrusion were replaced in 2002 with the implementation of an improved ozone grid designed to decouple the O_3 sample from the FIA base grid (Fig. 3). The changes in grid and site selection procedures allowed for larger openings and improved species and plant counts at each survey location.

[2]The FIA Intermountain region does not participate in the ozone biomonitoring program.

[3]The USFS Forest Inventory and Analysis program (FIA) collects data annually on a base grid that includes the integrated forest inventory and forest health plots known as Phase 2 (P2) and Phase 3 (P3), respectively. The ozone biomonitoring plots are part of P3 in FIA. Data collected on P3 plots provide estimates of health and condition for the Nation's forests.

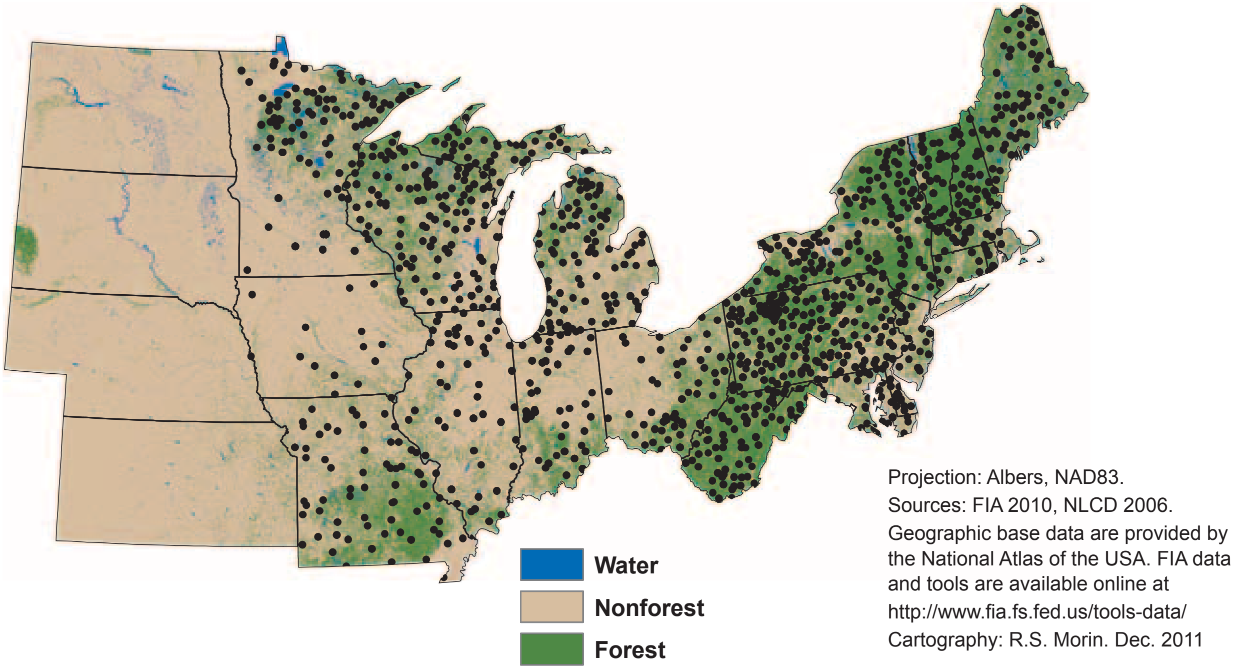

Figure 2.—NRS-FIA ozone biomonitoring sites, 1994-2001.

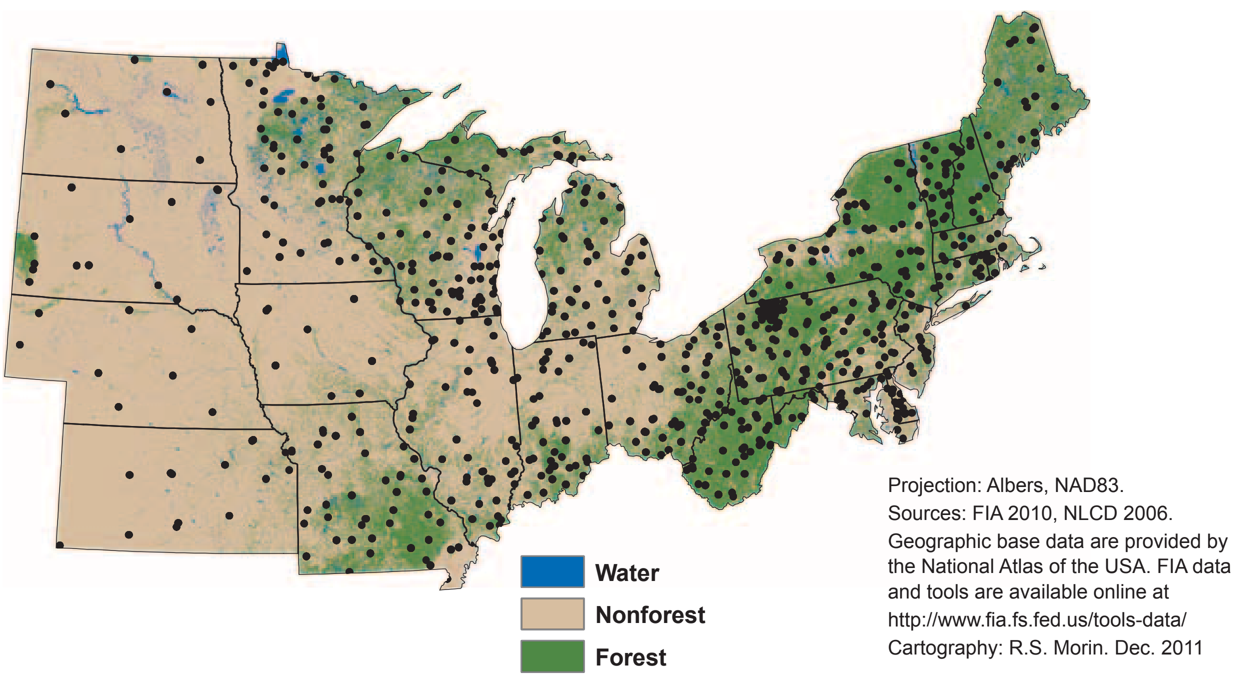

Figure 3.—NRS-FIA ozone biomonitoring sites, 2002-2010.

Core reports for the O_3 indicator include tabular data describing plot-level counts and injury indices by state and year and mapped data derived from spatially interpolated indices of O_3 impact (e.g., BI) and O_3 air quality (e.g., SUM06[4]). The SUM06 index data were obtained from the EPA, which monitors hourly ambient O_3 concentrations at stations across the Nation. Assessment of risk to the forest resource from ambient O_3 exposure is based on categorized BI data following spatial interpolation to the forested ground plots on the FIA base grid (Smith et al. 2008).

[4]SUM06 is defined as the sum of all hourly average ozone concentrations greater than or equal to 0.06 ppm that occur between June 1 and August 31, a widely recognized threshold for ozone injury to sensitive plants.

Regional Grid Development

This report focuses on the states in the NRS-FIA region, which has the longest record of O_3 biomonitoring in the country, from 1994 through 2010. The sample area includes 24 states, which are typically divided into two subregions. The Northeast (NE) subregion includes the New England States (Vermont, New Hampshire, Maine, Massachusetts, Connecticut, Rhode Island), New York, Ohio, and the Mid-Atlantic States (New Jersey, Pennsylvania, Delaware, Maryland, West Virginia), while the North Central (NC) subregion includes the Lake States (Michigan, Wisconsin, Minnesota), the East NC States (Indiana, Illinois, Iowa, Missouri), and the Plain States (Kansas, Nebraska, North Dakota, South Dakota). Field implementation began in 1994 in the six New England States and in the Lake States. Over the next 5 to 7 years, the NE plot network expanded into the Mid-Atlantic States and then Ohio (1997) and finally New York (1999), while the NC implementation moved from Indiana (1996) west to Missouri (2000) and finally into the Plain States. By 2002, the ozone grid in NRS-FIA was complete including all 24 states on the improved ozone grid.

Regional Air Quality

Ozone air quality for the NE and NC States varies considerably across the landscape without regard for state boundaries or otherwise useful groupings of states or physiographic regions. Both the NE and NC States include areas with relatively clean air characterized by background concentrations of O_3 that are inconsequential to plant health. Both subregions also include areas characterized by low, moderate, and high ambient O_3 exposures during the growing season where the risk of injury varies with site- and weather-related factors that influence whether the toxic O_3 molecule is able to enter the plant through open stomates. A regional map of average 3-month growing season SUM06 values for 1994 to 2009 (Fig. 4) describes most of northern New England and the northern Plains States as relatively clean (SUM06 < 8 ppm-hrs) with air quality worsening north to south from Maine to Maryland and from North Dakota to Kansas. Relatively low ozone exposures (SUM06 8-15 ppm-hrs) characterize more northerly portions of Wisconsin, Michigan, New York, and Massachusetts, while moderate to high seasonal O_3 exposures (SUM06 >15 ppm-hrs) are found in all or part of the East North Central States of Missouri, Iowa, Illinois, and Indiana, continuing east across Ohio, Pennsylvania, Maryland, and Delaware, and on into New Jersey. Although each O_3 season is unique and some years are substantially worse than others, the states typically characterized by the highest seasonal O_3 exposures every year include Ohio and the Mid-Atlantic States in the NE, and all or part of Illinois and Indiana in the NC. In 2002, one of the worst ozone years (Fig. 4), high O_3 concentrations extended beyond what was typical into Missouri and parts of Nebraska, Kansas, and southern Michigan, while blanketing most of the East North Central and Mid-Atlantic States, and southern New England. In contrast, 2004 was a year with relatively clean to low O_3 air (Fig. 4) extended across all states in NRS-FIA except in the more populated areas of Pennsylvania, New Jersey, Maryland, and Delaware.

OBJECTIVES

The 17-year record of biomonitoring in NRS-FIA (1994-2010) provides a unique opportunity to examine changes and trends in the ozone indicator over the long term. To that end, the primary objective of this report is to summarize the core ozone indicator data for all 24 states in the NRS-FIA region. Tables and maps are used to summarize information by state and by year. Comparisons are made between states or groups of states in clean, low, moderate, and high ozone exposure areas. Spatial interpolation is used to extend the information collected at biosites to the forest population and to estimate the acres of forest land and the volume of susceptible tree species at risk of O_3 impact.

A second objective is to examine relationships between injury and exposure within the context of variable site moisture conditions and wet vs. dry years. Long-term trends in foliar injury and air quality are discussed for the region as a whole with reference to national air quality standards and climate change.

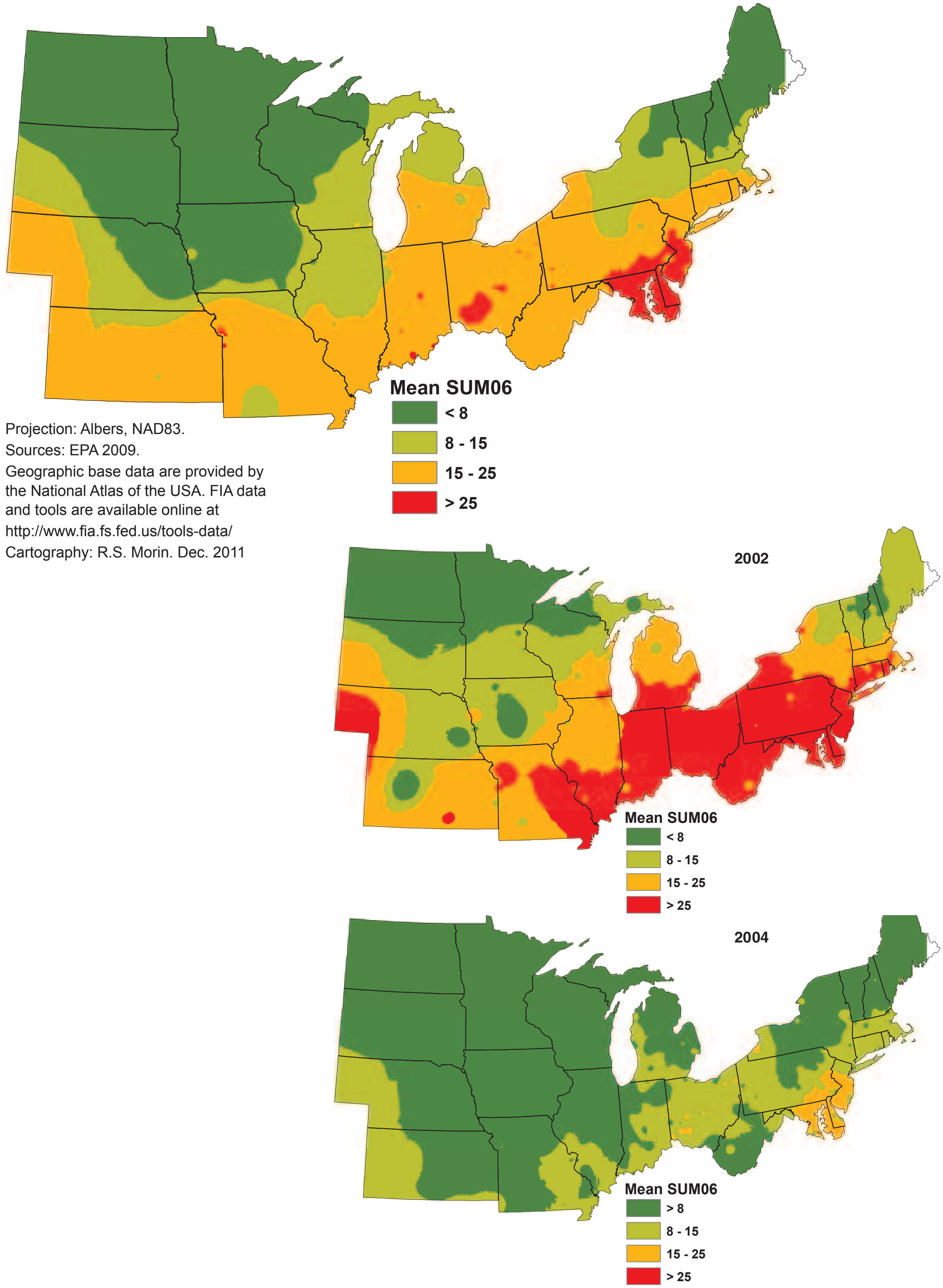

Figure 4.—Spatial interpolation of mean 3-month cumulative ozone concentrations (SUM06), in ppm-hrs, for the 16-year (1994 to 2009) sampling period and mean 3-month cumulative ozone concentrations (SUM06) for 2002 and 2004.

The following forest health assessment questions developed specifically for the ozone indicator provide the framework for this report:

1. How many biosites are evaluated/injured?
2. How many plants are evaluated/injured?
3. What species are used for biomonitoring?
4. Do the injury data indicate that phytotoxic concentrations of ozone are present in eastern forests?
5. Do the injury data indicate that ozone air quality is changing over time?
6. If so, is it improving or deteriorating?
7. Where is the injury most severe, or frequent?
8. What amount of forest land is subject to levels of ozone pollution that may cause injury?
9. What volume of ozone-sensitive species is at risk, and where is it?
10. What is the relationship between ambient ozone concentrations and the injury data?
11. Are there explanatory variables that improve the interpretability of the injury data?

METHODS

Sample Area

As of 2010, the NRS-FIA biomonitoring grid included 466 ground locations in 24 states (Fig. 3). The number of years of biomonitoring ranges from 8 to 17 depending on the start year for each state (Table 1). The field sites vary in size and do not have set boundaries. They are defined by the presence of ozone-sensitive indicator species indigenous to the NE and NC States (Table 2).

Ozone sampling occurs on a unique national grid based on the Environmental Monitoring and Assessment design (White et al. 1992). Biosite locations are mapped; geographic coordinates are recorded; and site characteristics are described in terms of size, elevation, terrain position, aspect, soil drainage, soil depth, and site disturbance. Crews are trained to select undisturbed, wide open areas (>3 acres) with more than 30 plants of more than three bioindicator species. The approximate locations of the plants used for evaluations are drawn on the site map so that the same population of plants is evaluated by regular and quality assurance (QA) crews on return visits to the site. Throughout this document, site, biosite, and plot are used interchangeably to refer to the ground locations where ozone-sensitive plants are evaluated every year.

Foliar Injury, the BI, and Risk Assessment

Ozone injury and our ability to detect injury increase over the course of the field season. For these reasons, injury assessment is limited to 3 to 4 weeks (from late July through mid-August) within which the ozone indicator is considered stable. Crews are trained and certified in O_3 injury recognition every year and submit injured leaf vouchers to a regional expert for validation of the field results.

The site-level biosite index (BI) is derived from the amount, severity, and incidence of ozone-induced foliar injury to ozone-sensitive bioindicator plants at each biosite (Smith et al. 2007). The BI values describe a gradation of plant injury response that quantifies the degree of O_3 injury conditions[5] on the biomonitoring plots. The BI is the average score (amount * severity) for each species averaged across all species on the biosite multiplied by 1,000 to allow risk categories to be defined by integers (Table 3). The BI is calculated as:

$$BI = 1000\left(m^{-1}\sum_{j=1}^{m} n_j^{-1} \sum_{p=1}^{n_j \geq 10} a_{pj}\, s_{pj}\right)$$

where
BI = biosite index
m = number of species evaluated
n_j = number of plants of the j·th species evaluated
a_{pj} = proportion of the injured leaves on the p^{th} plant of the $j^{\cdot th}$ species
s_{pj} = average severity of injury on the p^{th} plant of the $j^{\cdot th}$ species

[5]As defined by Smith et al. (2008): visible symptoms on bioindicator plants indicate that O_3 is present at concentrations that cause injury and that predisposing conditions (e.g., adequate site moisture) are coincident.

Table 1.—Number of years of biomonitoring, number of years with ozone injury, and year biomonitoring was started for the Northeast (NE) and North Central (NC) States, 1994-2010

Region and state	Number of years		Start year[a]
	Biomonitoring	Ozone injury detected	
Northeast States:			
Maine	17	9	1994
New Hampshire	17	15	1994
Vermont	17	17	1994
Massachusetts	17	17	1994
Connecticut	17	16	1994
Rhode Island	17	17	1994
New Jersey	17	15	1994
Maryland	17	17	1994
Delaware	15	14	1995
Pennsylvania	14	14	1995
West Virginia	16	16	1995
Ohio	14	14	1997
New York	12	12	1999
North Central States:			
Wisconsin	17	16	1994
Michigan	17	16	1994
Minnesota	17	5	1994
Indiana	15	15	1996
Illinois	14	14	1997
Iowa	11	7	2000
Missouri	11	8	2000
Kansas	9	5	2002
Nebraska	9	1	2002
North Dakota	9	0	2002
South Dakota	9	1	2002

[a]Data were not collected in Delaware in 1996 or in Pennsylvania in 1996 and 1997.

