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Ozone Bioindicators and Forest Health: A Guide to the Evaluation, Analysis, and Interpretation of the Ozone Injury Data in the Forest Inventory and Analysis Program

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Abstract

In 1994, the Forest Inventory and Analysis (FIA) and Forest Health Monitoring programs of the U.S. Forest Service implemented a national ozone (O_3) biomonitoring program designed to address specific questions about the area and percent of forest land subject to levels of O_3 pollution that may negatively affect the forest ecosystem. This is the first and only nationally consistent effort to monitor O_3 stress on the forests of the United States. This report provides background information on O_3 and its effects on trees and ecosystems, and describes the rationale behind using sensitive bioindicator plants to detect O_3 stress and assess the risk of probable O_3 impact. Also included are a description of field methods, analytic techniques, estimation procedures, and how to access, use and interpret the ozone bioindicator attributes and data outputs such as the national ozone risk map.

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Cover Photos

Front top right courtesy of Pat Temple, U.S. Forest Service; all others courtesy of Gretchen Smith, University of Massachusetts.

Front
- Top left: ozone injury assessment along a field edge at a biosite in New Hampshire.
- Top right: ozone chlorotic mottle on ponderosa pine in California.
- Bottom left: field evaluation of black cherry at a biosite in Vermont.
- Bottom right: leaves with obvious injury collected in the field for quality assurance purposes.

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- Left: plant press used in the field to preserve leaf samples for later examination by regional experts.
- Right: hand lens used in the field for close examination of leaves for ozone injury.

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INTRODUCTION

The Montreal Process was formed in 1994 to develop an internationally agreed upon set of criteria and indicators for the conservation and sustainable management of temperate and boreal forests (Anonymous 1995). In response, the Forest Inventory and Analysis (FIA) and Forest Health Monitoring (FHM) programs of the U.S. Forest Service implemented a national ozone (O_3) biomonitoring program to address specific questions about the area and percent of forest land subject to levels of O_3 pollution that may negatively affect the forest ecosystem. This is the first and only nationally consistent effort to monitor O_3 stress on the forests of the United States. This program provides critical baseline information on the current status of O_3 air quality and the potential effects of O_3 on forest health and productivity.

This report provides background information 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 the documentation of the field and laboratory procedures for data collection and quality control. Emphasis is placed on describing generalized approaches for summarizing, analyzing, and interpreting the O_3 bioindicator attributes and discussing the strengths and limitations of the data. Detailed information on the sampling and estimation techniques described in this report has been published elsewhere (Smith et al. 2007). This report is intended to educate and inform FIA/FHM analysts and other researchers interested in ozone and forest health, and provide guidance on ways to incorporate ozone bioindicator data into reports and research studies.

Program History

Beginning in the 1990s, FHM developed, tested, and implemented a suite of forest health indicators to respond to emerging demands for an assessment of the current condition and long-term sustainability of the Nation's forests (Lewis and Conkling 1994, Smith 2002). The ozone indicator or ozone biomonitoring program, as it is referred to in this report, was part of this new, large-scale, health-based monitoring effort along with crown condition, lichen abundance and diversity, vegetation structure and diversity, down woody materials, and soil properties. Within the FHM program, the ground surveys designed to collect baseline information on the forest health indicators and detect changes from those baselines over time are referred to as Detection Monitoring (http://fhm.fs.fed.us/fact/03/dm.pdf). When a potential forest health concern has been identified on Detection Monitoring ground plots, Evaluation Monitoring studies are used to examine the extent and severity of the problem and to investigate probable cause.

In 2001, the FHM health-based indicators were integrated into FIA, which has served as the primary source of information on the forest resources of the United States for more than 70 years (McRoberts et al. 2004). The design of the joint FHM and FIA monitoring programs has been described elsewhere (http://fia.fs.fed.us/library). Aspects of the FHM/FIA merger that are relevant to the ozone biomonitoring program are the integrated forest inventory and forest health plots known as the Phase 2 (125,000 plots nationally) and Phase 3 plots, respectively. In Phase 2 (P2), field crews collect data on more than 300 variables related to land ownership, tree species, tree size, and tree condition. Phase 3 (P3) plots, a subset of P2 plots, are measured for the broad suite of forest health indicators referred to in the previous paragraph. The ground survey portion of the FHM Detection Monitoring program is synonymous with P3 in FIA. The data collected on P3 plots provide estimates of health and condition for the P2 sample (Bechtold and Patterson 2005).

OZONE THE AIR POLLUTANT

Ozone, an extremely reactive colorless gas, is a natural component of the atmosphere that is always present at low concentrations. In the upper atmosphere (stratosphere), the beneficial O_3 layer screens out high energy radiation from the sun. In the lower atmosphere (troposphere), O_3 occurs largely because of human activities and is considered an air pollutant. It is a major constituent of photochemical smog and part of the mix of greenhouse gases that contribute to global climate warming (Krupa and Legge 1995). Tropospheric O_3 is toxic to human beings, plants, and many other life forms. Before the industrial age, the lower atmosphere was relatively free of O_3. Today, this toxic contaminant is found across all geographic and political boundaries and in areas previously believed to be pristine. Plant scientists consider ground-level O_3 the most pervasive air pollutant worldwide and a threat to world food, fiber, and timber production and conservation of natural plant communities (Percy et al. 2003a). Trends in surface O_3 concentrations indicate an increase in background O_3 concentrations over much of the world and a huge increase in the extent of forest areas at risk of O_3 exposure[1].

Ozone Formation, Sources, and Transport

Ground-level O_3 is a secondary pollutant, formed from the reactions of precursor pollutants, primarily nitrogen oxides (NO_x) and volatile organic compounds (VOCs) in the presence of sunlight.

$$VOC + NO_x + Sunlight = O_3$$

The formation of O_3 can be simplified to a reversible reaction between oxides of nitrogen and elemental oxygen driven by the energy of sunlight. The reversible reaction results in no net gain of O_3 due to the instability of the O_3 molecule. However, when VOCs are present, they interfere with the reverse reaction resulting in a buildup of O_3 in ambient air. This is known as the photochemical oxidation cycle. The complex sequence of reactions that define this cycle and promulgate surface O_3 concentrations is described by Krupa and Manning (1988) and Percy et al. (2003a). The simplified reaction described above provides enough information to characterize O_3 sources and sinks and their relation to forest health.

Sources of ground-level O_3 are both natural and human-made. Natural sources that contribute to background O_3 concentrations include lightning during thunderstorms and downward intrusions of O_3 from the upper atmosphere. Human-made sources of O_3 precursor molecules include highway vehicle exhaust (the single most important source), emissions from industrial facilities, combustion from electric utilities, gasoline vapors, and chemical solvents. Biogenic emissions from plants and trees (e.g., isoprene and monoterpenes) can be an important source of VOCs on hot, bright days in heavily vegetated areas. However, natural emissions rarely result in harmful O_3 levels such as those associated with the combined emissions of VOCs and NOx from anthropogenic sources (Percy et al. 2003a). Many urban areas are characterized by peak O_3 levels, but even rural areas with relatively low emission sources experience high O_3 levels as polluted air masses are transported hundreds of miles downwind of population centers (U.S. EPA 2004). The average lifetime of O_3 is about 16 hours, allowing time for air movement from urban sources to forest sinks. Long-range transport of O_3 and O_3 precursors from urban to rural areas contributes to the regional character of O_3 pollution, making it difficult to contain or localize either the sources or the effects.

[1]Key resources and Web sites on O_3 pollution and effects are listed in Appendix 1.

In a typical O_3 season, monthly average O_3 concentrations increase from January to June, stabilize at relatively high levels during the summer, and then decrease again from October through the year's end. This pattern is governed primarily by seasonal changes in sunlight intensity and air temperature, rather than seasonal changes in the amount of precursor emissions. Thus, periods of high O_3 concentration coincide with the growing season when plants are actively growing and most vulnerable to injury. During the warm summer months, stagnant air masses, varying in duration from one to several days, can prevent the upward dispersion of pollutants causing O_3 buildup and high surface O_3 concentrations on a regional scale. From May through September, forests are exposed from a few hours to several days of relatively high surface O_3 concentrations interspersed with longer periods of relatively low O_3.

In a typical urban atmosphere, O_3 concentrations over the course of the day show a typical diurnal pattern. O_3 concentrations increase rapidly in the early morning rush hour between 0800 and 1200, reach peak levels between 1200 and 1500 when the intensity of solar radiation is at a maximum, and then decrease into the evening hours with the loss of sunlight and precursor emissions. Rural areas throughout the urbanized corridors of the U.S. also experience this diurnal fluctuation in O_3 concentrations. However, in some upper elevation forests removed from the effects of fluctuating emission sources, O_3 concentrations can remain relatively steady and moderately high through the day and night.

Ambient Concentrations and Exposure Patterns

The U.S. Environmental Protection Agency (EPA) has designated O_3 one of six criteria air pollutants that must be regulated to reduce the risk of harmful effects to human beings, agricultural crops, forest ecosystems, and other resources. Regulation generally takes the form of emission control strategies for precursor pollutants. EPA has established a national ambient air quality standard (NAAQS) for O_3 that is intended to bring O_3 air pollution under control. However, as of December 2007, 347 counties across the U.S. were out of compliance with the 8-hr NAAQS for O_3 (http://www.asl-associates.com/).

Ozone concentrations in ambient air are measured in parts per million (ppm) but reported in parts per billion (ppb) so that values can be expressed as whole numbers. Air quality monitoring stations operated by EPA are located across the U.S., mainly near population centers where air quality effects on human health are paramount. Routine O_3 monitoring is summarized as hourly average O_3 concentrations. When forecasters report a smog alert on a summer day, they are indicating that average hourly O_3 concentrations are expected to exceed 84 ppb over an 8-hr period. A 1-hr ozone standard has been in place since 1979, and an 8-hr ozone standard has been in place since 1997. The 1-hr standard is met when the number of days per calendar year with maximum hourly average concentrations above 120 ppb is equal to or less than 1. The 8-hr standard is met when the 3-year average of the annual fourth highest daily maximum 8-hr average concentration is less than 80 ppb[2]. During some years, more than half of the states in the U.S. exceed the 8-hr standard more than 5 days (some states more than 20 days) during the growing season (http://airnow.gov/).

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[2]On March 12, 2008, EPA announced a revised 8-hr O_3 standard of 0.075 ppm. Details on the 2008 revised O_3 standard are provided in Appendix 1. The 1997 standard remains in place for implementation purposes as EPA undertakes rulemaking to address the transition from the 1997 O_3 standard to the 2008 O_3 standard. For this reason, the text of this document was not modified to reflect the March 12 announcement.

In the U.S., trends in ground-level O_3 concentrations indicate that peak values, or maximum 1-hr O_3 concentrations, have been reduced in those areas where O_3 precursor control programs are in place. However, control programs have had little impact on moderate O_3 concentrations, and background O_3 levels are increasing. A typical average background concentration of 30 to 40 ppb O_3 is found essentially everywhere in the world today and is expected to increase by between 0.3 and 1.0 percent per year for the next 50 years. Historically, the highest O_3 concentrations are found at urban sites and range from 80 ppb in the interior U.S. to 200 ppb in the West and Northeast. However, since 1996 (Percy et al. 2003a), 1-hr O_3 concentrations in rural areas have been greater than the corresponding values at urban sites. Between 1992 and 2001 average 8-hr O_3 levels measured in national parks increased by nearly 4 percent. This shift in greater O_3 concentrations from urban to rural areas increases the regional expanse of plant-damaging O_3 concentrations and puts more forest areas at risk.

All hourly average O_3 concentrations have the potential for impacting vegetation, yet the higher levels (>80 ppb) are often considered a greater threat to forest health than mid (60-80 ppb) to low (<60 ppb) levels. This is reflected in three cumulative O_3 exposure indices that are often used to characterize ambient O_3 exposure data: SUM06, W126, and N100. The SUM06 exposure index is defined as the sum of all hourly concentrations greater than or equal to 0.06 ppm O_3, which implies an injury exposure threshold of 60 ppb, a specific 1-hr O_3 value above which injury is expected. The W126 statistic does not use an exposure threshold but rather sums all hourly average O_3 concentrations: both the lower, less biologically effective concentrations, and the higher values (>40 ppb), which are given greater weight. The N100 statistic represents the number of hours with O_3 concentrations at or above 100 ppb. The Federal Land Manager Air Quality Related Values Workgroup (FLAG) recommends the combined use of W126 and N100 values to provide a biologically meaningful summation of hourly O_3 data (USDI 2000). Summary exposure indices can be integrated over a 24-hr period or over the 12-hr daylight period, and over an entire year or over the length of the growing season. When integrated over the daylight period of the growing season at the scale used in this document, the W126 and SUM06 indices are essentially interchangeable[3].

A typical O_3 season for the continental U.S. (see Appendix 2), whether viewed as a map of county-level exceedance data, or an interpolated cumulative exposure surface, shows many parts of the country and much of the forest land subject to ambient O_3 concentrations that exceed known injury thresholds for sensitive plants. The EPA Clean Air Scientific Advisory Committee (CASAC), the Northeast States for Coordinated Air Use Management (NESCAUM), and many state air quality agencies report that the current NAAQS for O_3 provides a poor measure of seasonal ground-level O_3 exposures, correlates poorly with plant stress, and is generally inadequate to protect natural and agronomic ecosystems (http://www.dnr.wi.gov/air/, www.nescaum.org). The consensus recommendation for a new ozone standard, based on a large body of scientific evidence, is that EPA should adopt the cumulative W126 secondary ozone standard of 7-21 ppm-hr for the 3 highest consecutive months during the growing season of one calendar year.

On March 12, 2008, EPA announced a revision of the primary (human health-related) and secondary (vegetation effects) ozone standards. EPA decided to adopt an 8-hr O_3 standard

[3]Injury thresholds for the SUM06, W126, and N100 indices of exposure are listed in Appendix 1.

of 0.075 ppm rather than the W126 cumulative O_3 exposure index described above. This represents a strengthening of the O_3 standard and recognition that the 1997 standard (0.08 ppm) did not adequately protect vegetation from O_3 exposure even though the form and level of the newly revised standard did not meet the consensus recommendations published by EPA's National Center for Environmental Assessment (U.S. EPA February 2006a,b,c) and EPA's Office of Air Quality Planning & Standards (U.S. EPA July 2007). Information on the O_3 standard setting process and links to scientific review documents are available online (http://www.epa.gov/groundlevelozone/).

Ozone Uptake and Plant Response

Open stomata provide the pathway for O_3 entry into the leaf. Once inside the leaf, O_3 immediately forms toxic derivatives that react with many components of the leaf cells. Many studies of foliar response to O_3 show that the cell membranes suffer the most injury characterized by changes in permeability and leakiness to important ions such as potassium (Fuhrer and Booker 2003, Krupa et al. 1998, Pell et al. 1997). Internal membranes are less affected because the toxic oxidants derived from O_3 are diluted and absorbed from the outside toward the inside of the cells. The first reaction to injury by oxidants is loss of chlorophyll, increased fluorescence, and changes in energy levels. As injury progresses and antioxidants come into play, carbon fixation is reduced, foliar and root respiration is increased, and there is a shift in the partitioning of carbon into different chemical forms and allocation patterns. At the most basic cellular level, a plant injured by O_3 is not the same as a plant without injury.

Plant response to O_3 is understood as an interaction among a triad of factors involving the susceptibility of the host plant, the concentration and duration of exposure to O_3, and the external cultural environment in which the host plant is growing (Fig. 1). These interacting factors compose a modified disease triangle as defined by Houston (1981) to describe the development of stress-induced disease in individual trees and tree populations, and as applied by Kohut (2005 and 2007) to ozone injury assessment. In this context, O_3 at certain concentrations is understood as the primary pathogen or causal agent capable of causing injury or disease under favorable conditions defined by the susceptibility of the host plant and predisposing cultural conditions. Ozone susceptibility varies with the genotype, genus, species, cultivar, or variety of the host plant. Age of the plant and phenological state of development also affect susceptibility. Cultural conditions that influence plant-pollutant interactions include nutrition (primarily nitrogen), moisture levels (primarily atmospheric humidity and soil moisture), solar radiation, temperature, and day length. Soil moisture status is often considered the most critical influencing factor because stomatal closure during periods of drought or low soil moisture can severely limit gas exchange (O_3 uptake). Plant response to O_3 is greatest and O_3 injury conditions optimal when a sensitive genotype, at a susceptible stage of development, is exposed to elevated O_3 concentrations in a predisposing environment for the minimum time period required for physiological dysfunction to occur. The result is an ozone-induced disease condition (Hepting 1968), which may or may not lead to significant impacts on the forest ecosystem (Smith 1974).

Some plants are ozone sensitive, while others show resistance to O_3 pollution or are able to tolerate it (Davis and Wilhour 1979, Dowsett et al. 1992, Neufeld et al. 2000, Temple 1989). Variation in response to O_3 is both interspecific and intraspecific, indicating that ozone

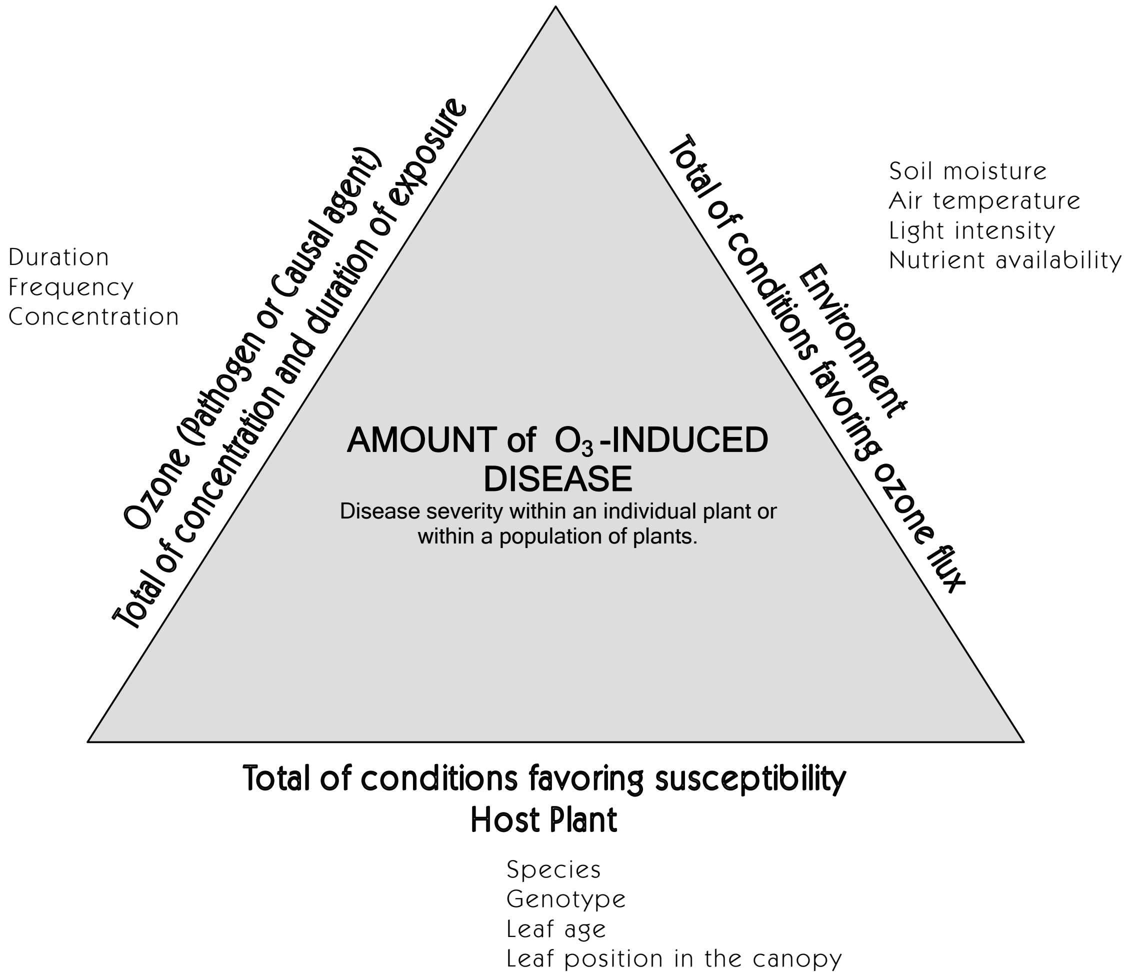

Figure 1.—Ozone and the disease triangle concept: A sensitive genotype, at a susceptible developmental stage, is exposed to elevated O_3 concentrations in a predisposing environment for the minimum time required for physiological dysfunction to occur. The result is an ozone-induced disease condition that may or may not lead to significant impacts on the forest ecosystem. Each component of the triangle displays considerable variability, and as one component changes, it affects the degree of disease severity within an individual plant and within a plant population.

sensitivity has a strong genetic component. Ozone-sensitive plants are divided into two groups: those that show a visible foliar response to O_3, and those that sustain injury or growth loss in the absence of visible symptoms (Reich and Amundson 1985). External growth conditions that cause stomates to close will prevent O_3 uptake and injury (Mansfield 1998, Schaub et al. 2003). Stomatal conductance is one of two factors regulating exposure-response relationships; the other factor is atmospheric conditions (e.g., air temperature and wind conditions) that regulate the rate of O_3 deposition onto the plant canopy.

Genetic variation in response to O_3 implies that O_3 pollution is capable of influencing plant populations through natural selection. Although challenging to prove with long-lived tree species, the selection pressure of ozone has been demonstrated with herbaceous plant material (Heagle et al. 1991, Lyons et al. 1997). In common plantain (*Plantago major*) and white clover (*Trifolium repens*), O_3 exposures under controlled conditions caused changes that increased the level of resistance to O_3 by reducing the genetic diversity of the plant populations (Kohut

2003). A similar effect has been postulated for white pine[4] in which the most ozone-sensitive genotypes (chlorotic dwarfs) appear to have been eliminated, leaving the residual population more tolerant of O_3 stress. The selective force of O_3 on aspen populations has also been demonstrated (Berrang et al. 1986, Karnosky et al. 2003).

Ozone exposure, ozone dose, and ozone flux are different terms used to describe plant/pollutant interactions. Ozone exposure refers to the concentration of O_3 present in ambient air, which cannot be assumed to represent the concentration available at the plant canopy for uptake and injury. Ozone dose refers to the amount of O_3 taken up into plant tissue, and ozone flux refers to the rate at which plant surfaces absorb O_3. Ambient ozone exposure may be relatively high, but if the stomates are closed, the ozone dose will be insignificant.

EVIDENCE THAT OZONE INJURES TREES

Scientists use various methods to study O_3 impacts on trees. Observational field studies documenting the visible foliar response of trees to ambient ozone concentrations are most common. Researchers also test for physiological sensitivity to O_3 and use exposure chambers to examine growth effects. Experimental studies are generally conducted on tree seedlings in a noncompetitive environment, and results are not necessarily transferable to mature trees growing in the forest. Recent developments using chamberless free air exposure systems provide an opportunity for longer term studies on larger plant material growing in stand-like conditions. The following observations have been made about the effects of ambient ozone concentrations on tree species:

- More than 50 tree species from eastern and western forest types have been identified as ozone sensitive based on foliar injury symptoms. Symptoms are prevalent both on young trees and in the canopies of mature trees.

- Ozone can affect the genetic base of sensitive species through the elimination of sensitive clones and hypersensitive genotypes in high O_3 areas.

- Ozone can reduce carbon fixation (photosynthesis), increase foliar and root respiration, shift the partitioning of carbon into different chemical forms, and disrupt carbon and nutrient allocation patterns.

- Ozone can suppress the movement of carbon to the roots, causing reductions in root biomass and effects on root function including reduced ability to form mycorrhizal associations and use water and nutrients efficiently.

- Ozone can alter tree physiology so that sensitive species are more susceptible to secondary stresses including insects, diseases, and weather extremes such as cold or drought.

- Ozone can alter the survivability of sensitive species in mixed forest stands so that the structure and function of the ecosystem are permanently changed.

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[4]The scientific names of tree and shrub species referred to in this report are listed in Appendix 4.

These statements are elaborated on in this report, starting with foliar injury effects and ending with documented effects on whole plant communities. Studies on individual tree species that have received most of the attention in the published literature are emphasized. The challenges of working with natural systems under ambient conditions of ozone exposure to assess and predict ozone impacts are discussed. For additional detail and a more comprehensive list of citations, see the 2006 EPA ozone criteria document available online at http://www.epa.gov/epahome/index.html. This document evaluates all the latest peer-reviewed data on ambient ozone environmental effects on vegetation and ecosystems, and it is a good source of information for researchers interested in stand-level and ecosystem-level modeling. There are also published reviews by Chappelka and Samuelson (1998), McLaughlin (1985), Miller et al. (1996), Percy et al. (2003a), and Karnosky et al. (2007). Chappelka and Samuelson (1998), who focus on the eastern U.S., and Percy (2003a), who looks at a more global perspective, provide an excellent summary of sources of error and uncertainty inherent in field assessment studies. Similar analytical concerns related to ozone injury assessment in western pine forests are addressed by Miller et al. (1996). Karnosky et al. (2007) focus ahead on ecosystems and future research needs.

Foliar Injury

Ozone cannot be identified as a causal agent of stress or disease for a given tree species unless the cause and effect relationship between the host species and O_3 has been established under controlled conditions of growth and exposure. Controlled fumigation studies were used early on to identify a large number of tree species as ozone sensitive based on foliar response. Visible symptoms on broadleaf plants and tree species are characterized primarily by changes in pigmentation that appear under magnification as small red, purple, or black stipples on the upper leaf surface. On conifers, the two most common symptoms are chlorotic mottle and tipburn. For both broadleaf and coniferous trees, injured leaves and needles may drop prematurely. Appendix 3 provides images of classic ozone injury on a variety of tree species and bioindicator plants, and Appendix 4 contains a comprehensive list of tree and shrub species identified as O_3 sensitive based on foliar injury response.

Visible foliar injury is categorized as either acute or chronic. Acute injury is normally associated with short exposures (hours) to relatively high ozone concentrations (>80 ppb) and usually appears 24 hr after exposure. Chronic injury, whether mild or severe, is associated with long-term or intermittent exposures to relatively low ozone concentrations (<60 ppb) over the entire growth cycle or lifespan of the plant. Acute injury symptoms normally involve significant pigment changes and cell death, and the injury may be bifacial or involve tip-dieback on conifers. Chronic injury symptoms develop slowly within days or weeks following exposure and are characterized by a general upper leaf surface pigmentation and premature leaf senescence. On conifers, chronic injury develops as mottled chlorosis of the needle tip, progressing basipetally until the entire needle is affected (Stolte 1996). Most forests in the U.S. are subject to chronic ozone exposure, although forest land downwind of major metropolitan areas also sustain occasional spikes (hours) or episodes (days) of acute exposures associated with temperature inversions. Chronic foliar injury symptoms are the norm under conditions of ambient ozone exposure and they become increasingly visible on sensitive plants over the course of the growing season.

Field surveys conducted in the Great Smoky Mountains National Park from 1987 to 1992 identified 33 tree species as sensitive to ambient ozone concentrations (Neufeld et al. 1992). An observational study conducted in Shenandoah National Park reported similar findings (Skelly et al. 1983). The species exhibiting the most severe and consistent injury response at both locations included black cherry, sassafras, yellow-poplar, and white ash. A field survey in Ohio and Indiana over a 2-year period demonstrated that drought conditions have a controlling influence on the development of visible injury symptoms on sensitive plants (Showman 1991). Although ambient ozone concentrations were very high in 1988, little injury was observed on sensitive tree species. In 1989 ozone concentrations were lower, but injury was much greater. Rainfall was much less in 1988 than in 1989 with drought conditions existing across the study area.

Visible foliar injury to ozone-sensitive trees indicates lost photosynthetic area, and it is reasonable to suggest that sustained foliar loss will have a negative impact on growth. Still, the preponderance of evidence indicates no consistent relationship between foliar injury and growth reductions except in some hypersensitive genotypes. Absence of a growth effect despite significant foliar injury suggests the presence of compensatory processes (Pye 1988). For example, photosynthetic rates in uninjured portions of the leaf or tree canopy may increase to compensate for reduced rates of photosynthesis in canopy leaf tissues damaged by O_3. For many shade-tolerant species and at least one shade-intolerant species, greater leaf sensitivity to O_3 has been observed in shaded vs. sunlit environments (Samuelson 1994, Tjoelker et al. 1993, Wei et al. 2004). This difference is related to the ability of shade-tolerant species to maintain high stomatal conductance and O_3 uptake in low light.

