# CHAPTER 8.

## National Trends in Ozone Injury to Forest Plants: 16 Years of Biomonitoring

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## INTRODUCTION

The ozone indicator, an important research component of the Forest Health Monitoring (FHM) Program of the Forest Service, U.S. Department of Agriculture, was developed and implemented to address specific concerns about the negative effects of ground-level ozone pollution on forest health and productivity. Ozone is a highly toxic air contaminant that has been shown repeatedly to damage tree growth and cause significant disturbance to forest 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.

Biomonitoring surveys, begun in 1994 in the Eastern United States and 1998 in the Western United States, provide important regional information on ozone air quality, and a field-based measure of ozone injury and probable impact unavailable from any other data source (Coulston and others 2003, Smith and others 2007). Currently, the national biomonitoring network consists of over 1,005 field sites in 40 States. At every site, the amount and severity of injury to the foliage of ozone-sensitive plants is used to formulate a plot-level injury index referred to as the ozone biosite index or BI (Smith and others 2007). BI values can be used to identify forested areas at risk of ozone impact (Coulston and others 2003) and to describe relative ozone air quality. This report does not address risk, per se, but does examine how emerging long term trends in the BI in different regions of the country may be informing the risk assessment process.

The Forest Inventory and Analysis (FIA) Program of the Forest Service took over implementation of the biomonitoring program in 2002. Data collection, documentation, and reporting are coordinated out of three regional FIA units, each belonging respectively to the Northern Research Station, the Southern Research Station, and the Pacific Northwest Research Station of the Forest Service, with the Northern Research Station FIA unit having the longest record of biomonitoring data, extending from 1994 to 2010. At the regional level, the ozone indicator was designed to assess if plant-damaging concentrations of ozone are present in U.S. forests, where ozone stress is highest and most frequent, and whether or not ozone stress is increasing or decreasing over time. The purpose of this report is to address these issues of forest health assessment with a summary review of the major findings of the ozone surveys for each region. The broad relationship between injury (BI) and ozone exposure is also discussed.

## METHODS

### Sample Area

Ozone sampling occurs on a unique national grid (Smith and others 2007, White and others 1992) that consists of a single panel of ozone biomonitoring sites that are measured every year (fig. 8.1). The field sites vary in size and do not have set boundaries. They are defined by the presence of ozone sensitive bioindicator species indigenous to each FIA region. The Northern Research Station study area covers 24 States, typically divided into the Northeast and North Central sub-regions; the Southern Research Station study area covers 13 States from Virginia to eastern Texas, with data available starting