Table 2.—List of species sampled on the ozone biomonitoring plots

Common name	Scientific name
Common and tall milkweed	*Asclepias* spp.
Black cherry	*Prunus serotina*
Blackberry	*Rubus allegheniensis*
Spreading dogbane	*Apocynum androsaemifolium*
White ash	*Fraxinus americana*
Sassafras	*Sassafras albidum*
Yellow-poplar	*Liriodendron tulipifera*
Big-leaf aster	*Aster macrophylum*
Sweetgum	*Liquidambar styraciflua*
Pin cherry	*Prunus pennsylvanica*
Mountain snowberry	*Symphoricarpos oreaphilus*
Quaking aspen	*Populus tremuloides*
Ponderosa pine	*Pinus ponderosa*
Western wormwood	*Artemesia ludoviciana*
Mugwort	*Artemesia douglasiana*
Skunk bush	*Rhus trilobata*

Table 3.—Classification scheme for the FIA biosite index (BI) describing the associated categories of foliar injury response, relative air quality, risk assumption, and probable impact

Bioindicator response category	Relative air quality	Assumption of risk	Probable impact
BI = 0 < 5 Little or no foliar injury	Good	None	Tree-level response: Visible injury to highly sensitive species, e.g., black cherry
BI = 5.0 < 15 Light to moderate foliar injury	Moderate	Low	Tree-level response: Visible injury to moderately sensitive species, e.g., yellow-poplar
BI = 15 < 25 Moderate to severe foliar injury	Unhealthy for sensitive species	Moderate	Tree-level response: Visible and invisible injury
BI ≥ 25 Severe foliar injury	Unhealthy	High	Ecosystem-level response: Visible and invisible injury leading to structural and functional changes

The BI value is used to assess the probable risk of O_3 injury to all plants in the general area represented by each biosite (Coulston et al. 2003, Smith et al. 2008). BI values are grouped into four categories of injury (none, low, moderate, and high) that reflect both decreasing air quality and increasing risk of ozone injury to the forest resource (Table 3). These categories were proposed by Smith (1995) and have been used consistently in reporting results from FIA ozone surveys (Campbell et al. 2000, 2007; Rose and Coulston 2009; Smith et al. 2008).

The inverse distance squared weighting technique was used for interpolating the BI data to generate an O_3 risk map that is applied to the FIA base grid to extend information collected at the biosite to the forest population. This approach is used to assign a BI value to each P2 ground plot and tree and then estimate, for each state, the acres of forest land and the volume of ozone-susceptible tree species in each BI risk category (none, low, moderate, and high). Each tree species measured on FIA plots was assigned a sensitivity ranking (sensitive, moderately sensitive, insensitive, or unknown) based on the literature review provided by Smith et al. (2007). The list of ozone-sensitive tree species includes but is not limited to the following species: red maple (*Acer rubrum*), yellow birch (*Betula alleghaniensis*), green ash (*Fraxinus pennsylvanica*), eastern white pine (*Pinus strobus*), quaking aspen (*Populus tremuloides*), and the established bioindicator species including black cherry, white ash, yellow-poplar, and sassafras.

Ozone Exposure

SUM06 and N100 are two cumulative O_3 exposure indices that are used to characterize ambient ozone exposures over a specified time period for assessing vegetation effects (U.S. EPA 2007). The inverse distance squared weighting technique was used for interpolating hourly ozone data obtained from the EPA (http://www.epa.gov/air/data/index.html) across the landscape and assigning an average growing season (June, July, and August) SUM06 (the sum of all hourly average ozone concentrations ≥ 0.06 ppm) value to each biosite and year. The same database is used to assign an N100 (the number of hours of ozone ≥ 100 ppb) value to each biosite and year. The SUM06 measure provides an indication of chronic O_3 stress for the growing season, and N100 is an indication of peak O_3 concentrations. Descriptive ozone exposure categories for this report are derived from the seasonal mean values of the SUM06 and N100 statistics as follows: Clean (SUM06 < 8 ppm-hrs; N100 < 5 hrs), Low O_3 (8 ≤ SUM06 < 15 ppm-hrs; 5 ≤ N100 < 15 hrs), Moderate O_3 (15 ≤ SUM06 < 25 ppm-hrs; 15 ≤ N100 < 25 hrs), and High O_3 (SUM06 ≥ 25 ppm-hrs; N100 ≥ 25 hrs).

Site Moisture

The two moisture indices used in this report are the Palmer Drought Severity Index (PDSI) and a plant moisture availability index (MI). Data sources include the National Climatic Data Center (http://www.ncdc.noaa.gov/paleo/pdsidata.html) and the PRISM Climate

Group (http://www.prism.oregonstate.edu/). The PDSI quantifies long-term drought as derived from current and cumulative weather patterns (http://www.ncdc.noaa.gov/oa/ncdc.html). The MI is derived from the ratio of monthly precipitation (moisture input) to potential evapotranspiration (moisture output) and quantifies the potential moisture available to plants (Rose and Coulston 2009). Average growing season (June, July, and August) PDSI and MI values were used to describe and compare moisture conditions by overlaying the annual PDSI and MI raster maps with biosite locations and assigning moisture values to each one; PDSI specifically to indicate soil moisture stress, and MI to indicate potential plant moisture deficits. Both PDSI and MI values were grouped into three categories: PDSI to represent wet (PDSI ≥ 1.25), near normal (-1.25 < PDSI < 1.25), and dry (PDSI ≤ -1.25) soil moisture, and MI to describe conditions of moisture surplus (MI ≥ 0.15), moisture balance (-0.15 < MI < 0.15), and moisture deficit (MI ≤ -0.15).

Analysis

Descriptive statistics presented here include the numbers of biosites and plants evaluated and injured by state, region, and year; the percentage of biosites in each BI injury category by state, region, and year; and the overall assessment of risk to the forest resource from ambient O_3 exposure for each state. Changes in BI over time are examined by calculating the regional mean BI by year for 1994 through 2010.

Additional descriptive statistics include the percentage of biosites in each ozone exposure (SUM06 and N100) and site moisture (PDSI and MI) category by region and year. Regional trends (1994 to 2009) in the calculated average growing season SUM06 and N100 are reported, as are trends in growing season precipitation (1994 to 2010) above and below the average for each state and year. Linear regression analysis was used to examine the relationship between ozone exposure and BI. Regression statistics were computed using mean ozone exposure and BI values within ozone exposure classes (clean, low, moderate, and high). Regression residuals and influence diagnostics including Cooks D and DFBETAs were evaluated to ensure normality and homogeneity of residuals as well as no undue influence from individual observations.

RESULTS AND DISCUSSION

As previously noted, field implementation began in New England and spread south to the Mid-Atlantic States, and west to the NC States; the number of years of biomonitoring ranged from 9 (4 states) to 11-16 (9 states) to 17 (11 states). From 1994 to 2010, O_3 injury was detected at least once in each participating state in NRS-FIA except North Dakota (Table 1). In the 13 NE States, injury was detected every year (Vermont, Massachusetts, Rhode Island, Maryland, Pennsylvania, West Virginia, Ohio, New York) or almost every year (New Hampshire, Connecticut, New Jersey, Delaware) in every state except Maine where injury was detected just over half the time (9 of 17 years). In the 11 NC States, injury was detected every year in Indiana and Illinois, every year but one in Wisconsin and Michigan, and more than half the time in Iowa, Missouri, and Kansas. Injury was detected in only 5 of 17 years in Minnesota and in only 1 of 9 years in Nebraska and South Dakota.

During the implementation phase on the 1994-2001 grid, numbers of sites per state and number of visits per plot varied by start year and by state-driven intensification of the grid in certain states including Vermont, Pennsylvania[6], Delaware, and Wisconsin (Fig. 5). With the implementation of the 2002 grid, most intensified plots were dropped and the number of sites per state and number of visits per plot tended to level out across the region (Fig. 6). In 2010, more than 46,000 plants were evaluated for ozone injury at 470 ground locations in NRS-FIA, up from an original count of about 4,800 plants at 118 locations in 1994 (Table 4).

[6]Special studies included an intensified grid in the Allegheny National Forest (ANF) and, by request of the State Cooperator, intensified grids in Delaware, Wisconsin, and Vermont. The ANF grid was maintained through 2010.

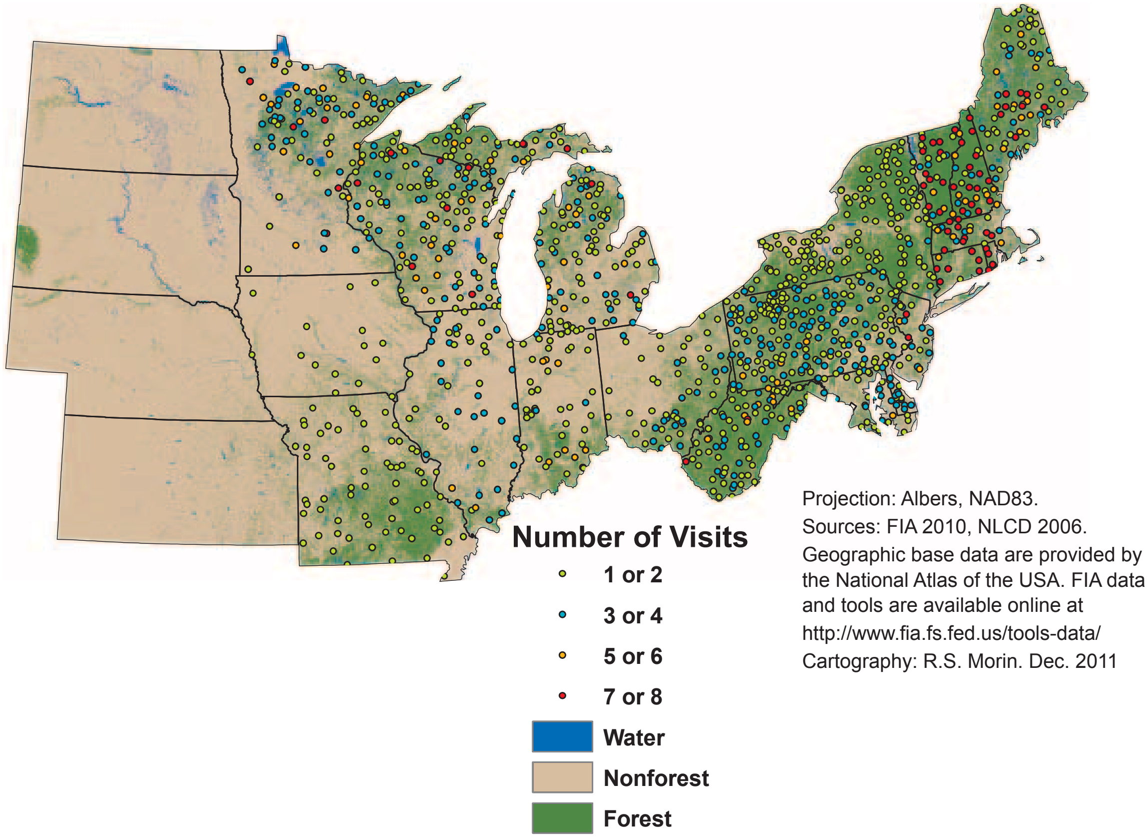

Figure 5.—Number of visits to ozone biomonitoring sites, 1994-2001.

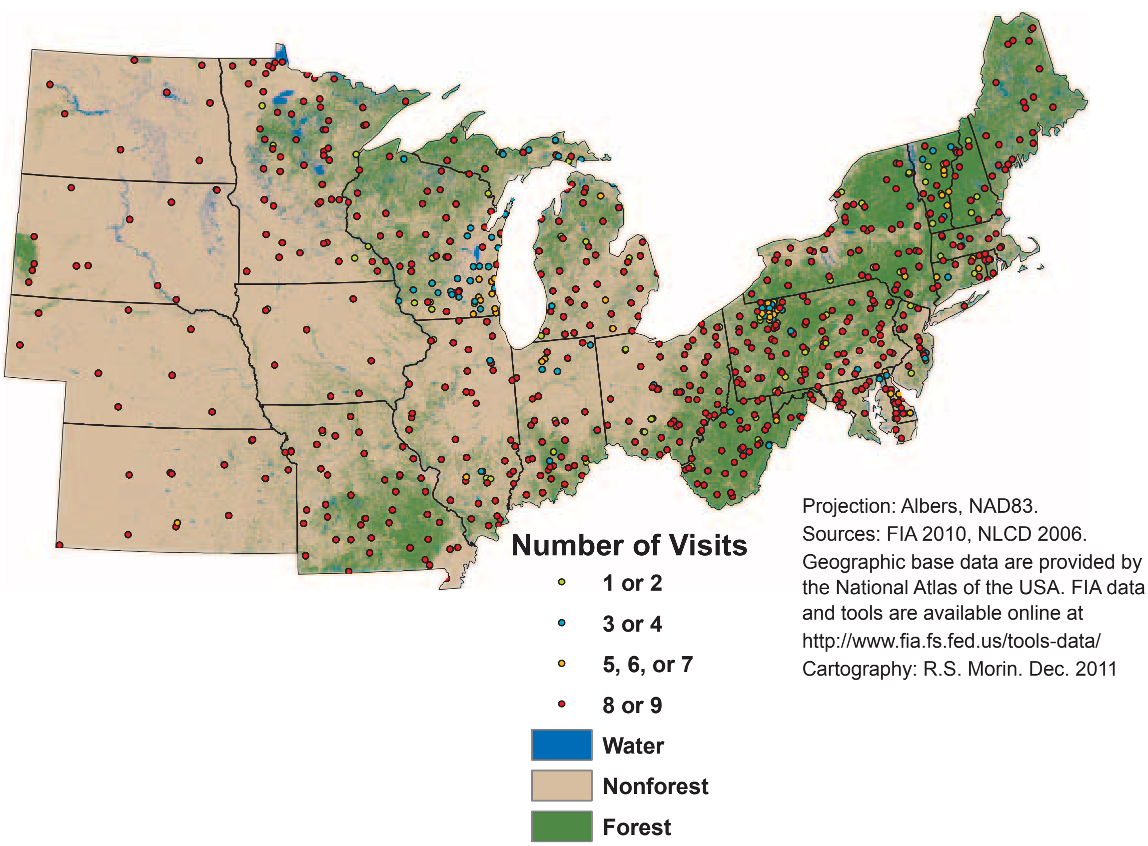

Figure 6.—Number of visits to ozone biomonitoring sites, 2002-2010.

Table 4.—Number of biosites and number of plants evaluated by year for the NE and NC States, 1994-2010

	NE States		NC States	
Year	Number of biosites	Number of plants	Number of biosites	Number of plants
1994	86	3,590	32	1,293
1995	147	6,049	137	5,245
1996	126	5,468	103	4,469
1997	151	7,156	123	5,764
1998	269	11,915	196	10,592
1999	372	19,467	188	14,237
2000	269	17,371	290	21,089
2001	341	29,399	233	17,445
2002	230	22,893	260	23,253
2003	229	22,793	269	23,628
2004	227	22,376	267	24,392
2005	232	23,360	240	23,130
2006	233	23,239	237	23,391
2007	227	22,823	236	22,777
2008	217	21,682	240	23,147
2009	228	23,454	239	23,512
2010	231	23,988	239	22,760

COMMON QUESTIONS ABOUT BIOMONITORING

What do the sites look like?

Grid changes implemented in 2002 allowed greater flexibility in the selection of ground locations for biomonitoring, which is reflected in the summarized site attribute data (Table 5). In the first 8 years (1994-2001), about half (29 to 64%) of the biosites were greater than or equal to 1.214 ha (3 acres) in size compared to more than 80 percent in the more recent 9-year period (2002-2010). Similarly, the number of sites with three or more species steadily increased over time, reaching highs of 90 to 97 percent from 2002 on. Generally, other basic site characteristics did not change as a result of the more flexible O_3 grid; in all years, trained crews tended to locate biosites on flat land (53 to 70%) with no appreciable aspect (69 to 87%), and approximately half of the sites (47 to 61%) were at elevations below 304.8 m (1,000 feet). Regardless of slope or elevation, crews selected open areas where the soil was well drained (>89%) with no obvious bedrock exposure (>92%) and no evidence of human activity or natural disturbance that might cause soil compaction (>82%). The data suggest that biosites in all states in the NRS-FIA region are relatively similar with respect to coded site attributes, although there are some obvious differences in the range of elevations and terrain positions that are largely determined by landscape features within each state or physiographic region (data not shown).

What species are used for biomonitoring?

The most common species evaluated on NE and NC biosites included blackberry, common and tall milkweed, black cherry, white ash, and spreading dogbane, generally in the range of 2,000 to 4,000 plants per year on the full grid (Tables 6, 7). Sassafras was also sampled widely (600 to 1,500 plants/year) in the NE and NC States as was yellow-poplar in NE and big-leaf aster in NC. Less commonly occurring species included pin cherry and sweetgum in NE and a variety of western bioindicator species in NC including ponderosa pine, mountain snowberry, skunkbush, and western wormwood that are found only in the more western portions of the Plain States. Field images of ozone-induced foliar injury to some of the more common bioindicator species are available at the FIA ozone indicator Web site: http://nrs.fs.fed.us/fia/topics/ozone/default.asp.