There is a large information base on the development and recognition of ozone-induced foliar injury symptoms on trees and forest vegetation: some in published texts (Krupa et al. 1998, Skelly et al. 1987) and some on agency Web sites[5]. Not all researchers agree about which species are ozone sensitive, especially at ambient O_3 concentrations, which is not surprising given that ozone sensitivity and the development of visible injury symptoms are affected by genotype, tree developmental stage, foliar position, leaf age, leaf position in the sun or shade, and a combination of edaphic and climatic factors that are not fully understood (Heck 1968, McCool 1998, Zierl 2002). There is agreement that ozone-induced foliar injury symptoms occur routinely on a variety of eastern and western forest tree species during the growing season. Further, the detection of foliar injury in natural areas is diagnostic for the presence of phytotoxic ozone concentrations in U.S. forests.

Growth and Vigor

Researchers studying O_3 effects on growth and growth-related processes work with tree seedlings because they are easy to manipulate and affordable. Experimental conditions can be controlled and hypotheses tested without the confounding influences of the natural environment. In general, the findings from controlled environment studies on tree seedlings demonstrate unequivocally that O_3 has the potential to cause a wide range of negative effects on growth and tree vigor (U.S. EPA 1996b, U.S. EPA February 2006b,c). Except in a few cases, it is not certain that these documented effects can be used to estimate or predict O_3 effects on saplings or mature trees in the forest.

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[5]Key references and Web sites on ozone injury symptoms are provided in Appendix 3.

Western Pines and Associated Species

Miller and his colleagues were responsible for much of the early work on ponderosa and Jeffrey pines in the San Bernardino Mountains downwind of the smog-laden Los Angeles Air basin (Miller et al. 1963, Miller and Elderman 1977, Miller et al. 1982, Miller et al. 1989, Williams 1980). Fumigation studies with tree seedlings revealed O_3 as the main cause of foliar injury manifested as chlorotic mottle and premature needle senescence. Current-year needles of ponderosa and Jeffrey pines become symptomatic when summer ozone exposure levels are high and soil moisture levels are favorable for ozone uptake through open stomata. Injury begins as the walls of the cell layer just below the epidermis degrade, causing the loss of cellular contents and a degradation of chlorophyll within the cells (Stolte 1996). The loss in chlorophyll beneath the epidermis appears on the needle surfaces as chlorotic blotches with diffuse borders that occur in no regular pattern, giving a yellow mottled appearance: hence the term chlorotic mottle. On ponderosa and Jeffrey pines, this foliar symptom indicates ozone pollution (Grulke and Lee 1997, Olson et al. 1992).

When ozone injury is severe, the disruption in biological processes in the needles eventually leads to accelerated needle loss, which leads in turn to a reduction in crown vigor, leaving the damaged pines more susceptible to secondary stress organisms. Researchers examined the relationships between ozone pollution and bark beetle attacks on ponderosa pines and found that trees with severe ozone injury suffered changes to the structure and chemistry of the phloem tissues, reducing the natural resistance of the trees to bark beetle attack (Cobb et al. 1968, Cobb and Stark 1970). Ozone does not kill trees, but it does weaken the host plants and leaves them vulnerable to aggressive infestation by bark beetles that do cause tree decline and mortality. Even in the absence of bark beetle attack, growth losses attributable to ozone pollution have been documented in both symptomatic and asymptomatic ponderosa and Jeffrey pines (Williams 1980).

The most ozone-sensitive ponderosa and Jeffrey pines have disappeared from the mixed conifer forest type of southern California, which is the only documented case where a tree-level effect induced by O_3 on a particular forest type has resulted in a significant disturbance to the structure and function of the ecosystem. Over a 14-year study period, Miller and his colleagues were able to demonstrate that ozone-sensitive ponderosa and Jeffrey pines lost basal area in relation to other species more tolerant of ozone. The elimination of ozone-sensitive pines and the accumulation of ozone-tolerant species in the understory present a fuel ladder that puts the remaining overstory trees in increased danger in the event of a catastrophic fire. Further, the ozone-tolerant species are more susceptible to fire damage because of thinner bark and branches closer to the ground.

More recent studies on the sensitive pine forests in the San Bernardino Mountains have confirmed that average ambient ozone concentrations of 50-60 ppb are sufficient to cause foliar injury, reduced carbon fixation, and significant growth declines in bigcone Douglas-fir, as well as ponderosa and Jeffrey pines (Bytnerowicz and Grulke 1992, Peterson et al. 1991). The combined effects of prolonged drought and high ozone (Arbaugh et al. 1999) and O_3 and high nitrogen deposition (Grulke and Balduman 1999) are contributing to growth disturbances in the forest that researchers believe may lead to the eventual replacement of pines by more nitrogen-tolerant and ozone-tolerant tree species (Arbaugh et al. 2003, Panek 2004) in the not too distant future. Other western species that have been tested for ozone sensitivity include western white pine and California black oak (foliar sensitivity), western hemlock (dry weight reduction), western redcedar (no effect), and giant sequoia (no effect).

Eastern White Pine

In the 1960s, researchers started reporting foliar symptoms on white pine thought to be caused by ozone pollution (Berry and Hepting 1964, Dochinger and Seliskar 1970). Symptomatic white pine were described as having foliage with needle blight, emergence tipburn, semimature needle blight, and chlorotic dwarf. Fumigation studies established that these symptoms were caused by O_3, although some reports suggested that foliar pathogens were contributing factors, and that semimature needle blight was a physiological disorder (Linzon 1967). Symptoms that are visible on young developing needles in early summer to midsummer involve collapse of the palisade cells next to the stomata, causing light flecking and chlorosis close to stomata openings. As injury and chlorophyll loss progress, chlorotic flecks become more visible and trees develop a yellowish-green color characteristic of ozone-induced symptoms on white pine. Affected needles may further exhibit brown needle necrosis and tipburn and eventually fall off. Many affected trees are found growing side by side with non-affected (ozone-tolerant) trees, indicating genotypic differences in susceptibility to O_3. Ozone-sensitive genotypes of white pine hold their needles for only 1 to 2 growing seasons compared to 3 to 5 growing seasons for ozone-tolerant white pine.

The most sensitive white pine genotypes have short stunted needles, poor needle retention, and only minimal height and diameter growth each year, resulting in a condition known as chlorotic dwarf (Dochinger 1968, Karnosky et al. 2007). These hypersensitive individuals appear to have been eliminated from the gene pool because they are no longer found in the forest. Reports of ozone-sensitive trees with the chlorotic fleck symptom are common throughout the range of eastern white pine. However, much of the resource remains unsampled (Bennett et al. 1994), leading some to suggest the sensitivity of the species has been exaggerated. Although there is evidence of a relationship between chlorotic fleck on ozone-sensitive white pine and reduced annual growth increment (Benoit et al. 1982), there is no indication that ozone stress has caused widespread mortality in the white pine growing stock.

Trembling Aspen and Aspen Clones

Aspen is another important and widely distributed tree species that is ozone sensitive (Karnosky 1976, 1989). Foliar injury symptoms on trembling aspen are visible as moderate to large, black, necrotic areas that extend across the leaf veins and are bifacial. Ozone exposure leads to accelerated physiological maturity and leaf senescence, decreased photosynthesis and chlorophyll, and adverse effects on growth such as root growth. Under controlled conditions in the greenhouse, researchers have found evidence that adverse effects of O_3 on aspen root growth can have indirect carryover effects on growth in the following growing season (Woodbury et al. 1994). Under natural conditions, an ozone-induced reduction in root growth might be expected to make trees more susceptible to drought and nutrient deficiency (Greitner et al. 1994). Trees stressed by O_3 are more susceptible to leaf rust fungi and a number of other foliar pathogens. Ozone predisposes aspen to attacks by leaf rust fungi by altering the leaf surface waxes so that leaves are more wettable, thereby creating a microenvironment on the leaf surfaces that is favorable for fungal spore germination and subsequent infection by fungi (Karnosky et al. 2002, Percy et al. 2003b).

Because there is much genetic variation in aspen response to high ambient ozone concentrations, forest geneticists postulate that O_3 has had an impact on aspen populations through natural selection in areas with relatively high ozone exposure. Evidence for this is provided by two fumigation studies conducted with aspen clones collected from natural populations growing in polluted and nonpolluted areas. Aspen collected from areas with high ambient ozone concentrations sustained less visible injury than clones collected from areas with low ambient ozone concentrations (Berrang et al. 1991). The authors inferred that the selective force of O_3 had already eliminated the more sensitive aspen genotypes in the more polluted areas. Sensitive aspen genotypes are not killed directly by O_3 but are eliminated through intraspecific competition for light, nutrients, and water with their ozone-resistant neighbors. Evidence from open-air exposure systems (e.g., FACE[6]) demonstrates that longer term exposure (5 to 10 years) to lower level ozone concentrations has a consistently negative effect on aspen, significantly reducing height and diameter growth, and increasing foliar susceptibility to herbivorous insects (Isebrands et al. 2001, Percy et al. 2003b).

Black Cherry

Black cherry is highly variable in its response to O_3 ranging from sensitive to intermediate to tolerant with respect to visible foliar symptoms (Lee et al. 1999). Ozone-induced symptoms on black cherry show up in the latter half of the growing season following repeated exposure to high ambient ozone concentrations. The symptoms are known as upper-leaf-surface stipple and appear as a reddish-purple or black pigmentation between the major veins of the leaf (Davis et al. 1982). Severely damaged leaves will drop prematurely. Season-long exposures to ambient O_3 have been shown to have many adverse effects on black cherry seedling growth, but ozone-induced symptoms on mature trees in the field leading to significant growth declines have not been demonstrated (Karnosky et al. 2007, Neufeld et al. 1995, Rebbeck 1996).

Chevone (2002) identified ozone-tolerant and ozone-sensitive genotypes of black cherry in the field based on foliar response and then measured photosynthetic activity and leaf gas exchange rates on these same plants. Because these two processes control carbon assimilation of the tree canopy, any adverse effects of ambient ozone concentrations on these processes will eventually cause a corresponding negative effect on biomass accumulation, growth, and reproductive capacity. Ambient ozone had a significant negative effect on the photosynthetic function of sensitive black cherry trees. As leaf symptoms increased, chlorophyll content decreased in a linear fashion. Measurements of maximum net photosynthetic rates followed a similar pattern. However, sampling was confined to a single leaf position on a small subsample of the canopy. Many more measurements of different aged leaves that have been exposed to O_3 for different lengths of time are needed to come up with an estimation of O_3 effects at the canopy level. Impaired canopy-level photosynthesis would be evidence of a direct link between ozone-induced visible foliar injury and biomass loss.

Other Eastern Species

Duchelle et al. (1982) used charcoal-filtered and ambient air open-top chambers to study O_3 effects on height growth of seven forest tree species native to the eastern U.S. After 2 years of exposure under natural field conditions, tulip-poplar and green ash seedlings exhibited growth

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[6]FACE = Free-Air Carbon Dioxide Enrichment. For more information, go to: http://aspenface.mtu.edu/.

reductions of 44 and 77 percent respectively, while black locust, Virginia pine, eastern white pine, table mountain pine, and eastern hemlock seedlings showed a range in height growth loss of 13 to 23 percent. Similar adverse effects of O_3 on tree growth have been reported for multi-year open-top field chamber studies with loblolly pine seedlings. Ozone-induced growth reductions of loblolly may occur with no visible evidence of needle injury or effects on pigment concentrations (Kress and Skelly 1982, Shafer and Heagle 1989).

Researchers differ in their assessment of possible O_3 effects on some of the commercially important southern pines like loblolly pine. Seasonal O_3 exposures have been shown to reduce needle net photosynthesis and growth in loblolly and shortleaf pine seedlings (Chappelka and Samuelson 1998), but a longer 3-year study indicated little effect of ambient ozone on loblolly (Kelly et al. 1993). Other southern pines where adverse growth effects have been reported include slash pine, Virginia pine, and table mountain pine. Species where experimental fumigations or field studies showed no adverse effect of O_3 on physiological processes or growth include red spruce and Fraser fir (Chappelka and Samuelson 1998).

Simini et al. (1992) examined ambient ozone effects on black cherry, yellow-poplar, northern red oak, and red maple seedlings and observed no effects on growth after 2 years even though both black cherry and yellow-poplar exhibited visible foliar injury and premature leaf drop in both years of the study. In a similar study, Rebbeck (1996) exposed black cherry, yellow-poplar, and sugar maple seedlings for two growing seasons to ambient and twice-ambient ozone concentrations and reported a significant decrease in aboveground biomass in black cherry but no effect of O_3 on the growth of yellow-poplar and sugar maple. Others have reported that yellow-poplar shows no negative effect of O_3 on net photosynthesis or growth despite this species being considered highly sensitive to O_3 based on foliar response (Chappelka and Samuelson 1998, Jensen 1973, Kress and Skelly 1982). After one growing season, significant growth reductions were observed in hybrid poplar (*Populus masimowiczii x trichocarpa,* NE 388), although not in eastern cottonwood or black locust exposed to either ambient (non-chambered) or nonfiltered (ambient air) chambers compared with plants grown at sub-ambient ozone levels (Wang et al. 1986).

Ecosystem Effects

Little work has been done with ozone effects on forest communities or ecosystems apart from that already mentioned for the mixed conifer forest type of southern California (Miller et al. 1996). In the early 1970s, Treshow and Stewart (1973) used portable field chambers to expose a community of 70 plant species to above-ambient (>0.15 ppm) ozone concentrations in the grassland, oak, aspen, and conifer communities in Utah. The fumigations caused visible injury to more than half the perennial forbs and woody species in the study area. This result led the authors to postulate that lower, ambient concentrations of O_3 over an extended exposure period might well be expected to impair growth and affect community vigor and stability. These effects were never validated in the field.

Barbo et al. (1998) in Alabama strengthened the argument that O_3 is having an impact on the eastern forest community. Open-top field chambers, with and without O_3, were placed in a pine forest that had been recently cleared, to study ozone effects on the regeneration of native plant species. After 2 years, the developing plant community in the carbon-filtered air (no O_3)

showed significantly greater canopy cover, more layers of foliage, and greater species diversity than the community of plants in the ozone chamber. The authors concluded that elevated O_3 can simplify plant community structure, presumably by altering competitive interactions between plants and eliminating some species.

Researchers have used scaling techniques and statistical approaches to develop risk assessment models that can simulate exposure/response scenarios and predict forest response to O_3 (Chappelka and Samuelson 1998, Karnosky et al. 2007). Models tested so far indicate that ozone is likely affecting forest growth in both eastern and western forest types (Hogsett et al. 1995, 2004; U.S. EPA February 2006b). Predicted growth losses have been estimated to be greater than 20 percent for black cherry and aspen, 5 to 12 percent for yellow-poplar, loblolly pine, sugar maple, and white pine, and zero percent for red maple and Virginia pine. Similarly, estimates of increasing growth loss for ponderosa pine correlate well with increasing ozone exposures (Tingey et al. 2001, 2004), results that appear to be substantiated by field studies along a natural ozone gradient (Grulke and Balduman 1999). The largest uncertainty factor in these models is their dependence on published seedling data to estimate mature forest response. Moreover, the models are not yet developed enough to take into account the relative influences of insect pests, biotic pathogens, and abiotic stressors (other than O_3) in contributing to the measured (modeled) changes in forest health and productivity (Chappelka and Samuelson 1998). An exhaustive discussion of modeling, scaling, and other techniques designed to translate known effects of O_3 on seedlings to potential impacts on mature trees, forest stands, and ecosystems is presented in the EPA air quality criteria document for O_3 and related photochemical oxidants (U.S. EPA February 2006c).

For forest health monitoring, it is reasonable to suggest that an ecosystem exposed year after year to increasing levels of ambient ozone, is not the same as an unexposed ecosystem even if we are unable to discern any immediate effects of O_3 due to the inherent complexity and variability of natural systems (Anderson and Grulke 2001, Teskey 1995). Bennett et al. (2006) were able to measure relationships between plant response and O_3 in field-grown black cherry and milkweed by using a growth attribute directly responsive to current-year ozone exposures (growing branch tips) and a very high sample count (thousands of plants). The authors suggest that increasing sample size allows relatively small effects occurring in real-world field conditions to be both measurable and statistically significant. Chappelka and Samuelson (1998) agree that increasing experimental replication and identifying the most ozone-responsive whole-tree measurement attribute will improve the accuracy of risk assessment models.

Modeled forest responses to O_3 depend on improved data from mature trees in natural settings such as that provided by McLaughlin et al. (2007a). The authors combined intensive field measurements with climatic data to test the hypothesis that ambient ozone concentrations increase water stress in forested ecosystems. Over a 3-year period, they examined relationships among stem growth, sap flow, and soil moisture measurements in a mixed deciduous forest in Tennessee and found compelling evidence that periods of peak ozone exposure throughout the growing season were followed by measurable increases in sap flow and tree-stem water loss that led to substantial losses in seasonal stem growth. The cumulative negative effects of O_3 on stem increment growth were evident in 9 of the 10 tree species tested and exceeded 30 percent in an average ozone year and 50 percent in a high ozone year. The most sensitive species (pitch pine and red oak) also suffered a pronounced inability to recover from periods of high moisture demand that frequently accompanied peak ozone exposures. In a companion study (McLaughlin et al. 2007b), the authors reported that ozone-induced increases in water use by forest trees were accompanied by significant reductions in soil moisture in the rooting zone of sample trees and contributed significantly to reduced late-season streamflow in the associated watersheds.

Clearly, the potential for harmful effects of O_3 on forest health has been demonstrated and the risk is rightly assumed to be great. The ongoing FIA ozone biomonitoring program maps geographical incidence and patterns of ozone stress to gain insight into plant/pollutant interactions. Each ozone season is unique, a result of the relationship between causal agent and host plant as influenced by each season's exposure environment and the ever variable interplay between predisposing and compensatory factors. The effort to understand the risk of O_3 to forest health demands a long-term commitment to observation, data collection, and study.

OZONE BIOMONITORING AND FOREST HEALTH ASSESSMENT

Ozone is the only regional gaseous air pollutant that has been measured at known phytotoxic levels at both remote and more urbanized forest locations across the continental United States (Heck and Cowling 1997, Lefohn and Pinkerton 1988). As such, O_3 is of primary concern for United States forests (Coulston et al. 2004). Ozone can be monitored using physical air quality monitors including UV photometric analyzers that continuously measure the amount (ppm) of O_3 in a sample of ambient air, and passive sampling devices that depend on air diffusing across a filter to provide an estimate of weekly or seasonal average ozone concentrations. UV photometric analyzers require expensive calibrations, shelter, electricity, and computer hookups and are used primarily in populated areas to assess the risk of unhealthy ozone concentrations on human health. Passive sampling devices are a less expensive alternative that have been used successfully for ozone sampling in national parks and other less populated areas (Ray and Flores 1994), but significant costs are still associated with setup, data collection, and lab analyses. Ozone can also be monitored by visually evaluating the amount and severity of ozone-induced foliar injury to sensitive bioindicator plants, an approach known as biomonitoring (Chappelka et al. 1997, Fedder 1978, Kohut et al. 1997, Krupa et al. 2001, Manning 2003). Biomonitoring provides information on ozone effects rather than ozone concentrations in ambient air, although dose-response models are available for some plant species. It is a low cost method that can be applied anywhere ozone-sensitive species are growing whether in urban, rural, or remote forested areas, and the findings are directly relevant to an assessment of O_3 stress on our Nation's forests.

The FIA ozone indicator is designed to determine the presence or absence of ozone injury conditions on the FIA Detection Monitoring plots also know as Phase 3 (P3) forest health plots. Ozone injury conditions are characterized by the prolonged exposure of sensitive plants to elevated ozone concentrations in a predisposing environment. Under these conditions, O_3 causes direct foliar injury to many native plant species. This visible injury response is used to detect and monitor ozone stress in the forest environment. The ozone-sensitive plants (individuals within a species) that exhibit typical foliar injury symptoms when exposed to O_3 are called bioindicators or, more specifically, ozone detectors (Krupa et al. 1998). Ozone bioindicators detect phytotoxic levels of O_3 when edaphic and atmospheric conditions are conducive to ozone uptake through the stomates. Detection of ozone-induced foliar injury on bioindicator plants tells us not only that ambient ozone concentrations were high for a particular time and place, but also that other necessary conditions that allow ozone uptake and injury (e.g., adequate light, nutrition, and soil moisture) were also present. This concept of necessary conditions for injury defines the biological relevance (i.e., value) of the FIA biomonitoring data. A physical, air sampling monitor (active or passive) may provide absolute concentrations of O_3, but it cannot indicate how much of the O_3 is taken up into plant tissues. In contrast, the bioindicator plant provides a visible record of the O_3 dose that has immediate biological relevance. Ambient O_3 levels may be high, but if trees do not "see" this ozone because the stomates are closed, then the ozone stress is insignificant. By the same token, moderate ozone concentrations may generate significant injury response if external conditions are such that ozone uptake is enhanced.

The Conceptual Model

The conceptual model for the ozone indicator (Fig. 2) illustrates how foliar injury can be used as an indicator of environmental stress (i.e., ozone air quality[7]) and forest condition (i.e., potential impacts of ozone on tree-level and ecosystem-level components). When O_3 contaminates the environment, the bioindicator plant shows a visible response. Other components of the ecosystem may show a physiological response, but the visible response is lacking. Some plants are resistant to ozone stress and do not respond. In Detection Monitoring, we are most concerned with the sensitive ozone bioindicator plants. This sensitive component of the system will allow us to detect any early change in forest condition that may be associated with poor air quality (i.e., O_3 pollution). Stress-induced changes in the structure and function of an ecosystem begin with the response of the most sensitive individuals of a population (Laurence and Anderson 2003, Reich 1987). As time passes, and the stress continues or is magnified, effects may be transmitted from tree level to ecosystem level. Examples of ozone-induced foliar injury, tree-level alterations in growth and vigor, and ecosystem-level changes in structure and function were outlined in the previous section of this report.

In the conceptual model, the bioindicator plant provides the visible link between ozone exposure and effects. When bioindicator species are also an important component of the forest community (e.g., *Prunus* and *Fraxinus* spp. in the East and *Pinus* and *Populus* spp. in the West), they provide an even more compelling record of environmental impact. In Detection Monitoring, the ozone indicator provides estimates of environmental stress and probable impact (risk) and detects changes in these two estimates over time. If and when changes are detected that are outside normal bounds, Evaluation Monitoring studies are warranted to more closely examine the causes and consequences of the change in health or condition of the forest ecosystem.

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[7]Ozone air quality is a commonly used phrase that refers to the amount of O_3 in the air. Ozone air quality may be good (low O_3), moderate (intermediate O_3), or poor (high O_3) with respect to potential effects or stress on biological systems.

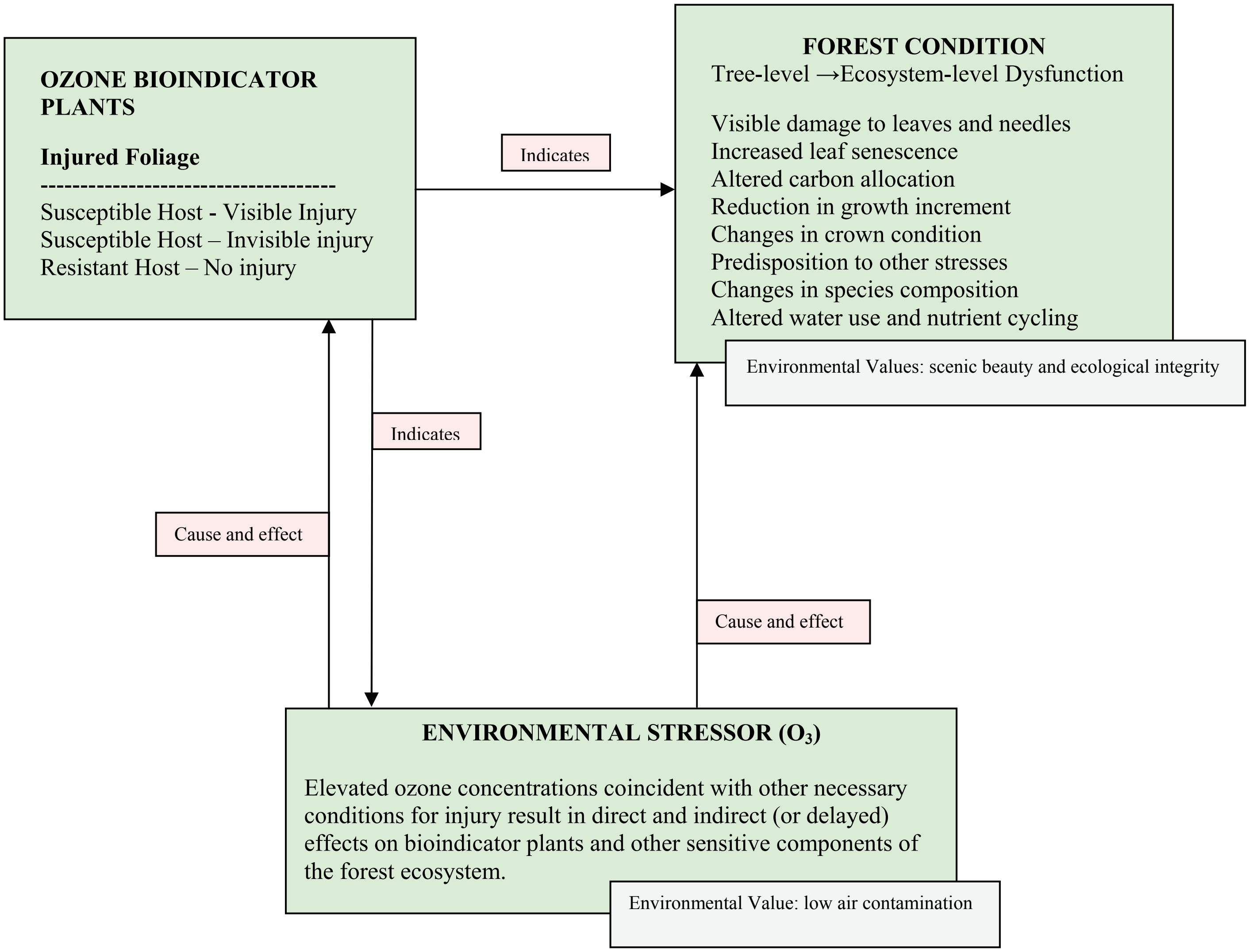

Figure 2.—Conceptual model for the ozone indicator. See text (page 18) for associated forest health assessment questions.

Assessment Questions

The ozone indicator has been part of Detection Monitoring activities in FHM since 1990 when the first forest health ground plots were established in New England. The early implementation of this indicator underscores its importance in current forest health issues and societal values (Montreal Process 1995). The specific environmental values that the ozone indicator addresses include both consumptive (e.g., growth increment) and nonconsumptive (e.g., scenic beauty) use of the forest resource. The following forest health assessment questions derive from the conceptual model (Fig. 2) and provide the essential rationale for implementing the ozone indicator in FIA.

1. Are phytotoxic concentrations of ozone present in the forest ecosystem?

2. Is regional air quality (e.g., ozone pollution) changing over time?

3. If so, is it improving or deteriorating?

4. In what percentage of a region or forest type is there an indication of ozone air quality impacts on scenic beauty as defined by measurable changes in leaf color, leaf size, or leaf number?

5. In what percentage of a region or forest type is there an indication of ozone air quality impacts on ecological integrity as defined by measurable changes in biodiversity, growth increment, crown condition, or damage?

Answers to questions 1, 2, and 3 provide a direct assessment of air quality (i.e., O_3 stress) across the landscape (environmental value = low air contamination). Answers to questions 4 and 5 address impact (environmental values = scenic beauty and ecological integrity). The link between the biological ozone data and issues of air quality is direct and of immediate interpretive value. The links to impacts on scenic beauty or growth are less direct and involve evaluating correlations between the foliar response data and other FIA indicators. Risk of impact is examined by mapping the overlay between areas of high biological response (i.e., moderate to severe foliar injury) and the natural range of certain ozone-sensitive species (Coulston et al. 2004). The use of the bioindicator data for forest health risk assessment is described later in this report.