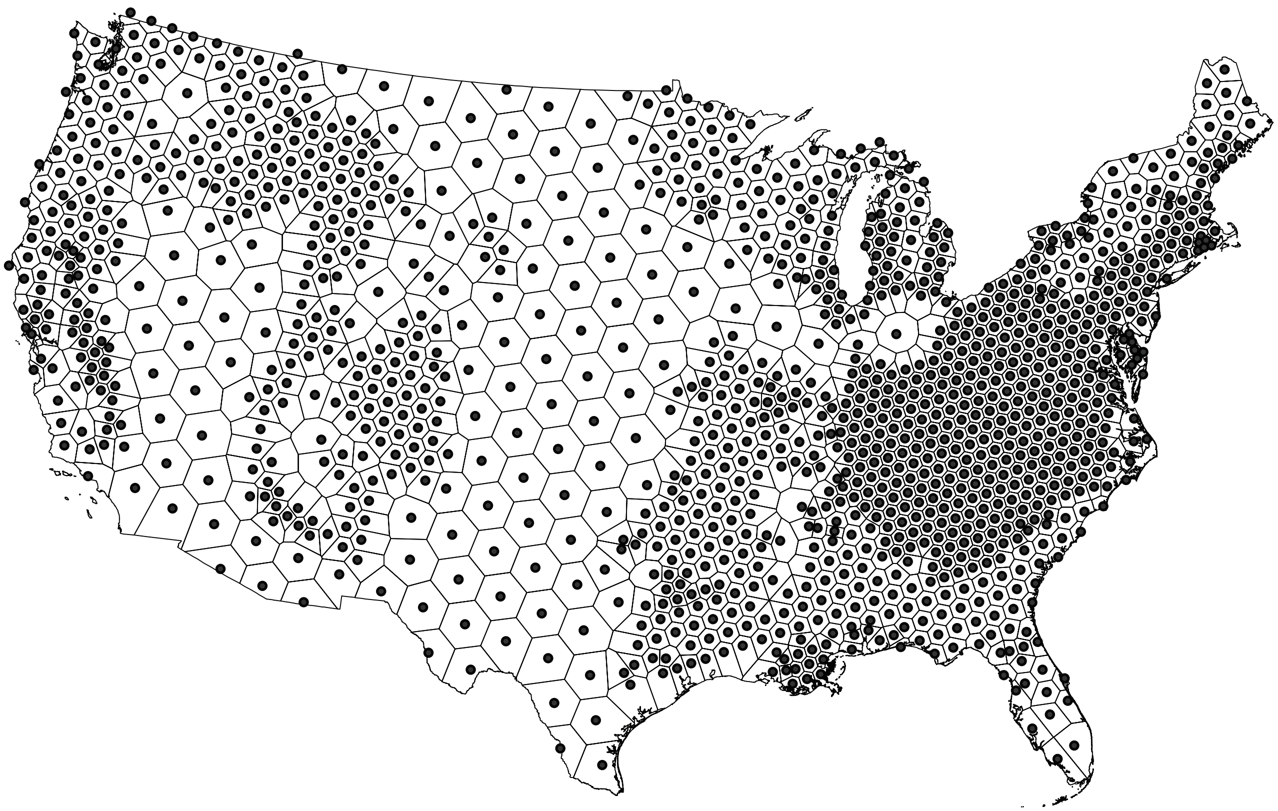

*Figure 8.1—Forest Inventory and Analysis ozone biomonitoring grid developed from the Environmental Monitoring and Assessment Program (EMAP) base grid (White and others 1992). The grid has four sampling intensities based on sensitive species and ambient ozone concentrations.*

in 1997; and the Pacific Northwest Research Station study area covers three States—California, Oregon, and Washington—with data from 2000. Procedures for biomonitoring are standardized nationally (USDA Forest Service 2006, Woodall and others 2010), using a defined temporal evaluation window to minimize variability associated with the seasonality of plant response to ozone exposure.

### Foliar Injury

Crews return to the same sites and evaluate the same species and general population of plants every year. Trained and certified in ozone injury recognition every year, the crews submit injured leaf vouchers to regional experts to validate 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 and others 2007). The site-level values describe a gradation of plant injury response that quantifies the degree of ozone injury conditions[1] on the biomonitoring plots.

### Ozone Exposure

SUM06 and N100 are two cumulative ozone exposure indices that are used to characterize ambient ozone exposures. Hourly ozone data obtained from the U.S. Environmental Protection Agency (EPA) (http://www.epa.gov/air/data/index.html) were used to interpolate an ozone exposure surface across the landscape and assign 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 was used to assign an N100 (the number of hours of ozone ≥ 100 ppb) value to each biosite and year. The SUM06 metric provides an indication of chronic ozone stress for the growing season, and N100 an indication of peak ozone concentrations.

### Analysis

Descriptive statistics presented here include the percent plots with validated ozone injury by year and region. Calculations of the average BI by year and region were also made. Additional plot-level estimates of ozone exposure and site moisture were obtained for the Northern region only to determine if fluctuations and trends in foliar injury over the 16-year period from 1994 to 2009 are correlated with trends in ozone exposure.

## RESULTS AND DISCUSSION

### Field Implementation

National field implementation began in New England in 1994 and spread south to the mid-Atlantic States, and west to the North Central States; new States entering the program every year. In the Northern Research Station study area, the number of years of biomonitoring varies from 9 to 17 depending on the start year

[1]As defined by Smith and others (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.

for each State (table 8.1) and an occasional year when sampling was interrupted. By 2002, the ozone grid was complete and all 24 States in the Northern Research Station area were participating in the biomonitoring program.