Table 5.—Percent of total biosites in each site attribute category, number of biosites evaluated, and percent of injured biosites by year for the 24-state NRS-FIA region, 1994-2010

Site Attribute	Percent of total biosites in each site attribute category																
	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Plot Size																	
Biosites ≥ 1.2 hectares (3 acres)	55	29	36	48	43	53	59	64	81	84	80	81	82	83	88	85	86
Biosites < 1.2 hectares (3 acres)	45	71	64	52	57	47	41	36	19	16	20	19	18	17	12	15	14
Number of Species																	
≥ 3 species	32	24	37	40	34	50	65	74	90	91	92	94	96	97	95	96	92
< 3 species	68	76	63	60	66	50	35	26	10	9	8	6	4	3	5	4	8
Aspect																	
No aspect (slope<5%)	82	71	79	74	83	87	81	74	73	76	72	73	71	73	69	70	73
Northeast facing slope	9	12	10	10	8	6	11	13	13	12	13	14	14	14	15	15	13
Southwest facing slope	9	17	11	16	9	7	8	13	14	12	15	13	15	13	16	15	14
Terrain Position																	
Flat land unrelated to slope	58	53	64	60	64	53	63	62	62	65	61	64	58	63	66	70	75
Lower slope, Bench, Upper Slope	42	47	36	40	36	47	37	38	38	35	39	36	42	37	34	30	25
Elevation																	
Low (≤ 304.8 meters; 1000 ft)	63	48	47	52	51	50	59	61	58	59	58	57	58	60	59	55	54
Moderate to High (> 304.8 m;1000 ft)	37	52	53	48	49	50	41	39	42	41	42	43	42	40	41	45	46
Soil Drainage																	
Soil is well drained	89	95	93	91	94	96	96	96	95	96	93	95	94	95	95	96	97
Soil is generally wet	7	3	4	5	4	3	3	4	3	3	5	1	2	2	4	3	2
Soil is excessively dry	4	2	3	4	2	1	1	-	2	1	2	4	4	3	1	1	1
Soil Depth																	
Bedrock is not exposed	94	96	96	95	92	95	96	97	97	98	97	96	97	97	96	97	98
Bedrock is exposed; soils shallow	6	4	4	5	8	5	4	3	3	2	3	4	3	3	4	3	2
Site Disturbance																	
None	82	88	90	92	98	98	99	99	99	89	89	90	94	94	97	95	92
Overuse: humans or natural disturbance	18	12	10	8	2	2	1	1	1	11	11	10	6	6	3	5	8
Total biosite count	118	284	229	274	465	560	559	574	490	498	494	472	470	463	457	467	499
Percent injured biosites	56	26	36	27	48	31	48	36	33	27	30	27	34	28	23	19	27

Table 6.—The number of evaluated and injured plants by species and year for the NE States, 1994-2010

	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	Totals
Big-leaf aster																		
Evaluated	0	0	0	0	60	258	13	135	32	120	60	413	301	165	391	300	210	2,458
Injured	0	0	0	0	4	0	0	0	0	10	9	3	1	0	3	0	0	30
Black cherry																		
Evaluated	739	771	965	906	1,995	3,424	2,745	4,944	4,008	3,612	3,335	3,638	3,766	3,644	2,531	2,950	3,066	47,039
Injured	176	147	132	101	356	100	201	172	235	111	105	86	137	35	39	9	10	2,152
Blackberry																		
Evaluated	1,252	1,952	1,477	1,851	2,750	3,343	3,358	5,122	4,395	4,676	4,428	3,956	4,296	3,432	4,303	4,506	4,844	59,941
Injured	396	246	247	172	799	230	447	458	449	256	226	155	210	151	111	8	85	4,646
Dogbane																		
Evaluated	154	407	259	661	1,070	3,049	2,177	4,935	3,495	3,318	3,336	4,122	3,841	4,110	3,835	4,346	4,469	47,584
Injured	15	12	50	17	38	95	29	67	79	28	65	39	51	56	38	17	49	745
Milkweed																		
Evaluated	933	1,644	1,650	1,591	3,378	5,695	4,003	5,722	4,111	4,502	4,453	4,591	4,438	4,637	4,566	4,580	4,954	65,448
Injured	227	108	184	75	515	114	288	177	220	169	369	103	163	124	103	35	89	3,063
Pin cherry																		
Evaluated	0	413	167	162	205	250	218	536	624	1,206	630	537	658	491	118	276	432	6,923
Injured	0	5	18	0	9	8	10	1	4	29	0	0	0	12	0	0	0	96
Sassafras																		
Evaluated	0	157	156	493	492	805	1,243	1,948	1,275	1,478	1,242	1,407	1,292	1,229	1,102	1,130	1,201	16,650
Injured	0	0	10	0	11	6	54	12	3	2	22	5	39	5	1	0	2	172
Sweetgum																		
Evaluated	43	30	30	141	279	361	255	220	447	437	469	441	499	489	493	315	430	5,379
Injured	19	0	0	1	69	49	6	5	9	28	1	52	25	52	11	4	3	334
White ash																		
Evaluated	448	590	639	882	1,254	1,868	2,207	4,350	3,665	3,312	3,450	3,326	3,186	3,467	2,917	3,218	3,269	42,048
Injured	83	56	75	67	121	24	101	103	46	23	71	45	62	83	27	53	75	1,115
Yellow-poplar																		
Evaluated	11	137	145	481	553	444	952	464	841	867	973	929	940	969	654	911	1,113	11,384
Injured	7	4	15	12	54	1	10	0	22	23	23	14	10	8	3	18	13	237
Totals																		
Evaluated	3,580	6,101	5,488	7,168	12,036	19,497	17,171	28,376	22,893	23,528	22,376	23,360	23,217	22,633	20,910	22,532	23,988	3,580
Injured	923	578	731	445	1,976	627	1,146	995	1,067	679	891	502	698	526	336	144	326	923
Percent	25.8	9.5	13.3	6.2	16.4	3.2	6.7	3.5	4.7	2.9	3.9	2.2	3	2.3	1.6	0.6	1.4	25.8

Table 7.—The number of evaluated and injured plants by species and year for the NC States, 1994-2010

	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	Totals
Aspen																		
Evaluated	0	0	0	0	0	0	0	0	44	11	0	0	0	0	65	72	60	252
Injured	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Big-leaf aster																		
Evaluated	60	960	426	589	1,388	1,380	1,126	759	768	917	1,103	772	809	681	751	722	771	13,982
Injured	0	5	0	1	20	14	4	4	0	4	1	0	0	0	0	0	0	53
Black cherry																		
Evaluated	266	780	735	863	1,714	2,218	4,016	3,359	2,983	3,225	3,257	2,593	2,606	2,372	2,037	1,948	1,972	36,944
Injured	11	14	34	15	34	47	251	182	65	24	41	8	33	4	8	0	3	774
Blackberry																		
Evaluated	412	1,519	645	1,669	1,848	2,626	3,225	2,281	2,315	2,103	2,206	1,647	2,439	2,243	2,256	2,013	2,767	34,214
Injured	0	38	80	211	245	210	128	45	23	57	12	27	36	8	53	37	84	1,294
Dogbane																		
Evaluated	170	656	772	983	1,758	2,675	3,258	2,329	3,913	3,934	4,335	4,251	3,855	4,124	4,162	4,443	4,176	49,794
Injured	3	16	22	6	80	67	82	51	15	24	23	26	46	33	22	19	43	578
Milkweed																		
Evaluated	394	1,282	1,355	1,624	2,999	3,620	6,023	4,646	5,368	5,358	5,409	5,174	5,083	5,100	5,357	5,274	5,412	69,478
Injured	44	60	44	34	269	285	534	254	126	97	166	88	105	80	126	103	206	2,621
Mugwort																		
Evaluated	0	0	0	0	0	0	0	0	0	0	0	0	300	282	30	30	0	642
Injured	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Pin cherry																		
Evaluated	0	18	30	52	30	130	301	260	382	366	395	431	312	247	249	243	312	3,758
Injured	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ponder. pine																		
Evaluated	0	0	0	0	0	0	0	0	182	247	135	270	240	185	200	169	217	1,845
Injured	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 7.—continued

		1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	Totals
Sassafras																			
	Evaluated	0	0	84	324	272	495	1,336	1,092	863	856	1,145	1,133	1,075	1,038	1,142	979	989	12,823
	Injured	0	0	0	0	3	0	9	12	0	0	6	6	3	3	2	9	0	53
Skunkbush																			
	Evaluated	0	0	0	0	0	0	0	0	299	334	280	319	300	368	375	423	373	3,071
	Injured	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1
Snowberry																			
	Evaluated	0	0	0	0	0	0	0	0	1,499	824	673	1,311	1,219	1,132	922	946	914	9,440
	Injured	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sweetgum																			
	Evaluated	0	0	30	87	110	116	143	211	254	302	252	256	248	221	230	263	260	2,983
	Injured	0	0	0	21	54	0	6	1	3	2	0	2	2	15	3	10	1	120
White ash																			
	Evaluated	21	30	202	528	1,036	1,350	2,616	2,150	2,693	2,293	4,260	4,166	4,181	4,024	3,998	3,938	3,864	41,350
	Injured	0	0	3	34	29	40	67	8	13	7	17	18	21	12	29	59	15	372
Wormwood																			
	Evaluated	0	0	0	0	0	0	0	0	548	531	554	662	382	390	370	457	384	4,278
	Injured	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Yellow-poplar																			
	Evaluated	0	0	130	412	363	437	565	358	290	339	298	273	252	311	292	307	289	4,916
	Injured	0	0	77	43	60	4	56	35	2	22	5	3	12	9	27	43	29	427
Totals																			
	Evaluated	1,323	5,245	4,409	7,131	11,518	15,047	22,609	17,445	22,401	21,640	24,302	23,258	23,301	22,718	22,436	22,227	22,760	289,770
	Injured	58	133	260	365	794	667	1,137	592	247	237	271	178	258	164	270	281	381	6,293
	Percent	4.38	2.54	5.9	5.12	6.89	4.43	5.03	3.39	1.1	1.1	1.12	0.77	1.11	0.72	1.2	1.26	1.67	2.17

The average number of plants evaluated per plot was similar for all species in the NE and NC States indicating that crews were following recommended plant selection criteria and generally maximizing plant counts for every available bioindicator species. However, there were differences in the percent injured plants and in the species-level foliar injury index (sppBI) both among species and between NE and NC (Tables 8, 9).

In the NE States, both the percent injured plants and the species BI were highest in the earliest sample years from 1994 to 1998, showing a sharp dropoff in 1999 that persisted through 2010 with very few exceptions (blackberry in 2002; big-leaf aster in 2004). The percentage of injured plants was highest in 1994 for all species, ranging from 9.7 percent for spreading dogbane to 63.6 percent for yellow-poplar with all other species above 18 percent. The associated BI values for 1994, however, were relatively low except for sweetgum and blackberry, indicating that although the injured plant count was high the severity of injury was not. The percentage of injured plants was high again for most NE species in 1998, a year when BI values also peaked for seven of the nine sampled species. Black cherry appeared to be the most ozone-responsive species for NE showing more than 10 percent injured plants every year from 1994 to 1998.

In the NC States, although the percent injured plants and species BI were high for sweetgum in 1998 and yellow-poplar in 1996, the injury index values for most species and years were much lower than in NE, particularly for the five most frequently sampled species (i.e., black cherry, blackberry, dogbane, milkweed, and white ash). As in NE, the percent injured plants and BI were highest for all species in the earlier years, tending to stay relatively high through 2001 when injury values dropped off and stayed low through 2010. There was some overlap in relatively high species BI in 1998 for three of the same species that showed high BI in NE (i.e., blackberry, milkweed, sweetgum). Still, no single species showed a consistently strong response to ozone (>10% percent injured plants), although milkweed is perhaps the most reliable bioindicator species for NC given its abundance and relatively high percentage of injured plants in 1994 to 2001.

Is ozone injury present?

The summary information demonstrates that the majority of the bioindicator species evaluated by NC and NE field crews over 1994 to 2010 showed evidence of ozone-induced foliar injury every year in some part of the sampling region, thus answering yes to the question, “Are phytotoxic ozone concentrations present in the forests of the NC and NE subregions?” Additional site-level injury statistics, summarized by state and year, provide information on where that injury is occurring and where it is most severe or frequent (Tables 10 - 13).

In 1994, the first year of sampling in NE, ozone injury was detected on 100 percent of the sampled sites (Table 10) in Connecticut, and more than half of the sampled plants (66%) showed injury symptoms (Table 11). Other NE States with a high percentage of injured sites in 1994 included New Jersey (78%), Maryland (100%), Massachusetts (79%), New Hampshire (83%), Rhode Island (100%), and Vermont (86%). Both Maryland (51%) and New Jersey (49%) also had high percentages of injury to sampled plants, but the percentages of injured plants in Massachusetts (19%), New Hampshire (21%), Vermont (23%), and Rhode Island (20%) were all similarly lower. In Maine, the only other state collecting injury data in 1994, O_3 injury was detected on only 24 percent of the sampled sites and the percent injured plants was a meager 6 percent. The majority of sites in Connecticut continued to show injury every year from 1995 through 1998 and again from 2000 through 2007. However, the percentage of injured plants dropped below 30 percent and eventually below 20 percent until the final year (2010) when for the first time no ozone injury was detected on any site or plant in Connecticut. The percentages of injured sites and plants were also relatively low in the years leading up to 2010 and in 1999 when injury was detected on only one-third of the sites in Connecticut on only 1 percent of plants. A similar pattern of ups and downs in the numbers of sites and plants with injury was typical of other NE States except for Maine where injury was detected in only 9 of the 17 years and never on more than 8 percent of the evaluated plants.

Table 8.—The percent of plants with injury and the biosite index (BI) by species and year for the NE States, 1994-2010

	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Big-leaf aster																	
% Injured Plants	0	0	0	0	6.7	0	0	0	0	8.3	15	0.7	0.3	0	0.8	0	0
Species BI	-	-	-	-	17.6	-	-	-	-	1.2	1.6	0.2	0	0	3.7	-	-
Black cherry																	
% Injured Plants	23.8	19.1	13.7	11.2	17.8	2.9	7.3	3.5	5.9	3.1	3.2	2.4	3.6	1	1.5	0.3	0.3
Species BI	4.3	11.1	7.4	5.5	19.8	1.4	4.4	2.2	4.9	1.6	1.3	0.9	1.5	0.4	0.7	0.1	0.1
Blackberry																	
% Injured Plants	31.6	12.6	16.7	9.3	29.1	6.9	13.3	8.9	10.2	5.5	5.1	3.9	4.9	4.4	2.6	0.2	1.8
Species BI	41.7	8.4	31.7	12.8	56.3	9.8	23.1	11.6	17.5	3.6	8.1	5.3	5.2	3.8	1.2	0.3	4.4
Dogbane																	
% Injured Plants	9.7	2.9	19.3	2.6	3.6	3.1	1.3	1.4	2.3	0.8	1.9	0.9	1.3	1.4	1	0.4	1.1
Species BI	12.4	0.1	3.1	4.1	2.5	2.2	0.8	1.4	1.7	0.7	0.9	0.7	0.7	0.6	0.3	0.3	1.2
Milkweed																	
% Injured Plants	24.3	6.6	11.2	4.7	15.3	2	7.2	3.1	5.4	3.8	8.3	2.2	3.7	2.7	2.3	0.8	1.8
Species BI	7.1	1.8	3.1	2.9	14.9	1.1	6.3	3.4	3.3	1.6	4.2	0.9	1.8	1	1.1	0.8	1.6
Pin cherry																	
% Injured Plants	0	1.2	10.8	0	4.4	3.2	4.5	0.2	0.6	2.4	0	0	0	2.4	0	0	0
Species BI	-			-							-	-	-		-	-	-
Sassafras																	
% Injured Plants	0	0	6.4	0	2.2	0.8	4.3	0.6	0.2	0.1	1.8	0.4	3	0.4	0.1	0	0.2
Species BI	-	-	3.6	-	2.5	1.2	0.7	0.4	-	0.1	0.7	0.2	1.2	0.3	0.2	-	0.1
Sweetgum																	
% Injured Plants	44.2	0	0	0.7	24.7	13.6	2.4	2.3	2	6.4	0.2	11.8	5	10.6	2.2	1.3	0.7
Species BI	45.1	-	-	0.1	38.2	14.9	0.1	1.4	0.7	1.9	0.4	4.9	1.9	6.8	3.3	0.6	4
White ash																	
% Injured Plants	18.5	9.5	11.7	7.6	9.7	1.3	4.6	2.4	1.3	0.7	2.1	1.4	1.9	2.4	0.9	1.7	2.3
Species BI	6.3	9.8	24.1	11.9	16.6	0.9	7.8	4.1	2.4	0.7	3.5	1.4	2	2.5	2.2	2.9	3.4
Yellow-poplar																	
% Injured Plants	63.6	2.9	10.3	2.5	9.8	0.2	1.1	<0.1	2.6	2.7	2.4	1.5	1.1	0.8	0.5	2	1.2
Species BI	3.8	0.1	0.9	0.7	6.3	0.1	0.3	0.2	0.7	0.5	1	0.2	0.6	0.1	0.6	1.3	1.3

Table 9.—The percent of plants with injury and the biosite index (BI) by species and year for the NC States, 1994-2010

	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Big-leaf aster																	
% Injured Plants	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Species BI	-	0.7	-	0.2	0.8	0.9	0.2	0.4	-	0.3	-	-	-	-	-	-	-
Black cherry																	
% Injured Plants	4.1	1.8	4.6	1.7	2	2.1	6.3	5.4	2.2	0.7	1.3	0.3	1.3	0.2	0.4	0	0.2
Species BI	2.4	0.5	1.3	0.6	0.5	0.4	1.6	1.6	1.4	0.2	0.8	0.1	0.6	0.1	<0.1	-	0.3
Blackberry																	
% Injured Plants	0	2.5	12.4	12.6	13.3	8	4	2	1	2.7	0.5	1.6	1.5	0.4	2.3	1.8	3
Species BI	-	1.8	33.9	21.3	33.1	10.3	6.9	4.4	1.7	2	1.7	1.9	2.3	0.8	2.9	2.3	4.2
Dogbane																	
% Injured Plants	1.8	2.4	2.8	0.6	4.6	2.5	2.5	2.2	0.4	0.6	0.5	0.6	1.2	0.8	0.5	0.4	1
Species BI	0.2	1.8	3.9	0.2	2.5	0.9	2.4	3.7	0.5	0.9	0.2	0.6	2.4	0.5	0.7	0.6	0.8
Milkweed																	
% Injured Plants	11.2	4.7	3.2	2.1	9	7.9	8.9	5.5	2.3	1.8	3.1	1.7	2.1	1.6	2.4	2	3.8
Species BI	1.4	1.3	1.4	0.2	5.9	3.7	4.9	3.5	2.3	0.8	2.4	2	1.2	0.7	0.7	0.4	1.8
Pin cherry																	
% Injured Plants	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Species BI	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Sassafras																	
% Injured Plants	0	0	0	0	1.1	0	0.7	1.1	0	0	0.5	0.5	0.3	0.3	0.2	0.9	0
Species BI	-	-	-	-	0.1	0	0.3	0.7	-	-	0.2	0.1	0.1	0.4	0.1	0.2	-
Sweetgum																	
% Injured Plants	0	0	0	24.1	49.1	0	4.2	0.5	1.2	0.7	0	0.8	0.8	6.8	1.3	3.8	0.4
Species BI	-	-	-	34.5	41.2	-	0.2	3.2	0.9	1.9	-	0	0.1	8.9	0.4	2.3	0.1
White ash																	
% Injured Plants	0	0	1.5	6.4	2.8	3	2.6	0.4	0.5	0.3	0.4	0.4	0.5	0.3	0.7	1.5	0.4
Species BI	-	-	0.6	2.9	2.5	2	2.5	0.2	0.4	0.1	1.2	0.8	0.3	0.3	1.2	1.2	1
Yellow-poplar																	
% Injured Plants	0	0	59.23	10.44	16.53	0.92	9.91	9.78	0.69	6.49	1.68	1.1	4.76	2.89	9.25	14.01	10.03
Species BI	-	-	137.3	6.2	28.3	0.8	10.8	7.3	0.7	2	0.5	1	0.5	0.8	6.3	19	6.6