Issues of Uncertainty

Despite the wealth of scientific studies documenting ozone injury on sensitive plants and the long history of bioindicators in air quality research, we lack a complete scientific understanding of the relationship between foliar injury and plant growth. Many studies have linked foliar damage to immediate or delayed impacts on a variety of growth processes. However, most studies conducted under artificially controlled conditions in the growth chamber have found little evidence of a direct relationship between foliar injury and growth. Further, adverse effects noted in the growth chamber have been indiscernible in the field. The only undisputed exception to these observations comes from the scientific record of ozone impact on ponderosa pine in California. Studies with other tree species where a direct relationship between foliar injury and growth increment has been indicated do not fully account for the influence of other biotic and abiotic factors on the results. Even in the sensitive pine forests of California, new evidence suggests drought and nitrogen are as important as ozone to the stress-driven changes in this ecosystem. Scientific uncertainty lies in whether significant changes are occurring in other forest types, at the ecosystem level, in response to chronic ozone exposure. The biomonitoring effort in FIA provides one way to address this uncertainty. The extensive biological network, represented by the FIA ozone biomonitoring program, provides detailed information on ozone exposure and plant response relationships under natural conditions and in the complex environment of the forest. As biomonitoring data from the FIA program become more widely available and are used more often for ecological assessments and forest health models, we expect to gain greater understanding of plant/pollutant interactions and reduce uncertainty.

Forest Health Assessment at the State and Regional Levels

The issue of O_3 and forest health is of interest and importance to policymakers, forest managers, university researchers, and the general public. The ozone indicator data are easily summarized in tables and maps to provide detection-level information on where ozone stress is occurring across a state, region, or ecological region. Reporting on the ozone indicator provides an opportunity to educate and inform the public about ground-level ozone, ozone effects on trees, and biomonitoring. Although the data should not be used to make definitive statements about forest health, it does provide easily interpreted information on the presence and absence of a specific environmental stress (i.e., ozone pollution) that clearly relates to the maintenance of forest health and vitality (Montreal Process 1995).

In relatively clean air regions of the U.S. (e.g., the Northern Plains), the data serve as a baseline of ozone stress and a documentation of the presence or absence of ozone stress in areas where historical air quality data are completely absent. In regions with relatively poor air quality (e.g., the mid-Atlantic), the emphasis should be on mapping the extent and severity of the stress across the landscape, any change in extent and severity of the stress over time, and an assessment of probable impacts with respect to the distribution of ozone-sensitive tree species in the region. Core data for the ozone indicator include tabular data describing plot-level counts and injury indices, and two national maps of interpolated ozone injury data and air quality.

Using the ozone summary tables and maps, analysts responsible for state and regional forest health assessment reports address the following questions:

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 the 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 is the relationship between ambient ozone concentrations and the injury data?

9. What amount of forest land is subject to levels of ozone pollution that may cause negative impacts?

10. What volume of ozone-sensitive species is at risk, and where is it?

If time and resources allow, the data should be further analyzed to identify localized areas of moderate to high risk where evaluation studies are warranted and to determine if there is a relationship between areas of moderate to high risk and other FIA indicators of tree health and condition. Results may be summarized by state and county but are more appropriately summarized and reported by region or ecological region.

DATA COLLECTION AND ESTIMATION

The primary objective of the field procedures for the ozone indicator is to establish a detection-level ozone biomonitoring site within each polygon on the FIA ozone grid (Fig. 1 in Smith et al. 2007). These sites are used to detect and monitor trends in ozone air pollution injury on sensitive species. The scope of the program is national, but procedures are amended regionally to reflect differences in ozone exposures, growing season, topography, and forest type. This section provides an overview of the sampling grid and sampling rules for the ozone indicator. Quality assurance procedures are reviewed and data quality results are summarized to demonstrate crew performance and the reliability of the data. Estimation procedures used to generate the national ozone risk map are briefly described.

National Protocol

Ozone sampling occurs on a unique national grid based on the Environmental Monitoring and Assessment (EMAP) design (White et al. 1992). The ozone grid consists of a single panel of ozone biomonitoring plots that are measured annually (Fig. 3). The grid design generates differing sampling intensities across the landscape based on the best available information on air quality regimes and potential loss due to ozone damage. The strata are defined as follows:

- Stratum 0 = one ozone biosite for every 5 million acres in areas less than 7.5 percent forest.

- Stratum 1 = one ozone biosite for every million acres of forest land in areas with relatively low ozone exposure (SUM06 <10 ppm-hr) and/or where tolerant genotypes exist (pinyon-juniper forest type).

- Stratum 2 = one ozone biosite for every 500,000 acres of forest land in areas with moderate ozone exposure (SUM06 10-25 ppm-hr).

- Stratum 3 = one ozone biosite for every 250,000 acres of forest land in areas with relatively high ozone exposure (SUM06 >25 ppm-hr).

Additional criteria are used to adjust and finalize the ozone sample (e.g., no state has less than five ozone biosites) to achieve a national total of 1,239 ozone biomonitoring sites, comparable

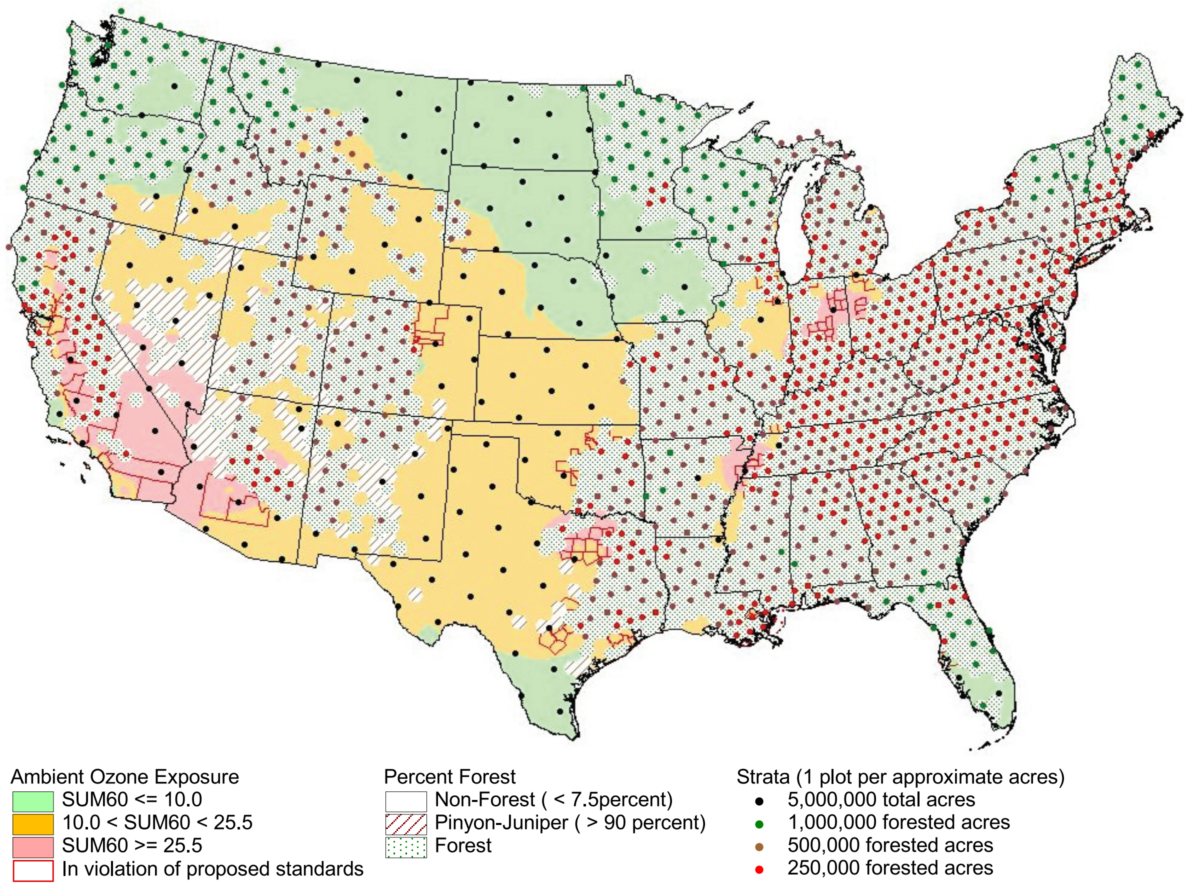

Figure 3.—FIA national ozone biomonitoring grid developed from the Environmental Monitoring and Assessment Program (EMAP) base grid (White et al. 1992). The grid has four sampling intensities based on sensitive species and ambient ozone concentrations (see: Smith et al. 2001).

in number to the P3 plot sample for other forest health indicators (Smith et al. 2001). Throughout this document, the ground locations used for biomonitoring are referred to as sites or biosites rather than plots to distinguish them from the forest inventory plots that make up the traditional P2 and P3 plot samples.

The ozone grid is purposive both at the grid level and at the biosite. Biosite locations on the ground are deliberately chosen first for ease of access and secondly for optimal size, species, and plant counts. The ozone biomonitoring 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. One biosite is required per polygon on the national ozone grid. Some states use an intensified ozone grid (e.g., Vermont and Wisconsin) with the result that two or more biosites may be located in each polygon on the base grid. Biosite locations are mapped, geographic coordinates are recorded, and the same sites are evaluated every year.

Ozone injury and our ability to detect injury increase over the course of the field season. For this reason, the sampling window for the ozone indicator is limited. In the East, to eliminate problems with seasonal variability in ozone response, all foliar evaluations are conducted during a 3-week period from late July to mid-August within which the indicator is considered stable (Smith 1995). This minimizes variability and the error associated with the data collection system. In the West, due to differences in growing season, topography, target species, and other regional factors that influence plant response to O_3, it is difficult to identify an optimum evaluation window for this indicator. Nevertheless, to maintain national consistency and improve crew logistics, the western regions use a defined window for foliar injury evaluations that extends from mid-July through mid-August.

Data collected at each site are entered into an electronic file that is part of the FIA National Information Management System (NIMS). Basic field equipment includes a 10x hand lens for close examination of plant leaves for ozone injury, a forester-grade plant press for the voucher leaf samples, and the field data sheets for mapping and quality control.

Field Methods

Basic procedures for biomonitoring are standardized nationally and updated annually in a detailed peer-reviewed field manual (U.S. Forest Service 2000). The most recent version of the manual is available online[8]. The manual details training and quality assurance requirements for field crews, criteria for selection of biomonitoring sites and plant species, injury evaluation procedures, and guidelines for proper collection and handling of the leaf vouchers.

The national list of ozone bioindicator species selected for use in the biomonitoring program (Tables 1 and 2) was gleaned from a variety of sources including the peer-reviewed scientific literature, interagency reports, and communications with Federal and university researchers experienced in ozone biomonitoring. Species selected are relatively common across a variety of forest types, are relatively easy to identify and distinguish from similar species, and are ozone sensitive based on a combination of field evidence and causative fumigation experiments. The eastern bioindicator species have a long history of application in ozone field studies (Krupa et al. 1998, Skelly et al. 1987, Skelly 2000). Some of the western bioindicator species are not as well tested under natural conditions of ozone exposure, but they have received enough testing to justify inclusion in the program (Brace et al. 1999, Campbell et al. 2000, Duriscoe and Temple 1996, Mavity et al. 1995, Temple 2000) and were all recently identified as good ozone bioindicators by a panel of experts (USDI 2003).

The sampling rules for the ozone biosites are as follows. Biosites must be wide-open areas, at least one acre in size, within or alongside forested areas. Each site must contain at least 30 individual plants of at least two bioindicator species. If 30 plants of two bioindicator species are not available at one location, two nearby open areas, within 3 miles of each other, may be combined to maximize plant counts. The 3-mile rule reflects the limit at which one can reasonably expect ozone levels for a given locale to be similar (Mohnen 1988). Access to the biosite locations must be easy, and they must be free of significant soil compaction and other human-made disturbance.

The characteristics of each site are described in terms of the size of the open area, elevation, terrain position, aspect, soil drainage (East) or plot wetness (West), soil depth, and site

[8]To download a copy of the Phase 3 Field Guide for Ozone Bioindicator Plants (Eastern U.S. and Western U.S.) go to: http://www.fia.fs.fed.us/ and click on FIA Library – Field Guides, Methods, and Procedures and scroll down to FIA Field Methods for Phase 3 Measurements.

Table 1.—Eastern bioindicator species

Scientific name	Common name
Asclepias spp.	common and tall milkweed
Prunus serotina	black cherry
Rubus allegheniensis	blackberry
Apocynum androsaemifolium	spreading dogbane
Fraxinus americana[1]	white ash
Sassafras albidum	sassafras
Liriodendron tulipifera	yellow-poplar
Aster macrophyllus[2]	bigleaf aster
Liquidambar styraciflua	sweetgum
Prunus pensylvanica	pin cherry

[1]*Fraxinus pennsylvanica* (green ash) is sampled occasionally in states where white ash is not available.
[2]Synonym for *Eurybia macrophylla*.

Table 2.—Western bioindicator species[1]

Scientific name	Common name
Symphoricarpos oreaphilus[2]	mountain snowberry
Populus tremuloides	quaking aspen
Pinus ponderosa[3]	ponderosa pine
Salix scouleriana	Scouler's willow
Physocarpus malvaceus	ninebark
Vaccinium membranaceum	huckleberry
Sambucus racemosa	red elderberry
Alnus rubra	red alder
Sambucus mexicana[4]	blue elderberry
Pinus jeffreyi	Jeffrey pine
Artemesia ludoviciana	western wormwood
Artemesia douglasiana	mugwort
Physocarpus capitatus	Pacific ninebark
Rhus trilobata	skunkbush
Asclepias spp.	milkweed
Oenothera elata	evening primrose

[1]Spreading dogbane (*Apocynum androsaemifolium*) is sampled in western regions as of 2008.
[2]*Symphoricarpos* spp. also included.
[3]*Pinus ponderosa var. scopulorum*: Rocky Mountain States; *P. ponderosa var.ponderosa*: West Coast States.
[4]Synonym for *S. cerulea*.

disturbance using a standardized coding system. If characteristics vary significantly across the biosite, then the area where most of the bioindicator species are growing is described and variations are recorded on the site map and notes. When two nearby open areas are used, each location is described separately. Only a small percentage (<1 percent) of the biosites are split between two locations.

Up to 30 plants of each species are randomly selected for injury evaluation. Plants less than 12 inches in height, suppressed, shaded, or with more than half the crown out of sight or reach are not evaluated. The approximate locations of the plants used for evaluations are drawn on the site map so that the same population of plants is evaluated on return visits to the biosite. The entire open area is sampled until 30 plants of two (ideally, three or more) species have been evaluated. The eastern and western FIA regions average 3.5 and 2.5 species per biosite, respectively (data not shown).

At each ozone biosite, 30 individual plants of two bioindicator species and between 10 and 30 individual plants of additional bioindicator species are evaluated for ozone injury. Each plant is rated for the proportion of leaves with ozone injury (injury amount) and the mean severity of symptoms (injury severity) using a Horsfall-Barratt (HB) scale with breakpoints at 0, 6, 25, 50, 75, and 100 percent (Horsfall and Cowling 1978). This scale uses class breakpoints that correspond to the ability of the human eye to distinguish gradations of healthy and unhealthy leaf tissue. The recognition of ozone injury symptoms in the field is not an exact science, and mimicking symptoms can make field diagnosis difficult. For this reason, crews are trained to record amount and severity ratings for injury they are unsure of, as well as the more obvious and classic injury symptoms. Voucher leaf samples (three leaves of each injured species evaluated at each location) are collected to provide the necessary validation of the ozone injury symptom observed in the field by the field crews.

The voucher leaf samples are a critical aspect of the data collection procedures. Field crews collect a minimum of three injured leaves (broadleaved plants) or two branch samples (pine species) from a random sample of individual plants that show obvious ozone injury, and then they mail pressed leaf samples to a regional expert for review. The experts are trained plant pathologists with much experience in ozone injury diagnosis. One expert reviews vouchers for eastern bioindicator species, and a second expert reviews western bioindicator species. Following microscopic examination, they validate injury for all samples that show a characteristic color and injury pattern for O_3, and that are otherwise free of confounding signs and symptoms of other mimicking stress agents (e.g., insects, disease, mites, or weather). If the symptoms are not typical of ozone-induced injury, then the field data associated with the invalidated leaf voucher are corrected to zero values[9]. If a leaf voucher is missing and unable to be validated, then the field data associated with the missing voucher are flagged so that they cannot be used in data summaries or analyses.

Quality Assurance

The ozone indicator is included in the FIA National QA Plan (U.S. Forest Service 2004). Just before the sampling window, ozone training and certification sessions are held in each region. All crews receive training in identifying bioindicator species, selecting sites, evaluating ozone injury, and handling vouchers. Crews with less than 2 years of experience collecting ozone data are audited in the first week of the sampling window. A training package is available that includes a detailed, well-illustrated presentation of procedures, data sheets and training

[9]Raw data collected by the field crews are maintained in each FIA region. Field data associated with an invalidated leaf voucher are corrected to zero values and maintained along with other edited files used for data summaries and analysis.

handouts, biosite-level measurement codes, definitions, and measurement quality objectives, and color slides of ozone injury and mimicking symptoms. Experienced crews in good standing with 3 or more years of field experience with the ozone indicator may use the training package for certification.

Experienced and certified QA staff conduct field revisits and audits on 10 percent of the biosites in each FIA region. Measurement quality objectives (MQOs) are defined for identification of bioindicator species, numbers of stems evaluated, numbers of stems injured, amount and severity of injury, and recognition of the ozone injury symptom (Pollard and Smith 2001). Endpoint data quality goals are also set for the calculated biosite index value (BI) and the leaf voucher data (Pollard 2004). Quality assurance procedures dictate that the O_3 injury symptom must be verified for each injured species on each site regardless of whether a regular crew or QA crew is evaluating the biosite. With respect to presence or absence of O_3 injury and core reports on numbers and distribution of biosites where O_3 injury is present, the voucher system virtually guarantees the accuracy of the plot value.

Field data are collected electronically on a portable data recorder (PDR) and are subject to computerized editing and validation. Paper data sheets are used to map the biosite and track the leaf vouchers and for backup in the event of a PDR failure. Examples of field data sheets and a chart detailing the flow of data from the field to the validated regional data archives are presented in Appendix 5.

Performance Evaluations and MQOs

The crew level of difficulty for the ozone indicator is low and no specialized equipment is needed. Field protocols have remained essentially unchanged since 1994. The sampling window is abbreviated within each region, minimizing index-period variability. The selected bioindicator species are relatively common, easy to identify, and characteristically ozone sensitive, showing foliar symptoms that are easy to diagnose. Results from field revisits and audits demonstrate that crews are effectively trained to detect ozone injury and discriminate against mimicking symptoms. Analysis of QA data from 1997 to 2002 and from 2004 to 2005 established the following: (1) For all measured biosites and based on actual crew performance, two independent crews will come up with a site-level injury index that varies by 2 percent or less 90 percent of the time; and (2) For all measured biosites and based on actual crew performance, two independent crews will come up with the same species count, plus or minus one species, 80 percent of the time. The voucher system was tested by asking crews to mark a subset of leaf vouchers as 100 percent certain or fairly certain for ozone injury. All the leaf vouchers submitted as 100 percent certain were confirmed by an expert as ozone injury while 78 percent of the vouchers submitted as fairly certain were confirmed as ozone injury. Normally, crews are trained to collect data and submit leaf vouchers whether they are 100 percent certain of their diagnosis or not. Leaf vouchers are reviewed, and the injury symptom validated by an expert for every injured species on every biosite. Ozone injury data are zeroed out if the leaf vouchers associated with the injury data are determined by an expert to be free of ozone-induced injury symptoms, or if ozone injury cannot be distinguished due to a preponderance of mimicking symptoms.

Table 3.—Classification scheme for the FIA biosite index

Biosite index[1]	Bioindicator response[2]	Assumption of risk	Relative air quality[3]	Probable impact
0 to < 5	Little or no foliar injury	None	Good	Visible injury to highly sensitive species, e.g. black cherry
5 to < 15	Light to moderate foliar injury	Low	Moderate	Visible injury to moderately sensitive species, e.g. tulip-poplar
15 to < 25	Moderate to severe foliar injury	Moderate	Unhealthy for sensitive species	Visible and invisible injury. Tree-level response.[4]
≥ 25	Severe foliar injury	High	Unhealthy	Visible and invisible injury. Ecosystem-level response.[4]

[1]The categorizations of the biosite index are subjective and based solely on expert opinion.

[2]Based on amount and severity of ozone-induced foliar injury symptoms as described in FIA Field Methods for Phase 3 Measurements (U.S. Forest Service 2006).

[3]Relative ozone air quality for plant receptors (e.g., trees, woody shrubs, and nonwoody herb species), not human receptors.

[4]According to EPA's final Guidelines for Ecological Risk Assessment EPA/630/R095/002F (U.S. EPA 1998).

Estimation Methods

The validated foliar injury data are used to calculate a biosite index (BI) for each site and year. Each ozone season is unique, influenced by variable ozone levels, weather, wind flow, and precipitation patterns. Therefore, 5-year averages of the BI are recommended to generate more representative estimates of ozone injury. Whether reported by year or as 5-year moving averages, the BI values are classified into four categories of risk (Table 3) based on groupings proposed by Smith (1995). The risk assigned to each category represents a relative measure of probable impacts from ambient ozone exposure (i.e., ozone risk). The same categories are used to describe relative ozone air quality.

Because the biomonitoring grid is independent of the FIA base grid, spatial interpolation is used to predict potential risk of ozone injury on the P2 ground plots. The interpolated surface of foliar injury response is referred to as the national ozone risk map. A new map is generated every year based on moving 5-year averages of the BI. The ozone risk map is intersected with P2 and P3 plot locations to provide an interpolated BI value (IBI) and other bioindicator attributes for all FIA ground plots. The IBI for each forest inventory (P2) and forest health (P3) plot can then be merged with other tree and plot attributes to generate population estimates for the ozone indicator as discussed in the Analytical Procedures and Risk Assessment section of this report. Additional details on the formulation of the BI, the spatial interpolation techniques used to develop IBI values for all P2 and P3 plots, and the methods used to estimate status and change in forested areas with respect to ozone risk are provided in the Ozone Bioindicator Sampling and Estimation report (General Technical Report NRS-20, Smith et al. 2007).

DATABASE STRUCTURE AND DOCUMENTATION

FIA uses the National Information Management System (NIMS) to process and store the ozone indicator data. Data files collected by the field crews and voucher validation files are loaded into five NIMS Oracle™ tables: OZONE_PLOT_TBL, OZONE_VISIT, OZONE_SPECIES, OZONE_PLOT_NOTES, and OZONE_VALIDATION. Further processing computes indices and creates three standard summary tables: OZONE_BIOSITE_SUMMARY, OZONE_PLOT_SUMMARY, and OZONE_SPECIES_SUMMARY. The data from these ozone tables (except for OZONE_PLOT_NOTES) are reformatted for public use and presented in the FIADB [10] (Forest Inventory and Analysis Database).

The FIADB is available for download through the FIA DataMart Web page[11]. The download data format is comma-separated-value (CSV), which can be opened in Microsoft Excel or other programs that import text files. To access ozone data from 1994 to the present, go to: http://fia.fs.fed.us/ and click on FIA Data and Tools – Download Inventory Data, and review various options for ozone reference data. The FIA Data and Tools Web page also includes a data tool called Forest Inventory Data Online (FIDO), which creates tables and maps from the FIADB Phase 2 plot data. FIDO applications are being developed for the ozone data.

This section provides an overview of measurement attributes, data tables, and map products associated with the ozone indicator. It describes field data attributes, biosite-level attributes derived from the field data, population-level attributes and maps, and leaf voucher attributes. Information on ozone crosswalk tables is also provided. Examples of standard tables and maps for the ozone indicator are provided in Appendix 2 and Appendix 7. Data storage tables as they appear in NIMS and the FIABD are introduced in Appendix 6. For detailed information on the ozone attribute codes and definitions, and guidance on interpreting summarized attributes for internal or external reports, all users should refer to the FIADB Database Description and Users Guide version 3.0 Phase 3 (Forest Health Indicators) available online[12] at the FIA Data Mart Web page.

Field Data

Field data attributes listed in the ozone visit table (OZONE_VISIT) are described in the ozone indicator field manual (http://www.fia.fs.fed.us/ - click on FIA Library—Field Guides, Methods, and Procedures - scroll down to FIA Field Methods for Phase 3 Measurements and click on Ozone Bioindicator Plants) and in the FIADB Users Guide (v3.0 P3 cited above). The field crew uses a standardized coding system to summarize identifying characteristics of the biosite with respect to site conditions and measurement status on the national ozone grid. Coded site attributes include plot size, elevation, aspect, terrain position, soil depth, soil drainage, plot wetness, and plot disturbance. Additional attributes identify the crew type and QA status of the data and whether or not the recorded values are intended for quality assurance purposes. The injury check attribute allows the field crew to document the presence or absence

[10] To protect landowner privacy, true biosite locations are obscured in the FIADB. For more information, or to obtain access to biosite coordinates, contact the National Ozone Advisor, John Coulston.

[11] http://fiatools.fs.fed.us/fiadb-downloads/fiadb3.html

[12] http://www.fia.fs.fed.us/tools-data/docs/pdfs/FIADB_user%20guide%203-0_P3_6_01_07.pdf

of ozone injury on nontallied[13] plants or species. The plot notes table (OZONE_PLOT_NOTES) provides additional descriptive information on site characteristics, plant species, and injury patterns that may influence the results. Biosite notes are not available in the public domain because they may contain information that compromises landowner privacy.

Standard Summary Tables and Derived Ozone Data

Every year, the results of the field crew injury surveys and expert review of the leaf vouchers are summarized at the regional level in three standard summary tables. Core data from the three tables are used to describe field crew activities and report on status and trends. The biosite summary table (OZONE_BIOSITE_SUMMARY) provides computed indices and summary statistics for each ozone biosite. The plot summary table (OZONE_PLOT_SUMMARY) contains summary statistics for each ground location. Ground location differs from ozone biosite when the data from two nearby locations are combined to meet the site selection requirements for the ozone indicator. The species summary table (OZONE_SPECIES_SUMMARY) provides computed indices and summary statistics by species. For each table, the attribute codes, computation specifications, and definitions are fully described in the FIADB Users Guide v3.0 P3. The most useful attributes for FIA regional reports are discussed below. If there are anomalies in the derived ozone data, the analyst should review the raw data files and notes for an explanation. Annual summary statistics may be summarized by species or by biosite and reported by county, state, FIA region, or ecological region.

Ozone Biosite Summary Table

The measurement variables in this table summarize ozone injury data by ozone plot number (O3PLOT) and inventory year (INVYR). The ozone plot number in the ozone summary tables provides a unique identifier that can be used in combination with inventory year and, for clarity, state and county codes to identify the ozone biomonitoring site. For each biosite, summary values are tabulated for the total number of species evaluated, the total number of plants evaluated, the total number of plants injured, the ratio of injured to evaluated plants, the percent of sampled plants in each HB injury severity class, and the biosite-level ozone injury index (BIOSITE_INDEX). These summary statistics may be used in an annual report to list how many biosites were visited, how many plants were evaluated, and how many (or what percent) of the total sites and plants sustained ozone injury. Over time, these summary statistics can be used to report on regional trends in ozone stress in terms of significant changes in the number and distribution of biomonitoring sites with ozone injury, changes in injury severity classifications, and increases or decreases in the ozone injury index.

Ozone Plot Summary Table

The measurement variables in this table summarize ozone injury, species counts, and site characteristics for each ground location visited by the field crews. Ground location differs from ozone biosite because there are a small number of ozone biosites that consist of two ground locations. Ozone biosites that consist of two locations are referred to as split plots[14]. Two

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[13] Nontallied refers to extra plants or species that are evaluated after the crew has tallied 30 injury amount and severity ratings for 5 different species. Nontallied plants are not part of the tally that is used to compute the site-level injury index, but they may be used to record the presence of ozone injury at a given location if the nontallied leaf voucher is validated by an expert. See FIADB Users Guide v3.0 P3 for details.

locations are used to increase species and plant counts for a single ozone biosite. If two locations are used, they are within 3 miles of each other. When a biosite is split, the ozone plot number (O3PLOT) is the same for both locations except for the last digit (1 or 2) and the two locations have different split plot identification numbers (SPLIT_PLOTID). The ozone plot number provides a unique identifier that can be used in combination with inventory year (INVYR) and, for clarity, state and county codes to uniquely identify each ground location. Coded site characteristics for each ground location include plot size, elevation, aspect, terrain position, soil depth, soil drainage, plot wetness, and plot disturbance.