In the Southern Research Station area, the first sites were established in Alabama, Georgia, and Virginia in 1997 and 1998, with nine new States added between 1999 and 2002. Two States, Mississippi and Oklahoma, have been participating since 2009. Sites are largely absent from the coastal areas of the more Southern States due to an absence of bioindicator species in these areas, and the generally wet conditions. The Pacific Northwest Research Station initiated pilot studies in 1998 and 1999, but considers 2000 the official start year for the ozone surveys. Pacific Northwest Research Station FIA crews have been sampling without interruption for the last 10 years.

For all three FIA units, the number of biosites evaluated every year tended to stabilize in 2002, when FIA took over implementation on an improved ozone grid (table 8.2).

**Table 8.1—Number of years of biomonitoring, number of years with ozone injury, and year biomonitoring was started, by region and State, 1994–2010**

| Region and year | Number of years | | Start year[a] |
|---|---|---|---|
| | Biomonitoring | Ozone injury detected | |
| **Northeast States** | | | |
| Connecticut | 17 | 17 | 1994 |
| Delaware | 15 | 14 | 1995 |
| Maine | 17 | 9 | 1994 |
| Maryland | 17 | 17 | 1994 |
| Massachusetts | 17 | 17 | 1994 |
| New Hampshire | 17 | 15 | 1994 |
| New Jersey | 17 | 15 | 1994 |
| New York | 12 | 12 | 1999 |
| Ohio | 14 | 14 | 1997 |
| Pennsylvania | 14 | 14 | 1995 |
| Rhode Island | 17 | 17 | 1994 |
| Vermont | 17 | 17 | 1994 |
| West Virginia | 16 | 16 | 1995 |
| **North Central States** | | | |
| Illinois | 14 | 14 | 1997 |
| Indiana | 15 | 15 | 1996 |
| Iowa | 11 | 6 | 2000 |
| Kansas | 9 | 5 | 2002 |
| Michigan | 17 | 16 | 1994 |
| Minnesota | 17 | 6 | 1994 |
| Missouri | 11 | 9 | 2000 |
| Nebraska | 9 | 1 | 2002 |
| North Dakota | 9 | 0 | 2002 |
| South Dakota | 9 | 3 | 2002 |
| Wisconsin | 17 | 17 | 1994 |

*continued*

**Table 8.1 (continued)—Number of years of biomonitoring, number of years with ozone injury, and year biomonitoring was started, by region and State, 1994–2010**

| Region and year | Number of years: Biomonitoring | Number of years: Ozone injury detected | Start year[a] |
|---|---|---|---|
| **Southern States** | | | |
| Alabama | 13 | 2 | 1998 |
| Arkansas | 10 | 3 | 2001 |
| Florida | 9 | 1 | 2002 |
| Georgia | 14 | 13 | 1997 |
| Kentucky | 11 | 11 | 2000 |
| Louisiana | 8 | 3 | 2001 |
| Mississippi | 2 | 1 | 2009 |
| North Carolina | 12 | 10 | 1999 |
| Oklahoma | 2 | 2 | 2009 |
| South Carolina | 12 | 12 | 1999 |
| Tennessee | 11 | 10 | 2000 |
| Texas | 9 | 4 | 2002 |
| Virginia | 14 | 11 | 1997 |
| **West Coast States** | | | |
| California | 10 | 10 | 2000 |
| Oregon | 10 | 0 | 2000 |
| Washington | 10 | 7 | 2000 |

[a] Some States are missing interim years between start date and current year.

**Table 8.2—Number of evaluated biosites by year and by Forest Inventory and Analysis region**

| Region and year | Number of biosites evaluated: Northern | Southern | Pacific Northwest |
|---|---|---|---|
| 1994 | 118 | - | - |
| 1995 | 284 | - | - |
| 1996 | 229 | - | - |
| 1997 | 274 | 19 | - |
| 1998 | 465 | 22 | - |
| 1999 | 560 | 90 | - |
| 2000 | 559 | 178 | 70 |
| 2001 | 574 | 248 | 77 |
| 2002 | 490 | 316 | 125 |
| 2003 | 498 | 320 | 134 |
| 2004 | 494 | 351 | 130 |
| 2005 | 472 | 359 | 136 |
| 2006 | 470 | 335 | 138 |
| 2007 | 463 | 314 | 132 |
| 2008 | 457 | 314 | 129 |
| 2009 | 467 | 382 | 134 |
| 2010 | 470 | 401 | 134 |

– = No biosites evaluated.