Table 10.—Number of evaluated biosites with ozone-induced foliar injury by NE State and year

	Year																
State	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Connecticut																	
Evaluated	4	7	7	7	5	6	7	6	7	7	5	8	5	7	7	8	5
Injured	4	6	6	4	5	2	6	6	7	7	3	7	5	5	3	2	0
Delaware																	
Evaluated	-	1	-	3	3	11	9	10	11	11	11	8	11	11	12	8	10
Injured	-	0	-	2	3	10	6	8	4	11	8	6	8	7	8	2	4
Maine																	
Evaluated	29	34	27	25	28	24	19	22	17	18	18	18	18	18	18	18	18
Injured	7	3	4	0	7	0	0	0	0	0	0	4	3	0	1	1	3
Maryland																	
Evaluated	9	9	5	5	12	10	7	27	8	9	9	9	9	8	9	8	8
Injured	9	9	5	4	12	3	2	16	3	2	3	9	5	4	1	2	2
Massachusetts																	
Evaluated	14	15	13	16	18	18	14	8	9	9	9	9	10	9	9	10	8
Injured	11	6	3	11	14	10	9	1	2	4	2	4	10	2	3	1	1
New Hampshire																	
Evaluated	6	23	24	21	25	23	20	19	5	5	5	8	6	5	5	5	5
Injured	5	10	7	1	10	4	1	3	0	0	1	3	2	1	1	1	3
New Jersey																	
Evaluated	9	6	6	7	11	9	9	2	10	7	8	9	8	8	8	8	8
Injured	7	5	4	0	11	1	1	0	4	1	5	5	7	6	3	4	4
New York																	
Evaluated	-	-	-	-	-	85	9	56	37	37	36	35	35	38	41	36	35
Injured	-	-	-	-	-	12	3	14	16	11	15	5	13	12	12	3	13
Ohio																	
Evaluated	-	-	-	19	19	18	19	34	34	34	34	34	34	35	34	36	40
Injured	-	-	-	10	12	4	5	8	8	9	12	10	7	4	4	5	9
Pennsylvania																	
Evaluated	-	12	-	-	100	129	100	104	50	50	48	59	67	56	43	58	62
Injured	-	5	-	-	51	24	63	39	33	17	19	17	31	24	7	9	17
Rhode Island																	
Evaluated	1	5	5	5	5	4	5	4	5	5	4	5	5	5	5	5	6
Injured	1	5	5	5	5	3	4	4	4	3	4	1	5	3	3	3	4
Vermont																	
Evaluated	14	18	16	17	17	21	22	18	17	18	20	18	14	13	11	12	13
Injured	12	5	13	9	9	7	6	4	5	5	4	4	5	1	4	4	2
West Virginia																	
Evaluated	-	18	23	26	26	14	29	30	27	27	28	28	28	28	32	31	28
Injured	-	2	11	2	19	2	3	3	13	12	6	6	6	15	9	7	9

Table 11.—Number of plants evaluated and injured[a] on biosites by NE State and year

	Year																
State	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Connecticut																	
Evaluated	212	304	382	411	331	405	491	514	654	701	470	867	519	643	713	659	570
Injured	140	78	110	30	72	5	49	79	66	46	68	76	106	26	19	11	0
Delaware																	
Evaluated	-	30	-	244	211	864	283	825	1065	1298	1176	845	1215	1235	1283	875	1373
Injured	-	0	-	16	68	159	34	80	29	212	143	80	99	73	91	4	21
Maine																	
Evaluated	962	1371	962	1098	1517	1063	799	940	1597	1539	1620	1632	1676	1810	1780	1729	1781
Injured	54	32	75	0	15	0	0	0	0	0	0	12	23	0	2	2	9
Maryland																	
Evaluated	392	316	248	240	414	338	261	1820	1109	762	833	671	844	922	830	932	909
Injured	202	79	76	57	86	29	27	143	49	31	35	94	18	16	1	14	9
Massachusetts																	
Evaluated	469	492	528	424	1,129	942	720	451	728	822	630	927	841	770	823	859	821
Injured	88	56	22	53	146	63	41	25	15	16	6	15	71	3	26	10	3
New Hampshire																	
Evaluated	325	1,001	1,032	887	1,205	1,014	947	1,214	405	258	321	790	524	478	498	590	536
Injured	68	67	27	2	88	8	7	14	0	0	5	7	4	1	1	3	50
New Jersey																	
Evaluated	347	238	216	210	991	810	817	178	802	700	619	579	676	678	674	682	855
Injured	171	91	40	0	264	1	9	0	36	5	92	42	67	54	13	13	21
New York																	
Evaluated	-	-	-	-	-	3,582	474	5,679	3,415	3,087	3,271	3,055	3,476	3,405	3,923	3,789	3,857
Injured	-	-	-	-	-	99	12	66	169	73	167	16	53	115	88	14	81
Ohio																	
Evaluated	-	-	-	1,417	926	810	1,713	3,114	3,175	3,366	3,357	3,060	3,124	3,208	3,270	3,092	3,731
Injured	-	-	-	69	72	22	41	92	42	29	73	29	29	22	13	20	18
Pennsylvania																	
Evaluated	-	478	-	-	2,299	7,177	7,402	11,147	5,548	5,598	5,303	6,245	5,807	5,430	3,607	5,801	6,483
Injured	-	51	-	-	652	140	778	405	439	97	195	64	118	116	13	31	72
Rhode Island																	
Evaluated	25	313	292	336	332	251	349	286	461	426	384	507	481	500	512	693	693
Injured	5	90	72	65	97	44	41	39	42	19	23	12	68	15	17	16	14
Vermont																	
Evaluated	858	1,169	1,049	1,092	946	1,382	1,544	1,335	1,409	1,639	1,752	1,435	1,235	1,186	1,120	1,105	1,188
Injured	195	22	200	139	98	40	74	29	23	25	18	8	13	15	16	5	7
West Virginia																	
Evaluated	-	359	759	797	1,614	829	1,571	1,831	2,525	2,465	2,640	2,747	2,799	2,558	2,829	2,738	2,357
Injured	-	12	109	14	318	17	33	56	157	103	66	47	29	70	41	12	30

[a]Injury validated by expert.

Table 12.—Number of evaluated biosites with ozone-induced foliar injury by NC State and year

State	Year																
	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Illinois																	
Evaluated	-	-	-	9	19	26	40	43	27	28	29	28	28	32	31	31	31
Injured	-	-	-	9	18	22	35	14	5	15	17	17	24	18	22	20	25
Indiana																	
Evaluated	-	-	8	10	17	19	26	31	22	31	28	26	23	25	25	25	26
Injured	-	-	7	6	16	13	23	23	7	12	11	10	10	13	13	17	18
Iowa																	
Evaluated	-	-	-	-	-	-	8	7	7	7	7	7	4	7	7	8	7
Injured	-	-	-	-	-	-	0	0	0	4	0	1	4	5	3	1	1
Kansas																	
Evaluated	-	-	-	-	-	-	-	-	9	12	12	13	13	12	13	13	12
Injured	-	-	-	-	-	-	-	-	0	1	1	0	0	2	1	4	0
Michigan																	
Evaluated	12	40	27	30	59	43	54	49	45	45	45	45	45	48	50	50	51
Injured	2	8	3	0	7	15	30	30	18	7	13	13	13	8	6	9	14
Minnesota																	
Evaluated	4	32	40	40	59	46	41	26	29	29	29	29	29	29	29	28	29
Injured	0	0	0	1	1	0	1	1	0	0	0	0	0	0	0	1	0
Missouri																	
Evaluated	-	-	-	-	-	-	57	38	39	38	38	38	38	38	38	41	40
Injured	-	-	-	-	-	-	19	12	9	4	7	0	1	1	2	0	0
Nebraska																	
Evaluated	-	-	-	-	-	-	-	-	8	7	8	8	8	8	8	8	8
Injured	-	-	-	-	-	-	-	-	0	0	0	0	0	0	0	0	1
North Dakota																	
Evaluated	-	-	-	-	-	-	-	-	8	8	8	8	8	8	8	8	8
Injured	-	-	-	-	-	-	-	-	0	0	0	0	0	0	0	0	0
South Dakota																	
Evaluated	-	-	-	-	-	-	-	-	12	12	12	13	13	13	12	12	12
Injured	-	-	-	-	-	-	-	-	0	0	0	0	0	1	0	0	0
Wisconsin																	
Evaluated	16	65	28	34	42	54	64	39	55	57	55	33	31	29	29	29	29
Injured	8	9	14	9	25	41	49	20	25	13	22	12	6	4	3	0	5

Table 13.—Number of plants evaluated and injured[a] on biosites by NC State and year

	Year																
State	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Illinois																	
Evaluated	-	-	-	451	758	1934	3149	2919	2703	1951	2236	2436	2354	2289	2321	2673	2474
Injured	-	-	-	171	220	154	246	64	22	66	74	44	88	56	122	73	130
Indiana																	
Evaluated	-	-	589	729	822	1441	2245	2440	1384	1809	1857	2002	1896	2161	2581	2458	2501
Injured	-	-	193	84	223	176	352	177	27	85	47	68	53	58	109	156	134
Iowa																	
Evaluated	-	-	-	-	-	-	312	326	598	643	666	768	420	776	664	655	633
Injured	-	-	-	-	-	-	0	0	0	6	0	3	10	11	8	2	3
Kansas																	
Evaluated	-	-	-	-	-	-	-	-	822	1060	965	1084	1119	994	893	866	6561
Injured	-	-	-	-	-	-	-	-	0	1	1	0	0	7	2	32	0
Michigan																	
Evaluated	512	1447	1236	1189	2353	3359	4238	4271	4649	4467	4648	4643	4902	4531	4412	4302	4673
Injured	11	54	31	0	22	120	195	163	62	30	50	35	65	24	40	49	107
Minnesota																	
Evaluated	129	588	647	1059	2594	1963	1617	1157	1633	2565	2729	2863	3084	3028	2538	2649	2971
Injured	0	0	0	1	5	0	2	1	0	0	0	0	0	0	0	1	0
Missouri																	
Evaluated	-	-	-	-	-	-	2,912	2,581	4,057	3,062	2,990	3,365	3,764	3,662	4,028	4,191	4,163
Injured	-	-	-	-	-	-	83	83	29	7	24	0	4	2	9	0	0
Nebraska																	
Evaluated	-	-	-	-	-	-	-	-	835	720	816	855	781	816	931	801	863
Injured	-	-	-	-	-	-	-	-	0	0	0	0	0	0	0	0	3
North Dakota																	
Evaluated	-	-	-	-	-	-	-	-	866	695	752	775	720	720	881	875	925
Injured	-	-	-	-	-	-	-	-	0	0	0	0	0	0	0	0	0
South Dakota																	
Evaluated	-	-	-	-	-	-	-	-	753	1,264	1,170	1,406	1,432	1,340	1,278	1,273	1,142
Injured	-	-	-	-	-	-	-	-	0	0	0	0	0	1	0	0	0
Wisconsin																	
Evaluated	652	3,210	1,997	2,336	4,065	5,540	6,616	3,751	4,953	5,392	5,473	2,933	2,809	2,460	2,694	2,800	2,904
Injured	47	79	36	40	252	195	218	104	107	45	75	24	38	5	6	0	6

[a]Injury validated by expert.

In the NC States, biomonitoring began in 1994 in only Minnesota (no injury detected), Wisconsin (injury detected on 8 of 16 sites), and Michigan (injury detected on 2 of 12 sites). In the first year of biomonitoring in Indiana (1996) and Illinois (1997), injury was detected on 88 percent and 100 percent of the sites, respectively (Table 12). As other NC States entered the program, the highest percentages of injured sites and plants continued to occur in Indiana and Illinois with occasional high percentages of injured sites in Michigan and Wisconsin, particularly from 1998 to 2002. The percentage of injured plants tended to be lower than those recorded in the NE States, ranging from 12 to 38 percent in Indiana and Illinois in the earliest years, but then falling to generally less than 10 percent in all NC States and to less than 2 percent in all states except Indiana and Illinois after 2002 (Table 13).

Both the number (Fig. 7) and percent (Fig. 8) of visits with injury when viewed on a regional scale tended to reflect the regional air quality data (Fig. 4) with some important exceptions. For example, high percentages of visits with injury occurred in northern Vermont and northern Wisconsin even though relatively low SUM06 concentrations are typical of these areas. On the other hand, Kansas is characterized by moderate SUM06 exposures, but the number and percent of visits with injury were minimal except perhaps in 2009 when injury was detected on 4 of 13 evaluated sites. For the most part, however, the areas where average growing season SUM06 values were relatively high were also the areas where crews detected ozone injury more than half the time over the sampling period. The areas of greatest injury incidence include Illinois, Indiana, and southern Michigan of the NC States, and virtually all of the NE States except for northern New Hampshire and Maine.

Along with injury incidence and distribution, injury severity, as indicated by the site-level BI values, must be considered when assessing O_3 impact. The percentage of sites in each BI foliar injury class is presented in the appendix by state and year (Appendix 1: Table 1A-NE, Table 1B-NC). The categorized BI classes are none, low, moderate, and high injury indicating increasing probability of ozone impact (Table 3). In the none and low BI classes, there is little risk of O_3 impact other than visible foliar injury, but as the BI increases, the risk of impact shifts from visible injury to sensitive species to less visible effects on growth and vigor and, at the highest level, the increased probability of adverse impacts on population structure and function.

In 1994, as previously noted, injury was detected on all evaluated sites in Connecticut. More importantly with respect to O_3 impact, all of those sites fell into the moderate ozone impact category. More severe injury was recorded in New Jersey where the majority of sites fell into the moderate (33%) and high (22%) BI classes. In other NE States, even though injury was detected on many sites in 1994, most of the injury was slight, indicating little or no risk of ozone impact other than visible foliar symptoms to the most sensitive plants. From 1994 to 1998, Maryland and New Jersey stand out as states where more than half of the evaluated sites sustained moderate to high foliar injury every year, as did Connecticut for 3 of those 4 years, and West Virginia and Rhode Island for 1 year. After 1998 and continuing through 2010, the majority of evaluated sites in all NE States fell into the none and low BI categories every year except for sites in Delaware and Rhode Island in 1999.

In the NC States, sites with a high percentage of plants in the moderate high BI classes were typical of Indiana in 1996 and 1998 and of Illinois in 1997 and 1998 with a small percentage of sites in the high BI class also occurring in Wisconsin, Michigan, and Missouri on occasion. Similar to the NE States, the majority of evaluated sites in all NC States fell into the lowest BI class from 1999 through 2010 except in 2001 in Indiana when the majority of sites were split between the lowest BI class and the three higher BI categories.

The regional summary table for percentage of biosites in each BI foliar injury class (Table 14) indicates that moderate to high foliar injury symptoms were more often recorded in the earliest sampling years (1994 to 1998) in both NE and NC. The years with the highest percentage of biosites in the higher BI categories were 1994, 1996, and 1998 in NE and 1996, 1997, and 1998 in NC. The regional average biosite index was highest

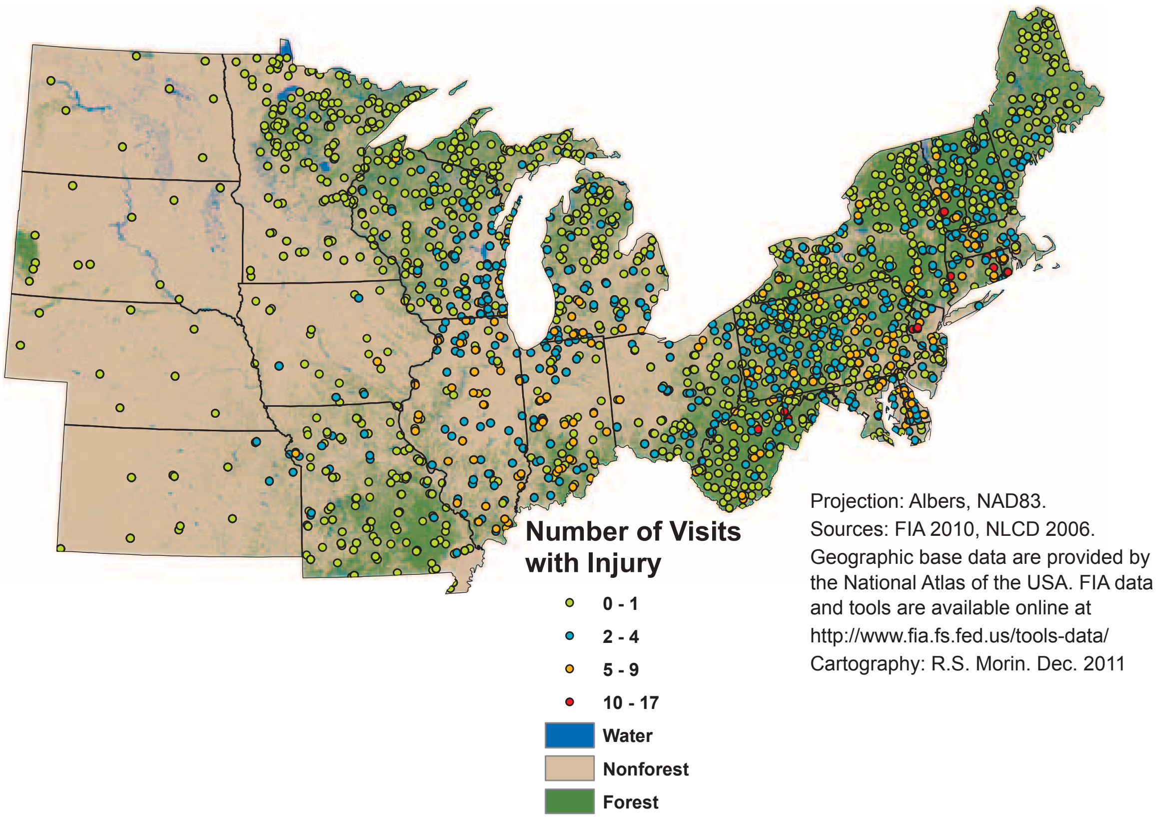

Figure 7.—Number of visits to ozone biomonitoring sites with injury, 1994-2010.