The location-specific attributes in this table provide the opportunity to examine certain site characteristics (e.g., elevation, plot size) more closely. For example, ambient ozone concentrations vary with elevation due to the influences of global radiation, air temperature, and wind on ozone exposure. However, there are no detailed field studies on how changes in elevation that are typical of the ozone sample might affect plant response to ozone (Skelly et al. 2003). Plants at higher elevations may be stressed by poor site conditions and be less responsive to ozone exposure than plants at lower elevations. Ozone exposures also vary with the size of the opening used for biomonitoring. Open areas that are more than 3 acres in size are ideal because they optimize ozone air mixture, but not all biomonitoring sites are this open.

Although a calculated biosite index is provided in this table for each ground location, the preferred summary statistic for Detection Monitoring reports is the biosite-level injury index presented in the biosite summary table.

Ozone Species Summary Table

The measurement variables in this table summarize ozone injury, plant counts, and site characteristics for each bioindicator species (BIOSPCD) evaluated at each ground location. At each location, every plant evaluated by the field crews is rated for amount and severity of ozone injury. The minimum, maximum, and mean values for these two indices are summarized by species. Injury amount is an estimate of the percent injured leaves on each plant. Injury severity is an estimate of the mean severity of symptoms on injured foliage. Both attributes should be considered. Some plants may have slight to moderate injury on all leaves; others may have severe injury on a small number of leaves. The injury pattern may be species specific or may relate to the stage of development at the time of ozone exposure. Injury may also depend on site characteristics that have a greater or lesser influence on amount and severity of injury depending on the species. Site characteristics presented by species at each ground location include plot size, elevation, aspect, terrain position, soil depth, soil drainage, plot wetness, and plot disturbance.

A species-level ozone injury index (BIOSPCD_INDEX) is also presented. This index provides an opportunity to make comparisons among sites using indices derived from the same species. A species-specific analysis may be appropriate for certain Evaluation Monitoring studies. However, for Detection Monitoring reports, the preferred summary statistic is the biosite-level ozone injury index presented in the biosite summary table.

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[14]In these cases, there are two data records for a biosite in the OZONE_PLOT_SUMMARY table and only one record in the OZONE_BIOSITE_SUMMARY table because the data from both locations are combined in the biosite summary attributes.

Population-Level Core Tables and Maps

In addition to the standard summary tables described in the previous section, two core ozone maps are available for download from the FIADB DataMart[15] along with a core list of ozone-sensitive tree and shrub species (Appendix 4). The map products are derived from weighted data that are not readily available, and true biosite locations that are not in the public domain[16]. The first map product is the national ozone risk map, which is based on the 5-year rolling average of the biosite index (BIOSITE_INDEX), and provides an interpolated surface of probable ozone injury across the landscape. The second map product is an interpolated surface of ambient ozone concentrations (e.g., SUM06 data). Data users select their area of interest (e.g., state, FIA region, or ecological region) from these two map products and use the procedures outlined in the Ozone Bioindicator Sampling and Estimation report (Smith et al. 2007) to calculate and interpret population estimates for the ozone indicator. Core products for the ozone indicator include the ozone risk map and tables or graphs that document status and trends in ozone population estimates for a state, FIA region, or ecological region.

The national ozone risk map is used to generate an estimated BI value for forested ground plots on the FIA P2 grid. This interpolated biosite index (IBI) and accompanying plant count attribute are part of the larger P2 table of forest plot attributes in the FIADB. With the map surface and IBI, any user can examine relationships between the ozone indicator and other FIA indicators of tree growth, forest health, and forest condition. Similarly, the national ozone risk map can be used in conjunction with the interpolated surface of ambient ozone concentrations to help interpret FIA findings. Overlays are also possible with other external databases or map surfaces such as climate or seasonal drought.

Validation Data Table

Coded attributes in the ozone validation table (OZONE_VALIDATION) are used by the FIA data processor in each region to edit the field data before they are loaded into the three standard summary tables described previously. The biosite summary statistics do not load properly unless the validation table is complete and in accord with the data files entered by the field crews. The following steps describe the process. The field crew collects a leaf voucher for every bioindicator species at every location where ozone injury is recorded. These are mailed to an expert ozone diagnostician who reviews the leaf vouchers, generates the ozone validation file, and returns the validation table to each region for data processing. The validation table provides a record of whether the ozone injury rated by the field crews was validated or not for every species at every ground location. If the injury is not validated, or if the voucher is missing, the crew data file is modified to reflect this fact. Occasionally, the field crew submits leaf vouchers for plants or species that are not included in the injury data file. These are considered nontallied leaf vouchers as defined by the injury check attribute (see Field Data section, page 27). If injury on nontallied plants or species is validated, this is reflected in the validation file. Injury to nontallied plants or species can be used only to tabulate or map presence and absence of ozone

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[15]http://nrs.fs.fed.us/fia/topics/ozone/pubs/pdfs/Nationalpercent20Ozonepercent20Riskpercent20Map.pdf http://nrs.fs.fed.us/fia/topics/ozone/pubs/pdfs/Nationalpercent20SUM06percent20Surface.pdf

[16]Contact John Coulston, the National Ozone Advisor, if data links presented in this document are no longer active or for data not readily available in the public domain: jcoulston@fs.fed.us

injury. Only validated data from tallied plants and species are used in the computation of ozone summary statistics for core tables and maps.

Crosswalks and Site Identification Data

Data stored in the ozone crosswalk table (OZONE_CROSSWALK) are used to track changes to the ozone sample over time. The ozone indicator was part of the FHM grid sample from 1994 through 2001. When FIA assumed administration of the P3 forest health indicators in 2002, the ozone indicator moved to a new sample grid constructed to meet the unique needs of the ozone indicator. The new grid allowed greater flexibility to select optimal sites for biomonitoring (i.e., large, undisturbed open areas with adequate soil moisture, and high plant and species counts). The concept of split plots was introduced to maximize plant counts in more challenging areas. The 2002 grid was adjusted in 2007 to address Detection Monitoring concerns in the Interior West. These changes to the O_3 sample have resulted in changes to O_3 site identification numbers even though ground locations have been stable. The ozone crosswalk table allows data collected at site number A_1 in 1994 on the FHM grid to be linked to data collected at the same ground location that is identified as site number A_2 on the O3GRID_2002, and site number A_3 on the O3GRID_2007. Further, starting with the 2002 ozone sample grid, ozone biomonitoring sites were assigned to one of four possible strata and the data must be weighted accordingly for interpretive analyses. Strata weights change as the sample grid changes, as it did in 2007. Weights, calculated annually, are available from John Coulston, the FIA National Ozone Advisor.

A second set of crosswalk tables track changes to the ozone plot coordinates (GPS_LAT and GPS_LON) and provide links to the fuzzed coordinates (LAT and LON) that are generated for public use. Field crews are trained to replace sites that become overgrown or disturbed, although the site identification number (FIELD_ID) stays with the relocated plot. Changes in ground location that exceed 3 miles are documented in these base plot tables using the ground location attribute (GROUND_LOC_CD). The crosswalk tables are not part of the FIADB DataMart, nor are they readily accessible to FIA analysts. However, analysts should be aware that these files exist so that they make full use of older (1994 to 2002) and more current (2003 to current year) ozone data files.

DATA SUMMARIES

Core summary statistics for the ozone indicator are discussed in this section by state, FIA region, and year. The intent is to provide information on the scope of the national ozone biomonitoring program and gain appreciation for regional differences (e.g., East versus West) that may influence results and reporting. All the data summarized here are available in the FIA databases (NIMS and FIADB) beginning with the first year the ozone indicator was implemented in a given state up to the most recent field season. The sample graphics and accompanying text can be modified to fit the particular concerns of the FIA reporting unit.

National Program Summary

Currently, there are 1,130 ozone biomonitoring sites in 45 states. Three pilot sites in Alaska are not included in this count. Only New Mexico, Mississippi, Oklahoma, and Hawaii are not yet involved in the program. Numbers of sites vary by state depending on the availability of bioindicator species in certain forest types and the intensity of the sampling grid for O_3. For example, there are relatively few sites in northern Maine due to a scarcity of bioindicator species in the dominant spruce-fir forests of that region, while the numbers of ozone sites are relatively high in Pennsylvania due to increased sampling activity on the part of the state cooperator. The number of biosites evaluated increased over the years as new states were added to the program, stabilizing in 2002 when the FIA ozone sampling grid was finalized (Table 4). More biosites with injury and more injured plants are detected in eastern regions then in the West because most of the eastern United States experiences high ambient ozone concentrations across the landscape during the growing season (Cleveland and Graedel 1979, Lefohn et al. 1997, Skelly 2000). In contrast, except for the Los Angeles basin area, and limited air sheds around Las Vegas, Phoenix, and Salt Lake City, ozone air quality is relatively good across wide areas of the West (U.S. EPA 1996a, Lee and Hogsett 2000, Lee et al. 2003, Miller et al. 1996).

From 1994 to 2006, ozone injury was detected at least once, often every year, in every state in the eastern FIA regions except Nebraska, North Dakota, and South Dakota (Table 5). Some of the Southern States with low injury counts (e.g., Florida) have trouble finding undisturbed, open areas with bioindicator species. The low count in Alabama is not easily explained and may reflect a sampling problem given the routine detection of ozone injury in the neighboring states of Georgia and Tennessee. However, the absence of injury in the three Plains States (Nebraska, North Dakota, and South Dakota) is not surprising especially because the neighboring states in the Rocky Mountain region are also without injury. In fact, no injury has been detected across the Interior West States in 7 years of biomonitoring except in Utah, downwind of Salt Lake City in a state park planted with ponderosa pine not indigenous to the area.[17] On the West Coast, ozone injury has not been detected in Oregon but has been detected repeatedly in the same irrigated location in Washington and routinely in numerous locations throughout California. Regardless of whether injury is detected every year in a given state or region, or only infrequently, the percent of sampled plants that sustain injury is relatively small ranging from less than 1 percent to 26 percent (Table 4). Most ozone-sensitive bioindicator plants remain free of ozone injury symptoms in all regions and all years. This finding agrees with other ozone surveys that have demonstrated that a relatively low percentage of any given population of ozone-sensitive plants will show a visible injury response to elevated ozone concentrations under natural conditions of ambient exposure (Davis and Orendovici 2006, Skelly et al. 1987, Treshow and Stewart 1973). It is noteworthy when ozone injury is detected in a state or region previously thought to be free of ozone stress, even if the injury occurs on a single plant. Bioindicator plants with injury have been detected for the first time by FIA crews in Washington and the northernmost portions of states in the Northeast and North Central U.S., thus providing important baseline data for the ozone indicator in these areas. In those states where ozone injury is detected every year (Table 5: KY, NC, SC, and TN in the Southeast; CT, MD, MA, NY, OH, PA, RI, VT, and WV in the Northeast; IL, IN, and WI in the North Central), the results underscore the fact that a large area and percent of forest land in this country is subject to levels of ozone pollution that may negatively affect the forest ecosystem.

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[17]Ozone injury was observed at Rocky Mountain National Park in Colorado on cutleaf coneflower (*Rudbeckia laaciniata v. ampla*) over a period of 3 years ending in 2008 (R. Kohut, pers. comm.). Coneflower is currently on the FIA list of trial bioindicator species, but at the time when FIA crews were evaluating biosites in the Rocky Mountain region (1997 to 2004) not enough was known about the ozone sensitivity of this species to include it on the official bioindicator list.

Table 4.—Number of biosites evaluated and injured, number of plants evaluated and injured, and percent sampled plants uninjured and injured by region and state for the years 1997 to 2006

Region and year	Number of biosites		Number of plants		Percent of sampled plants	
	Evaluated	Injured	Evaluated	Injured	Uninjured	Injured
Southern States						
1997	19	8	697	101	86	14
1998	22	12	1,419	260	82	18
1999	90	33	4,495	405	91	9
2000	178	62	9,070	535	94	6
2001	248	76	14,623	660	96	4
2002	314	62	26,836	628	98	2
2003	319	96	29,026	877	97	3
2004	351	61	30,890	364	99	1
2005	359	43	29,267	333	99	1
2006	335	27	29,085	161	99	1
Northeast States						
1994	86	56	3,590	923	74	26
1995	147	56	6,049	578	90	10
1996	126	58	5,468	731	87	13
1997	151	48	7,156	445	94	6
1998	269	158	11,915	1976	84	16
1999	372	82	19,467	627	97	3
2000	269	109	17,371	1146	93	7
2001	341	106	29,399	1028	97	3
2002	230	98	22,893	1067	95	5
2003	229	82	22,793	660	97	3
2004	227	80	22,376	891	96	4
2005	232	79	23,360	502	98	2
2006	233	103	23,239	700	97	3
North Central States						
1994	32	10	1,293	58	96	4
1995	137	17	5,245	133	97	3
1996	103	24	4,469	260	94	6
1997	123	25	5,764	296	95	5
1998	196	67	10,592	722	93	7
1999	188	91	14,237	645	95	5
2000	290	157	21,089	1096	95	5
2001	233	100	17,445	592	97	3
2002	260	64	23,253	247	99	1
2003	269	55	23,628	240	99	1
2004	267	71	24,392	271	99	1
2005	240	52	23,130	174	99	1
2006	237	58	23,391	258	99	1
Rocky Mountain States[1]						
1998	79	0	3,068	0	100	0
1999	84	0	3,481	0	100	0
2000	113	0	5,271	0	100	0
2001	129	0	6,043	0	100	0
2002	72	0	5,298	0	100	0
2003	116	0	9,269	0	100	0
2004	161	0	13,698	0	100	0

continued

Table 4.—continued

Region and year	Number of biosites		Number of plants		Percent of sampled plants	
	Evaluated	Injured	Evaluated	Injured	Uninjured	Injured
West Coast States						
1998	67	0	3,691	0	100	0
1999	90	1	3,576	2	100	<0.05
2000	64	7	3,323	105	97	3
2001	67	12	3,728	120	97	3
2002	118	19	8,621	177	98	2
2003	129	17	9,847	123	99	1
2004	126	22	9,626	139	99	1
2005	134	23	9,445	259	97	3
2006	134	24	9,915	185	98	2

[1]There are no data available for the Rocky Mountain States after 2004.

Table 5.—Number of years of biomonitoring, number of years with ozone injury, and year biomonitoring was started by region and state for the years 1994 to 2006

Region and year	Number of years		Start year[1]
	Biomonitoring	Ozone injury detected	
Southern States			
Alabama	7	1	1994
Arkansas	6	3	2001
Florida	5	1	2002
Georgia	10	9	1994
Kentucky	7	7	2001
Louisiana	5	1	2001
North Carolina	8	8	1998
South Carolina	8	8	1998
Tennessee	7	7	1998
Texas	5	2	2001[2]
Virginia	10	9	1994
Northeast States			
Connecticut	13	13	1994
Delaware	11	10	1995
Maine	13	6	1994
Maryland	13	13	1994
Massachusetts	13	13	1994
New Hampshire	13	11	1994
New Jersey	13	11	1994
New York	8	8	1999
Ohio	10	10	1997
Pennsylvania	10	10	1995
Rhode Island	13	13	1994
Vermont	13	13	1994
West Virginia	12	12	1995
North Central States			
Illinois	10	10	1997
Indiana	11	11	1996
Iowa	7	3	2000
Kansas	5	2	2002
Michigan	13	12	1994
Minnesota	13	4	1994

continued

Table 5.—continued

Region and year	Number of years: Biomonitoring	Ozone injury detected	Start year[1]
Missouri	7	6	2000
Nebraska	5	0	2002
North Dakota	5	0	2002
South Dakota	5	0	2002
Wisconsin	13	13	1994
Rocky Mountain States[3]			
Arizona	3	0	2002
Colorado	7	0	1997
Idaho	5	0	1997
Montana	2	0	2003
Nevada	3	0	2000
Utah	5	0	2000
Wyoming	4	0	1997
West Coast States			
California	9	8	1998
Oregon	9	0	1998
Washington	9	6	1998

[1]Some states are missing interim years between start date and current year.
[2]West Texas started in 2004.
[3]There are no data for Rocky Mountain States after 2004 and for Idaho and Wyoming after 2001.

The most common species found on eastern biomonitoring sites are blackberry, milkweed, black cherry, and white ash (Table 6). In addition, regional differences in the natural range of certain species affect usage. For example, sweetgum, sassafras, and yellow-poplar are common bioindicator species in the Southern States, much less so in the Northeast and North Central States; and several bioindicator species used in the westernmost states of the North Central region are not found at all in the South and Northeast. Species selection is prioritized in the field procedures to increase the likelihood that most sites in the East will contain similar species. Even so, gathering foliar injury data from a range of herbaceous and woody plant species common to the forest environment increases the responsiveness of the ozone injury index (BI) for a given locale (W.D. Smith, pers. comm.). Over the years, we have learned that certain species are more useful as ozone detectors in cool, wet years (e.g., milkweed), while others (e.g., black cherry) are more useful in hot, dry years. Biosites that have both these species are more likely to provide a consistent, uncompromised response to O_3 across years with variable temperature and precipitation patterns.

Quaking aspen in the Rocky Mountain States and ponderosa pine in the West Coast States are the most common tree species on western biomonitoring sites (Table 7). Associated shrub species that are widely sampled in both the interior and coastal states include snowberry, blue and red elderberry, and skunkbush. In many parts of the West, the forested landscape is characterized by large natural openings populated by a single overstory species (e.g., aspen or ponderosa pine). It can be challenging to find nearby locations that include one or more of the understory bioindicator species. For this reason, western crews average 2.5 species per site compared to 3.5 species per site for the eastern crews. All the eastern and western species used for biomonitoring are relatively common across a variety of forest types, relatively easy to identify and distinguish from similar species, and ozone sensitive based on a combination

Table 6.—List of bioindicator species and numbers of evaluated plants by species for the 2004 field season in the Southern, Northeast, and North Central States

	Number of plants evaluated (2004[1])			
Bioindicator species	Southern States	Northeast States	North Central States[2]	Totals
Blackberry	9,552	4,428	2,206	16,186
Milkweed	1,464	4,453	5,439	11,356
Black cherry	4,312	3,335	3,287	10,934
White ash	1,171	3,450	4,260	8,881
Spreading dogbane	403	3,336	4,335	8,074
Sweetgum	6,996	469	252	7,717
Sassafras	3,307	1,242	1,175	5,724
Yellow-poplar	3,343	973	298	4,614
Pin cherry	352	630	395	1,377
Bigleaf aster	30	60	1,103	1,193
Mountain snowberry	-	-	673	673
Western wormwood	-	-	554	554
Skunkbush	-	-	280	280
Ponderosa pine	-	-	135	135

[1]The year 2004 was selected as representative for all regions. Data are available by year (1994 to current year) and by species in the FIA national database.

[2]In the North Central States, evening primrose, green ash, and quaking aspen are sampled occasionally.

Table 7.—List of bioindicator species and numbers of evaluated plants by species for the 2004 field season in the Rocky Mountain and West Coast States

	Number of plants evaluated (2004[1])		
Bioindicator species	Rocky Mountain States	West Coast States[2]	Totals
Mountain snowberry	3,851	1,793	5,644
Ponderosa pine[3]	2,718	2,129	4,847
Quaking aspen	3,654	932	4,586
Scoulers's willow	259	990	1,249
Blue elderberry	469	569	1,038
Skunk bush	584	328	912
Western wormwood	50	30	880
Red elderberry	417	400	817
Red alder	0	734	734
Ninebark	612	111	723
Mugwort	02	602	704
Jeffrey pine	30	652	682
Huckleberry	42	334	376
Pacific ninebark	60	22	82
Milkweed	50	-	50

[1]The year 2004 was selected as representative for all regions. Data are available by year (1994 to current year) and by species in the FIA national database.

[2]In the West Coast States, California black oak, chokecherry, and thimbleberry were sampled in 1998-2000 and then dropped from the bioindicator species list.

[3]*Pinus ponderosa var. scopulorum* in Rocky Mountain States; *var. ponderosa* in West Coast States.

of field evidence and causative fumigation experiments. They were all recently identified as excellent ozone detectors by a panel of experts (USDI 2003, http://www2.nature.nps.gov/air/).

Having to use different bioindicator species in each region presents some concern for national reports. The classification scheme for the biosite index (Table 3) is based on knowledge and experience gained largely in eastern forest types. It is not clear, for example, how a biosite value derived from eastern species (e.g., black cherry) compares to a biosite value derived from western species (e.g., ponderosa pine). The index appears to work well in all regions based on a comparison of the two map products for the ozone indicator as long as the data summarization period covers multiple years. When a national map derived from the 5-year rolling average of the BI data is compared to a national map of interpolated SUM06 data for the same time period, it is apparent that low, moderate, and high risk zones for probable ozone impact (IBI data) generally match low, moderate, and high risk zones for ozone exposure (SUM06 data) regardless of whether the zones are in California or the mid-Atlantic region. The exception to this observation is the Interior West (Colorado, Utah, and Arizona in particular) where low moisture conditions during the growing season and resistant genotypes of ozone-sensitive plant species appear to limit the biological response of plant receptors to ozone pollution (Duriscoe and Temple 1996).

Regional Summaries and State Reports

Earlier sections of this report answer questions about what ozone pollution is, how it injures trees, and what types of health assessment questions are addressed by the FIA ozone biomonitoring program. These topics should be worked into any issue-driven report on the ozone indicator. As suggested in the national program summary, it is useful to summarize the data for the years and area of concern by mapping the distribution of biosites across a state or region and reporting on the numbers of biosites evaluated and injured, the numbers of species and plants evaluated and injured, the severity of injury as reflected in the field assessed injury scores (i.e., HB rating), and the categorized risk of probable impact as described by the biosite index (BI). Additional interpretive information is gained by examining injury patterns across the state or region relative to spatial and temporal variations in ambient ozone concentrations, precipitation patterns, and soil moisture indices. Examples of this approach are presented here using data from the states in FIA-North and the sampling period 1997 through 2006. Additional examples of state reports that serve as models for FIA analysts include the 5-year summary reports for South Carolina (Conner et al. 2004) and Indiana (Woodall et al. 2005) and the two published general technical reports by Campbell et al. (2000 and 2007) that include data from Washington, Oregon, and California. A general technical report for the southern FIA region is in progress (Rose and Coulston, In press).

An initial step in assessing the interpretive value of ozone biomonitoring data is to examine the relationship between the FIA plant injury data (e.g., calculated BI values) and the more traditional ozone exposure data (e.g., SUM06: sum of all hourly average ozone concentrations $\geq$0.06 ppm) derived from air quality monitoring stations operated by EPA. Using this approach, analysts working with Indiana data (1997-2002) reported the following: (1) Indiana's ozone exposures (SUM06 values) are the highest in the North Central region; (2) essentially all the forested acreage in the state is exposed to elevated ozone concentrations; (3) Indiana has the highest amount and severity of foliar injury to ozone-sensitive species among the North Central States; and (4) the highest injury index scores coincided with the highest ozone exposure levels in south-central

Table 8.—Regional differences in maximum and mean ozone exposure data for 1994-2005

Region[1]	Range of maximum ozone exposure values (SUM06)[2] 1994-2005	Mean value 1994-2005	Ozone exposure category[3]
Northern New England	8.25 - 29.20	6.22	Clean
Southern New England	14.94 - 34.73	18.03	Moderate
Mid-Atlantic States	15.58 - 110.25	26.27	Unhealthy
Northern Plains	1.50 - 39.14	7.53	Clean
East North Central	8.61 - 54.34	18.20	Moderate
South	13.01 - 120.68	21.62	Moderate
Northwest	5.11 - 50.41	8.26	Clean
Interior West	19.58 - 85.97	20.15	Moderate
Southwest	76.80 - 117.34	28.73	Unhealthy

[1]Regions are defined as follows. Northern New England = ME, NH, VT; Southern New England = MA, CT, RI; Mid-Atlantic = DE, MD, NJ, PA, WV; Northern Plains = IA, KS, MN, NE, ND, SD; North Central = IL, IN, MI, MO, OH, WI; South = AL, AR, GA, KY, LA, NC, SC, TN, VA; Northwest = ID, MT, OR, WA, WY; Interior West = AZ, CO, NV, UT; and Southwest = CA.

[2]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. Identical mean values for 1994 and 1995 in Kansas, Nebraska, and Missouri were considered outliers and dropped from the analysis.

[3]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.

Indiana (Woodall et al. 2005). The summarized BI data, together with information on the distribution of ozone exposures and tree species in Indiana, led analysts to suggest that forests across the state are at risk of ozone-induced negative effects. In contrast, a similar comparison of BI and air quality data in South Carolina (1999-2001) allowed state analysts to report that even though much of the northern half of the state is subject to moderate to high ozone exposures, low BI scores taken together with several years of below average rainfall suggest the probability of ozone impacts on forests in South Carolina is low to none (Conner et al. 2004).

The relationship between plant injury and ozone exposure may also be examined at the regional level. For example, along the northeast corridor from Maine to Virginia, there is an obvious gradient of increasing ozone exposure from the relatively clean air states of northern New England, across the moderate ozone states of southern New England to the mid-Atlantic States (Table 8)[18]. Similarly, air quality in the Northern Plains States is clearly different from that found in the industrialized east North Central States. An examination of the plant injury summary statistics for the Northeast and North Central regions indicates that the average biosite index (BI) and percent sampled plants with higher HB severity ratings were highest in the states characterized by high ozone exposure, intermediate in the states characterized by moderate ozone exposure, and lowest in the relatively clean air states of northern New England and the Northern Plains (Table 9). In moderate and high ozone exposure groupings, the average BI value was highest in 1998, showing a sharp drop in value for all exposure groupings in 1999. According to data

[18]New York is not included in the regional summaries presented in Tables 8, 9, and 10 due to differences in sampling period and size. Data collection began in 1999 as compared to 1994 and 1997 for other states in the Northeast. Conditions vary considerably across the state so New York is not easily grouped with either New England or the mid-Atlantic States. State averages for injury (BI=2.38) and O_3 level (SUM06=14.1 ppm-hr) do not accurately reflect conditions of probable O_3 impact in the southeastern portion of New York that borders the mid-Atlantic States.

Table 9.—Number of biomonitoring sites evaluated for ozone-induced foliar injury, number of biosites with injury, average biosite index, and percent of sampled plants in each HB injury severity category for groups of states with low, moderate, and high ozone exposure regimes across the FIA-North region

State group[1] and year	Number of biosites evaluated	Number of biosites with injury	Average biosite index[2]	HB injury severity categories[3] 0	1	2	3	4	5
Northern New England (ME, NH, VT)				Percent sampled plants[3]					
1997	63	10	6.76	95	1	2	1	<1	<1
1998	70	26	6.56	94	2	2	1	<1	<1
1999	68	11	0.46	98	1	<1	<1	<1	-
2000	61	7	0.99	97	1	1	<1	<1	-
2001	59	7	0.69	99	<1	<1	<1	-	-
2002	36	5	0.41	99	<1	<1	<1	<1	-
2003	39	5	0.30	99	<1	<1	<1	-	-
2004	40	5	2.05	99	-	<1	<1	<1	<1
2005	39	11	1.44	99	<1	<1	-	-	-
2006	35	10	0.60	99	<1	<1	-	-	-
Southern New England (MA, CT, RI)									
1997	28	20	6.85	87	6	5	1	<1	-
1998	28	24	19.81	82	7	7	3	<1	<1
1999	28	15	8.38	93	2	3	1	<1	<1
2000	26	19	3.97	91	4	3	1	-	-
2001	18	11	8.54	89	5	4	1	<1	-
2002	20	13	4.47	93	3	3	<1	<1	-
2003	20	13	1.77	96	2	1	<1	-	-
2004	17	9	3.06	93	4	2	<1	<1	-
2005	21	12	2.33	95	2	2	<1	-	-
2006	18	18	7.50	87	5	6	2	-	-
Mid-Atlantic States (DE, MD, NJ, PA, WV, VA)									
1997	50	11	12.30	92	1	2	1	1	<1
1998	168	103	34.82	76	5	8	6	3	2
1999	199	46	13.40	96	1	1	1	<1	<1
2000	179	85	4.87	91	3	3	1	1	<1
2001	203	77	5.08	96	1	1	1	<1	<1
2002	128	58	7.06	94	1	2	1	1	<1
2003	133	52	2.89	96	1	2	<1	<1	<1
2004	140	45	5.10	96	2	1	<1	<1	-
2005	143	41	6.68	98	1	1	<1	-	-
2006	149	51	4.24	98	1	1	<1	-	-
Northern Plains States (IA, KS, MN, NE, ND, SD)									
1997	40	1	0.08	99	-	-	<1	-	-
1998	59	1	0.09	99	<1	<1	-	-	-
1999	46	0	<0.01	100	-	-	-	-	-
2000	49	1	<0.01	99	<1	-	-	-	-
2001	33	1	0.15	99	-	-	-	<1	-
2002	73	0	<0.01	100	-	-	-	-	-
2003	73	5	0.09	99	<1	<1	<1	-	<1
2004	74	1	<0.01	99	<1	-	-	-	-
2005	74	1	0.05	99	-	<1	-	-	-
2006	71	4	0.35	99	<1	<1	<1	-	-
East North Central States (IL, IN, MI, MO, OH, WI)									
1997	102	34	14.28	94	1	2	2	1	-
1998	156	78	20.11	91	3	3	2	1	-
1999	160	95	4.34	95	3	2	<1	-	-

continued

Table 9.—continued.