## Air Quality and the Ozone Grid

Differences in maximum and mean ozone exposure statistics help to define the FIA regions and States in terms of ozone air quality during the growing season (table 8.3). Relatively clean air States are found in Northern New England (Maine, New Hampshire, and Vermont), the Northern Plains (Nebraska, South Dakota, and North Dakota), and the Northwest (Oregon and Washington); while moderate air quality States are found in southern New England (Massachusetts, Connecticut, and Rhode Island), the East North Central region (Illinois, Indiana, and Ohio), and the South (Georgia, South Carolina, North Carolina, Tennessee, and Kentucky). States with unhealthy air quality are in the mid-Atlantic region (Virginia, West Virginia, Maryland, Delaware, Pennsylvania, New Jersey, and New York), and the Southwest (California). Additional States, e.g., Kansas, Iowa, and the Great Lakes States (Minnesota, Wisconsin, and Michigan), tend to fall into an intermediate air quality category or have a wide range of ozone exposures from clean to moderate depending on proximity to population centers within each State.

The exposure characteristics of a given State or sub-region do not always line up with the results of the ozone survey in terms of how

**Table 8.3—Regional differences in maximum and mean ozone exposure data, 1994–2005**

| Region[a] | Range of maximum ozone exposure values (SUM06)[b] 1994-2005 | Mean value 1994-2005 | Ozone exposure category[c] |
|---|---|---|---|
| Northern New England | 8.3 - 29.2 | 6.2 | Clean |
| Southern New England | 14.9 - 34.7 | 18.0 | Moderate |
| Mid-Atlantic States | 22.2 – 71.2 | 25.9 | Unhealthy |
| Northern Plains | 7.7 – 24.2 | 6.1 | Clean |
| East North Central | 17.1 – 52.3 | 20.7 | Moderate |
| South | 20.9 – 92.8 | 16.9 | Moderate |
| Northwest | 6.5 – 25.1 | 5.9 | Clean |
| Southwest | 76.8 - 117.3 | 28.7 | Unhealthy |

[a] Regions are defined as follows. Northern New England: Maine, New Hampshire, Vermont; Southern New England: Massachusetts, Connecticut, Rhode Island; Mid-Atlantic: Delaware, Maryland, New Jersey, New York, Pennsylvania, Virginia, West Virginia; Northern Plains: Nebraska, North Dakota, South Dakota; East North Central: Illinois, Indiana, Ohio; South: Alabama, Georgia, Kentucky, North Carolina, South Carolina, Tennessee; Northwest: Oregon, Washington; and Southwest: California.
[b] SUM06 = Sum of hourly ozone concentrations ≥0.06 ppm. Maximum and mean values are calculated by State and year and then averaged for each region.
[c] Descriptive ozone exposure categories are based on mean values. Clean: SUM06 <10 ppm-hr; Moderate: SUM06 10-25 ppm-hr; Unhealthy: SUM06 >25 ppm-hr.

often ozone-induced foliar injury is detected on the ozone grid (table 8.1). For example, over the 1994 to 2010 time period, ozone injury was detected every year in almost every State in the Eastern United States, from Maine (clean) south to Georgia (moderate), and from Ohio (moderate) west to Kansas and north to Wisconsin; and in the Western United States, in Washington (clean) as well as California (unhealthy). The only States with no ozone injury or very few years with injury detected are North Dakota, South Dakota, Nebraska, Oregon, Alabama, Arkansas, Florida, Louisiana, and east Texas.

It is noteworthy from a monitoring perspective when ozone injury is detected in a State or region previously thought to be free of ozone stress, even if the injury occurs on only a small number of the bioindicator plants or sites. This is the case in the State of Washington, where the repeated detection of ozone injury at a single location is, at least in part, explained by the soil moisture conditions at the biosite, and in northern portions of Vermont, which may be influenced by polluted air masses moving north from the mid-Atlantic region or by the absence of other pollutants which react with $O_3$ and effectively remove it from the air. FIA ozone surveys also detected injury for the first time at several locations in the more northern portions of California (Campbell and others 2007) starting in 2005. In the many States where ozone injury is detected every year, or almost every year, the survey results underscore that a large area of forest land in this country, in both the East and the West, is subject to levels of ozone pollution that may negatively affect the forest ecosystem.