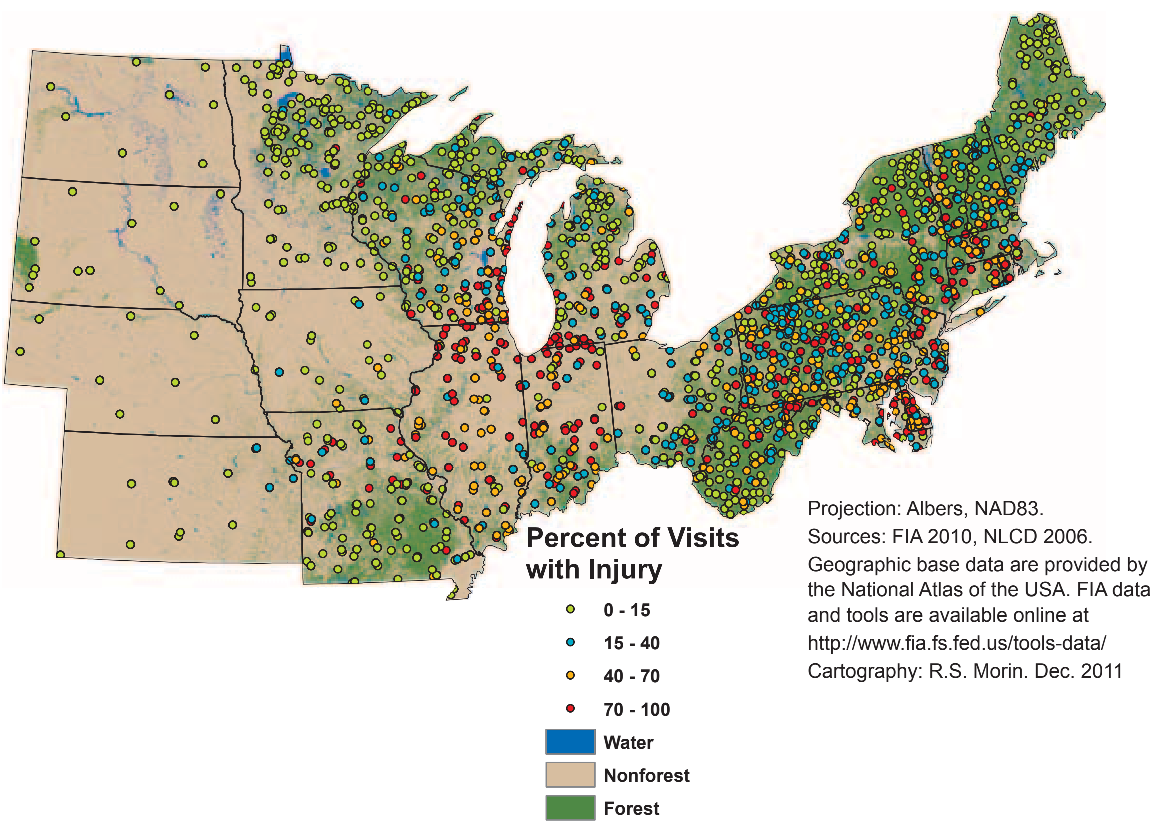

Figure 8.—Percent of visits to ozone biomonitoring sites with injury, 1994-2010.

Table 14.—Percentage of biosites in each foliar injury category (BI)[a] in the NE and NC States by year, 1994-2010

Biosite Index	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
0 to 4.9 (least injured)																	
Northeast	43.1	66.2	49.5	75.2	44.6	84.1	85	77.7	78.6	89	82.6	85.5	76.8	90.8	91.2	88.9	86
North Central	95.2	95.4	75.4	75.6	59.7	81.3	86.7	88.2	96.4	97.4	96.5	98.3	94.3	98	96.5	94.8	95.8
5.0 to 14.9																	
Northeast	10.1	13.5	18.4	7.2	9.7	3.9	8	12.4	12.6	9.5	9.6	6.2	15.2	6.7	8.6	9.8	7.7
North Central	2.8	3.2	0.9	6.8	7.2	13.5	8.4	7.4	3.1	1.7	2.7	0.9	4.8	1.9	2.5	4.6	2.9
15 to 24.9																	
Northeast	28.7	10.1	11.7	6.8	14.7	5.2	4	4.6	4.3	0.9	3.7	2.7	6.3	1.8	0.2	1.7	5.1
North Central	2.1	0	0	2.2	8.3	1.8	1.8	2	0.2	0	0.5	0.2	0.9	0	0.5	0.2	0.5
≥25 (most injured)																	
Northeast	18.1	10.2	20.4	10.8	30.9	6.7	3	5.3	4.5	1.3	4.1	5.4	1.7	0.7	0	1.5	2.7
North Central	0	1.3	23.7	15.3	24.8	3.3	3	2.4	0.2	0.9	0.2	0.5	0	0	0.4	0.4	0.7
Average BI	12.6	3.6	10.6	5.5	17.6	2.9	4.7	3.2	2.9	1.1	2.1	1.5	1.6	1.1	1	0.9	1.6

[a]BI index and risk categories: 0 to 4.9 = little or no foliar injury and no risk of ozone impact; 5 to 14.9 = low foliar injury and low risk; 15 to 24.9 = moderate foliar injury and moderate risk; ≥ 25 = severe foliar injury and high risk of ozone impact.

in 1998, reflecting peak foliar injury scores in both NE and NC. Even in years with high injury (e.g., 1998), more than half of all sites fell into the none and low BI categories, suggesting that areas of high O_3 risk are localized in relatively small pockets of poor air quality and predisposing conditions.

Regional BI data were also summarized by SUM06 ozone exposure class. For all sites, and for all injured sites (BI > 0), the average site-level foliar injury index (BI) increased as the SUM06 ozone exposure level increased from clean to high (Fig. 9). Similarly, the percent injured biosites increased with increasing O_3 exposure class, at least for the earliest (1994-1998) and most damaging sampling period (Fig. 10). In the middle (1999-2004) and more recent (2005-2010) sampling periods, the percent injured biosites increased initially from the clean to the low or moderate exposure classes, but then tended to level off or decline slightly. This response reflects changing conditions in regional air quality that are discussed in some detail in the following section on trends.

Has injury changed over time?

Sixteen-year trends (1994-2009) in foliar injury were examined separately for biosites grouped in clean, low, moderate, and high ozone exposure zones. Within each ozone exposure group, annual mean values for BI were calculated and plotted over the 16 years from 1994 to 2009 (Fig. 11). Regression procedures were used to determine if the slope of the line for BI within each exposure group was significantly different from zero and, if so, the slope direction (Table 15).

The SUM06 groupings described above for O_3 exposure imply certain injury thresholds for ozone air quality, both in terms of the visible foliar injury that crews rate in the field and the possibility of growth impacts. Biosites grouped in the clean ozone exposure group are expected to sustain little or no foliar injury (BI close to zero) and no risk of growth impacts. However, biosites in the low, moderate, and high O_3 exposure categories may have a wide range of BI values depending on a

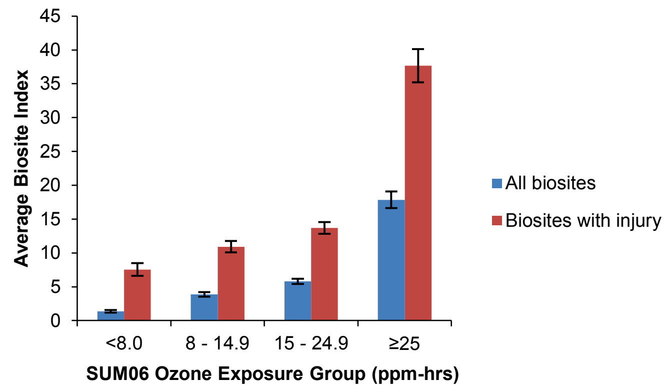

Figure 9.—Biosite index by SUM06 ozone exposure class, 1994-2009.

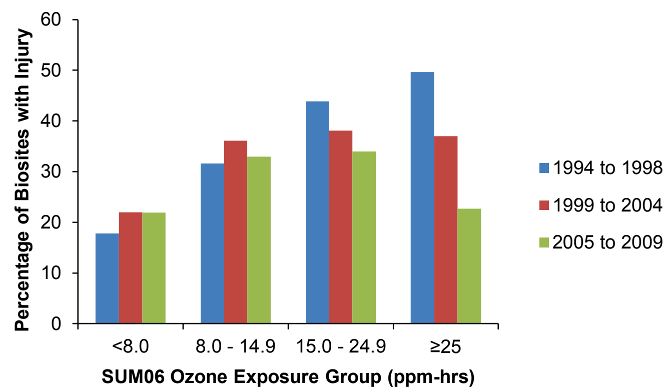

Figure 10.—Percentage of biosites with injury by SUM06 ozone exposure class for the early (1994-1998), middle (1990-2004), and more recent (2005-2009) sampling periods.

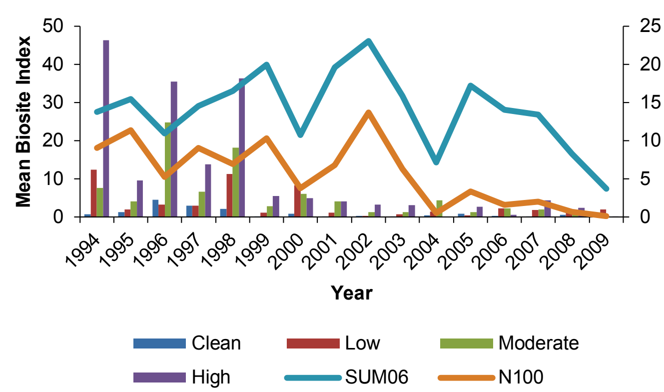

Figure 11.—Mean BI (biosite index) for clean, low, moderate, and high ozone exposure sites, and mean SUM06 and N100 values by year, 1994-2009.

Table 15.—Regression model statistics for 16-year trends in mean foliar injury (BI) for biosites grouped in clean, low, moderate, and high ozone exposure categories, 1994-2009

Ozone Exposure Group	BI (foliar injury)		
	p-values	R^2	Slope direction
Clean	0.085	0.2	negative
Low	0.076	0.21	negative
Moderate	0.031	0.31	negative
High	0.006	0.49	negative

variety of site conditions (e.g., soil moisture), exposure factors (e.g., air temperature), and plant response mechanisms (e.g., O_3 scavenging and repair processes) that control whether ozone in the air actually moves into the plant through open stomates and causes injury.

Seasonal mean foliar injury values for biosites in the clean ozone exposure group were all quite low (BI < 4.9) and, although there appeared to be a slight downward trend in BI over the 16-year sample period, this trend was not significant ($p = 0.085$; Table 15). In contrast, biosites in the moderate and high ozone exposure groups showed a significant downward trend ($\alpha = 0.05$) in seasonal mean BI over the 16-year period with the significance of the trend increasing from the moderate ($p = 0.031$) to high ($p < 0.006$) ozone exposure group (Table 15). Changes in the 3-year rolling average of the BI (data not shown) showed similar results, indicating that annual fluctuations in BI, especially over 1994 to 1998, were not unduly influencing the significance of the downward trend.

When seasonal mean values for SUM06 and N100 were plotted over the 16 years from 1994 to 2009 along with the categorized BI data, it was clear that both of the cumulative ozone exposure indices were declining over time as well, and this may largely explain the downward trends in foliar injury. However, it is also true that the year-to-year fluctuations in the seasonal BI values do not correspond well with the fluctuating SUM06 and N100 values. For example, the spike in seasonal BI in 1994 and 1996 in the high O_3 group does not correspond to a spike in ozone exposures although SUM06 and N100 values for both years are above accepted thresholds for ozone injury (Lefohn et al. 1997). Similarly, O_3 exposures were high in 1999 and highest in 2002, years when BI values were relatively low in all exposure groups. Additionally, regression procedures examined the relationship between seasonal mean BI and SUM06 within each ozone exposure group and found no significant results.

An overall downward trend in injury incidence (percent injured plants) and severity (species BI) was also noted by species over the 17-year survey period as previously described (Tables 8, 9). The average percent injured plots also declined somewhat over 1994 to 2010, more so in NE than in NC (Fig. 12). In 1994, injury was detected on more than 60 percent of the evaluated sites in NE and on about one-third of the sites in NC. Except in 1999, the percent injured sites remained above 30 percent in NE through 2007, dropping to 25.2 percent in 2008 and 18.1 percent in 2009 before increasing to 28.9 percent in 2010. In NC, percent injured biosites rose initially from 31.2 percent in 1994 to 54.1 percent in 2000 before dropping back down to less than 26 percent from 2002 through 2010. It would appear that despite an obvious drop in the severity of O_3 injury to ozone-sensitive bioindicator plants as reflected in the BI trend data (Fig. 11), O_3 injury was still detected in 2010 on more than 25 percent of the evaluated sites regionwide.

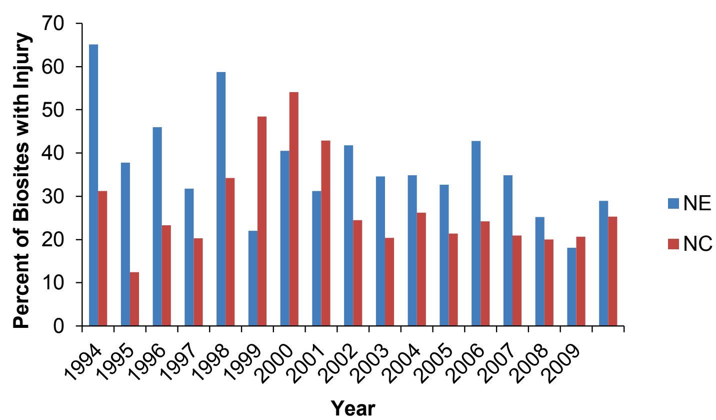

Figure 12.—Percent of biosites with injury by year for the NE and NC States, 1994-2010.

Does site moisture influence injury?

There were both wet and dry O_3 seasons over the course of the 1994 to 2010 sampling period (http://www.ncdc.noaa.gov/oa/climate/research/cag3/state.html). In NE, the trend for most states over the 17 years of biomonitoring was from dry to wet with the majority of years before 2003 having below average growing season precipitation and the majority of years from 2003 forward having above average growing season precipitation (Appendix 2: Table 1). NC States were less uniform with respect to growing season precipitation trends. Six states (Nebraska, Kansas, Missouri, Iowa, Illinois, and Indiana) showed a dry to wet trend very similar to NE, while the remaining four more northerly states showed either no trend or a slight wet to dry trend over 1994 to 2010. For most states with relatively high seasonal O_3 exposures (e.g., the Mid-Atlantic States and Indiana and Illinois), the years when average growing season precipitation was lowest (1995, 1999, 2002, and 2005) corresponded to the years with the highest seasonal O_3 exposures. This finding is expected given that prolonged periods of hot, dry weather tend to drive O_3 formation and lead to temperature inversions that trap O_3 at ground level.

The moisture indices (PDSI and MI) intersected with the biosite ground locations provide a more site-specific indicator of wet and dry ozone seasons (1994-2007). Both PDSI and MI fluctuated from one year to the next (Figs. 13, 14). Soil moisture was low in 1995, limiting (PDSI < -1.25) in 1999 in high O_3 areas, and it was near normal for most of the remaining years with particularly wet soil moisture conditions prevailing in 1996 and 2004. Plant moisture deficits (MI < -0.15) were indicated for 11 of the 14 years of this sample with the most extreme plant moisture deficits occurring in 1995, 1999, 2002, 2005, and 2007 especially in high O_3 areas. By either measure, 1999 was clearly the driest year of the 14-year period, with 1995 a close second. The dry years correspond to a dropoff in foliar injury from 1994 to 1995 and again from 1998 to 1999 even though seasonal mean ozone concentrations increased from one year to the next (Fig. 11). By the same token, injury increased from 1995 to 1996, a relatively wet year, despite a drop in seasonal mean O_3 concentrations.

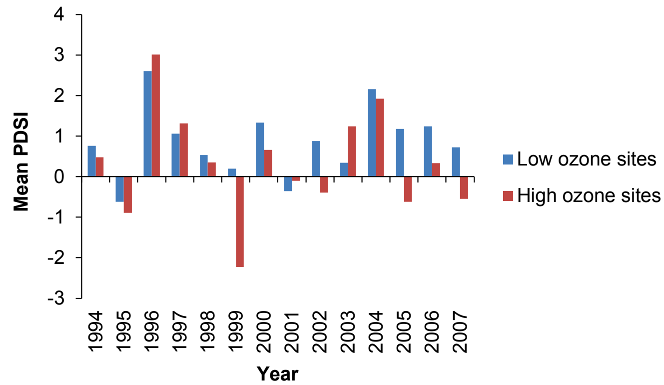

Figure 13.—Mean Palmer Drought Severity Index (PDSI) values for low and high ozone exposure groups by year, 1994-2007.

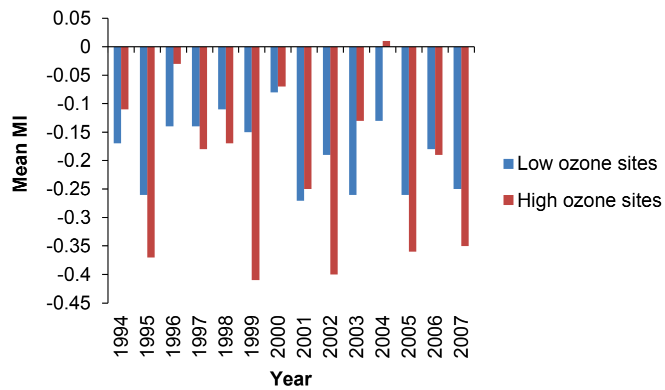

Figure 14.—Mean plant moisture index (MI) value for low and high ozone exposure sites by year, 1994-2007.