State group[1] and year	Number of biosites evaluated	Number of biosites with injury	Average biosite index[2]	HB injury severity categories[3]					
				0	1	2	3	4	5
2000	260	161	5.60	95	3	2	<1	-	-
2001	234	107	3.85	96	1	1	<1	<1	<1
2002	221	72	1.21	99	<1	1	-	-	-
2003	230	59	1.24	99	<1	<1	-	-	-
2004	227	82	1.52	98	1	<1	-	-	-
2005	200	61	1.15	99	<1	<1	-	-	-
2006	200	61	1.27	99	<1	<1	-	-	-

[1]States are grouped by ozone air quality characteristics. Northern New England States and Northern Plains States have relatively clean air: SUM06 <10 ppm-hr; Southern New England States and East North Central States have moderate air quality: SUM06 10-25 ppm-hr; Mid-Atlantic States have relatively poor air quality: SUM06 >25 ppm-hr.

[2]Average biosite index values were calculated for each state grouping.

[3]Injury severity is an estimate of the mean severity of symptoms on injured foliage (0 = no injury; 1 = 1- 6%; 2 = 7-25%; 3 = 26-50%; 4 = 51-75%; 5 = >75%). Calculated percents are rounded to the nearest whole number.

obtained from the regional climate center at Cornell University (http://met-www.cit.cornell.edu/), 1998 was a comparatively wet year and 1999 was very dry for much of the Northeast. Percent sampled plants with no injury (HB severity class = 0) was lowest in 1998 regardless of the ozone exposure grouping.

From 1997 to 2006, average BI values ranged from <1.0 in northern New England and the Northern Plains to 19.81 in southern New England, 20.11 in the east North Central States, and 34.82 in the mid-Atlantic States. These results suggest that reporting a single regionwide injury index for FIA-North would clearly mask state-level gradations in air quality and plant response, making it difficult to assess changes in the ozone indicator over time. Even using seemingly logical state groupings may cause some important state-level information to be lost. For example, Vermont stands out in the northern New England States as having a greater number of biosites with injury and more severe ozone injury across greater forested acreage than either New Hampshire or Maine (state-level data not shown), which becomes visually apparent when the site-level biosite data are interpolated across the landscape (Fig. 4). A simpler map showing the distribution of biosites with and without ozone injury, or weighted by the number of years with and without injury over a 5- to 10-year period, is just as effective as a reporting tool. Outside of FIA-North, many of the larger states to the west and south have sharply different ozone exposure zones in areas with different topography or population densities, making it entirely inappropriate to calculate mean values by state or by some geographical grouping of states as described above. Air quality in northern California, for example, is relatively clean and more similar to Oregon and Washington than central and southern portions of the state, which sustain some of the highest ozone concentrations in the country.

A second example of state-level sampling statistics using the same state groupings presents mean growing season BI alongside corresponding data on ozone air quality, precipitation norms, and soil moisture indices (Table 10). The classification schemes for the various indices are derived from the literature and expert opinion (Table 11). The classification scheme for the biosite index has already been described (Table 3). The ozone season is characterized by ozone exposure level based on categorizations of SUM06 data and 8-hr exceedance days. Seasonal mean SUM06 values range from zero to more than 30 ppm-hr reflecting an increasing number of hours during the growing season when the ambient ozone concentrations exceeded a threshold value (0.06

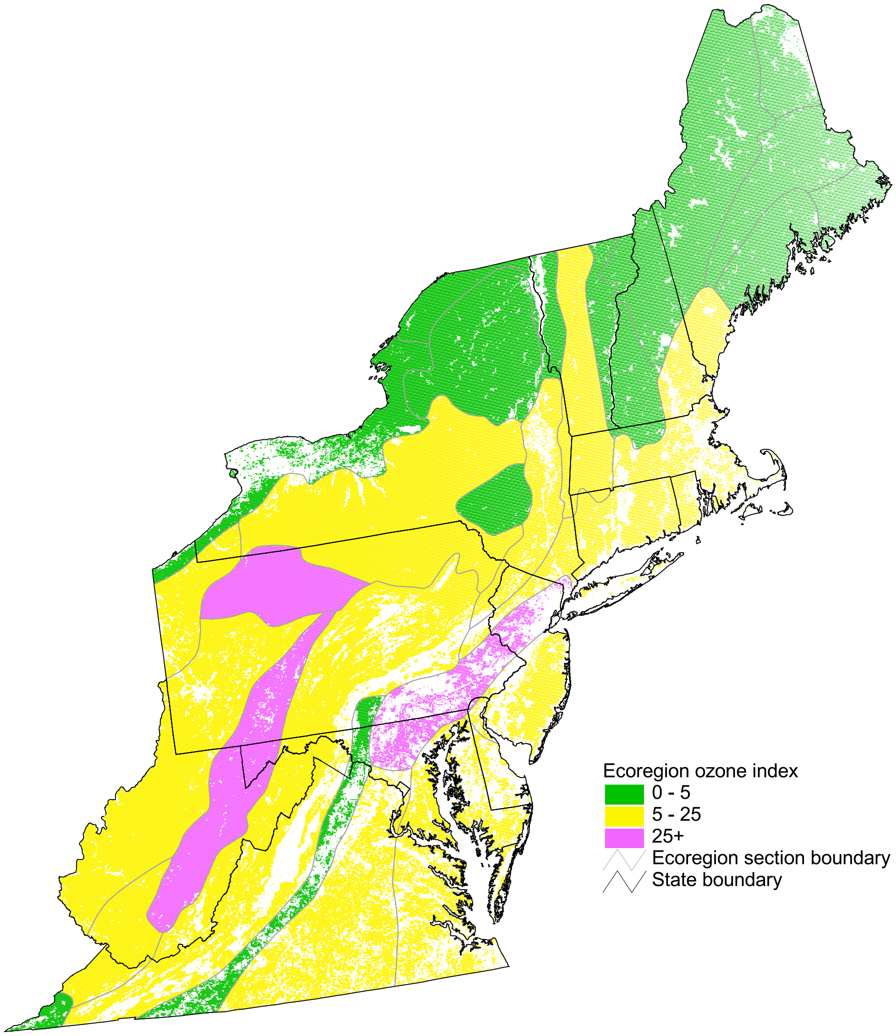


Figure 4.—Example of the intersection of interpolated biosite index (IBI) values and ecoregions in the Northeast showing areas of increasing risk with respect to probable O_3 impact. Green areas indicate low risk of impact (BI = 0 to <5), yellow areas indicate moderate risk (BI = 5 to <25), and pink areas indicate high risk of ozone impact (BI >=25).

ppm O_3) above which ozone is considered phytotoxic. Similarly, mean 8-hr exceedance days range from zero to more than 20, reflecting an increasing number of days when peak ozone concentrations exceed the 8-hr NAAQS (0.084 ppm O_3) set to protect plants from ozone injury. The SUM06 statistic serves as a good indicator of chronic ozone stress, whereas the 8-hr exceedance statistic provides an indication of peak ozone concentrations, or maximum stress. The soil moisture indices (PDSI and Palmer Z) and precipitation measurements (percent normal) were categorized using generally accepted terms to describe a progression from dry to near normal to wet conditions[19]. The Palmer Z index measures short-term drought while the Palmer Drought Severity Index (PDSI) provides a measure of long-term cumulative drought. Seasonal mean values for all measurement variables were calculated by state and by year and then averaged within previously described state groupings after it was determined that precipitation indices within each group varied by no more than one class 100 percent of the time.

[19]National Climate Data Center, U.S. Palmer Drought Indices: http://www.ncdc.noaa.gov/oa/ncdc.html.

Table 10.—Seasonal averages of the biosite index, air quality, soil moisture, and precipitation indices by year (1997 to 2005) for groups of states with varying air quality

State group[1] and year	Biosite index[2]	Seasonal ozone SUM06 (ppm-hr)	Seasonal ozone 8 hr exceedance days	Seasonal soil moisture (PDSI)	Seasonal precipitation (% normal)	Seasonal soil moisture (Z Index)
Northern New England (ME, NH, VT)						
1997	6.76	6.9	4.3	1.90	100	0.57
1998	6.56	5.2	3.7	2.46	141	2.82
1999	0.46	8.5	5.3	-2.15	77	-1.50
2000	0.99	2.6	1.7	2.64	94	0.59
2001	0.69	6.9	4.3	-2.03	79	-1.16
2002	0.41	8.9	7.7	-0.33	90	-0.15
2003	0.30	5.5	1.0	-0.41	98	0.15
2004	2.05	3.7	2.0	1.76	118	1.86
2005	1.44	4.6	2.0	2.72	106	0.47
Mean values	2.18	5.9	3.6	0.73	100	0.41
Southern New England (CT, MA, RI)						
1997	6.85	19.4	15.3	-0.73	86	-0.46
1998	19.81	16.2	8.0	1.03	132	1.50
1999	8.38	21.1	13.3	-2.29	52	-2.30
2000	3.97	12.8	5.0	1.89	125	1.71
2001	8.54	20.0	14.7	0.64	116	0.89
2002	4.47	25.4	16.3	-0.57	80	-0.62
2003	1.77	16.9	8.3	2.00	125	1.27
2004	3.06	11.8	3.7	1.03	103	0.45
2005	2.33	16.3	8.0	-0.88	75	-1.22
Mean values	6.57	17.8	10.3	0.24	99	0.14
Mid-Atlantic States (DE, MD, NJ, PA, WV)						
1997	12.30	30.5	18.2	0.86	89	-0.44
1998	34.82	31.4	28.4	0.14	88	-0.53
1999	13.40	35.0	22.4	-3.55	71	-2.19
2000	4.87	18.5	10.8	1.25	120	1.28
2001	5.08	26.4	15.8	0.21	110	0.57
2002	7.16	34.9	24.4	-2.11	79	-1.38
2003	2.89	20.4	6.8	3.50	144	2.39
2004	5.10	12.8	4.6	3.30	122	1.31
2005	6.68	19.7	9.2	-0.38	93	-0.78
Mean values	10.25	25.5	15.6	0.36	102	0.03
Northern Plains States (IA, KS, MN, NE, ND, SD)						
1997	0.08	6.1	0	3.11	102	1.09
1998	0.09	2.3	1.0	2.79	117	0.56
1999	<0.01	3.9	0	4.59	115	1.82
2000	<0.01	3.5	0.5	1.04	94	0.97
2001	0.15	6.2	1.5	1.80	93	-0.68
2002	<0.01	9.3	0.8	-1.45	101	-0.54
2003	0.09	10.1	0.8	-0.74	78	-0.96
2004	<0.01	3.3	0	0.94	96	0.57
2005	0.05	9.5	0.8	1.97	114	1.40
Mean values	0.09	6.0	0.6	1.56	101	0.47
East North Central States (IL, IN, MI, MO, OH, WI)						
1997	14.28	17.6	9.4	1.50	101	0.70
1998	20.11	18.4	16.2	0.82	110	0.71
1999	4.34	19.8	17.8	-0.62	96	-0.05
2000	5.60	12.8	5.3	1.25	115	1.44
2001	3.85	19.0	11.3	0.67	101	0.34

continued

Table 10.—continued

State group[1] and year	Biosite index[2]	Seasonal ozone SUM06 (ppm-hr)	Seasonal ozone 8 hr exceedance days	Seasonal soil moisture (PDSI)	Seasonal precipitation (% normal)	Seasonal soil moisture (Z Index)
2002	1.21	23.5	22.0	-0.11	88	-0.71
2003	1.24	16.9	7.5	0.77	100	0.54
2004	1.52	6.2	1.5	2.50	109	1.33
2005	1.15	19.5	10.8	-1.74	92	-0.80
Mean values	5.92	17.1	11.3	0.56	101	0.39

[1]State groups are allowed based on the similarity of precipitation values and air quality data. All the combined states held state-level mean Z values that agreed within one category 100 percent of the time.

[2]Classification schemes for the biosite index, seasonal ozone, seasonal soil moisture, and seasonal precipitation data are described in Table 11 of this report.

The results suggest that BI values are highest within each state grouping when seasonal soil moisture and precipitation indices indicate near normal to wet conditions. When seasonal soil moisture and precipitation indices indicate dry to drought conditions, the BI value tends to be relatively low even when seasonal ozone exposure indices are relatively high. In southern New England, for example, mean values for the 1997 to 2005 study period were in the low to moderate foliar injury class for BI and in the low to moderate class for ozone exposure. In 1997, precipitation and soil moisture conditions were near normal and the ozone exposure and injury indices stayed close to the mean. In 1998, ozone exposure values were slightly lower than the 1997 values, but the BI value almost tripled from 6.85 (low to moderate injury class) to 19.81 (moderate to severe injury class) presumably caused by wet conditions favoring ozone flux. In 1999, the seasonal precipitation index plummeted to 52 percent of normal, and even though the ozone exposure value was relatively high at 21.1 ppm-hr (moderate O_3 exposure class), the BI value dropped back down to 8.38 suggesting the plant stomates were closed. Seasonal ozone exposures values were highest in 2002, both in terms of SUM06 data (25.4 ppm-hr) and number of 8-hr exceedance days (16.3), but the BI statistic was relatively low at 4.47 (little or no foliar injury class). Seasonal precipitation was 80 percent of normal with soil moisture indices on the dry side of near normal conditions. Additional or more site-specific information on the exposure environment of the sample plants is needed to know what contributed to the below average BI value in 2002.

Trends in ozone injury and exposure are examined for FIA-North by looking at changes in average ozone injury and exposure indices for the consecutive 5-year periods, 1997 to 2001 and 2002 to 2006 (Table 12). Along the northeast ozone gradient, the percent injured biosites has not changed significantly from one 5-year period to the next, but in areas with moderate to high ozone exposures (including the east North Central States) the percent injured plants has decreased considerably as has the average biosite index. Both periods are characterized by fluctuating precipitation and soil moisture indices (refer back to Table 10), suggesting that weather alone does not appear to be the controlling factor in the regionwide trend toward less injury. The average ozone exposure indices suggest no significant change in chronic ozone exposure as reflected in the SUM06 index. Average number of ozone exceedance days dropped slightly, suggesting a reduction in peak ozone exposure levels. In the high ozone subregion of the mid-Atlantic, for example, the average number of exceedance days was greater than 15 in 4 of the 5 years from 1997 to 2001 and less than 10 in 4 of the 5 years from 2002 to

Table 11.—Classification schemes for the seasonal indices[1] of foliar injury (BI), ozone exposure (SUM06 and 8-hr exceedance days), soil moisture (Palmer Drought Severity Index and Palmer Z), and precipitation (percent normal)

Foliar Injury Response
Biosite-level injury index values (BI)[2]
0 to 5 = little or no foliar injury; no risk of ozone impacts
>5 to 15 = low to moderate foliar injury; low risk
>15 to 25 = moderate to severe foliar injury; moderate risk
>25 = severe foliar injury; high risk
Seasonal Ozone Exposure
SUM06 values (sum of all hourly average ozone concentrations ≥0.06 ppm O_3)[3]
0 to 10 ppm-hr = clean (no O_3)
>10 to ≤20 ppm-hr = low O_3
>20 to ≤30 ppm-hr = moderate O_3
>30 ppm-hr = high O_3
8-hr exceedance days (number of days with an exceedance of the 8-hr O_3 standard)[3]
0 to 10 days = low O_3
>10 to 20 days = moderate O_3
>20 days = high O_3
Seasonal Soil Moisture
PDSI (long-term drought) and Palmer Z (short-term drought) values[4]
≥3.00 = very wet
2.00 to 2.99 = moderately wet
1.00 to 1.99 = slightly wet
-0.99 to 0.99 = near normal
-1.0 to -1.99 = mild drought
-2.0 to -2.99 = moderate drought
≥-3.00 = severe drought
Seasonal Precipitation
% Normal
>134 = very wet
110 to 134 = wet
85 to 109 = near normal
60 to 84 = dry
< 60 = very dry

[1]All seasonal mean values were calculated by state and by year and then averaged within a state grouping.

[2]The BI classification scheme describes the degree of foliar injury response and assumption of probable ozone injury ranging from little or no foliar injury and no risk of impact to low, moderate, and severe foliar injury and low, moderate, and high risk of ozone impact to the forest ecosystem.

[3]The ozone exposure classifications describe a progression from clean to moderate to unhealthy air quality. Seasonal mean SUM06 values were categorized as clean (0-10 ppm-hr), low (>10-20 ppm-hr), moderate (>20-30 ppm-hr), and high (≥30 ppm-hr). Mean 8-hr exceedance days were categorized as low (0-10), moderate (>10-20), and high (>20).

[4]The soil moisture and precipitation measurement variables describe a progression from dry to normal to wet conditions. The Palmer Drought Severity Index shows how long-term cumulative moisture conditions have changed over the past 12 months. The Palmer Z Index shows how monthly (short-term) moisture conditions depart from normal.

Table 12.—Differences in calculated mean values for percent injured biosites, percent injured plants, average biosite index, and ozone exposure indices for consecutive 5-year sampling periods from 1997 to 2001 and from 2002 to 2006

State group[1] and year	Percent injured biosites	Percent injured plants	Average biosite index[2]	Average SUM06 value	Average exceedance days
Northern New England (ME, NH, VT)					
1997-2001	18.4	3.0	3.09	6.0	3.9
2002-2006	19.0	0.8	0.96	5.7	3.2
Southern New England (MA, CT, RI)					
1997-2001	68.8	11.5	9.51	17.9	11.3
2002-2006	68.0	6.9	3.83	17.6	9.1
Mid-Atlantic States (DE, MD, NJ, PA, WV, VA)					
1997-2001	38.2	7.8	14.14	28.4	19.1
2002-2006	35.8	4.3	5.19	21.9	11.3
Northern Plains States (IA, KS, MN, NE, ND, SD)					
1997-2001	1.8	<0.1	0.11	4.4	0.5
2002-2006	3.0	<0.1	0.16	8.1	0.6
East North Central States (IL, IN, MI, MO, OH, WI)					
1997-2001	52.1	5.4	9.64	17.5	12.0
2002-2006	31.1	1.4	1.28	16.5	10.5

[1]State and air quality groupings are defined as follows: Northern New England = ME, NH, VT (SUM06 <10 ppm-hr); southern New England = MA, CT, RI (SUM06 10-25 ppm-hr); mid-Atlantic = NJ, PA, MD, DE, WV, VA (SUM06 >25 ppm-hr); Northern Plains = IA, KS, MN, NE, ND, SD (SUM06 <10 ppm-hr); east North Central = IL, IN, MI, MO, OH, WI (SUM06 10-25 ppm-hr)
[2]Average biosite index values were calculated for each state grouping.

2006. This finding is in accord with national trends in O_3 air quality that show that air quality control strategies have reduced maximum 1-hr O_3 concentrations but have had little impact on moderate O_3 concentrations.

Trend data for the Northeast suggest that changes in ozone exposure have had less of an effect on the numbers of injured biosites than on the BI index. Injury is detected on about the same number of sites every year, often the same sites every year, but the BI value that associates injury amount, injury severity, and incidence of injury at each site tends to fluctuate in response to changes in ozone level and the ozone exposure environment. This result is indicative of the biological responsiveness of the BI index and underscores the need for analysts to include ancillary data when presenting and interpreting results. It is generally true for states in FIA-North that ozone stress is causing visible foliar injury to ozone-sensitive species on less than 20 percent of the biomonitoring sites in years or states with relatively clean air, and often on more than 30 percent of the biomonitoring sites in years or states with moderate to high ozone exposure. The year 1998, characterized by relatively high O_3 and adequate growing season moisture, is the only year when foliar injury and the presumed risk of ozone stress were moderate to severe across large portions of FIA-North. The remaining years during the 1997 to 2006 sampling period were relatively free of ozone injury from a regional perspective. However, there are localized areas and significant portions of ecological regions where BI values are relatively high year after year (Fig. 4), and these high risk zones for probable ozone impact should be investigated further.

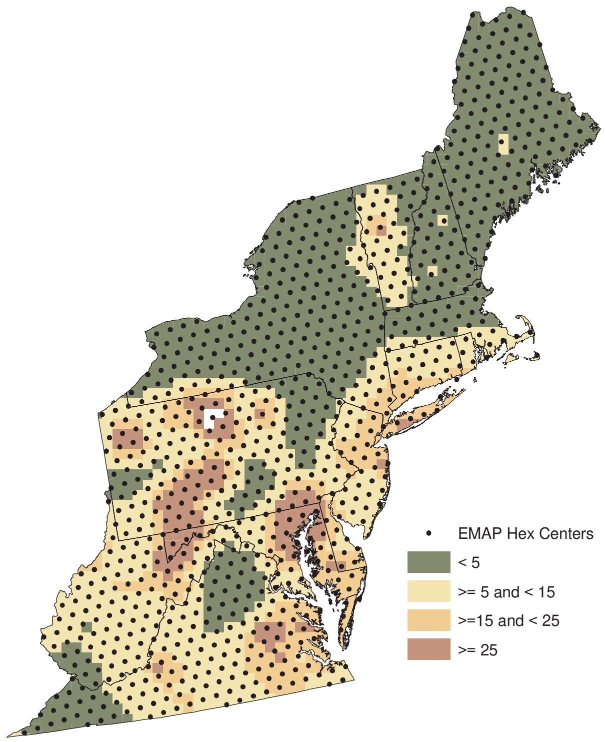
ANALYTICAL PROCEDURES AND RISK ASSESSMENT

In Detection Monitoring, the biomonitoring data are used to identify forested areas that may be at risk from ozone stress. Foliar injury to a bioindicator plant is a function of the interaction between ozone level and the exposure environment of the plant. For injury to occur, ozone must be present above some threshold concentration and the exposure environment must be favorable for gas exchange and the overall responsiveness of the plant. For Detection Monitoring, bioindicators detect "phytotoxic" ozone conditions, i.e., the combination of ozone level and exposure environment that leads to uptake and injury. Quantifying the amount and severity of foliar injury to bioindicator plants with the site-level biosite index (BI) provides a comparative measure of ozone injury conditions on the Detection Monitoring plots. Given what we know about the adverse affects of O_3 on trees and understory species, we can infer that as the injury index increases, so does the risk of ozone impacts. Although the injury index developed for this biomonitoring program cannot measure ozone impact, it can be used to provide a reliable estimate of the risk of probable ozone impact to the more ozone-sensitive trees and forests. Risk analysis has been defined as the process of quantifying, either qualitatively or quantitatively, the probability and potential impacts of some risk (Vose 2000). Detection Monitoring analyses using the ozone biomonitoring data are both qualitative (presence or absence) and quantitative (injury index) and fall under the category of risk analysis.

Population Estimates

Plot-level attributes required for population estimates are developed by spatial interpolation of the biosite data. Additional details on the estimation procedures are provided in the Ozone Bioindicator Sampling and Estimation report (Smith et al. 2007). Spatial interpolation techniques are widely used in the analysis of air pollution, environmental, and ecological data. For example, EPA provides interpolated maps of ozone air quality that cover the landscape even though air quality monitoring stations are often limited to population centers. In a similar fashion, the measurements of ozone injury on the FIA biomonitoring plots are used to create an interpolated bioindicator response surface across the U.S.

Bioindicator attributes are estimated yearly for all P2 and P3 plots by intersecting the map of interpolated values with P2 and P3 plot locations (Fig. 5a,b). As a result, each P2 plot (and tree) is assigned an interpolated biosite index value (IBI) and accompanying plant count attribute and then placed in a defined category of ozone risk and relative air quality as previously described (Table 3). These bioindicator attributes are merged with other tree plot attributes in the FIA database to generate population estimates using nationally standardized procedures (Bechtold and Patterson 2005, Johnson et al. 2003). Population estimates for the ozone bioindicator include, but are not limited to, (1) proportion of forest land in each biosite index category by region, ecoregion, and state; (2) acres of forest land in each biosite index category by region, ecoregion, and state; and (3) volume of ozone-susceptible species in each biosite index category by region, ecoregion, and state. Analysts may also use the map of interpolated values to examine relationships between the IBI and other FIA indicators of tree growth, forest health, and forest condition.



(a) Block kriging and intersecting FIA P3 plot locations.

Plot number	Biosite index	Injured plants (%)
27120110311029	13.8	15.8
27120110311156	16.1	18.0
27120110319064	0.1	1.1
27120110319251	20.8	40.8
27120110319361	19.9	25.0
27120110319385	9.7	10.4
27120110712093	1.7	3.8
27120110712438	8.4	8.0
27120110712720	6.1	7.9
27120110712907	24.5	30.8
27120110713096	10.6	10.0
27120110713107	20.9	14.5
27120110713459	14.0	12.9
27120110759099	13.6	6.8
27120110759237	2.8	5.0

(b) Interpolated biosite index values and plant count attribute.

Figure 5.—Biosite index values are estimated for all P2 and P3 plots by intersecting the map of interpolated values with P2 and P3 plot locations (a). This results in a biosite index value estimate for each P2 and P3 plot (b). For additional detail on the interpolation method, see Smith et al. (2007).