Every year, the EPA publishes an ozone exceedance map (http://www.asl-associates.com/revised_8-hr_075.htm), which highlights the counties in each State that are out of compliance with the National Ambient Air Quality Standard (NAAQS) for $O_3$ set to protect vegetation from harmful effects. In preparation for the 2007 review of the ozone standard, the EPA overlaid Forest Service biomonitoring data with the exceedance map and found that there were many counties in compliance with the existing $O_3$ standard where FIA field crews were routinely documenting ozone injury to sensitive plants (U.S. EPA 2007). This study was one of several that served as evidence that the secondary ozone standard needed to be strengthened, a recommendation that was adopted by the EPA Clean Air Scientific Advisory Committee and the EPA Administrator, and that became law in 2008. Currently, there is a new proposal by the EPA to establish a distinct cumulative, seasonal "secondary" standard, referred to as the W126 index, which is designed to protect sensitive vegetation and ecosystems, including forests, parks, wildlife refuges, and wilderness areas (http://www.epa.gov/air/ozonepollution/actions.html#jan10s). The multi-year findings of the FIA field-based biomonitoring program suggest that this protective action has scientific merit.

## Trend Data

**Air**—EPA reports that ground-level $O_3$ concentrations are 10 percent lower in 2008 than in 2001 across the Nation with the most notable decline occurring after 2002 (U.S. EPA 2010[2]). Still, there are localized areas such as parts of the Los Angeles air basin, and in or near Atlanta, where ground-level $O_3$ is increasing. There are also growing concerns about ozone air quality in parts of the Interior United States (e.g., Wyoming, Utah, and Idaho), where increased activity associated with the natural gas industry is contributing to previously undocumented peaks in localized $O_3$ concentrations. A comparison of trend data from California versus the Eastern United States shows that the majority of ozone improvement in recent years occurred in the East as a result of successfully implemented pollution control measures leading to large reductions in $NO_x$ emissions (ozone precursor pollutants) beginning in 2003.

**Injury**—The percent of injured biosites indicates how widespread ozone injury conditions are for the Northern Research Station, Southern Research Station, and Pacific Northwest Research Station regions by year from 1994 to 2010 (fig. 8.2). Percent of injured sites for the North fluctuated from one year to the next showing an overall downward trend over 17 years of biomonitoring. The highest percent injury occurred in 1994 (55.9 percent), 1998 (48.4 percent), and 2000 (47.6 percent), the lowest in 2008 (23.2 percent) and 2009 (19.9 percent). In the years prior to 2003, percent injured plots averaged above 30 percent for 7 of the 9 years, and for only 3 of the 8 years from 2003 on. Although the overall trend was downward, percent injured plots was back up above 30 percent in 2010, perhaps signaling a change in injury conditions.

For the first seven sample years in the South (1997 to 2003), the percent injured biosites was often similar to those in the North and the overall trend was downward. Values were