For this report, data summarized by ozone exposure (SUM06) and site moisture (PDSI and MI) classes demonstrate that regardless of ozone exposure level (clean, low, moderate, high), there is a reduced percent of injured biosites (Figs. 15, 16) and a much lower BI (Figs. 17, 18) in areas with moisture deficits (PDSI < -1.25; MI < -0.15) than in areas with adequate or surplus soil and plant moisture conditions. Regionwide, the highest BI and percent injured plots occur under high ozone-wet conditions, followed by high ozone-dry, low ozone-wet, and finally low ozone-dry (Table 16).

These findings suggest that although high ambient O_3 concentrations are the driving force behind the proportion of biosites that sustain injury and the severity of that injury in any given year, the site moisture conditions are also a very strong influence on the biomonitoring data. In Maryland, for example, moderate to high injury was detected at every site from 1994

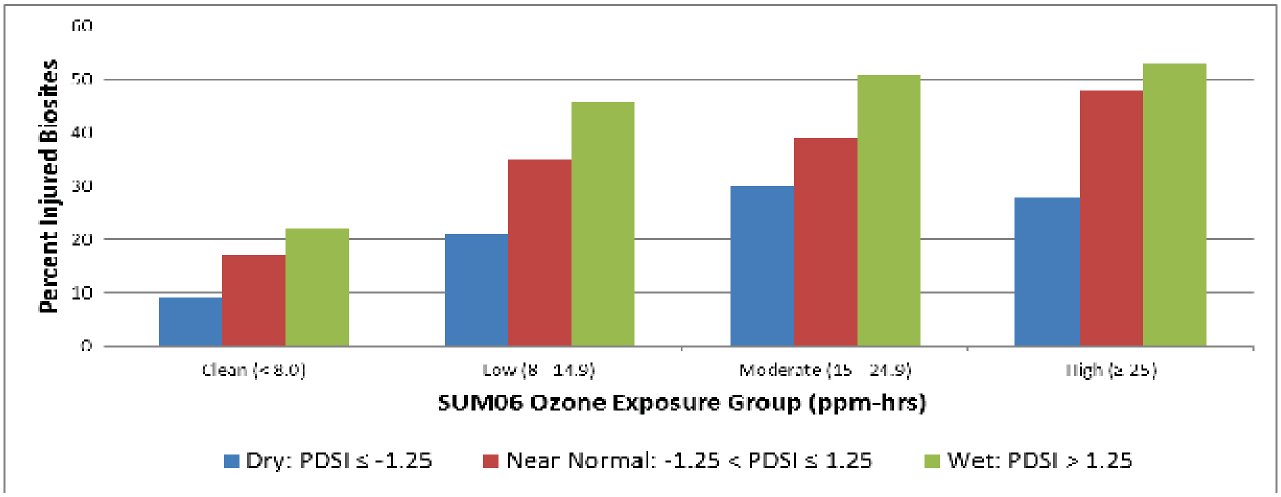

Figure 15.—Percent of biosites with injury by ozone exposure group for dry, near normal, and wet soil moisture condition (PDSI) sites, 1994-2007.

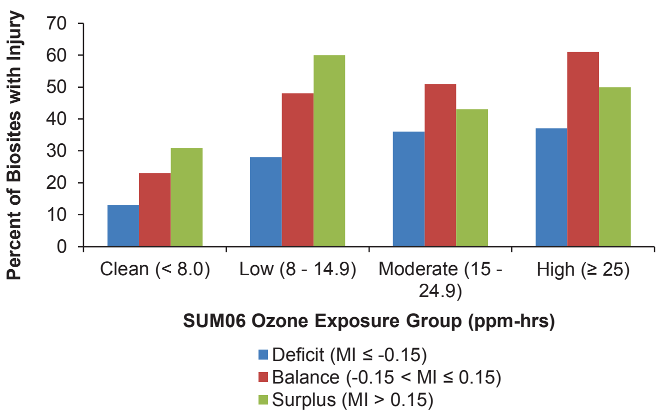

Figure 16.—Percent of biosites with injury by ozone exposure class for plant moisture deficit, balance, and surplus condition (MI) sites, 1994-2007.

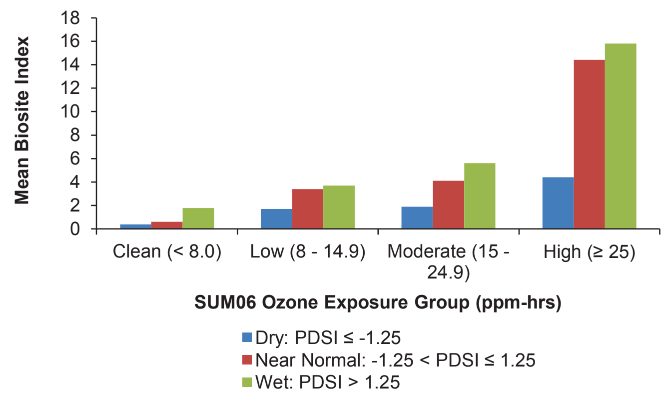

Figure 17.—Mean biosite index (BI) by ozone exposure class for dry, near normal, and wet soil moisture (PDSI) sites, 1994-2007.

through 1998 under conditions of high O_3 exposure (seasonal mean SUM06 >25 ppm-hr) and variable site moisture (wet and dry). In 1999, after two growing seasons of below average rainfall, mean site moisture values indicated severe drought (PDSI = -3.22) and severe plant moisture deficits (MI = -0.45), and although seasonal mean SUM06 concentrations remained high (SUM06 = 39 ppm-hr), no injury was detected on seven of nine evaluated sites. Similar results were obtained in other states in 1999 and again in 2002, another very dry year regionwide (PDSI = -3.90; MI = -0.53), but generally only in high O_3 areas such as Indiana and Illinois and the Mid-Atlantic States. In areas or years of low to moderate O_3 exposures, or areas and years lacking extreme moisture deficits, the interrelationships among

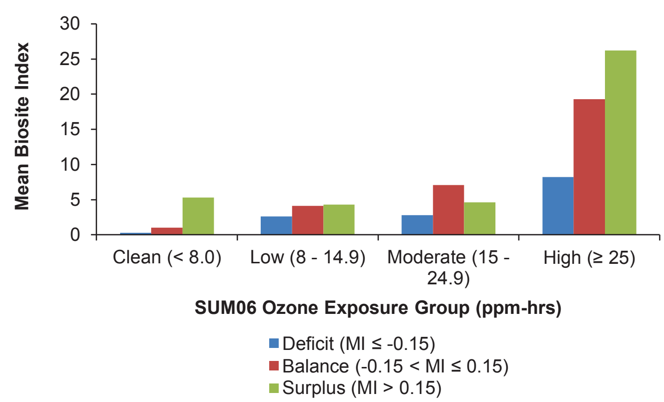

Figure 18.-—Mean biosite index (BI) by ozone exposure class for plant moisture deficit, balance, and surplus condition (MI) sites, 1994-2007.

Table 16.—Calculated means for foliar injury (BI) and percent injured biosites for sites grouped in wet and dry categories of soil (PDSI) and plant (MI) moisture in areas of low and high ozone

	PDSI Soil Moisture				MI Plant Moisture			
SUM06	Biosite Index		% Injured Biosites		Biosite Index		% Injured Biosites	
	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry
Low	1.4	0.4	20.2	9.2	2.2	0.3	25.3	12.6
High	6.2	2.7	44	27.2	7.7	4.1	51.6	34

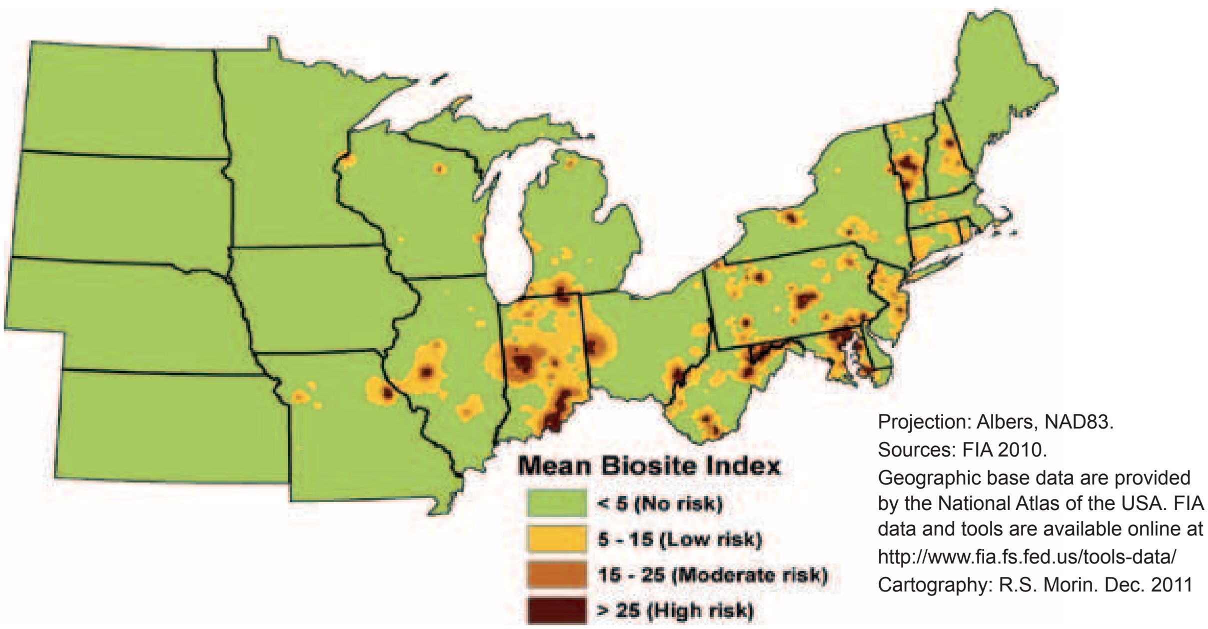

Figure 19.—Spatial interpolation of the mean biosite index for 1994 to 2010.

injury, exposure, and site moisture are less predictable (Smith 2011, Wang et al. 2012).

What is the risk of ozone injury?

Spatial interpolation of the BI data is performed to generate a regional map of O_3 risk to plants as defined by Smith et al. (2008). In this report, 17 years of BI data were used to create an interpolated bioindicator response surface (Fig. 19) that was then used to interpret the risk of ozone impact to the forest resource across the NRS-FIA region. Using procedures outlined by Bechtold and Patterson (2005), the BI map was merged with P2 tree plot data to generate state-level estimates of acres of forest land and volume of ozone-susceptible species in each BI category from least injured and no risk of impact to low, moderate, and high levels of injury and probable impact. The areas of greatest risk included Illinois, Indiana, West Virginia, Maryland, Pennsylvania, and New Jersey. There were also large and small pockets of high O_3 risk in Missouri, Wisconsin, Michigan, Ohio, New York, and all of New England except Maine.

In Connecticut, the majority of ozone-sensitive tree volume (1,543 million cubic feet) is at risk of O_3 impact (Table 17); about 1.2 million acres (63%) of forest land with 62 percent of the tree volume of ozone-susceptible trees are at risk (Table 18), although the risk level is low (BI = 5.0-14.9). In Maryland, 0.61 million acres (23%) with 22 percent of the volume of ozone-susceptible trees are at high risk of O_3 impact (BI ≥ 25), about half that amount is at moderate risk (BI 15-24.9), and 1.0 million acres (38%) with 39 percent of the tree volume is at low risk of ozone impact. Less than one-third (27%) of the susceptible tree volume is at no risk. New Jersey is the

Table 17.—Estimated volume in million cubic feet of live trees 5 inches in diameter and greater on forest land by biosite index risk category, ozone-sensitivity category, and NE State, 2010

	Biosite Index[a]			
State and ozone-sensitivity category[b]	0 to 4.9 (no risk)	5.0 to 14.9 (low risk)	15.0 to 24.9 (moderate risk)	≥25 (high risk)
Connecticut				
Unknown	265	561	0	0
Insensitive	590	838	0	0
Moderately sensitive	158	450	0	0
Sensitive	783	1,093	0	0
Delaware				
Unknown	100	16	0	0
Insensitive	79	6	0	0
Moderately sensitive	64	6	0	0
Sensitive	532	47	8	0
Maine				
Unknown	1,553	33	0	0
Insensitive	12,976	229	0	0
Moderately sensitive	1,179	19	0	0
Sensitive	9,213	249	0	0
Maryland				
Unknown	340	504	170	232
Insensitive	209	366	228	301
Moderately sensitive	181	255	57	158
Sensitive	1,122	1,592	482	911
Massachusetts				
Unknown	527	167	29	0
Insensitive	2,052	524	54	0
Moderately sensitive	577	171	2	0
Sensitive	3,752	952	74	0
New Hampshire				
Unknown	392	235	74	41
Insensitive	2,498	1,356	243	87
Moderately sensitive	387	190	19	13
Sensitive	3,056	1,629	173	52
New Jersey				
Unknown	242	611	45	5
Insensitive	252	372	59	14
Moderately sensitive	183	326	32	6
Sensitive	560	1,313	128	94
New York				
Unknown	4,252	672	49	19
Insensitive	12,091	1,420	121	36
Moderately sensitive	966	114	8	2
Sensitive	14,232	1,929	113	95
Ohio				
Unknown	3,209	853	134	82
Insensitive	2,761	755	93	90
Moderately sensitive	901	212	19	27
Sensitive	5,842	1,267	220	149
Pennsylvania				
Unknown	4,889	1,644	297	246
Insensitive	7,226	2,435	354	220
Moderately sensitive	1,322	525	84	52
Sensitive	11,204	4,404	707	463
Rhode Island				
Unknown	22	45	0	0
Insensitive	65	123	4	0
Moderately sensitive	79	111	4	0
Sensitive	100	303	32	0
Vermont				
Unknown	508	287	92	116
Insensitive	2,953	1,606	566	428
Moderately sensitive	254	128	58	63
Sensitive	2,300	1,256	393	324
West Virginia				
Unknown	4,308	2,406	400	254
Insensitive	4,665	2,647	585	385
Moderately sensitive	1,359	974	148	80
Sensitive	6,250	3,268	687	523
Total	135,580	43,495	7,045	5,568

[a]Biosite index based on interpolated values for each FIA plot.
[b]Ozone-sensitivity categories are based on both field observations and fumigation trials (Smith et al. 2007).

only other NE State besides Connecticut and Maryland with less forest land in the no risk category than in the combined elevated risk categories. Other NE States with from 0.07 to 0.50 million acres of forest land with some percentage of tree volume at high risk of ozone impact include New Hampshire, Vermont, New Jersey, New York, Ohio, Pennsylvania, and West Virginia. These states also include some percentage of tree volume and forest land in the low and moderate risk categories although the majority of trees are at no risk. In Delaware and Maine, the majority of ozone-susceptible trees and forest land are not at risk of ozone impact although both states have small percentages of tree volume in the low risk category.

In Indiana, about 1.8 million acres of forest land with 42 percent of the tree volume of susceptible species are classified at low risk of O_3 impact, about 0.8 million acres with 18 percent of the tree volume are at moderate risk, and 0.6 million acres with 11 percent of the tree volume of susceptible species are classified at high risk of O_3 impact (Tables 19, 20). This leaves less than one-third of the forest land and susceptible tree volume in Indiana at no risk of ozone impact. Other NC States with small percentages (2-3%) of forest land in the high risk category include Illinois, Michigan, Missouri, and Wisconsin, but in all of these states most of the ozone-susceptible tree volume is at no risk of ozone impact. Similarly, most of the forest land in Minnesota is at no risk of ozone impact although there are 0.08 million acres of forest land with 0.6 percent of the susceptible tree volume at low risk and 0.02 million acres with 0.1 percent of the susceptible tree volume at moderate risk. All of the forest land in Iowa, Kansas, Nebraska, North Dakota, and South Dakota is at no risk of O_3 impact.

Modeling Risk

It has been argued that to assess O_3 risk to a given population of plants, one needs to know the effective O_3 dose for that plant population. Effective ozone dose is a term used to define the sensitivity of a plant per unit of O_3 uptake and is thus intended to reflect the inherent and often complex traits that define plant response including avoidance, tolerance, detoxification, and repair (Matyssek et al. 2008, 2010; Paoletti et al. 2010). At any given site, a given plant's response to O_3 is likely to be further compounded by local weather conditions, insect and disease pests, plant age, and many other factors (Zhang et al. 2010). Unraveling and quantifying (modeling) these factors may be an impossible task. Biomonitoring provides an alternative and much simplified approach to risk assessment. Documenting the response of ozone-sensitive bioindicator plants to ambient ozone concentrations in the natural forest environment provides the needed integration of biotic and abiotic factors for risk assessment. The bioindicator plant reveals the effective ozone dose and thus the process is simplified to one of careful observation and a commitment to high sample size and standardization.

The 17 years of data summarized in this report demonstrate that plant response to O_3 is highly variable. Every ozone season is unique, and no two plants, no matter how close together they are growing or whether they arise from the same rhizome or are different in genus and species, will show the same visible response to O_3. This fact is inherent to a plant-based injury response index and strengthens rather than detracts from the reliability of the data. The plant-to-plant and year-to-year variability is representative of the natural environment and, therefore, provides an accurate and defensible assessment of O_3 impact to the forest resource.

SUMMARY AND CONCLUSIONS

Summary statistics in this report validate Web-based reports from the U.S. EPA (2007) and U.S. DOI (2003) that peak ozone concentrations (> 100 ppb O_3) during the growing season are on the decline although mid-level values (60 to 90 ppb O_3) are not. Additional evidence of changing trends in ozone air quality comes from studies conducted both within and outside the United States. Lefohn et al. (2008 and 2010) reported a reduction in the frequency of higher hourly average ozone concentrations from both urban and rural monitoring stations in the U.S., while also noting that lower hourly average ozone concentrations are shifting toward more moderate levels. Similar findings are reported from the UK and other European countries (Dawnay and Mills 2009, Percy et al. 2003). Reductions in peak ozone concentrations are due to the implementation of

Table18.—Estimated area in acres of forest land by biosite index risk category and NE State, 2010

State	Biosite Index[a] 0 to 4.9 (no risk)	5.0 to 14.9 (low risk)	15.0 to 24.9 (moderate risk)	≥25 (high risk)
Connecticut	702,391	1,199,166	0	0
Delaware	310,277	27,288	3,003	
Maine	17,393,361	249,086	0	0
Maryland	683,811	1,000,443	371,332	608,932
Massachusetts	2,556,978	754,101	63,472	0
New Hampshire	2,873,376	1,515,164	200,635	71,922
New Jersey	596,085	1,257,367	147,887	69,189
New York	14,975,772	1,801,806	132,415	76,272
Ohio	6,231,378	1,593,082	223,923	182,336
Pennsylvania	11,558,304	4,120,829	635,146	409,943
Rhode Island	111,639	254,418	12,058	0
Vermont	2,762,448	1,363,859	468,390	414,566
West Virginia	7,190,437	4,148,528	912,397	497,527
Total	67,946,256	19,285,137	3,170,658	2,330,686

[a]Biosite index based on interpolated values for each FIA plot.