The National Ozone Risk Map

The interpolated bioindicator response surface is referred to as the national ozone risk map (Fig. 6). A new map is created every year for status and trend analyses. Analysts are expected to extract areas of interest (e.g., states or ecoregions) from the national map for regional reports. An example of this approach is provided by Campbell et al. (2007) for the Pacific Northwest (PNW). Analysts from the PNW Research Station extracted Washington, Oregon, and California from the national map (average 2000 to 2005 BI) to examine risks of ozone impact to forests in West Coast States. Using 6-year averages of the biosite index, they estimated acres of forest land and volume of ozone-susceptible tree species in each ozone risk category. In Oregon and Washington, all the forest land and all susceptible species are classified in the lowest biosite index category with no risk of impact. In contrast, the ozone risk map identified areas of low, moderate, and high risk in California. Areas of greatest risk are in the southern Sierra Nevada Mountains, portions of the central coast, and much of the area east of Los Angeles (Fig. 2 in Campbell et al. 2007). Most of the ozone-sensitive tree resource in California is not at risk. Seventy-four percent of the forest land with 88 percent of the tree volume of ozone-sensitive tree species is classified in the lowest risk category. However, more than 8.7 million acres with 4.7 billion cubic feet (11 percent) of ozone-sensitive tree species are at low, moderate, or high risk of ozone injury. Species-specific analyses indicate that about 18 percent of ponderosa pine volume and 29 percent of Jeffrey pine volume fall into the low to moderate risk category. The authors of the PNW report suggest that the ozone indicator map of ozone risk for California

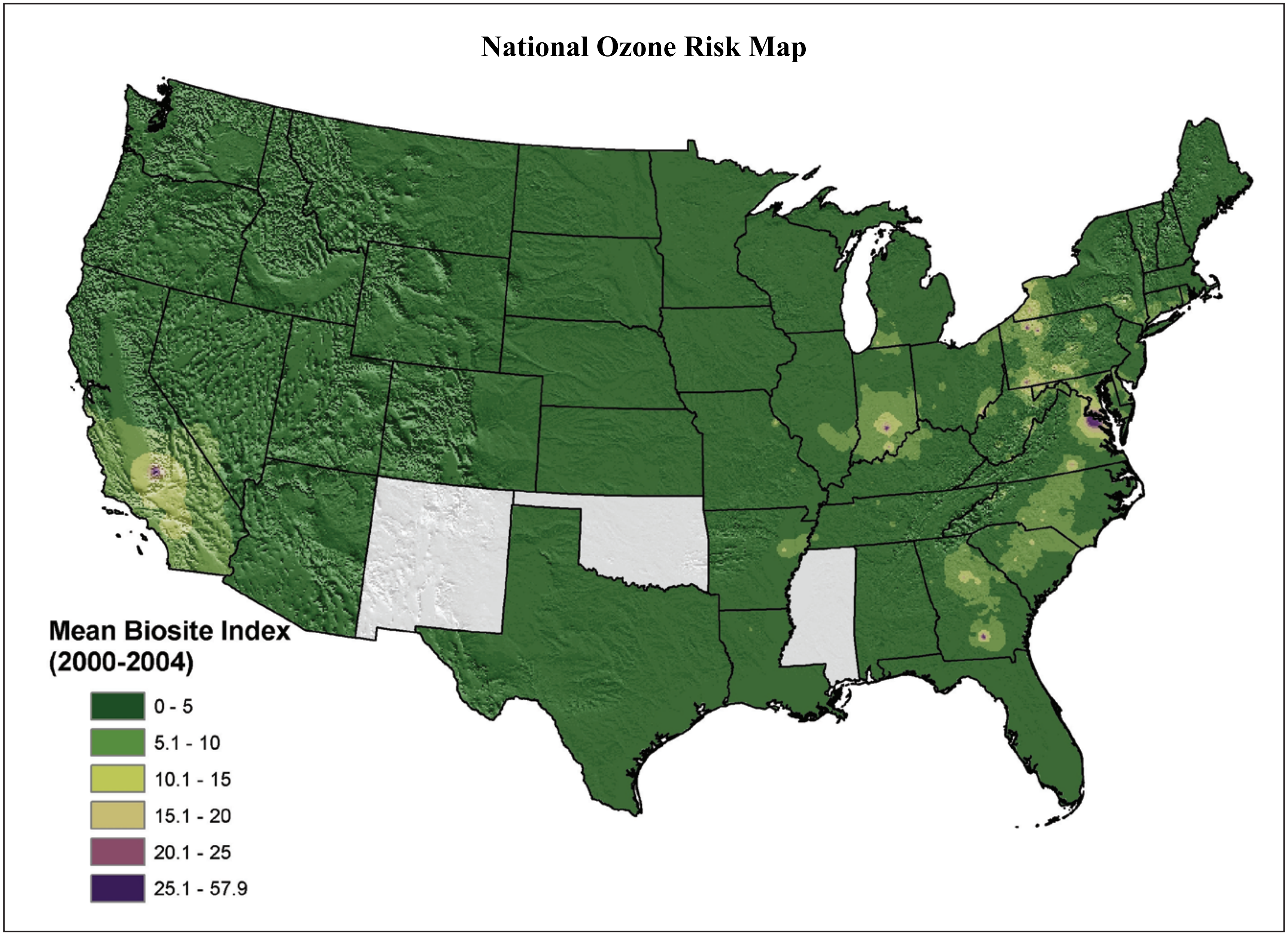


Figure 6.—Spatial interpolation of the mean biosite index for the 2000 to 2004 sampling period. Interpolated biosite index estimates are used to categorize the risk of probable ozone impact to forest ecosystems. Dark green indicates areas of relatively low risk, light green areas of moderate risk, and purple indicates areas of relatively high risk. Areas in white were not sampled.

is generally consistent with other models derived from nonbiological databases. Models that take into account environmental factors that influence ozone flux such as air temperature, precipitation, elevation, and wind patterns are more spatially and temporally explicit.

Air quality data from South Carolina indicate that this state has some of the highest ozone concentrations in the Southeast. Peak ozone levels are often in excess of the national 8-hr standard of 0.085 ppm, and cumulative growing season exposures (e.g., SUM06 data) rival those of southern California, suggesting that forest land in South Carolina is at high risk of ozone injury. Population estimates derived from spatial interpolation of the biosite data differ (Conner et al. 2004). In South Carolina, about 16.7 billion cubic feet of tree volume is in the lower ozone risk categories, slightly more than half of which is made up of ozone-sensitive tree species (Table 13). Thirty-eight percent of the total volume is in the no risk ozone category, 60 percent in the low risk category, 2 percent in the moderate ozone risk category, and zero percent in the high ozone risk category. Ozone injury is detected in the state on sensitive bioindicator plants almost every year, and more injury occurs in those parts of the state with higher ambient ozone concentrations. Nevertheless, the particular physiographic conditions of South Carolina and genotypic characteristics of the indigenous ozone-sensitive species indicate that most of the forest land in the state is not at any significant risk of ozone impact. Similar findings were reported for Virginia (Rose 2007). The sampling period discussed here (1998-2002) covers a period of below average rainfall during the growing season[20] that undoubtedly influenced the results. This situation could change dramatically if predisposing factors favorable for gas exchange and physiological responsiveness shift toward conditions that favor ozone injury such as might happen if rainfall amounts and distribution during the growing season shift from below normal (drought conditions) to a near normal or wet precipitation pattern for South Carolina and the entire Southeast. Other researchers working in the Southeast reported that drought conditions during the 1988 to 1999 time period overrode any potentially adverse effects of ozone on growth in the central Appalachian Mountains (Edwards et al. 2004).

As with other detection-level activities, there is a high noise to signal ratio with the application of the national ozone risk map (Smith et al. 2007). For this reason, Evaluation Monitoring is an essential part of the risk assessment process. The categories of risk defined by the ozone indicator (Table 3) are broad enough that analysts should be able to easily determine if the risk of probable ozone injury in their area of interest differs from the rest of the state, region, or ecological region, or if it changes significantly over time. If differences are detected, analysts need to examine explanatory variables and pursue appropriate correlative analyses. The appropriate analytical technique and explanatory variables depend greatly on the spatial scale of interest. For large-scale analyses, climate information and ambient ozone levels are important covariates in analysis (Smith et al. 2001). For smaller scale analyses, site factors such as terrain position, elevation, aspect, and soil drainage may also be important. Certain explanatory variables (e.g., site characteristics and ambient ozone statistics) are part of the FIA database for the ozone indicator. Climate variables may be more readily available from sources outside the FIADB, such as the National Climatic Data Center (http://www.ncdc.noaa.gov/oa/ncdc.html). Analysts are strongly encouraged to examine both internal and external databases related to ozone exposure characteristics, plant properties, and external growth conditions when

[20]National Climate Data Center: http://www.ncdc.noaa.gov/oa/ncdc.html

Table 13.—Acres of forest land, total tree volume, tree volume of ozone-sensitive tree species, and sensitive volume as a percent of total volume by ozone risk category for South Carolina (2002 data)

Population estimates for South Carolina[1]	Biosite index and risk estimation[2] 0 to 5 No risk	>5 to 15 Low risk	>15 to 25 Moderate risk	>25 High risk	Totals for each estimate
Forest land area (thousand acres)	4,780.4	7,404.0	270.4	0.0	12,455
Total tree volume (million cu. ft.)	6,316.7	10,047.4	321.1	0.0	16,685
Volume of ozone-sensitive species (million cu. ft.)	3,275.0	5,381.9	143.9	0.0	8,801
Sensitive volume as a percent of total volume (%)	51.8	53.6	44.8	-	53

[1]According to Conner et al. 2004.

[2]Categories of biosite index and risk estimation as are described in Table 3 of this report.

presenting and interpreting results for the ozone indicator. The national ozone risk map provides a detection-level assessment of ozone stress across the landscape, but it should not be used to make location-specific statements of cause and effect about O_3 and forest health.

Link to Evaluation Monitoring

When regional or national analyses of detection-level data indicate areas of potential impact on forest productivity and sustainability, these areas are evaluated through additional studies on an intensified grid. For example, the biomonitoring data may indicate a band of high ozone stress across a state or region, which may prompt the regional analyst to ask if the finding is real or some artifact of data collection. The next logical step is an evaluation study to take a closer look at the area of concern. For the ozone indicator, an evaluation study should include an intensified sampling grid and an analysis of air quality and environmental data that influence plant response to O_3. It may also be important to examine species distribution maps available from the FIA forest inventory database. An example of ozone Detection Monitoring identifying a potential problem area and Evaluation Monitoring verifying the problem is summarized below.

In a published report (Coulston et al. 2003), FHM researchers examined the bioindicator data from the Northeast and mid-Atlantic for the sampling period 1994 through 1999. With the techniques described in the ozone estimation document (Smith et al. 2007), the FIA biomonitoring data were used to generate a spatial distribution of probable ozone injury to plants that was then related to the spatial distribution of forest tree species in the study area. The objective was to identify forest tree species likely to exhibit regional-scale ozone impacts. One of the findings of this study indicated that large portions of western Pennsylvania experienced conditions where plant injury from O_3 was expected. Black cherry, an ozone-sensitive bioindicator species, was a major component of the forests in this area. This finding prompted FHM researchers to wonder if the biosite data were unduly influenced by the distribution pattern of black cherry in Pennsylvania.

To address this question, an intensified biomonitoring grid was designed for the area of concern in southwestern Pennsylvania (Skelly et al. 2003). Ten plots were identified and evaluated for ozone exposures and foliar injury symptoms on a variety of ozone-sensitive species (trees, shrubs, and herbaceous material) weekly from June through early September. The study also examined weather (precipitation amounts, departure from normal) and soil-site conditions (gravimetric soil moisture) that might have a controlling influence on the plant injury data. The results of this investigation established that the area of concern was in fact characterized by high ozone concentrations and that ozone-induced injury symptoms were evident on a variety of bioindicator species on the 10 study plots. Typical symptoms of ozone injury were prominent not just on black cherry, but also on blackberry, milkweed, white ash, and tulip-poplar. This conclusion confirmed the findings of the original report authored by Coulston et al. (2003). Questions raised by Detection Monitoring were investigated through an intensified sampling design and answered in such a way as to support and strengthen the findings and analytical approach of the detection-level biomonitoring program.

Other questions of regional ozone impact raised by Coulston et al. (2003) await further study. Four ozone-sensitive tree species (black cherry, loblolly pine, sweetgum, and serviceberry) and two tree species of unknown ozone sensitivity (southern red oak and sweet birch) were identified as at risk on a regional scale from ambient levels of ozone pollution. A wealth of information from the P2 ground plots could be used to support an indepth study of actual impacts on growth increment, species composition, or some other measurable indicator of ecosystem health and stability. This type of intensified analysis is needed to provide more informed responses to forest health assessment questions posed by the FIA ozone indicator (page 18).

A second evaluation monitoring project conducted by Bennett et al. (2006) attempted to measure and compare ozone-induced growth effects on milkweed and black cherry growing in two areas west and east of Lake Michigan that were similar except for the ambient ozone environment. The study plots west of Lake Michigan were subject to relatively low seasonal ozone exposures (low risk of impact) while the field plots to the west were subject to relatively high ozone exposures (high risk of impact). As expected, foliar injury was detected on both milkweed and black cherry over the 3-year study period, and the severity of foliar injury symptoms and quantitative effects of O_3 were greater in the high risk area. Although findings were complicated by fluctuating environmental factors and natural variability in sample populations, the statistical analyses indicated that branch elongation in black cherry and stem height and pod production in milkweed were significantly reduced by ambient ozone concentrations. This evaluation study was informative because the authors had selected growth attributes directly responsive to current-year ozone exposures (i.e., growing branch tips in black cherry) and very high sample counts (thousands of plants). The authors suggested increasing sample size allows relatively small effects occurring in real-world field conditions to be both measurable and statistically significant. In agreement with this point, Chappelka and Samuelson (1998) stated that increasing experimental replication and identifying the most ozone-responsive whole-tree measurement endpoint will improve the accuracy of risk assessment models.

Link to Air Quality Standards

EPA operates a network of more than 1,100 active ozone monitors generally sited near population centers that continuously measure ozone concentrations in ambient air (http://www.epa.gov/air/data/index.html). The data are summarized as hourly average ozone concentrations that can be used to identify counties that are out of compliance with the NAAQS for O_3 (http://www.asl-associates.com/). Point-level ozone data from the network of EPA monitoring stations are used by analysts to interpolate a uniform surface of ozone air quality across the landscape, thereby allowing researchers to estimate O_3 concentrations anywhere on the ground (Appendix 2, Fig. 1). In a similar fashion, the measurements of ozone injury on the FIA biomonitoring plots are used to generate the national ozone risk map (Fig. 6). The mapped EPA data provide an indication of what is in the air, whereas the mapped FIA data provide an indication of what is getting into the plants, or where site conditions are generally conducive to O_3 uptake and injury. One of the goals of the FIA biomonitoring program is to support national policy on plant health protection. The biological information provided by both the biomonitoring plot data and the national ozone risk map can be used to help inform and influence the establishment of meaningful air quality standards to protect plants from O_3 damage.

The 1970 Clean Air Act requires EPA to periodically review its air quality standards to ensure continued protection of human health (primary standard) and the environment (secondary standard) and to update the standards if necessary. EPA last updated the standards for O_3 in 1997[21]. At that time there was considerable discussion in the plant science community about the need for a more stringent secondary standard (Heck et al. 1998). Heck and Cowling (1997) highlighted the following key points and recommendations: (1) plants are more sensitive to O_3 than humans and thus require a more restrictive standard; (2) unlike its effect on humans, the effect of ozone on plants is both cumulative and longterm (therefore, the secondary standard should be both cumulative and long term); and (3) the SUM06 summed over a running 90-day maximum (June, July, August), using values from a 12-hr (0800-1959) daily window should be accepted as the biologically relevant form of the ozone standard. Further, the report recommended a SUM06 range of values from 8 to 15 ppm-hr as sufficient to protect the more sensitive endpoints (e.g., foliar injury) for natural ecosystems. EPA did not adopt these recommendations in 1997 and for the past 10 years the secondary standard has retained the form of a 1-hr (0.120 ppm) and 8-hr (0.084 ppm) average value.

The year 2007 marks the year of a new scientific review of the national ambient air quality standards for ozone (U.S. EPA 2007), and this time the recommendations of the scientific community may prevail. In July of 2007, EPA published a final staff paper on ozone that recommends a standard that is a cumulative, weighted total of daily 12-hr exposures over a 3-month period within the growing season. For the first time, FIA biomonitoring data were included in the review, demonstrating the importance of the program to the establishment of meaningful air quality standards. Peer-reviewed publications of the ozone program by Smith et al. (2003), and Coulston et al. (2003, 2004), as well as national technical reports from FHM (Coulston et al. 2005) were cited in EPA's 2007 policy assessment of scientific and technical information on the ozone standard (U.S. EPA 2007) and in EPA's 2007 Report on the Environment (http//www.epa.gov/indicators/roe).

A collaborative study conducted by EPA and FIA staff demonstrates the usefulness of the FIA data to the standard setting process (U.S. EPA July 2007). The study was designed to assess how meeting various O_3 standard levels (e.g., the current standard and alternative levels under consideration) affected the incidence of visible foliar injury on the biomonitoring plots (Table 14). Between 235 and 286 counties had both EPA ozone monitoring stations

[21]On March 12, 2008, after considerable scientific review (U.S. EPA 2007) EPA announced a revised 8-hr O_3 standard of 0.075 ppm. Details on the 2008 revised O_3 standard are provided in Appendix 1.

Table 14.—Number of counties with FIA biomonitoring sites and EPA air quality sampling stations and the percent of the total number of counties with visible foliar injury to bioindicator plants at various air quality standard levels for the years 2001 to 2004

Year	Number of counties with EPA O_3 monitoring and FIA biomonitoring sites	Ozone standard levels			
		$O_3 \leq 0.084$ ppm[1] (current)	SUM06 ≤ 25 ppm-hr[2] (1996 proposal)	$O_3 \leq 0.074$ ppm[1] (proposed)	SUM06 ≤ 15 ppm-hr[2] (proposed)
		Percent counties with foliar injury			
2001	235	39	49	25	23
2002	270	21	26	12	12
2003	285	28	34	11	25
2004	286	35	37	30	35

[1]These standard levels represent the annual fourth highest 8-hr maximum average.
[2]These standard levels represent the sum of the number of hours greater than 0.06 ppm O_3.

and FIA biomonitoring plots during 2001 to 2004. These matched data were compared for number of counties with and without visible foliar injury to discern the degree of protection provided by the current form and level of the secondary ozone standard. The data demonstrate unequivocally that visible foliar injury to ozone-sensitive bioindicator plants is occurring in counties that are meeting the current 8-hr average O_3 standard (0.084 ppm) and the alternative secondary standard option of SUM06 ≤ 25 ppm-hr proposed in 1996. By comparison, the two lower air quality alternatives (0.074 ppm 8-hr average and SUM06 ≤ 15 ppm-hr) provide more protection from visible foliar injury across all years (2001-2004) than either of the aforementioned standards. Even with these more stringent alternatives to the current standard, however, the percent of counties showing injury ranged from 12 to 35 percent. The principal authors suggest that if protection from foliar injury is an agreed upon objective for natural systems and forest stands, then a 3-month 12-hr SUM06 value of 8 to 12 ppm-hr should be recommended as first proposed in the 1996 consensus workshop held on the secondary O_3 standard (Heck and Cowling 1997).

Evidence that the current NAAQS is inadequate to protect natural systems from adverse ozone effects is summarized in the conclusions and recommendations of the EPA staff report (U.S. EPA July 2007). First, the FIA biomonitoring sites show widespread evidence of ozone-induced foliar injury in forested ecosystems. Second, studies conducted at the Aspen FACE site in Wisconsin on quaking aspen (Percy and Karnosky 2007), along an urban-to-rural ozone gradient in New York on cottonwood (Gregg et al. 2003), and in the mixed deciduous forests of eastern Tennessee on mature trees of different species (McLaughlin et al. 2007a) confirm the detrimental effect of ambient ozone exposures on tree growth. In the report, EPA staff propose a more stringent secondary ozone standard derived from differentially weighted peak concentrations and cumulative seasonal exposures. The W126 statistic is recommended over the SUM06 statistic because it has no minimum ozone concentration threshold and only lightly weights the lower ozone concentrations. The form of the 12-hr W126 is defined as the sigmoidally weighted 3-month sum of all ozone concentrations observed during the daily 12-hr period between 0800 and 2000. The 3 months are the maximum consecutive 3 months during the ozone season. The recommended upper and lower air quality levels of 12-hr W126 are 21 and 13 ppm-hr, respectively.

Advantages and Disadvantages of the Data

The ozone indicator provides a simple analytical tool to discuss the very real and naturally complex relationship between ozone pollution and forest health. The key cautionary note for analysts working with the biomonitoring data is to keep it simple. The summarized data provide an opportunity to educate and inform the public on forest health risks associated with ozone exposure. However, the presentation and discussion of summarized field data and population estimates should stay within the bounds of Detection Monitoring. The ozone indicator documents the amount and severity of ozone-induced foliar injury to ozone-sensitive bioindicator plants on a national grid of ozone biomonitoring sites. Unlike most P3 (forest health) indicators, the ozone indicator documents and attempts to quantify the effects (foliar injury) of a specific environmental stress (ozone). Independently, the information gathered at biomonitoring sites identifies whether conditions exist for plant injury to occur. This information alone can be used to report status and trends with respect to the ozone indicator (Smith et al. 2001). For example, if field crews detect symptoms of ozone injury on bioindicator plants in northern Michigan, then we know something more about forest health in Michigan than we did without this information. We know that ambient ozone levels are capable of reaching phytotoxic concentrations in an area of the state that may have previously been considered risk free with respect to ozone exposure. What we do not know is whether the detected presence of phytotoxic ozone concentrations in northern Michigan is having any measurable impact on the health of individual trees or species in the forests there. Answering questions about impact requires additional information, an investment in Evaluation Monitoring or other research-oriented programs.

Written summaries of the ozone indicator data should include information on the number and distribution of plus ozone sites across a state or region, as well as the relative severity of that injury as quantified by the site-level injury index (BI). Five consecutive years of detection-level findings should be reviewed to assess the presence or absence of significant ozone stress in a given state or region. We need to know, for example, if field crews detect relatively low, moderate, or severe injury in northern Michigan, and whether this happens every year or only once in a 5-year period. Changes in the number and distribution of plus ozone plots, as well as increases or decreases in the BI from one 5-year period to the next, provide a simple trend analysis for the ozone indicator.

Analysts working with ozone indicator data obtained from overlaying the national ozone risk map and the P2 plots should present their findings in a risk analysis framework, keeping in mind that the purpose of the overlay and the resulting calculations of population estimates is, once again, Detection Monitoring. Continuing with the Michigan example, we may learn that the risk of probable impact to ozone-sensitive tree species in northern Michigan is relatively low, meaning that the interpolated BI values in northern Michigan are relatively low compared to the interpolated BI values from other areas in Michigan and the region. A risk assessment approach provides different information from that obtained from the summarization of sampling statistics (i.e., we can talk about populations rather than plot counts), but we are no closer to answering questions about impact with any certainty. This is an expected limitation of Detection Monitoring. The intent is for the regional FIA analyst to highlight areas of concern where the overlay of biomonitoring data and the P2 sample indicate a large number of ozone-sensitive tree species in a zone of elevated ozone risk. Detecting such a finding should trigger additional correlative analyses to help explain the results or a field-based Evaluation Monitoring study. Significant changes to the national ozone risk map provide the basis for an analysis of long-term trends in population estimates for the ozone indicator.

The national ozone risk map provides a nationally uniform template for extracting and reporting regional population estimates for the ozone indicator. A weakness of the system is that the population of interest is forest trees while the bioindicator data are collected on bioindicator plants on biomonitoring sites. Information collected from one population (bioindicator plants) is used to indicate probable conditions in the population of interest (forest trees). However, there is a long history of research using bioindicator plants to detect and monitor for ozone injury conditions in the surrounding forest. There is no other way to get biological response data under ambient conditions of ozone exposure in the natural environment of the forest. Most of the available data are from artificial systems (e.g., open-top chambers and exposure rings), or small-scale survey projects limited to a particular national park, national wildlife refuge, or Class I Wilderness Area (Davis and Orendovici 2006, Hildebrand et al. 1996, Kohut 2007, Manning et al. 1996, Neufeld et al. 1992, Pronos and Vogler 1981). This is the first time a highly standardized biomonitoring program has been implemented on a national scale. To its advantage, the crew level of difficulty is low, no specialized personnel or equipment is required, and there have been no significant changes to the field protocols since 1994. Further, the ozone injury symptoms identified by crews in the field are verified by an expert in the laboratory, virtually guaranteeing the accuracy of the site-level injury value. We know a lot about the effects of O_3 on tree physiology and growth, and scientists agree that ground-level O_3 is a significant threat to forest health. Knowledge gained from empirical studies conducted under controlled conditions of ozone exposure is not easily translated to the complex environment of the forest. Researchers and forest health modelers are eager for ozone injury data from natural systems such as that provided by the FIA biomonitoring program.

SUMMARY AND RECOMMENDATIONS

The FIA ozone biomonitoring data are the only source of information available that documents plant injury from air pollution using consistent protocols. The ozone bioindicator provides a biological index of ozone stress on a nationwide system of biomonitoring sites. Ozone biomonitoring is part of the FIA P3 sample and is based on the documentation of visible foliar injury to known ozone-sensitive plant species under conditions of ambient exposure. The field methods, site variables, and site-level biosite index were developed with support from the scientific research community (Smith 1995), and the sampling procedures and analytical techniques have been peer reviewed (Coulston et al. 2003, Smith et al. 2003). The following comments and recommendations summarize the key points in this report with respect to data collection, data analysis, and reporting.

Summary Comments

Ozone is considered the most pervasive air pollutant in the United States and a worldwide threat to sustainable forest management. There is ample evidence that O_3 injures trees and has the potential to have negative impacts on ecosystem structure and function. Due to the complexity of plant/pollutant interactions, it is almost impossible to determine dose/response relationships in natural forest systems. Researchers who have developed risk assessment models for O_3 and forest growth using the best available information from controlled exposure studies report growth loss percentages at ambient ozone concentrations of zero to 26 percent. The FIA biomonitoring data should help to strengthen the reliability of these models.

Data illustrate that ozone-induced foliar injury on FIA biomonitoring plots is widespread, affecting all 13 states in the Northeast region, 8 of 11 states in the North Central region, all 11 states in the Southern region, and 2 of 3 states in the West Coast region. No injury has been detected on regular biomonitoring plots in the Rocky Mountain region or in Alaska. Severity of injury has generally been greater in states and years with higher ambient ozone concentrations, although localized conditions cause much site-level variation. Conditions of drought or other significant disturbance during the growing season inhibit the response of sensitive plants to O_3, thus lowering the risk of impact. Ozone injury occurs routinely in areas currently identified as meeting the NAAQS, suggesting that the form and level of the ozone standard need to be updated. Although there is no obvious evidence linking ozone stress to a specific tree health problem or regional decline, little or no analytical work has been done to address this possibility. The national ozone risk map clearly identifies millions of acres of ozone-sensitive tree species in both eastern and western regions at varying levels of risk of ozone injury. However, only California, Indiana, and South Carolina have tried to quantify this phenomenon. This situation should improve as FIA analysts gain experience working with forest health (P3) indicators. Planned advances in P3 information management will ensure public access to the core products for the ozone indicator including site-level summary statistics and the national ozone risk map.

The usefulness of the biomonitoring data to national air quality policy was demonstrated when EPA scientists included the data in the most recent scientific review of the secondary ozone standard. Four years of results from the FIA ozone sample were analyzed and discussed within the framework of tree risk assessments using foliar injury as an assessment endpoint. The analysis led EPA staff to conclude that foliar injury would be reduced and forest protection enhanced with a more stringent secondary ozone standard. This finding agreed with all other scientific evidence put forth by the EPA Office of Air Quality Planning and Standards for this most recent mandated review.

The biomonitoring program will remain useful to both internal and external users as long as the strengths and weaknesses of the data are understood and respected. As stated in the EPA staff paper, visible injury is a valuable indicator of the presence of phytotoxic concentrations of O_3 in ambient air, but it is not always a reliable indicator of damage, or other injury endpoints. When evaluating ozone risk, analysts need to be aware that for some tree species, ozone-induced foliar injury correlates with biomass loss or some other adverse effect, but for a larger group of trees, no correlation between foliar symptoms and biomass loss has been demonstrated. The combined total of tree species that can be categorized in either of these groups as sensitive, resistant, or tolerant of ozone stress is rather small. We know even less about nontree species or about the sensitive vegetative component of forested systems that suffers nonvisible, indirect, or delayed effects from ozone exposure.

There is a need for increased use of computer models and simulations to help suggest or predict outcomes of the many complex interactions of O_3 and various combinations of environmental factors (e.g., insects, disease, competing plants, mineral nutrients, increased atmospheric CO_2). These models are only as reliable as the input data used for parameterization. The FIA biomonitoring program provides a biologically relevant database (e.g., identified gradients of ozone risk across a forest type or ecological region) that can be used to test assumptions of ecosystem response to ambient ozone exposure and provide a focus for basic and applied research studies on plant/pollutant interactions in natural systems, thereby generating information that will improve the reliability of air quality, forest health, and climate change models.

Recommendations

The biomonitoring program underscores the commitment of the Forest Service to sustainable forest management and forest productivity loss protection as defined by the Montreal Process (1995). The program makes a significant contribution to forest health professionals and the scientific research community by collecting ozone effects data from a wide range of forest environments at a high level of standardization, quality, and scale. The following recommendations are directed at maintaining the quality of the program while expanding its usefulness and application to forest health issues.

The training and quality assurance procedures for the field crews and QA staff must be maintained in every FIA region. New training programs in data analysis and reporting should be developed. Access to summarized data and map products must be easy and quick so that both internal and external users can start to incorporate the results into their own research and modeling projects which will increase the visibility of the ozone indicator and facilitate linkage to interdisciplinary and international projects such as has already been initiated with the FACTS II (Aspen FACE) project near Rhinelander, Wisconsin (http://aspenface.mtu.edu/).