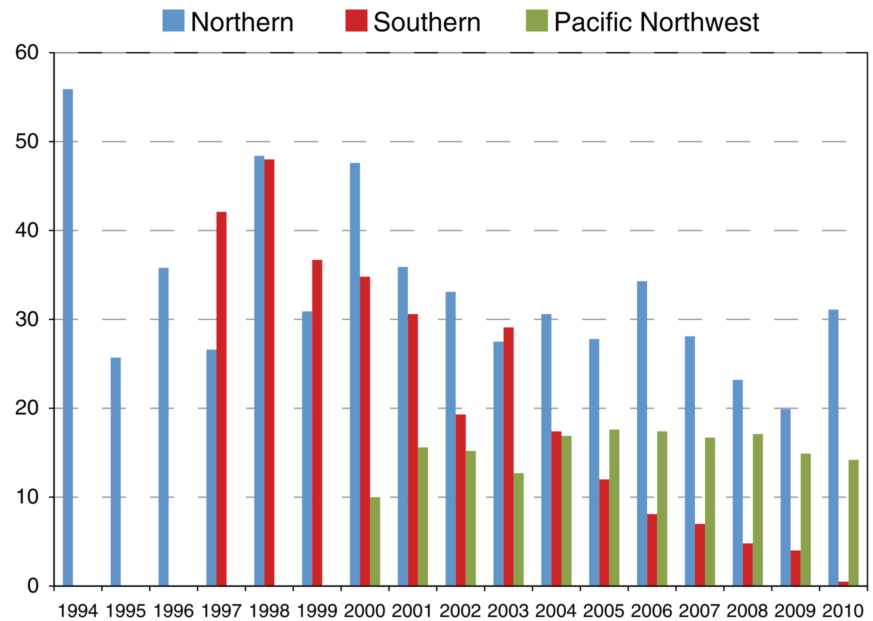


*Figure 8.2—Ozone injury to forest plants in the United States by Forest Inventory and Analysis region: percent injured plots by year, 1994 to 2010.*

[2] http://www.epa.gov/airtrends/2010/.

relatively high (>30 percent) in 1997 through 2001, dropping to 19.3 percent in 2002, increasing again to 29.1 percent in 2003 before dropping sharply to <10 percent in 2006, and continuing to decline to a minimum percent injured plots (<1 percent) in 2010. In contrast, the percent injured plots in the Pacific Northwest fluctuated between 10 and 17 percent for all 11 years of biomonitoring showing, if anything, a slight increasing trend in percent injured biosites over the 2000 to 2010 time period.

Even more than percent injured biosites, the BI values are expected to fluctuate from one year to the next in response to variable ozone exposure levels and other factors that influence ozone flux. BI values provide a comparative measure of injury severity with increasing values indicating an increased risk of probable ozone impacts to sensitive trees and ecosystems (Smith and others 2007). Site-level BI data for the Northern Research Station are presented with estimated SUM06 and N100 data (fig. 8.3) to

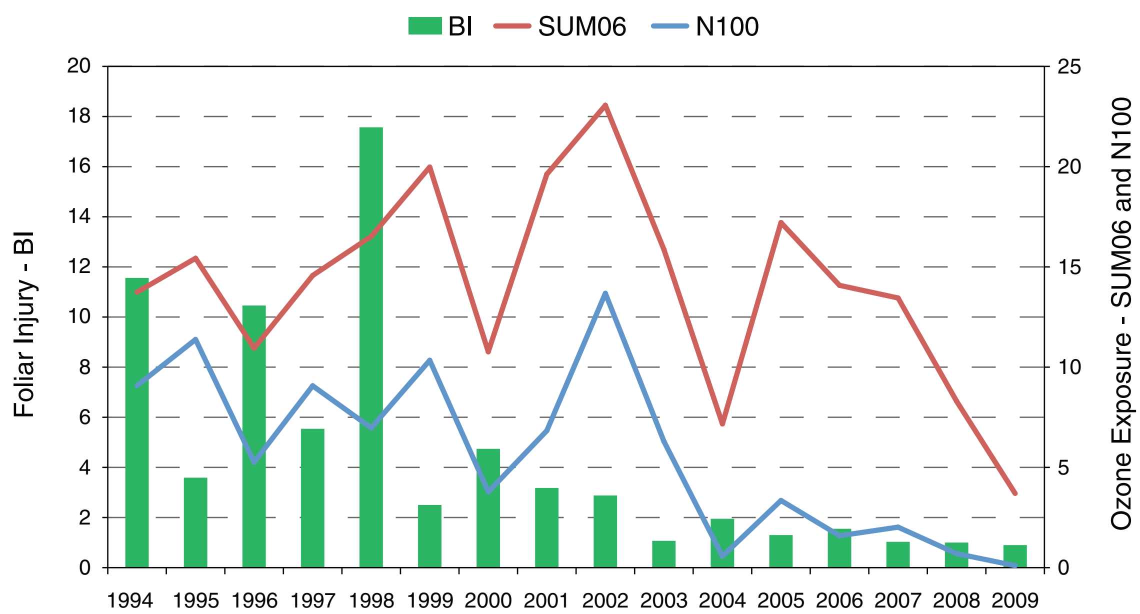


*Figure 8.3—Trends in ozone-induced foliar injury (BI) and ozone exposure (SUM06 and N100) in the Forest Inventory and Analysis Northern Region from 1994 to 2009.*

show possible associations between foliar injury and ozone exposure over the 1994 to 2009 time period.[3]