Table 19.—Estimated area in acres of forest land by biosite index risk category and NC State, 2010

State	Biosite Index[a] 0 to 4.9 (no risk)	5.0 to 14.9 (low risk)	15.0 to 24.9 (moderate risk)	≥25 (high risk)
Illinois	3,912,578	888,020	54,109	6,833
Indiana	1,144,739	1,840,471	756,703	548,420
Iowa	3,026,078	0	0	0
Kansas	2,437,401	0	0	0
Michigan	18,566,996	1,239,615	153,391	43,415
Minnesota	17,175,228	84,331	21,984	0
Missouri	15,029,386	364,182	50,292	49,906
Nebraska	1,520,468	0	0	0
North Dakota	772,427	0	0	0
South Dakota	1,883,024	0	0	0
Wisconsin	16,249,748	526,245	68,486	27,924
Total	81,718,074	4,942,864	1,104,965	676,498

[a]Biosite index based on interpolated values for each FIA plot.

Table 20.—Estimated volume in million cubic feet of live trees 5 inches in diameter and greater on forest land by biosite index risk category, ozone-sensitivity category, and NC State, 2010

State and ozone-sensitivity category[b]	Biosite Index[a] 0 to 4.9 (no risk)	5.0 to 14.9 (low risk)	15.0 to 24.9 (moderate risk)	≥25 (high risk)
Illinois				
Unknown	3,033	648	34	7
Insensitive	1,549	430	14	8
Moderately sensitive	869	196	10	0
Sensitive	1,664	307	26	1
Indiana				
Unknown	582	1,079	383	328
Insensitive	502	984	449	284
Moderately sensitive	241	392	133	87
Sensitive	1,041	1,427	634	413
Iowa				
Unknown	2,511	0	0	0
Insensitive	934	0	0	0
Moderately sensitive	301	0	0	0
Sensitive	647	0	0	0
Kansas				
Unknown	2,094	0	0	0
Insensitive	136	0	0	0
Moderately sensitive	90	0	0	0
Sensitive	777	0	0	0
Michigan				
Unknown	2,389	306	100	3
Insensitive	14,084	826	90	21
Moderately sensitive	1,611	228	33	13
Sensitive	11,749	825	134	76
Minnesota				
Unknown	3,384	11	3	0
Insensitive	5,963	32	13	0
Moderately sensitive	1,527	3	2	0
Sensitive	7,433	56	10	0
Missouri				
Unknown	8,126	297	44	28
Insensitive	5,538	150	32	16
Moderately sensitive	4,789	53	6	9
Sensitive	1,444	54	3	19
Nebraska				
Unknown	829	0	0	0
Insensitive	81	0	0	0
Moderately sensitive	35	0	0	0
Sensitive	1,076	0	0	0
North Dakota				
Unknown	256	0	0	0
Insensitive	19	0	0	0
Moderately sensitive	52	0	0	0
Sensitive	384	0	0	0
South Dakota				
Unknown	226	0	0	0
Insensitive	88	0	0	0
Moderately sensitive	32	0	0	0
Sensitive	1,940	0	0	0
Wisconsin				
Unknown	2,389	77	4	0
Insensitive	9,802	313	40	9
Moderately sensitive	1,938	60	12	4
Sensitive	8,784	280	42	8
Total	112,938	9,033	2,251	1,334

[a]Biosite index based on interpolated values for each FIA plot.

[b]Ozone-sensitivity categories are based on both field observations and fumigation trials (Smith et al. 2007).

successful pollution control policies that have reduced emissions of ozone precursor pollutants such as nitrogen oxides (NO_x), carbon monoxide (CO), and volatile organic compounds (VOCs). Working against this trend are the equally important increases in human-made sources of these pollutants (from Asia and India, for example) that increase NO_x, CO, and VOCs emissions on a global scale (Percy et al. 2003). The projected result for forest areas around the globe is a reduction in the magnitude of peak ozone exposure accompanied by an increase in long-term chronic exposure. Long-range transport of polluted air masses on the local scale from urban to rural areas, and on the global scale from Asia to North America and from North America to Europe, also contributes to higher background concentrations. This finding suggests we must remain vigilant in our O_3 monitoring efforts and devise new ways to measure and model relatively small effects of ozone on our most sensitive populations (Bennett et al. 2006, Matyssek et al. 2010).

Other researchers have reported that both ozone uptake and foliar injury correlate with increased availability of soil water in the forest environment (Davis and Orendovici 2006, Mclaughlin et al. 2007, Orendovici et al. 2010, Rose and Coulston 2009, Showman 1991, Zhang et al. 2010). In this 24-state ozone survey, the field sample is much larger than that of any previous field-based study, and the range of site conditions, from genotype to soil type, is highly variable both in space (Maine to Kansas) and time (1994-2010). Not surprisingly then, although we found certain clusterings of the data that support the concept that site moisture has a strong influence on plant response to ozone, we could not document a consistent and predictable relationship among injury, ozone, and site moisture conditions. The injury indices calculated from the field data suggest that the percentage of injured sites and the severity of foliar injury are highest on sites categorized as high ozone-wet, followed by high ozone-dry, low ozone-wet, and low ozone-dry, but these differences are not statistically significant (Wang et al. 2012). There is just too much variability in the plant/ozone interaction under natural conditions, at least on the scale reported here; and this is compounded by the fact that under natural conditions, so many of the injury values are at or near zero (Wang et al. 2012), thus generating a skewed dataset. And yet, it is clear that injury drops dramatically in areas of high ambient O_3 (e.g., Mid-Atlantic States) when drought conditions prevail as happened in 1999, and that injury is minimized when seasonal ozone concentrations, especially peak (N100) O_3 concentrations, drop below a certain threshold as in 2004 through 2009. Without additional research, we may not be able to predict ozone injury, but we can say with confidence that there will be little or no injury when and where there are extreme plant moisture deficits and where low levels of ozone combine with low plant available moisture.

In conclusion, the results of 17 years of ozone injury detection provide indisputable evidence that ozone-induced foliar injury symptoms occur routinely on ozone-sensitive bioindicator plants across much of the forested landscape of the NC and NE States, and in areas previously thought to be relatively ozone free. This report provides state-level information on where O_3 stress occurs and whether O_3 stress is increasing or decreasing over time, and it provides state-level estimates of the acres of forest land and volume of ozone-susceptible species at risk of O_3 impact. Summarized results for the 1994 to 2010 time period are as follows:

- Ozone injury occurs frequently (70 to 100% of visits) on many sites in most NC and NE States including Missouri, Wisconsin, Michigan, Illinois, Indiana, Ohio, West Virginia, Maryland, Delaware, Pennsylvania, New York, New Jersey, Connecticut, Rhode Island, Massachusetts, New Hampshire, and Vermont.
- Ozone injury occurs only infrequently (<40% of visits) on most sites in South Dakota, Nebraska, Kansas, Iowa, Minnesota, and Maine, and not at all in North Dakota.
- Many thousands of ozone-sensitive plants are evaluated every year with the percent injured plants ranging from 26 percent in 1994 to less than 1 percent in 2009 in NE, and from 7 percent in 1998 to less than 1 percent in 2007 in NC.

- Although the percent injured plants and the BI (injury severity) declined from 1994 to 2010, the percent injured sites showed a less obvious downward trend.
- Although seasonal mean SUM06 concentrations and N100 values show a declining trend from 1994 to 2010, ambient ozone concentrations remain at plant-damaging levels; one in four evaluated sites continues to show injury every year even though the severity of that injury has declined over time.
- The seasonal mean SUM06 and N100 values tend to mirror each other in year-to-year fluctuations although N100 values drop close to zero by 2004 while SUM06 values remain at more moderate levels through 2007 and 2008.
- For sites in high O_3 areas (seasonal mean SUM06 >25 ppm hr), there is a direct correlation between injury (BI) and ozone exposure.
- Sites with injury (BI > 0) and sites with no injury (BI = 0) occur at all O_3 exposure levels (clean, low, moderate, and high). However, at all ozone exposure levels, there is a lower percentage of injured sites and less severe injury in dry vs. wet areas.
- The years with the highest soil moisture and plant moisture stress correspond to the years with the lowest BI in areas of high seasonal O_3 exposure (SUM06 > 25 ppm hrs).
- Based on 17 years of data, the areas of greatest risk of impact from ambient ozone exposures during the growing season include Illinois, Indiana, and the Mid-Atlantic States of West Virginia, Maryland, Pennsylvania, and New Jersey.
- Pockets of high ozone risk to the forest resource also occur in Missouri, Wisconsin, Michigan, Ohio, New York, Connecticut, Rhode Island, Massachusetts, New Hampshire, and Vermont.
- There is little or no risk of O_3 impact to the forest resource in Maine, Minnesota, Iowa, Kansas, Nebraska, South Dakota, and North Dakota.
- The documented trends in O_3 exposure (SUM06 and N100) and injury (BI) indicate that ozone air quality for the NC and NE States is improving over time.

To find additional guidance on ozone biomonitoring, data analysis, and interpretation, and to access reports from other FIA regions, see the downloadable material on the ozone Web site: http://nrs.fs.fed.us/fia/topics/ozone/default.asp

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APPENDIX 1

Table 1A.—Percentage of biosites by bioindicator response category by NE State and year (the four BI categories are intended to describe increasing risk of probable ozone impact to the forest resource as follows: no risk (BI <5); low risk (BI = 5-15); moderate risk (BI = 15-25); and high risk (BI > 25) of ozone impact)

	Biosite Index			
Year and State	0 to 4.9	5.0 to 14.9	15.0 to 24.9	≥25
1994				
Connecticut	0.0	0.0	100.0	0.0
Maine	93.1	6.9	0.0	0.0
Maryland	0.0	11.1	22.2	66.7
Massachusetts	57.1	21.4	14.3	7.1
New Hampshire	50.0	16.7	16.7	16.7
New Jersey	44.4	0.0	33.3	22.2
Vermont	57.1	14.3	14.3	14.3
1995				
Connecticut	42.9	14.3	14.3	28.6
Delaware	100.0	0.0	0.0	0.0
Maine	94.1	2.9	0.0	2.9
Maryland	11.1	33.3	33.3	22.2
Massachusetts	80.0	20.0	0.0	0.0
New Hampshire	91.3	4.3	4.3	0.0
New Jersey	33.3	0.0	16.7	50.0
Pennsylvania	83.3	8.3	0.0	8.3
Rhode Island	20.0	60.0	20.0	0.0
Vermont	77.8	5.6	16.7	0.0
West Virginia	94.4	0.0	5.6	0.0
1996				
Connecticut	28.6	14.3	14.3	42.9
Maine	88.9	7.4	0.0	3.7
Maryland	0.0	0.0	20.0	80.0
Massachusetts	84.6	7.7	7.7	0.0
New Hampshire	83.3	12.5	4.2	0.0
New Jersey	33.3	16.7	33.3	16.7
Rhode Island	20.0	80.0	0.0	0.0
Vermont	50.0	18.8	12.5	18.8
West Virginia	56.5	8.7	13.0	21.7

	Biosite Index			
Year and State	0 to 4.9	5.0 to 14.9	15.0 to 24.9	≥25
1997				
Connecticut	71.4	14.3	14.3	0.0
Delaware	100.0	0.0	0.0	0.0
Maine	100.0	0.0	0.0	0.0
Maryland	40.0	0.0	0.0	60.0
Massachusetts	81.3	6.3	12.5	0.0
New Hampshire	100.0	0.0	0.0	0.0
New Jersey	100.0	0.0	0.0	0.0
Ohio	57.9	10.5	15.8	15.8
Rhode Island	20.0	40.0	20.0	20.0
Vermont	64.7	0.0	11.8	23.5
West Virginia	92.3	7.7	0.0	0.0
1998				
Connecticut	0.0	0.0	60.0	40.0
Delaware	33.3	0.0	33.3	33.3
Maine	92.9	7.1	0.0	0.0
Maryland	16.7	25.0	0.0	58.3
Massachusetts	72.2	27.8	0.0	0.0
New Hampshire	80.0	4.0	8.0	8.0
New Jersey	9.1	9.1	9.1	72.7
Ohio	52.6	15.8	0.0	31.6
Pennsylvania	61.0	7.0	1.0	31.0
Rhode Island	20.0	0.0	40.0	40.0
Vermont	70.6	5.9	5.9	17.6
West Virginia	26.9	15.4	19.2	38.5
1999				
Connecticut	100.0	0.0	0.0	0.0
Delaware	18.2	27.3	18.2	36.4
Maine	100.0	0.0	0.0	0.0
Maryland	80.0	0.0	10.0	10.0
Massachusetts	88.9	0.0	5.6	5.6
New Hampshire	95.7	4.3	0.0	0.0
New Jersey	100.0	0.0	0.0	0.0
New York	96.5	2.4	0.0	1.2
Ohio	83.3	11.1	0.0	5.6
Pennsylvania	92.2	2.3	1.6	3.9
Rhode Island	50.0	0.0	25.0	25.0
Vermont	95.2	4.8	0.0	0.0
West Virginia	92.9	0.0	7.1	0.0

Table 1A.—continued

Year and State	Biosite Index 0 to 4.9	5.0 to 14.9	15.0 to 24.9	≥25
2000				
Connecticut	57.1	28.6	14.3	0.0
Delaware	44.4	22.2	22.2	11.1
Maine	100.0	0.0	0.0	0.0
Maryland	100.0	0.0	0.0	10.0
Massachusetts	92.9	7.1	0.0	0.0
New Hampshire	100.0	0.0	0.0	0.0
New Jersey	100.0	0.0	0.0	0.0
New York	100.0	0.0	0.0	0.0
Ohio	78.9	5.3	10.5	5.3
Pennsylvania	69.0	9.0	6.0	16.0
Rhode Island	80.0	20.0	0.0	0.0
Vermont	86.4	9.1	0.0	4.5
West Virginia	93.1	3.4	0.0	3.4
2001				
Connecticut	33.3	33.3	33.3	0.0
Delaware	70.0	30.0	0.0	0.0
Maine	100.0	0.0	0.0	0.0
Maryland	55.6	22.2	3.7	18.5
Massachusetts	87.5	0.0	12.5	0.0
New Hampshire	89.5	5.3	5.3	0.0
New Jersey	100.0	0.0	0.0	0.0
New York	96.4	1.8	0.0	1.8
Ohio	82.4	5.9	0.0	11.8
Pennsylvania	82.7	7.7	4.8	4.8
Rhode Island	25.0	50.0	0.0	25.0
Vermont	94.4	5.6	0.0	0.0
West Virginia	93.3	0.0	0.0	6.7
2002				
Connecticut	75.0	25.0	0.0	0.0
Delaware	72.7	18.2	9.1	0.0
Maine	100.0	0.0	0.0	0.0
Maryland	75.0	0.0	0.0	25.0
Massachusetts	100.0	0.0	0.0	0.0
New Hampshire	100.0	0.0	0.0	0.0
New Jersey	80.0	10.0	10.0	0.0
New York	81.1	5.4	2.7	10.8
Ohio	88.2	11.8	0.0	0.0
Pennsylvania	58.0	22.0	8.0	12.0
Rhode Island	20.0	60.0	20.0	0.0
Vermont	94.1	0.0	5.9	0.0
West Virginia	77.8	11.1	0.0	11.1

Year and State	Biosite Index 0 to 4.9	5.0 to 14.9	15.0 to 24.9	≥25
2003				
Connecticut	71.4	28.6	0.0	0.0
Delaware	54.5	36.4	9.1	0.0
Maine	100.0	0.0	0.0	0.0
Maryland	77.8	11.1	0.0	11.1
Massachusetts	100.0	0.0	0.0	0.0
New Hampshire	100.0	0.0	0.0	0.0
New Jersey	100.0	10.0	0.0	0.0
New York	94.6	2.7	2.7	0.0
Ohio	94.1	5.9	0.0	0.0
Pennsylvania	98.0	0.0	0.0	2.0
Rhode Island	80.0	20.0	0.0	0.0
Vermont	94.4	5.6	0.0	0.0
West Virginia	92.6	3.7	0.0	3.7
2004				
Connecticut	40.0	40.0	20.0	0.0
Delaware	54.5	27.3	9.1	9.1
Maine	100.0	0.0	0.0	0.0
Maryland	100.0	0.0	0.0	0.0
Massachusetts	100.0	0.0	0.0	0.0
New Hampshire	80.0	0.0	0.0	20.0
New Jersey	62.5	12.5	12.5	12.5
New York	83.3	11.1	0.0	5.6
Ohio	91.2	8.8	0.0	0.0
Pennsylvania	85.4	12.5	0.0	2.1
Rhode Island	100.0	0.0	0.0	0.0
Vermont	95.0	5.0	0.0	0.0
West Virginia	82.1	7.1	7.1	3.6
2005				
Connecticut	75.0	25.0	0.0	0.0
Delaware	62.5	25.0	0.0	12.5
Maine	100.0	0.0	0.0	0.0
Maryland	44.4	22.2	0.0	33.3
Massachusetts	100.0	0.0	0.0	0.0
New Hampshire	100.0	0.0	0.0	0.0
New Jersey	66.7	0.0	11.1	22.2
New York	100.0	0.0	0.0	0.0
Ohio	97.1	2.9	0.0	0.0
Pennsylvania	98.3	1.7	0.0	0.0
Rhode Island	80.0	0.0	20.0	0.0
Vermont	94.4	0.0	0.0	5.6
West Virginia	92.9	3.6	3.6	0.0