The data record from the biomonitoring network helps to confirm and strengthen what is known about common bioindicator species. FIA crews also look for and identify ozone-like injury symptoms on forest trees, shrubs, and herbs that have never been evaluated for ozone sensitivity under controlled conditions. This effort provides immediate benefit to the research community as the challenge of identifying and field testing new bioindicator species is advanced. Once fumigation trials are complete, these additional species offer the possibility of expanding the biomonitoring sample in areas where traditional bioindicator species are lacking.

This report provides an introduction to analysis and interpretation of the ozone injury index (BI) alongside seasonal measurements of soil moisture, rainfall, and ozone levels. Much more ancillary data can be reviewed and analyzed to increase the interpretability of the ozone indicator. The FIA database includes additional information on soil/site conditions (e.g., aspect and elevation) at each biomonitoring site. Additional climate attributes (e.g., air temperature and humidity) and environmental factors (e.g., CO_2 concentration) should be investigated. Similarly, analysts must begin to examine relationships among the biosite summary data or population estimates and other indicators of forest health and condition including growth increment, crown condition, soil nutrient status, vegetation diversity, and lichen communities.

In conclusion, the purpose of this report is to provide FIA analysts and other interested parties with a comprehensive understanding of the ozone biomonitoring program and its importance to forest health assessment. Background material on ozone is provided along with evidence that ozone injures trees, assessment questions to guide analysis and reporting, detailed information on field procedures and database structure, examples of biosite-level summary statistics, a description of spatial interpolation, and guidance on how to interpret status and change for the ozone indicator. Also included are examples of output for site-level data and examples of output for ozone risk assessment. The appendices include a current list of tree and shrub species susceptible to ozone, summarized plot data from each FIA region, and several additional documents to assist FIA analysts with ozone data access and management. The tree sensitivity lists will be updated as more information becomes available. The interpolation techniques will be improved over time, other methods of estimating change (e.g., spatio-temporal kriging) will be investigated, and periodic recommendations will be made to analysts as QA results become available. FIA analysts are encouraged to refer to the companion Ozone Bioindicator Sampling and Estimation report (GTR NRS-20, Smith et al. 2007) and to review recommended reference materials and Web sites to stay informed on the issues of ozone air quality and forest health protection.

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APPENDIX 1.—KEY RESOURCES AND WEB SITES

Air Quality Data and the 2008 Revised Ozone Standard

EPA's air data Web site gives you access to air pollution data for the entire United States. Find out what the highest ozone level measured in your state was last year, where air pollution monitoring sites are located, and whether there are sources of air pollution in your area. EPA produces reports and maps of air pollution data based on criteria you specify. http://www.epa.gov/air/data/index.html

A.S.L. & Associates is a private company that has developed extensive experience and resources for assessing the potential impacts of air pollution on the environment. http://www.asl-associates.com/

AIRNow is a government-backed, cross-agency program that provides information and data on air quality forecasts, air quality conditions, and historical data. Use this Web site to generate an air quality report for your county or state. http://www.airnow.gov/

On March 12, 2008, EPA announced its decision to adopt a new 8-hr ozone standard of 0.075 ppm rather than the W126 cumulative ozone exposure index described on page 4 of this report. The new 8-hour standard is met when the 3-year average of the annual fourth highest daily maximum 8-hr average concentration is less than 75 ppb O_3. Summer smog alerts are reported when average hourly O_3 concentrations are expected to exceed 75 ppb over an 8-hr period. For more information on the standard setting process, go to: http://www.epa.gov/groundlevelozone/

Air Quality Indices

Foliar injury thresholds for the SUM06, W126, and N100 indices of ozone exposure:

SUM06 is defined as the running 90-day maximum sum of the 0800 to 2000 hourly concentrations of O_3 equal to or greater than 0.06 ppm (Heck and Cowling 1997).

Class of vegetation	SUM06 injury index
Natural ecosystems	8-12 ppm-hr (foliar injury)
Tree seedlings	10-16 ppm-hr (10-12% reduction in growth)
Agricultural crops	15-20 ppm-hr (10% reduction in 25-35% of crops)

W126 is defined as the weighted sum of the twenty-four 1-hr O_3 concentrations daily from April through October plus N100 which is defined as the number of hours of exposure greater than or equal to 100 ppb during that same period (Lefohn et al. 1997).

Ozone sensitivity class	W126 injury index	N100
Highly sensitive species	5.9 ppm-hr	6
Moderately sensitive species	23.8 ppm-hr	51
Low sensitivity	66.6 ppm-hr	135

Research Studies and Educational Material

The Montréal Process is the Working Group on Criteria and Indicators for the Conservation and Sustainable Management of Temperate and Boreal Forests. It was formed in Geneva, Switzerland, in June 1994 to develop and implement internationally agreed criteria and indicators for the conservation and sustainable management of temperate and boreal forests. http://www.mpci.org

The National Park Service Air Resources Division provides links to many resources on ozone air quality and the impacts of ozone on ecological systems. http://www2.nature.nps.gov/

IUFRO is a nonprofit, nongovernmental international network of forest scientists that promotes global cooperation in forest-related research and enhances the understanding of the ecological, economic, and social aspects of forests and trees. http://www.iufro.org/iufro/.

The Aspen FACE (Free-Air Carbon Dioxide Enrichment) Experiment is a multidisciplinary study to assess the effects of increasing tropospheric ozone and carbon dioxide levels on the structure and function of northern forest ecosystems. http://aspenface.mtu.edu/.

The Agricultural Research Service (ARS) is the U.S. Department of Agriculture's chief scientific research agency. Follow links to its air quality program. http://www.ars.usda.gov/

The U.S. Forest Service Forest Health Monitoring Program produces a national technical report every year that presents results from forest health data analyses including air pollution (sulfates, nitrates, and ozone) and the relationship of air pollution data to other forest health indicators. http://www.treesearch.fs.fed.us/

Peer-reviewed Journals

Many fine journals publish articles on air quality and forest health, but the journal most often used by researchers in the United States is Environmental Pollution.
http://www.elsevier.com/locate/envpol

The following special issues and articles from Environmental Pollution are available online:

- Volume 50 Nos. 1& 2 (1988) ISSN 0269-7491 Toxic Substances in the Environment
- Volume 115 (2001) Impacts of Air pollution on Forest Ecosystems
- Volume 147 (2007) Air Pollution and Climate Change: A Global Overview of Effects on Forest Vegetation
- Volume 149 (2007) Air Pollution and Vegetation Effects Research in National Parks and Natural Areas: Implications for Science, Policy and Management

Refer to the reference section of this document for additional peer-reviewed journals that publish articles on air quality issues and ozone effects research.

Air Pollution Workshop

The 40th Air Pollution Workshop was held in Raleigh, NC, April 7-10, 2008. Since 1969, plant scientists interested in air pollution effects on all forms of vegetation and natural ecosystems have met each year at various locations around the U.S., Canada, and Mexico. Participants are from research programs within universities, agricultural experiment stations, and Federal agencies such as EPA, USDA, and National Park Service. In addition, many state and local officials have attended meetings when held near their offices. A strong contingent of European colleagues interested in air pollution and vegetation effects attended the most recent workshops. For more information, go to: http://www.apworkshop.org/index.htm

Additional helpful links can be found at: http://www.apworkshop.org/links.htm

Climate Change Issues and Links

Ground-level O_3 is a major constituent of photochemical smog and part of the mix of greenhouse gases that contribute to global climate warming. Data from the ozone biomonitoring program described in this report help assess the risk of climate change on forest health in the U.S. For more information about Forest Service initiatives on climate change, go to: http://www.fs.fed.us/research/fsgc/climate-change/

For comprehensive information on the issue of climate change and U.S. climate policy, visit the EPA climate change Web site at: http://epa.gov/climatechange/index.html

The Intergovernmental Panel on Climate Change (IPCC) was established to give decision makers and others interested in climate change an objective source of information about climate change. The IPCC is a scientific intergovernmental body set up by the World Meteorological Organization (WMO) and by the United Nations Environment Program (UNEP). Go to: http://www.ipcc.ch/

Visit the FIA ozone biomonitoring program Web site for links to the field manual, data, publications, regional contacts and other information.
http://nrs.fs.fed.us/fia/topics/ozone/default.asp/

APPENDIX 2.—NATIONAL MAPS OF OZONE AIR QUALITY

Figure 1 is a cumulative O_3 exposure surface (SUM06) for the continental United States. Interpolated SUM06 values (sum of all hourly O_3 concentrations ≥0.06 ppm) were averaged over the growing season (June, July, August) for the 2000 to 2004 sampling period. Cumulative O_3 exposures are generally characterized as relatively clean (<10 ppm-hr), low (10 to ≤20 ppm-hr), moderate (>20 to ≤30 ppm-hr), and high (>30 ppm-hr).
Map source: http://www4.ncsu.edu/~jwcouls1/dep/
Data source: U.S. EPA

Figure 2 identifies the U.S. counties that are in violation of the revised national ambient air quality standard for O_3. Additional counties may be listed when EPA issues final designations of attainment and nonattainment (target date = March 2009).

Map source: A.S.L. & Associates©2008, asl-associates.com/map.htm
Data source: US EPA

Figure 1.—Spatial interpolation of mean 3-month cumulative ozone concentrations (SUM06) for the 2000 to 2004 sampling period.

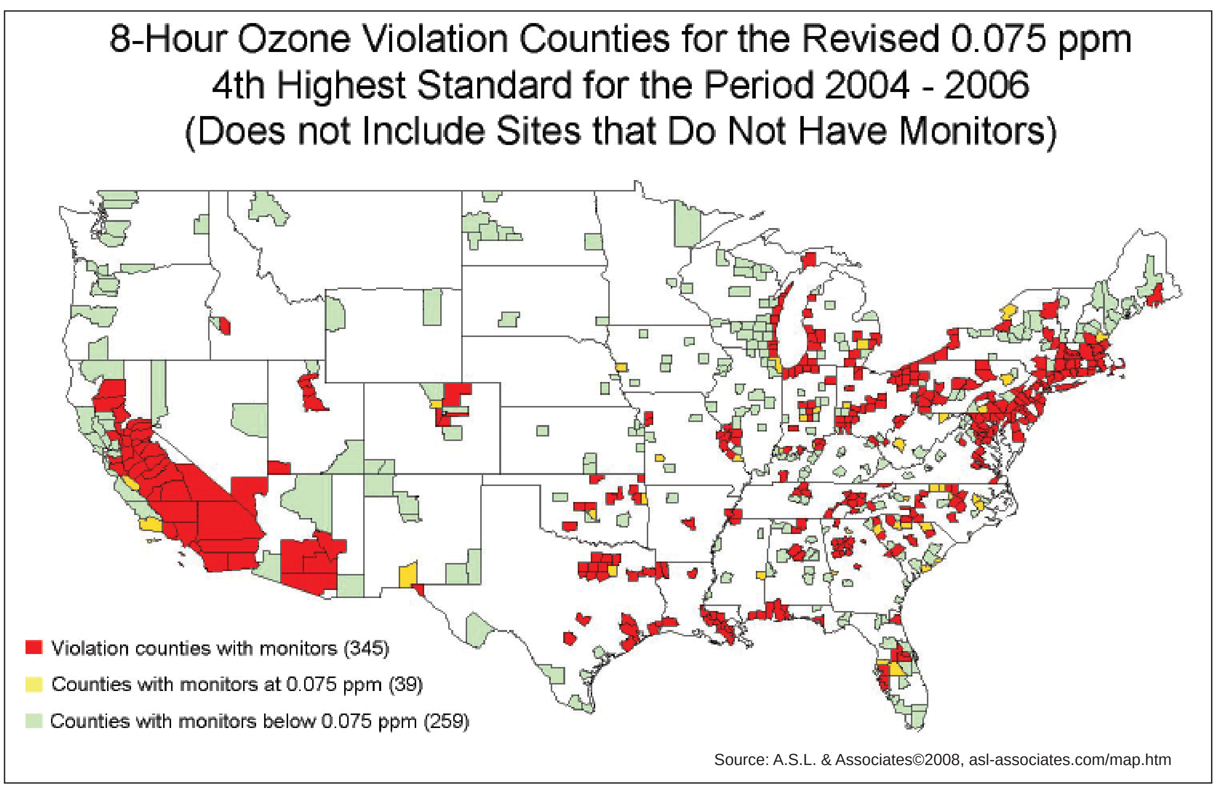


Figure 2.—U.S. counties with O_3 air quality monitors in violation of the revised O_3 standard of 0.075 ppm for 2004 to 2006.

APPENDIX 3.—FIELD IMAGES OF OZONE INJURY ON EASTERN AND WESTERN BIOINDICATOR SPECIES

Under natural conditions of O_3 exposure, there is considerable variation in visible foliar injury between and among species, and many biotic and abiotic stresses cause mimicking symptoms. Ozone-induced injury may be confounded by the presence of fungal fruiting structures, insect feeding damage, sun scorch, and water stress. Because classic injury symptoms are not always encountered in the field, leaves and needles evaluated for O_3 injury by FIA field crews are collected and mailed to a regional expert for review and validation of the O_3 injury symptom. Field images of bioindicator species with O_3 injury from eastern and western biomonitoring sites, along with a list of reference books and Web sites that provide images of O_3 injury on various species, are provided below.

http://nrs.fs.fed.us/fia/topics/ozone/default.asp - click on: 'ozone sensitive species'
http://www.ozone.wsl.ch/index-en.ehtml

A Guide to Ozone Injury in Vascular Plants of the Pacific Northwest
Available from: Pacific Northwest Research Station, 333 S.W. First Avenue, Portland, OR 97208-3890. (Brace et al. 1999)

Diagnosing Injury to Eastern Forest Trees: a manual for identifying damage caused by air pollution, pathogens, insects, and abiotic stresses
Available from: Publications Distribution Center, The Pennsylvania State University, 112 Agricultural Administration Building, University Park, PA 16802. (Skelly et al. 1997)

Evaluating Ozone Air Pollution Effects on Pines in the Western Unites States
Available from: http://www.psfs.gov. (Miller et al. 1996)

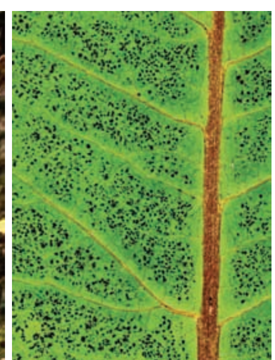
Ozone and Broadleaved Species: A guide to the identification of ozone-induced foliar injury
Available from: http://www.wsl.ch/publikationen/books/4295_EN?redir=1& (Innes et al. 2001)

Recognition of Air Pollution Injury to Vegetation: A Pictorial Atlas 2nd Edition
Available from: Publications Order Department, Air & Waste Management Association, P.O. Box 1020, Sewickley, PA 15143-1020. (Flagler 1998)

Blackberry

Photos courtesy of Gretchen Smith, University of Massachusetts (top and bottom left), and Ron Kelley, VT Department of Forests, Parks & Recreation

Common Milkweed



Photos courtesy of Bill Manning, University of Massachusetts, (left and top right), and Gretchen Smith, University of Massachusetts (bottom right)

Black cherry

Photo courtesy of Bill Manning, University of Massachusetts

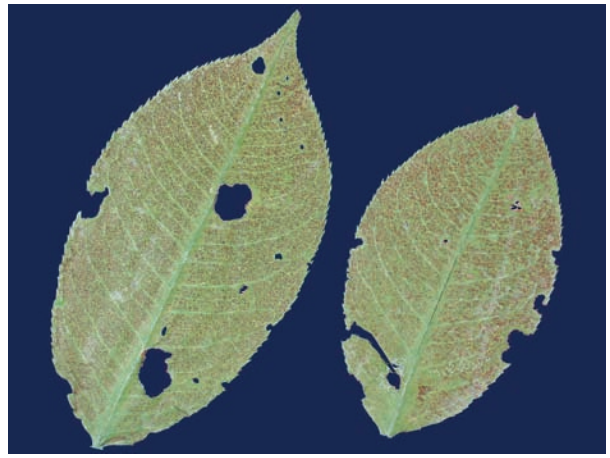


Photo courtesy of Ron Kelly,
VT Department of Forests, Parks & Recreation

Pin cherry

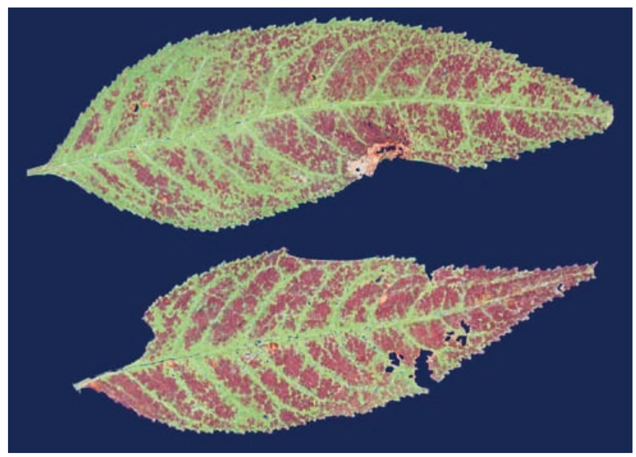


Photo courtesy of Ron Kelly,
VT Department of Forests, Parks & Recreation

Spreading dogbane

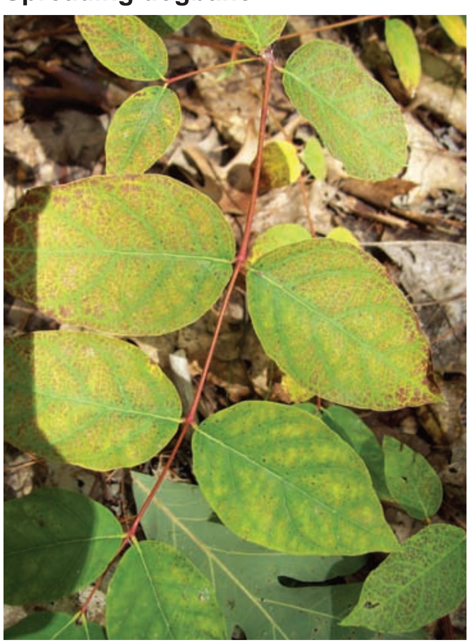


Photo courtesy of Chris Bergweiler,
University of Massachusetts

Big leaf aster

Photo courtesy of Ron Kelly,
VT Department of Forests, Parks & Recreation

White ash

Photo courtesy of Ron Kelly,
VT Department of Forests, Parks & Recreation

Photo courtesy of Ed Jepsen, WI Department of Natural Resources

Photo courtesy of Gretchen Smith,
University of Massachusetts

Sassafras

Photo courtesy of Jim Renfro, National Park Service

Yellow-poplar

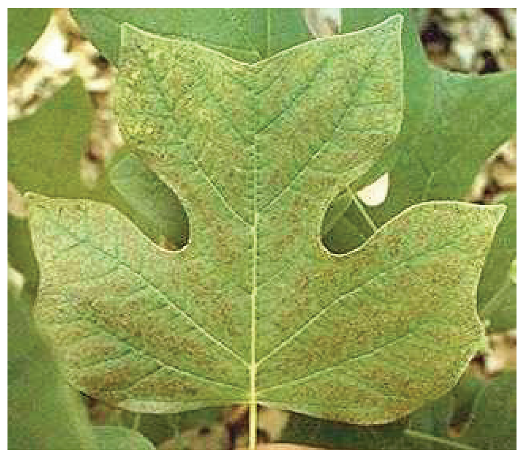


Photo courtesy of Gretchen Smith, University of Massachusetts

Sweetgum

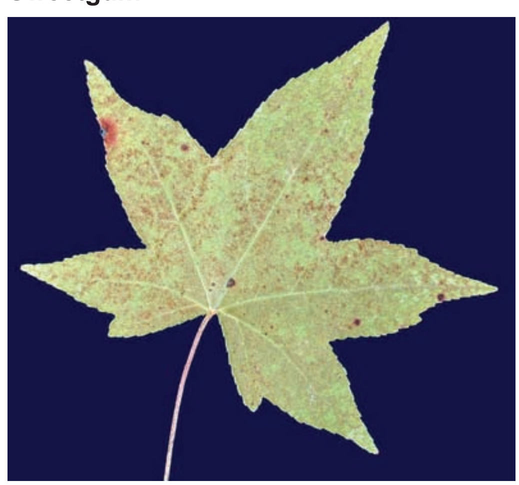


Photo courtesy of Ron Kelly,
VT Department of Forests, Parks & Recreation

Eastern biomonitoring sites

Photos courtesy of Gretchen Smith, University of Massachusetts

Western biomonitoring site

Photo courtesy of Dan Duriscoe, National Park Service

Ponderosa pine

Blue elderberry

Jeffrey pine

Quaking aspen

Evening primrose

Above photos courtesy of Dan Duriscoe, National Park Service

Cutleaf coneflower

Photo courtesy of Bob Kohut, BTI at Cornell University

Cutleaf coneflower

Photo courtesy of Howie Neufeld, Appalachian State University

Left: Ozone injury on cutleaf coneflower (*Rudbeckia laciniata* v. *ampla*) at Rocky Mountain National Park where the plant is found along watercourses and on moist sites. The injury is markedly different from the bronzing found on *R. laciniata* v. *laciniata* in the Smokies (right).

APPENDIX 4.—OZONE SENSITIVITY OF TREE AND SHRUB SPECIES

The abbreviations used to assign sensitivity in the following tables are as follows:
Sen = ozone sensitive, ModSen = moderately sensitive, InSen = ozone insensitive, Unk = unknown ozone sensitivity because of conflicting evidence from different observers. Regional analysts should review both tables because species listed as eastern may be found in limited areas in Western states and vice versa. Additional ozone sensitivity lists for plants common to the forest environment can be found at: http://www2.nature.nps.gov/air/Pubs/pdf/BaltFinalReport1.pdf.

Table 1.—List of eastern tree and shrub species and their ozone sensitivity

Eastern species		Sensitivity	Citation
balsam fir	*Abies balsamea*	InSen[1]	Smith 1981
Fraser fir	*Abies fraseri*	InSen	Renfro 1987-1992
boxelder	*Acer negundo*	ModSen[1]	Smith 1981
striped maple	*Acer pensylvanicum*	Unk	
red maple	*Acer rubrum*	Sen	Eckert et al. 1999
silver maple	*Acer saccharinum*	Unk	USDI 2003
sugar maple	*Acer saccharum*	InSen	Renfro 1987-1992
mountain maple	*Acer spicatum*	Unk	
Ohio buckeye	*Aesculus glabra*	Unk	USDI 2003
yellow buckeye	*Aesculus octandra*	Sen[2]	USDI 2003
tree-of-heaven	*Ailanthus altissima*	Sen[2]	USDI 2003
speckled alder	*Alnus rugosa*	Sen[2]	USDI 2003
serviceberry	*Amelanchier arborea*	Sen	Renfro 1987-1992
Allegheny seviceberry	*Amelanchier laevis*	Unk	USDI 2003
pawpaw	*Asimina triloba*	Unk	
yellow birch	*Betula alleghaniensis*	Sen	Renfro 1987-1992
sweet birch	*Betula lenta*	Unk	Dowsett 1992
paper birch	*Betula papyrifera*	ModSen	Eckert et al. 1999
gray birch	*Betula populifolia*	ModSen	Eckert et al. 1999
bitternut hickory	*Carya cordiformis*	Unk	
pignut hickory	*Carya glabra*	InSen	Dowsett 1992
shagbark hickory	*Carya ovata*	InSen	Dowsett 1992
hickory sp.	*Carya sp.*	Unk	
mockernut hickory	*Carya tomentosa*	InSen	Dowsett 1992
hackberry	*Celtis occidentalis*	InSen	Dowsett 1992
common buttonbush	*Cephalanthus occidentalis*	Unk	USDI 2003
eastern redbud	*Cercis canadensis*	ModSen, Sen[2]	Renfro 1987-1992, USDI 2003
yellowwood	*Cladrastis lutea*	Unk	USDI 2003
Virgin's bower	*Clematis virginiana*	Sen[2]	USDI 2003
flowering dogwood	*Cornus florida*	ModSen	Renfro 1987-1992
American hazelnut	*Corylus americana*	Sen[2]	USDI 2003
hawthorn	*Crataegus sp.*	Sen[3]	Krupa et al. 1998
common persimmon	*Diospyros virginiana*	Unk	
American beech	*Fagus grandifolia*	InSen	Dowsett 1992
white ash	*Fraxinus americana*	Sen	Skelly 2000
black ash	*Fraxinus nigra*	Sen[3]	Krupa et al. 1998
green ash	*Fraxinus pennsylvanica*	Sen	Krupa and Manning 1988
black huckleberry	*Gaylussacia baccata*	Sen[2]	USDI 2003
witch-hazel	*Hamamelis virginiana*	Unk	USDI 2003
American holly	*Ilex opaca*	InSen[1]	Smith 1981
black walnut	*Juglans nigra*	InSen	Dowsett 1992, Smith 1981
eastern redcedar	*Juniperus virginiana*	Unk	

continued

Table 1.—continued

Eastern species		Sensitivity	Citation
tamarack (native)	*Larix laricina*	Unk	
sweetgum	*Liquidambar stryraciflua*	Sen	Krupa et al. 1998
spicebush	*Lindera benzoin*	Unk	USDI 2003
yellow-poplar	*Liriodendron tulipifera*	Sen	Krupa and Manning 1988
maleberry	*Lyonia ligustrina*	Sen[2]	USDI 2003
cucumbertree	*Magnolia acuminata*	Unk InSen	Dowsett 1992
apple sp.	*Malus sp.*	Unk	
blackgum	*Nyssa sylvatica*	ModSen	Renfro 1987-1992
sourwood	*Oxydendrum arboreum*	ModSen	Renfro 1987-1992
Virginia creeper	*Parthenocissus quinquefolia*	Sen[2]	USDI 2003
sweet mock orange	*Philadelphus coronarius*	Sen[2]	USDI 2003
Norway spruce	*Picea abies*	InSen[1]	Smith 1981
white spruce	*Picea glauca*	InSen[1]	Smith 1981
black spruce	*Picea mariana*	Unk	
red spruce	*Picea rubens*	InSen	Eckert et al. 1999
jack pine	*Pinus banksiana*	Sen[2]	USDI 2003
shortleaf pine	*Pinus echinata*	ModSen[1]	Smith 1981
table mountain pine	*Pinus pungens*	Sen	Renfro 1987-1992
red pine	*Pinus resinosa*	InSen[1]	Smith 1981
pitch pine	*Pinus rigida*	InSen, Sen[2]	Eckert et al. 1999, USDI 2003
eastern white pine	*Pinus strobus*	Sen	Krupa and Manning 1988
Scotch pine	*Pinus sylvestris*	ModSen[1]	Smith 1981
loblolly pine	*Pinus taeda*	Sen	Taylor 1994
Virginia pine	*Pinus virginiana*	ModSen, Sen[2]	Renfro 1987-1992, USDI 2003
American sycamore	*Platanus occidentalis*	Sen	Krupa and Manning 1988
balsam poplar	*Populus balsamifera*	Sen[3]	Krupa et al. 1998
eastern cottonwood	*Populus deltoides*	Sen[3]	Krupa et al. 1998
bigtooth aspen	*Populus grandidentata*	Sen[3]	Krupa et al. 1998
quaking aspen	*Populus tremuloides*	Sen	Krupa and Manning 1988
wild plum	*Prunus americana*	Unk	USDI 2003
pin cherry	*Prunus pensylvanica*	ModSen	Renfro 1987-1992
black cherry	*Prunus serotina*	Sen	Krupa and Manning 1988
choke cherry	*Prunus virginiana*	ModSen	Renfro 1987-1992
white oak	*Quercus alba*	InSen	Renfro 1987-1992
scarlet oak	*Quercus coccinea*	ModSen[1]	Smith 1981
northern pin oak	*Quercus ellipsoidalis*	ModSen[1]	Smith 1981
southern red oak	*Quercus falcata*	Unk	
shingle oak	*Quercus imbricaria*	InSen[1]	Smith 1981
bur oak	*Quercus macrocarpa*	InSen[1]	Smith 1981
pin oak	*Quercus palustris*	ModSen[1]	Smith 1981
willow oak	*Quercus phellos*	Unk	Dowsett 1992
chestnut oak	*Quercus prinus*	Unk	Dowsett 1992
northern red oak	*Quercus rubra*	InSen	Eckert et al. 1999
post oak	*Quercus stellata*	Unk	
black oak	*Quercus velutina*	ModSen[1]	Smith 1981
winged sumac	*Rhus copallina*	Sen[2]	USDI 2003
black locust	*Robina pseudoacacia*	ModSen, Sen[2]	Renfro 1987-1992, USDI 2003
Allegheny blackberry	*Rubus allegheniensis*	Sen[2]	USDI 2003
thornless blackberry	*Rubus canadensis*	Sen[2]	USDI 2003
sand blackberry	*Rubus cuneifolius*	Sen[2]	USDI 2003
black willow	*Salix nigra*	Unk	
American elder	*Sambucus canadensis*	Sen[2]	USDI 2003

continued

Table 1.—continued

Eastern species		Sensitivity	Citation
sassafras	*Sassafras albidum*	Sen	Krupa et al. 1998
common snowberry	*Symphoricarpos albus*	Sen[2]	USDI 2003
northern white-cedar	*Thuja occidentalis*	InSen	Eckert et al. 1999
American basswood	*Tilia americana*	InSen[1]	Smith 1981
Chinese tallow	*Triadica sebifera*	Sen[2]	USDI 2003
eastern hemlock	*Tsuga canadensis*	InSen	Renfro 1987-1992
American elm	*Ulmus americana*	Unk	Dowsett 1992
slippery elm	*Ulmus rubra*	Unk	
northern fox grape	*Vitis labrusca*	Sen[2]	USDI 2003

[1]Based on relative sensitivity to acute ozone exposure.
[2]Based on sensitivity to ambient ozone concentrations in the field and exposure chamber.
[3]Based on relative sensitivity of genus, not species.