Mean regional BI values are relatively high in 1994 but fluctuate down and up again over the next 4 years reaching a maximum value of 17.6 in 1998 before dropping off sharply in 1999. BI increases in 2000 but then starts a downward trend to relatively low values suggesting very little risk of ozone impact on a regional scale from 2003 on. Both SUM06 and N100 also fluctuate from one year to the next, but there is little direct association between injury and exposure. In 1995 and 1999, for example, BI values drop off from the previous year even though ozone exposure values are increasing. This can be explained by the fact that 1995 and 1999 were two of the driest years over the 1994 to 2009 survey period especially in the high ozone areas of the Northern Research Station such as the mid-Atlantic States (Smith and others 2008, Smith 2009). Dry conditions caused plant stomata to close, thus preventing ozone uptake and subsequent injury. This result demonstrates the biological relevance of the biomonitoring data since the BI values reflect how much ozone gets inside the plant rather than what can be measured in the ambient air.

Focusing on trends, it is clear that injury severity and the implied risk of ozone impact as described by the BI data have been steadily decreasing in recent years. As suggested earlier, ground-level ozone concentrations have also been decreasing in the East since 2002, peak concentrations (N100) much more so than the more moderate concentrations captured in the SUM06 statistic. In this sense, the trend in BI and percent injured plots for the North region mirrors the ozone exposure data showing an overall declining trend from 1994 through 2009.

BI data from the South are not available for the most recent years (2008 and 2009), but for the 1997 to 2007 time period there is no obvious decline in BI values (fig. 8.4). In contrast, the

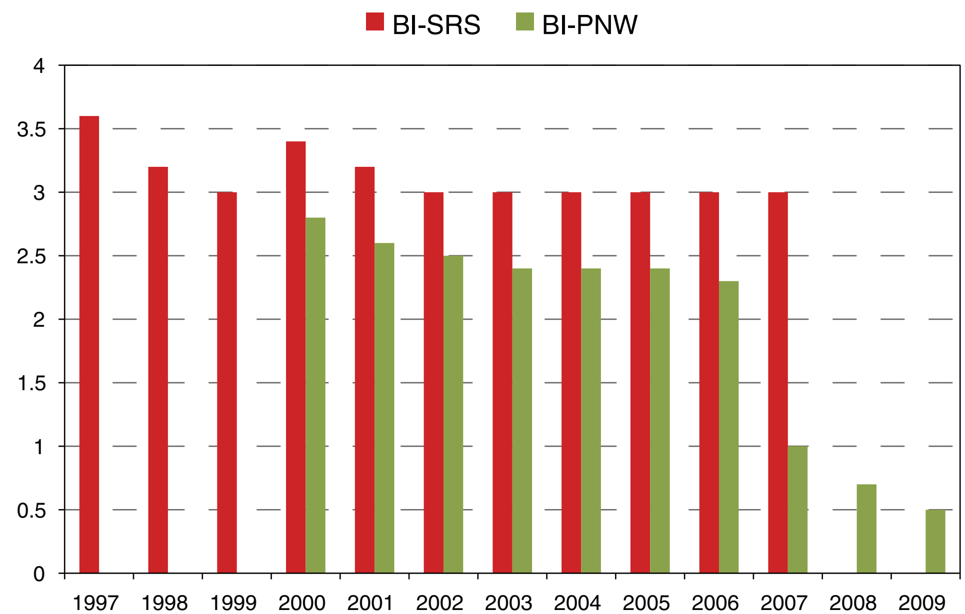


*Figure 8.4—Trends in ozone-induced foliar injury (BI) in the Southern Research Station Forest Inventory and Analysis and Pacific Northwest Research Station Forest Inventory and Analysis regions from 1997 to 2009.*

[3]Air quality data for 2010 were not available from the EPA for inclusion in this report.

BI data for the Pacific Northwest does suggest a decreasing trend in foliar injury severity and probable ozone impact, especially for California, where the majority of sites and plants with injury are located.