Table 1A.—continued

Year and State	Biosite Index 0 to 4.9	5.0 to 14.9	15.0 to 24.9	≥25
2006				
Connecticut	0.0	80.0	20.0	0.0
Delaware	72.7	9.1	9.1	9.1
Maine	94.4	5.6	0.0	0.0
Maryland	100.0	0.0	0.0	0.0
Massachusetts	70.0	30.0	0.0	0.0
New Hampshire	100.0	0.0	0.0	0.0
New Jersey	50.0	12.5	25.0	12.5
New York	97.1	2.9	0.0	0.0
Ohio	100.0	0.0	0.0	0.0
Pennsylvania	92.5	3.0	4.5	0.0
Rhode Island	40.0	40.0	20.0	0.0
Vermont	92.9	7.1	0.0	0.0
West Virginia	89.3	7.1	3.6	0.0
2007				
Connecticut	85.7	14.3	0.0	0.0
Delaware	81.8	9.1	9.1	0.0
Maine	100.0	0.0	0.0	0.0
Maryland	100.0	0.0	0.0	0.0
Massachusetts	100.0	0.0	0.0	0.0
New Hampshire	100.0	0.0	0.0	0.0
New Jersey	75.0	12.5	12.5	0.0
New York	92.1	2.6	0.0	5.3
Ohio	97.1	2.9	0.0	0.0
Pennsylvania	87.5	10.7	1.8	0.0
Rhode Island	80.0	20.0	0.0	0.0
Vermont	92.3	7.7	0.0	0.0
West Virginia	89.3	7.1	0.0	3.6
2008				
Connecticut	71.4	28.6	0.0	0.0
Delaware	83.3	16.7	0.0	0.0
Maine	100.0	0.0	0.0	0.0
Maryland	100.0	0.0	0.0	0.0
Massachusetts	88.9	11.1	0.0	0.0
New Hampshire	100.0	0.0	0.0	0.0
New Jersey	75.0	25.0	0.0	0.0
New York	90.2	9.8	0.0	0.0
Ohio	97.1	2.9	0.0	0.0
Pennsylvania	97.7	2.3	0.0	0.0
Rhode Island	100.0	0.0	0.0	0.0
Vermont	90.9	9.1	0.0	0.0
West Virginia	90.6	6.3	3.1	0.0

Year and State	Biosite Index 0 to 4.9	5.0 to 14.9	15.0 to 24.9	≥25
2009				
Connecticut	87.5	12.5	0.0	0.0
Delaware	100.0	0.0	0.0	0.0
Maine	94.4	5.6	0.0	0.0
Maryland	87.5	12.5	0.0	0.0
Massachusetts	90.0	10.0	0.0	0.0
New Hampshire	80.0	20.0	0.0	0.0
New Jersey	75.0	12.5	0.0	12.5
New York	100.0	0.0	0.0	0.0
Ohio	94.4	2.8	2.8	0.0
Pennsylvania	94.8	3.4	0.0	1.7
Rhode Island	60.0	40.0	20.0	0.0
Vermont	91.7	8.3	0.0	5.6
West Virginia	100.0	0.0	0.0	0.0
2010				
Connecticut	100.0	0.0	0.0	0.0
Delaware	100.0	0.0	0.0	0.0
Maine	94.4	5.6	0.0	0.0
Maryland	87.5	0.0	12.5	0.0
Massachusetts	100.0	0.0	0.0	0.0
New Hampshire	40.0	20.0	20.0	20.0
New Jersey	50.0	25.0	12.5	12.5
New York	91.4	5.7	0.0	2.9
Ohio	100.0	0.0	0.0	0.0
Pennsylvania	80.6	17.7	1.6	0.0
Rhode Island	100.0	0.0	20.0	0.0
Vermont	92.3	7.7	0.0	0.0
West Virginia	82.1	17.9	0.0	0.0

Table 1B.—Percentage of biosites by bioindicator response category by NC State and year (the four BI categories are intended to describe increasing risk of probable ozone impact to the forest resource as follows: no risk (BI <5); low risk (BI = 5-15); moderate risk (BI = 15-25); and high risk (BI > 25) of ozone impact)

	Biosite Index			
Year and State	0 to 4.9	5.0 to 14.9	15.0 to 24.9	≥25
1994				
Michigan	91.7	8.3	0.0	0.0
Minnesota	100.0	0.0	0.0	0.0
Wisconsin	93.8	0.0	6.3	0.0
1995				
Michigan	92.5	5.0	0.0	2.5
Minnesota	100.0	0.0	0.0	0.0
Wisconsin	93.8	4.6	0.0	1.5
1996				
Indiana	12.5	0.0	0.0	87.5
Michigan	92.6	3.7	0.0	3.7
Minnesota	100.0	0.0	0.0	0.0
Wisconsin	96.4	0.0	0.0	3.6
1997				
Illinois	11.1	11.1	11.1	66.7
Indiana	70.0	20.0	0.0	10.0
Michigan	100.0	0.0	0.0	0.0
Minnesota	100.0	0.0	0.0	0.0
Wisconsin	97.1	2.9	0.0	0.0
1998				
Illinois	10.5	15.8	36.8	36.8
Indiana	5.9	11.8	0.0	82.4
Michigan	98.3	1.7	0.0	0.0
Minnesota	98.3	1.7	0.0	0.0
Wisconsin	85.7	4.8	4.8	4.8
1999				
Illinois	65.385	26.923	3.846	3.846
Indiana	63.158	21.053	5.263	10.526
Michigan	83.721	13.953	0	2.326
Minnesota	100	0	0	0
Wisconsin	94.444	5.556	0	0

	Biosite Index			
Year and State	0 to 4.9	5.0 to 14.9	15.0 to 24.9	≥25
2000				
Illinois	72.5	20.0	2.5	5.0
Indiana	67.7	12.9	6.5	12.9
Iowa	100.0	0.0	0.0	0.0
Michigan	85.7	12.2	2.0	0.0
Minnesota	96.2	3.8	0.0	0.0
Missouri	93.0	3.5	1.8	1.8
Wisconsin	92.2	6.3	0.0	1.6
2001				
Illinois	90.7	9.3	0.0	0.0
Indiana	46.2	30.8	7.7	15.4
Iowa	100.0	0.0	0.0	0.0
Michigan	90.7	3.7	3.7	1.9
Minnesota	100.0	0.0	0.0	0.0
Missouri	92.1	5.3	2.6	0.0
Wisconsin	97.4	2.6	0.0	0.0
2002				
Illinois	92.6	7.4	0.0	0.0
Indiana	86.4	13.6	0.0	0.0
Iowa	100.0	0.0	0.0	0.0
Kansas	100.0	0.0	0.0	0.0
Michigan	91.1	6.7	2.2	0.0
Minnesota	100.0	0.0	0.0	0.0
Missouri	92.3	5.1	0.0	2.6
Nebraska	100.0	0.0	0.0	0.0
North Dakota	100.0	0.0	0.0	0.0
South Dakota	100.0	0.0	0.0	0.0
Wisconsin	98.2	1.8	0.0	0.0

Table 1B.—continued

Year and State	Biosite Index 0 to 4.9	5.0 to 14.9	15.0 to 24.9	≥25
2003				
Illinois	92.9	3.6	0.0	3.6
Indiana	80.6	12.9	0.0	6.5
Iowa	100.0	0.0	0.0	0.0
Kansas	100.0	0.0	0.0	0.0
Michigan	100.0	0.0	0.0	0.0
Minnesota	100.0	0.0	0.0	0.0
Missouri	100.0	0.0	0.0	0.0
Nebraska	100.0	0.0	0.0	0.0
North Dakota	100.0	0.0	0.0	0.0
South Dakota	100.0	0.0	0.0	0.0
Wisconsin	98.2	1.8	0.0	0.0

Year and State	0 to 4.9	5.0 to 14.9	15.0 to 24.9	≥25
2004				
Illinois	89.7	6.9	3.4	0.0
Indiana	89.3	10.7	0.0	0.0
Iowa	100.0	0.0	0.0	0.0
Kansas	100.0	0.0	0.0	0.0
Michigan	88.4	9.3	2.3	0.0
Minnesota	100.0	0.0	0.0	0.0
Missouri	94.7	2.6	0.0	2.6
Nebraska	100.0	0.0	0.0	0.0
North Dakota	100.0	0.0	0.0	0.0
South Dakota	100.0	0.0	0.0	0.0
Wisconsin	100.0	0.0	0.0	0.0

Year and State	0 to 4.9	5.0 to 14.9	15.0 to 24.9	≥25
2005				
Illinois	96.4	3.6	0.0	0.0
Indiana	96.2	0.0	0.0	3.8
Iowa	100.0	0.0	0.0	0.0
Kansas	100.0	0.0	0.0	0.0
Michigan	88.9	6.7	2.2	2.2
Minnesota	100.0	0.0	0.0	0.0
Missouri	100.0	0.0	0.0	0.0
Nebraska	100.0	0.0	0.0	0.0
North Dakota	100.0	0.0	0.0	0.0
South Dakota	100.0	0.0	0.0	0.0
Wisconsin	100.0	0.0	0.0	0.0

Year and State	Biosite Index 0 to 4.9	5.0 to 14.9	15.0 to 24.9	≥25
2006				
Illinois	96.4	3.6	0.0	0.0
Indiana	82.6	13.0	4.3	0.0
Iowa	75.0	25.0	0.0	0.0
Kansas	100.0	0.0	0.0	0.0
Michigan	88.9	8.9	2.2	0.0
Minnesota	100.0	0.0	0.0	0.0
Missouri	97.4	2.6	0.0	0.0
Nebraska	100.0	0.0	0.0	0.0
North Dakota	100.0	0.0	0.0	0.0
South Dakota	100.0	0.0	0.0	0.0
Wisconsin	96.8	0.0	3.2	0.0

Year and State	0 to 4.9	5.0 to 14.9	15.0 to 24.9	≥25
2007				
Illinois	96.9	3.1	0.0	0.0
Indiana	84.0	16.0	0.0	0.0
Iowa	100.0	0.0	0.0	0.0
Kansas	100.0	0.0	0.0	0.0
Michigan	97.9	2.1	0.0	0.0
Minnesota	100.0	0.0	0.0	0.0
Missouri	100.0	0.0	0.0	0.0
Nebraska	100.0	0.0	0.0	0.0
North Dakota	100.0	0.0	0.0	0.0
South Dakota	100.0	0.0	0.0	0.0
Wisconsin	100.0	0.0	0.0	0.0

Year and State	0 to 4.9	5.0 to 14.9	15.0 to 24.9	≥25
2008				
Illinois	90.3	9.7	0.0	0.0
Indiana	80.0	16.0	0.0	4.0
Iowa	100.0	0.0	0.0	0.0
Kansas	100.0	0.0	0.0	0.0
Michigan	92.0	2.0	6.0	0.0
Minnesota	100.0	0.0	0.0	0.0
Missouri	100.0	0.0	0.0	0.0
Nebraska	100.0	0.0	0.0	0.0
North Dakota	100.0	0.0	0.0	0.0
South Dakota	100.0	0.0	0.0	0.0
Wisconsin	100.0	0.0	0.0	0.0

Table 1B.-—continued

Year and State	Biosite Index			
	0 to 4.9	5.0 to 14.9	15.0 to 24.9	≥25
2009				
Illinois	96.8	3.2	0.0	0.0
Indiana	56.0	40.0	0.0	4.0
Iowa	100.0	0.0	0.0	0.0
Kansas	100.0	0.0	0.0	0.0
Michigan	90.0	8.0	2.0	0.0
Minnesota	100.0	0.0	0.0	0.0
Missouri	100.0	0.0	0.0	0.0
Nebraska	100.0	0.0	0.0	0.0
North Dakota	100.0	0.0	0.0	0.0
South Dakota	100.0	0.0	0.0	0.0
Wisconsin	100.0	0.0	0.0	0.0

Year and State	Biosite Index			
	0 to 4.9	5.0 to 14.9	15.0 to 24.9	≥25
2010				
Illinois	96.8	3.2	0.0	0.0
Indiana	69.2	23.1	3.8	3.8
Iowa	100.0	0.0	0.0	0.0
Kansas	100.0	0.0	0.0	0.0
Michigan	88.2	5.9	2.0	3.9
Minnesota	100.0	0.0	0.0	0.0
Missouri	100.0	0.0	0.0	0.0
Nebraska	100.0	0.0	0.0	0.0
North Dakota	100.0	0.0	0.0	0.0
South Dakota	100.0	0.0	0.0	0.0
Wisconsin	100.0	0.0	0.0	0.0

APPENDIX 2

Table 1.—State-level precipitation data for the June through August growing season obtained from the National Climate Data Center at the following Web site: http://www.ncdc.noaa.gov/oa/climate/research/cag3/state.html (mapped data are summarized below to highlight, for each state, the years above and below average precipitation, the driest and wettest years, and the overall trend in growing season precipitation for the 1994 to 2010 sampling period)

NE States	Above average precipitation	Below average precipitation	Driest	2nd Driest	Wettest	2nd Wettest	Trend
Maine	1996, 1998, 2004-2006, 2008-2010	1994-1995, 1997, 1999-2003, 2007	19952	2001	2009	2008	Dry to wet
New Hampshire	1998, 2003-2006, 2008-2009	1994-1997, 1999-2002, 2007, 2010	1995	1999	2006	2008	Dry to wet
Vermont	1994, 1996-1998, 2000, 2002-2010	1995, 1999, 2001	1999	2001	1998	2008	Dry to wet
Massachusetts	1994, 1996, 1998, 2000-2001, 2003-2004, 2006, 2008-2009	1995, 1997, 1999, 2002, 2005, 2007, 2010	1995	1999	2009	2006	Dry to wet
Connecticut	1994, 1996-1998, 2000-2004, 2006, 2008-2009	1995, 1999, 2005, 2007, 2010	1999	1995	2009	2006	Dry to wet
Rhode Island	1994, 1996-1998, 2000-2001, 2003-2004, 2006, 2008-2010	1995, 1999, 2002, 2005, 2007	1999	1995	2006	2009	Dry to wet
New York	1994, 1996, 1998, 2000, 2003-2006, 2008-2010	1995, 1997, 1999, 2001-2002, 2007	1999	1995	2006	2009	Dry to wet
New Jersey	1994, 1996-1997, 2000, 2003-2004, 2006-2007, 2009	1995, 1998-1999, 2001-2002, 2005, 2008, 2010	20102	1995	2009	2003	Dry to wet
Delaware	1994, 1996, 2000-2001, 2003-2004, 2006, 2009	1995, 1997-1999, 2002, 2005, 2007-2008, 2010	1995	1999	2003	2001	Dry to wet
Maryland	1994, 1996, 2000-2001, 2003-2004, 2006, 2009	1995, 1997-1999, 2002, 2005, 2007-2008, 2010	20022	1995	2003	1996	-
Pennsylvania	1994, 1996, 2000, 2003-2004, 2006-2007, 2009	1995, 1997-1999, 2001-2002, 2005, 2008, 2010	1995	1999	2003	2006	Dry to wet
West Virginia	1994, 1996, 1998, 2000-2001, 2003-2004, 2006, 2008-2010	1995, 1997, 1999, 2002, 2005, 2007	1999	2002	2003	1996	-
Ohio	1994-1995, 1997-1998, 2000, 2003-2004, 2006-2010	1996, 1999, 2001,2002, 2005	2002	1999	2003	1998	Dry to wet
NC States							
Indiana	1996-1998, 2000-2001, 2003-2006, 2008-2010	1994-1995, 1999, 2002, 2007	2002	1999	1998	2003	Dry to wet
Illinois	1998, 2000-2001, 2004, 2006-2010	1994-1997, 1999, 2002, 2005	2005	1999	2010	2000	Dry to wet
Iowa	1994, 1998-2000, 2002, 2007-2010	1995-1997, 2001, 2003-2006	2003	2001	2010	2008	Dry to wet
Missouri	1995, 1998, 2000-2001, 2004-2005, 2008-2010	1994, 1996-1997, 1999, 2002-2003, 2006-2007	2002	2007	1998	2008	Dry to wet
Michigan	1994-1996, 1999-2000, 2002, 2004, 2008-2010	1997-1998, 2001, 2003, 2005-2007	1998	2003	1994	2010	Wet to dry
Wisconsin	1994-2002, 2007-2008, 2010	2003-2006, 2009	2003	2005	2010	1999	Wet to dry
Minnesota	1994-1995, 1997-2000, 2002, 2005, 2010	1996, 2001, 2003-2004, 2006-2009	2006	2003	2002	2010	Wet to dry
North Dakota	1994-1995, 1996-2002, 2005, 2008, 2010	1996, 2003-2004, 2006-2007, 2009	2006	2003	2005	2002	Wet to dry
South Dakota	1994-1995, 1996-1999, 2001, 2005, 2007-2010	1996, 2000, 2002-2004, 2006	2006	2003	2010	2009	Dry to wet
Nebraska	1994, 1996, 1998-1999, 2005, 2007, 2009-2010	1995, 1997, 2000-2004, 2006, 2008	2002	2003	2010	2009	Dry to wet
Kansas	1995-1999, 2004-2010	1994, 2000-2003	2002	2003	2005	2004	Dry to wet

Smith, Gretchen C.; Morin, Randall S.; McCaskill, George L. 2012. **Ozone injury to forests across the northeast and north central United States, 1994 - 2010.** Gen. Tech. Rep. NRS-103. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 46 p.

Ozone is a highly toxic air contaminant that has been shown to decrease tree growth and cause significant disturbance to forested ecosystems. Ozone also causes distinct foliar injury symptoms to certain species (bioindicator plants) that can be used to detect and monitor ozone stress (biomonitoring) in the forest environment. In the early 1990s, the U.S. Forest Service, in partnership with the U.S. Environmental Protection Agency, developed and implemented a suite of forest health indicators to respond to emerging demands for a comprehensive assessment of the health of U.S. forests. This report focuses on the states in the Northern Research Station-Forest Inventory and Analysis region, which has the longest record of ozone biomonitoring in the country, from 1994 through 2010. The results of 17 years of ozone injury detection provide indisputable evidence that ozone-induced foliar injury symptoms occur routinely on ozone-sensitive bioindicator plants across much of the forested landscape and in areas previously thought to be relatively ozone free. This report provides state-level information on where ozone stress occurs and whether ozone stress is increasing or decreasing over time. It also provides state-level estimates of the acres of forest land and volume of ozone-susceptible species at risk of ozone impact.

KEY WORDS: biomonitoring, FIA, forest health, indicator species, ozone


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