## Injury and Exposure—Regional Summaries

**Pacific Northwest Research Station Study Area—** Reporting on results for 2000–05, Campbell and others (2007) noted that ozone injury occurs frequently on biosites in California demonstrating that ozone is present at toxic levels. Injury generally correlated with ambient ozone concentrations such that areas with the highest SUM06 values had the highest percent injured sites and highest mean BI. Although the highest percentage of biosites with injury occurred in southern California, new areas of previously unreported injury were detected in northern parts of the State. This early study did not discern any trends in ozone injury between 2000 and 2005. However, with the additional data from 2006 through 2010, we can now suggest that even though the percent injured biosites has not changed much, there is a discernible downward trend in injury severity.

**Southern Research Station Study Area—**Rose and others (2009) examined biomonitoring results for 2002–06 and concluded that even though ambient ozone concentrations were reportedly on the decline in the South during that time period, ozone-induced foliar injury was still occurring every year, particularly in Georgia and South Carolina where BI values were highest. However, a 5-year average of the BI data suggested that most of the forest land in the South is at low risk of ozone impact. The authors suggest that a prolonged region-wide drought may have served to protect the southern forests from ambient ozone concentrations and lower the regional mean BI values. Examining relationships between injury and exposure, they were able to demonstrate that the difference between sites with and without injury had more to do with site moisture conditions, or the combination of site moisture and ozone exposure, than with ozone exposure alone. No trend data were reported. However, the findings reported here suggest that the percent injured biosites has been declining steadily since 2003.

**Northern Research Station Study Area—**Differences in calculated mean values for percent injured biosites and average BI suggest that ozone stress is highest in the mid-Atlantic States, similarly moderate in the east North Central States and southern New England, and relatively low in northern New England and the Northern Plains States. Region-wide trends suggest that ozone injury is declining possibly in response to a decline in peak ozone concentrations in normally high ozone areas. Biosites with injury occur at all SUM06 and N100 exposures, but when SUM06 and N100 are relatively low, the percentage of uninjured sites (BI=0) is much greater than the percentage of injured sites (BI>0); and at all SUM06 and N100 exposures, when site moisture is limiting, the percentage of uninjured sites (BI=0) is much greater than the percentage of injured sites (BI>0). These findings are in accordance with results reported by Campbell and others (2007) for western forests. They reported a general association of injury and exposure, but found that when looking at individual biosites, high levels of injury can occur in areas of low ozone exposure and low levels of injury can occur in areas of high ozone exposure.

## SUMMARY AND CONCLUSIONS

Ozone has long been considered one of the most widespread and damaging air pollutants to forest health (Percy and others 2003). In addition, it acts as a greenhouse gas contributing significantly to atmospheric warming on a global scale. Campbell and others (2007) make the point that although air quality is improving in the United States as result of emission reductions, ozone standards meant to protect plant health are still being exceeded in many areas. Regionally, there are increased sources of ozone pollution as populations increase and more ozone precursor pollutants are moving into the United States from Asia via long-range transport. Ozone precursor pollutants are also expected to increase with the regional expansion of the oil and gas industry both in the Interior States and in the Northeastern United States. On a global scale, as the climate continues to warm, we can expect ground-level ozone concentrations to increase in all areas due to the fact that $O_3$ formation is driven, in large part, by high sunlight intensity and warm temperatures.

In this report, the ozone indicator data establish the fact that plant-damaging concentrations of $O_3$ are present in U.S. forests, occurring frequently, if not every year, in most States in the Northern Research Station, Southern Research Station, and Pacific Northwest Research Station regions. Region specific studies have demonstrated a general association between injury and exposure such that areas with the highest SUM06 values have the highest percent injured sites and mean BI. In Eastern forests, annual fluctuations in injury are strongly influenced by both exposure and site moisture conditions. Years of extreme drought result in a sharply reduced BI despite high ozone exposures. Trend data suggest that ozone stress is decreasing over time in all regions particularly in recent years possibly due to a national declining trend in peak ozone concentrations. This trend may reverse with the combined pressure of increasing population, increasing ozone precursor pollutants, and rising temperatures during the growing season.

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