Table 2.—List of western tree and shrub species and their ozone sensitivity

Western Species		Sensitivity	Citation
red alder	*Alnus rubra*	Sen[3]	Brace et al. 1996
Sitka alder	*Alnus sinuata*	Sen	Brace et al. 1996
western serviceberry	*Amelanchier alnifolia*	ModSen[3]	Brace et al. 1996
single-leaf ash	*Fraxinus anomala*	Sen[4]	USDI 2003
twinberry	*Lonicera involucrata*	Sen[4]	USDA 2003
lodgepole pine	*Pinus contorta*[1]	ModSen[3]	Brace et al. 1996
Jeffrey pine	*Pinus jeffreyi*	Sen	Miller et al. 1996
western white pine	*Pinus monticola*	Sen[4]	Arbaugh et al. 1999
ponderosa pine	*Pinus ponderosa*[2]	Sen	Smith 1981
Monterey pine	*Pinus radiata*	Sen[4]	USDI 2003
Pacific ninebark	*Physocarpus capitatus*	Sen[3]	Brace et al. 1996
mallow ninebark	*Physocarpus malvaceus*	Sen[3]	Brace et al. 1996
Fremont cottonwood	*Populus fremontii*	Sen[4]	USDI 2003
quaking aspen	*Populus tremuloides*	Sen	Smith 1981
black cottonwood	*Populus trichocarpa*	ModSen[3]	Brace et al. 1996
big cone Douglas-fir	*Pseudotsuga macrocarpa*	Sen[4]	Arbaugh et al. 1999
Douglas-fir	*Pseudotsuga menziesii*	ModSen[3]	Brace et al. 1996
California black oak	*Quercus kelloggii*	ModSen	Miller et al. 1996
skunk bush	*Rhus trilobata*	Sen	Temple 2000
thimbleberry	*Rubus parviflorus*	Sen[4]	USDI 2003
Gooding's willow	*Salix gooddingii*	Sen[4]	USDI 2003
Scouler's willow	*Salix scouleriana*	Sen[4]	Brace et al. 1996
willow sp.	*Salix sp.*	ModSen[5]	Krupa and Manning 1988
blue elderberry	*Sambucus mexicana*	Sen	Temple 2000
red elderberry	*Sambucus racemosa*	ModSen[3]	Brace et al. 1996
giant sequoia	*Sequoiadendron giganteum*	InSen	Arbaugh et al. 1999
common snowberry	*Symphoricarpos albus*	Sen[4]	USDI 2003
snowberry sp.	*Symphoricarpos sp*	Sen[5]	Smith 1981
western redcedar	*Thuja plicata*	InSen	Arbaugh et al. 1999
western hemlock	*Tsuga heterophylla*	ModSen[3]	Brace et al. 1996
huckleberry	*Vaccinium membranaceum*	Sen[4]	USDI 2003
huckleberry sp.	*Vaccinium sp.*	ModSen[3]	Brace et al. 1996

[1]*Pinus contorta* var. *latifolia*.
[2]*Pinus ponderosa* var. *ponderosa*.
[3]Based on relative sensitivity to acute ozone exposure.
[4]Based on sensitivity to ambient ozone concentrations in the field and exposure chamber.
[5]Based on relative sensitivity of genus, not species.

APPENDIX 5.—FIELD DATA SHEETS AND DATA FLOW CHART FOR THE OZONE BIOINDICATOR

Examples of standardized field data sheets used by crews working in FIA-North are provided along with a sample site location map. The data sheets for other FIA regions are similar although different species are used for injury evaluations. Regions may modify the data sheets for ease of handling and interpretation as long as the content remains the same. Ozone injury data are collected electronically. The injury data sheets are used for backup in the event of PDR failure. The voucher data sheets must be filled out by hand and mailed with the leaf samples to the regional ozone expert for review. The site map and site characteristics data sheets are filled out by hand and stored in the region so that they are available to regular and QA crews every year.

A flow chart showing movement of the ozone indicator data from the field to the FIA database is also provided.

OZONE BIOINDICATOR FOLIAR INJURY DATA SHEET • NORTH

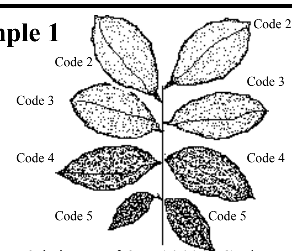
STATE	COUNTY	FIELD ID (O3 Hex Num)	SPLIT PLOT ID	MONTH	DAY	CREW ID	Circle QA STATUS
							STANDARD -- QA BLIND CHK

Code	Species
915	**Blackberry**
762	**Black Cherry**
365	**Milkweed**
621	Yellow Poplar
541	White Ash
931	Sassafras
366	Spreading Dogbane
364	Big Leaf Aster
611	Sweetgum
761	Pin Cherry

Amount of Injury – % of leaves injured relative to the total leaf number
Severity of Injury – Average severity of symptoms on the injured leaves

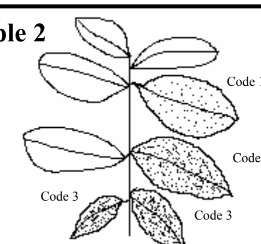
Code	Scale
0	No Injury
1	1-6%
2	7-25%
3	26-50%
4	51-75%
5	>75%

Example 1



Amount: 8 inj out of 8 = 100%, Code 5
Severity: mean of 8 inj lvs = Code 4

Example 2



Amount: 4 inj out of 8 = 50%, Code 3
Severity: mean of 4 inj lvs = Code 2

	Species Code		Species Code		Species Code		Species Code		Species Code	
Plant	Amount	Severity	Amount	Severity	Amount	Severity	Amount	Severity	Amount	Severity
1										
2										
3										
4										
5										
6										
7										
8										
9										
10										
11										
12										
13										
14										
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22										
23										
24										
25										
26										
27										
28										
29										
30										

Did you collect 3 leaves that clearly show ozone stipple, for each injured species? Enter injury location and injury type codes for the sampled plants.

√=yes					
	Location = Type =	**Location = Type =**	**Location = Type =**	**Location = Type =**	**Location = Type =**

Refer to the Ozone Bioindicator Plants section of the FIA Field Guide for codes and definitions. Mail hardcopy of injury data for supplemental species to G.Smith.

Notes:

OZONE BIOINDICATOR PLANTS • BIOSITE CHARACTERISTICS • NORTH

Crew Reminders: Take this sheet to the Biosite. Complete it in the field. This sheet must be completed in the field only if you are *not* recording this same information electronically on the FIA data recorder.

To be filled out by the FIELD CREW or Cooperator: Refer to Ozone Field Guide for code definitions.

State	County	FIELD ID (O3 hex number)	SPLIT PLOT ID[1]	Month	Day	Crew ID	QA Status (circle one)
							Standard QA blind check

[1]Split Plot ID refers to the number of locations (1 or 2) used for each hexagon number (F_ID). A separate sheet should be used for each location.

√ Please put a check mark beside the correct information. Please complete all data fields.

Ozone Sample Kind: [O3SK]	
	Initial biosite establishment on the FIA ozone grid. (Data collection in a previously empty polygon)
	Remeasurement of a previously established biosite, or a replacement site within 3 miles of last year's GPS location.
	Remeasurement when the replacement biosite is more than 3 miles away from last year's GPS location.

Biosite size (Plot Size): [SIZE]		Terrain position: [TERR]	
	> 3.0 acres (1.2 hectares)		Ridge top or upper slope
	1to 3 acres (0.4 – 1.2 hectares)		Bench or level area along a slope
	Other: please describe		Lower slope
			Flat land unrelated to slope
			Bottom land with occasional flooding

Aspect: 000° = no aspect; 360° = N aspect [ASP]	Elevation: record estimate in feet or meters [ELEV]	
Record to nearest degree =	Feet =	Meters =

Soil Drainage: [SDRA]		Soil Depth: [SDEP]	
	Well-drained		Bedrock not exposed
	Wet		Bedrock exposed
	Excessively dry		

Disturbance: Disturbance on the site or in localized areas where the bioindicator plants are growing. [DSTB]	
	No recent or significant disturbance; Do not count disturbance >3 years old.
	Evidence of overuse; Human activity causing obvious soil compaction or erosion.
	Evidence of natural disturbance including fire, wind, flooding, grazing, pests, etc.

Fill in below all that apply. Check here if geographic coordinates were obtained from a topographic map: ☐
Latitude and longitude are recorded in degrees, minutes, and seconds.

GPS Unit [UNIT] =	GPS Datum [GPSD]=	GPS Serial Number [GPS#] =
Latitude [N] =		GPS Error [ERRS]=
Longitude [W] =		Number of GPS Readings [READ] =
Elevation [ELEV]=		GPS File Name (optional) =

[1]If no GPS Unit is available, please use a map and record estimated latitude, longitude, and elevation for each biosite location.

Comments: Include information on additional species in the area, safety, directions, or additional site characteristics that may be useful.

File this completed data sheet with the sheet used for mapping the Bioindicator Site Location and then store it in the appropriate Ozone Plot Folder for your State or Region.

OZONE BIOINDICATOR PLANTS

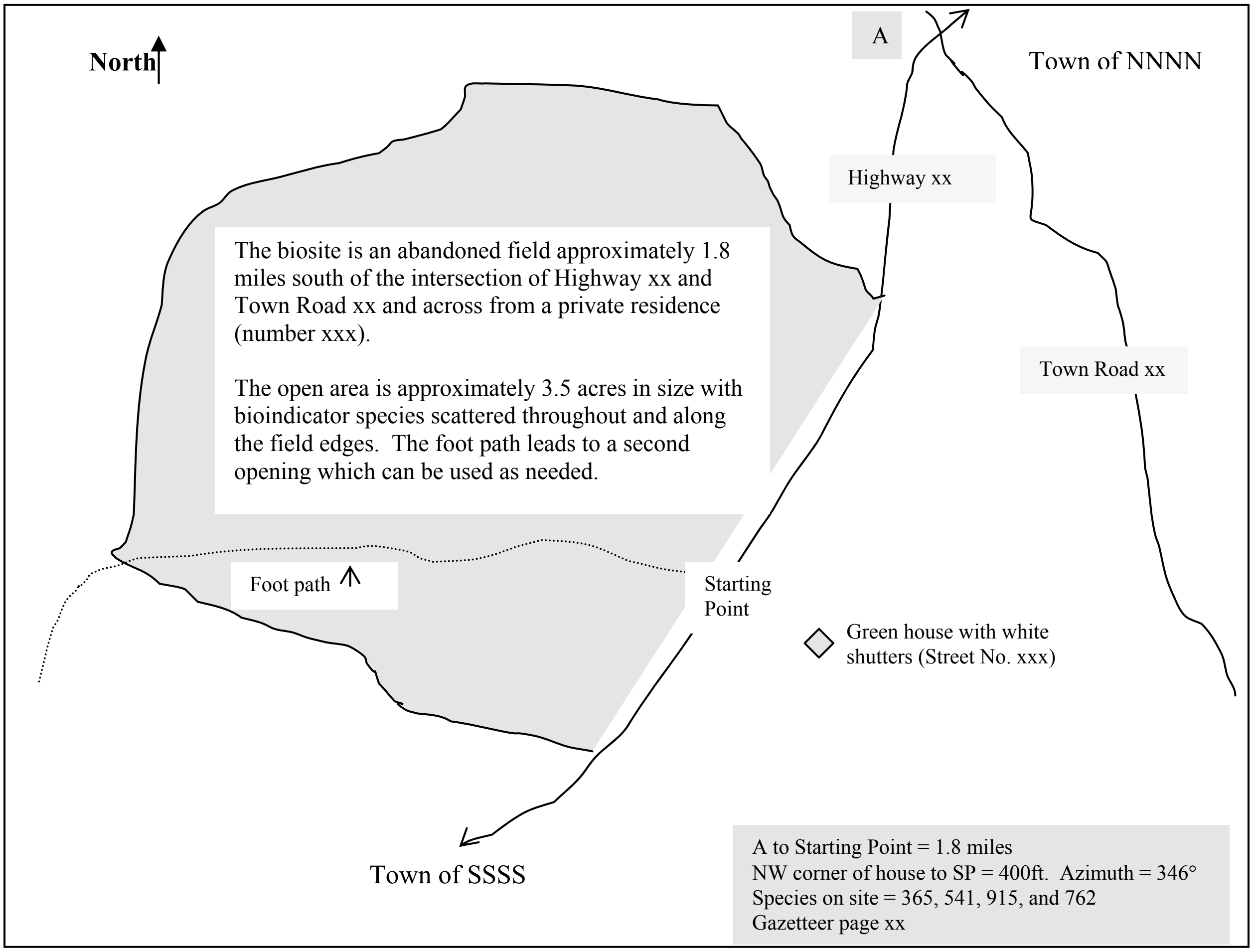
Data Sheet for Directions and Mapping for the Bioindicator Site Location

Use the back of this sheet to document directions (mileage and key landmarks) to the ozone biosite.

To be filled out by the FIELD CREW or Cooperator: Refer to Field Guide for code definitions.

STATE	COUNTY	OZONE HEXAGON NUMBER	OZONE PLOT NUMBER[1]	MONTH	DAY	YEAR	CREW ID
xx	xxx	xxxxxxx	x	xx	xx	xxxx	xxxx

[1]O3Plot Number refers to the number of locations (1 or 2) used for each hexagon number. A separate sheet should be used for each location.



Include the following information on the map:

1. **Location of the site relative to some obvious and permanent marker.**
2. **Road names and distances as needed.**
3. **North arrow.**
4. **Species codes and approximate location of plant groupings used for the ozone injury evaluations.**
5. **Location and distance to two major roads; distance and direction to two major towns.**
6. **Gazetteer reference page if available.**

Return the original of this map to the corresponding Biosite Folder so that it can be used by audit and regular crews in subsequent visits to the plot. Mail a copy to the National Indicator Advisor the year that the site is established.

GPS UNIT: x	**GPS DATUM = cccnn**	**GPS SERIAL NUMBER: xxxxxx**	
Latitude = xx xx xxxx		**GPS ERROR = xxx**	
Longitude = xxx xx xxxx		**NUMBER OF READINGS = xxx**	
Elevation = xxxxxx		**GPS FILE NAME = xxxxxxxx.xxx**	
EASTING:	**NORTHING:**	**+/-Error(ft.):**	**Grid Zone:**

Note: This biosite consists of two locations and there are 2 maps on file for this biosite. The second location is approximately two miles south on Highway xx in the town of SSSS.

OZONE BIOINDICATOR PLANTS

Data Sheet for the Voucher Leaf Samples

- NORTH -

To be filled out by the FIELD CREW or Cooperator: Refer to the Ozone Field Guide for code definitions.

State	County	FIELD ID (O3 Hex Number)	SPLIT PLOT ID[1]	Month	Day	Crew ID	√ QA STATUS
							Standard Blind Chk

[1]**SPLIT PLOT ID refers to the number of locations (1 or 2) used for each hexagon number (F_ID). Use separate sheets for each location.**

Fill in the required codes. ONE SPECIES PER LINE. Code definitions are in the Field Guide.

Bioindicator Species Code or Common Name		Injury Location	Injury Type		Is the leaf sample injury close to 100% ozone stipple (√), or is some other upper-leaf-surface injury also present (e.g., insect injury or fungal lesions)?
1st					Close to 100% ______ Estimated percent other _______
2nd					Close to 100% ______ Estimated percent other _______
3rd					Close to 100% ______ Estimated percent other _______
4th					Close to 100% ______ Estimated percent other _______

Species codes:
915 Blackberry
762 Black cherry
365 Milkweed
621 Yellow poplar
541 White ash
931 Sassafras
611 Sweetgum
761 Pin cherry
366 Spreading dogbane
364 Bigleaf aster.
998 Supplemental
(write out common name)
999 Unknown

Injury Location codes:
1 = greater than 50% of the injured leaves are younger leaves.
2 = greater than 50% of the injured leaves are mid-aged or older.
3 = injured leaves are all ages.

Injury type codes:
1 = greater than 50% of the injury is upper-leaf-surface stipple.
2 = greater than 50% is not stipple; may be flecks, bifacial, gen. discolor.
3 = injury is varied or difficult to describe.

Biosite Notes: (use back of sheet as needed)

CHECK √ all that apply:	Species codes with undersized leaves:
Voucher leaves are from 1 plant: Voucher leaves are from multiple plants: Biosite growth conditions are poor: Biosite conditions are unsafe: Weather has been very dry: Weather has been very wet: See comments on back:	Species codes for which normal sized leaves were uninjured or unavailable: Species codes for voucher leaves that are from NON-TALLIED plants:

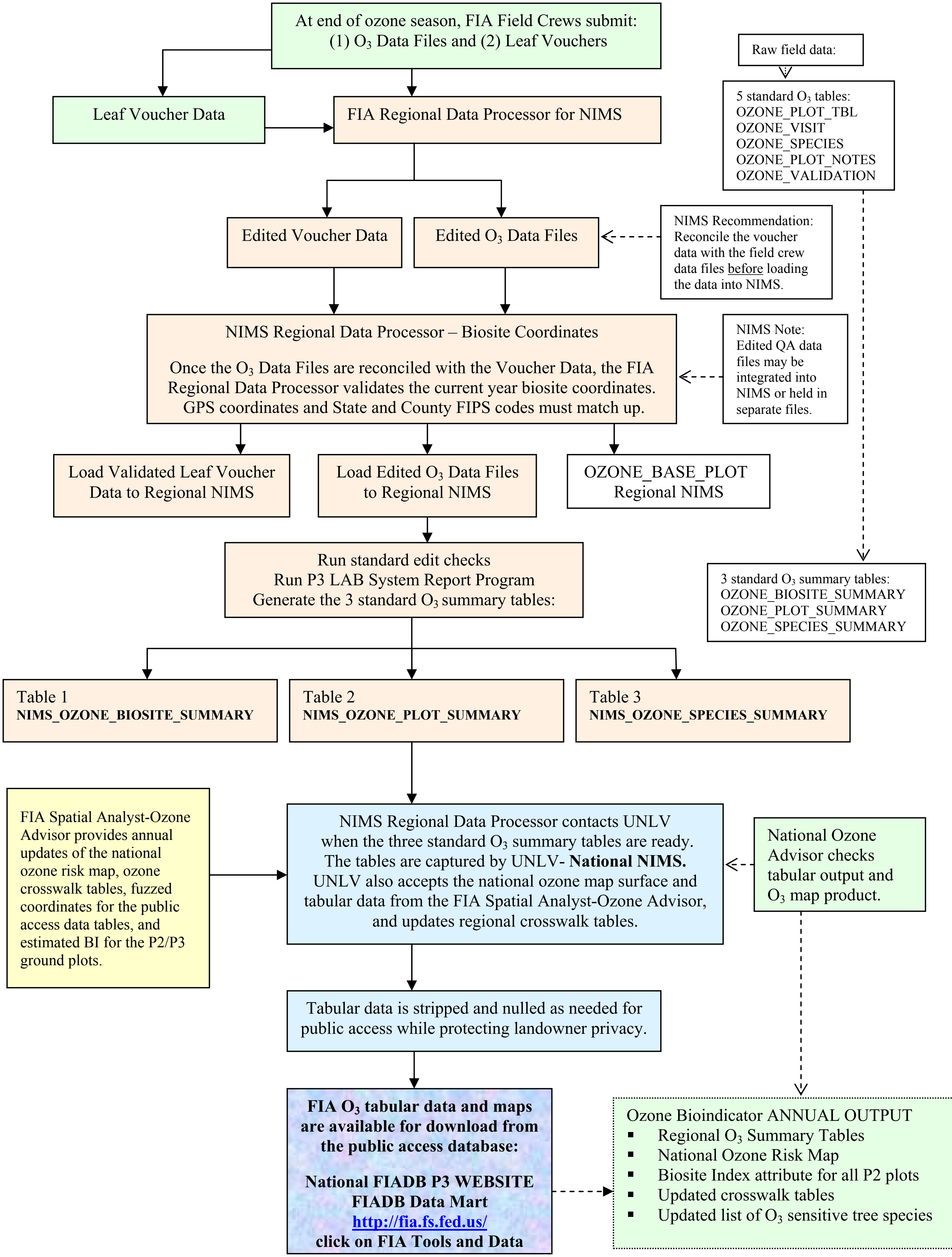
Mail this sheet with the leaf samples to:

Gretchen Smith
Department of Natural Resources Conservation
160 Holdsworth Way
University of Massachusetts
Amherst, MA 01003

QA/QC PERSON: To be filled out by the National Ozone Advisor or Regional Expert. √

Date checked	Date rechecked	Sample condition			Biosite O_3 Status	
		GOOD easy to read - ID obvious	FAIR	POOR samples unreadable or not labeled correctly	(+ozone)	(- ozone)

Bioindicator Species	Positive for ozone	Negative for ozone	Explanation


At end of ozone season, FIA Field Crews submit: (1) O_3 Data Files and (2) Leaf Vouchers
Leaf Voucher Data
FIA Regional Data Processor for NIMS
Raw field data:
5 standard O_3 tables:
OZONE_PLOT_TBL
OZONE_VISIT
OZONE_SPECIES
OZONE_PLOT_NOTES
OZONE_VALIDATION
Edited Voucher Data
Edited O_3 Data Files
NIMS Recommendation: Reconcile the voucher data with the field crew data files before loading the data into NIMS.
NIMS Regional Data Processor – Biosite Coordinates
Once the O_3 Data Files are reconciled with the Voucher Data, the FIA Regional Data Processor validates the current year biosite coordinates. GPS coordinates and State and County FIPS codes must match up.
NIMS Note: Edited QA data files may be integrated into NIMS or held in separate files.
Load Validated Leaf Voucher Data to Regional NIMS
Load Edited O_3 Data Files to Regional NIMS
OZONE_BASE_PLOT Regional NIMS
Run standard edit checks
Run P3 LAB System Report Program
Generate the 3 standard O_3 summary tables:
3 standard O_3 summary tables:
OZONE_BIOSITE_SUMMARY
OZONE_PLOT_SUMMARY
OZONE_SPECIES_SUMMARY
Table 1 NIMS_OZONE_BIOSITE_SUMMARY
Table 2 NIMS_OZONE_PLOT_SUMMARY
Table 3 NIMS_OZONE_SPECIES_SUMMARY
FIA Spatial Analyst-Ozone Advisor provides annual updates of the national ozone risk map, ozone crosswalk tables, fuzzed coordinates for the public access data tables, and estimated BI for the P2/P3 ground plots.
NIMS Regional Data Processor contacts UNLV when the three standard O_3 summary tables are ready. The tables are captured by UNLV- National NIMS. UNLV also accepts the national ozone map surface and tabular data from the FIA Spatial Analyst-Ozone Advisor, and updates regional crosswalk tables.
National Ozone Advisor checks tabular output and O_3 map product.
Tabular data is stripped and nulled as needed for public access while protecting landowner privacy.
FIA O_3 tabular data and maps are available for download from the public access database:
National FIADB P3 WEBSITE
FIADB Data Mart
http://fia.fs.fed.us/
click on FIA Tools and Data
Ozone Bioindicator ANNUAL OUTPUT
Regional O_3 Summary Tables
National Ozone Risk Map
Biosite Index attribute for all P2 plots
Updated crosswalk tables
Updated list of O_3 sensitive tree species

APPENDIX 6.—OZONE SUMMARY TABLES

Ozone summary tables are produced from the field data files and leaf voucher validation files for the FIA National Information Management System (NIMS) and the FIA database (FIADB) for public use. For detailed information on the ozone attribute codes and definitions and for guidance on interpreting summarized attributes for internal or external reports, all users should refer to the FIADB Database Description and Users Guide version 3.0 Phase 3 (Forest Health Indicators) available online at the FIA Data Mart Web page.

http://fiatools.fs.fed.us/fiadb-downloads/fiadb3.html

http://www.fia.fs.fed.us/tools-data/docs/pdfs/FIADB_user%20guide%203-0_P3_6_01_07.pdf

Brief descriptions of the tables are as follows:

OZONE_VISIT: The measurement attributes in this table summarize identifying characteristics of the ozone plot or biosite with respect to site conditions evaluated by the field crew and measurement status on the ozone grid.

OZONE_VALIDATION: The measurement attributes in this table provide a record of whether or not the ozone injury rated by the field crews was validated by an expert for every species at every biosite.

OZONE_BIOSITE_SUMMARY: The measurement attributes in this table summarize biosite-level data including species and plant counts and injury indices. When biosites are split between two locations, data are summarized to represent one biosite.

OZONE_PLOT_SUMMARY: The measurement attributes in this table summarize location-specific data including species and plant counts, site characteristics, and injury indices. Location-specific data differ from biosite-level data for the small number of biosites that are split between two locations.

OZONE_SPECIES_SUMMARY: The measurement attributes in this table summarize plant counts, site characteristics, and injury indices for each bioindicator species evaluated at each ground location.

OZONE_VISIT		
NIMS		FIADB Version 3.0
Column Name		Column Name
INVYR	Inventory year	INVYR
STATECD	State code	STATECD
COUNTYCD	County code	COUNTYCD
FIELD_ID	Field identification number	FIELD_ID[1]
SPLIT_PLOTID	Split plot identification number	SPLIT_PLOTID
O3PLOT	Ozone plot number	O3PLOT
SMPKNDCD	Ozone sample kind code	SMKNDCD
MEASDAY	Measurement day	MEASDAY
MEASMON	Measurement month	MEASMON
MEASYEAR	Measurement year	MEASYEAR
PLTSIZE	Plot size	PLTSIZE
ASPECT	Aspect	ASPECT
TERRPOS	Terrain position	TERRPOS
SOILDPTH	Soil depth	SOILDPTH
SOILDRN	Soil drainage	SOILDRN
PLOTWET	Plot wetness	PLOTWET
PLTDSTRB	Plot disturbance	PLTDSTRB
QASTATCD	Quality assurance status code	QASTATCD
CRWTYPCD	Crew type code	CRWTYPCD
INJCHECK	Injury check	INJCHECK
GRIDDEN	Ozone grid density	GRIDDEN

[1]In the FIADB, FIELD_ID is a system generated number used to replace the sensitive field identification number stored in NIMS. SPLIT_PLOTID is a number used to identify the distinct locations sampled for a particular biosite. O3PLOT is a concatenation of FIELD_ID and SPLIT_PLOTID and a unique identifier used in combination with INVYR to identify a biomonitoring site.

OZONE_VALIDATION		
NIMS		FIADB Version 3.0
Column Name		Column Name
INVYR	Inventory year	INVYR
STATECD	State code	STATECD
COUNTYCD	County code	COUNTYCD
FIELD_ID	Field identification number	FIELD_ID[1]
SPLIT_PLOTID	Split plot identification number	SPLIT_PLOTID
O3PLOT	Ozone plot number	O3PLOT
BIOSPCD	Bioindicator species code	BIOSPCD
QASTATCD	Quality assurance status code	QASTATCD
CRWTYPCD	Crew type code	CRWTYPCD
LEAFVCHR	Leaf voucher	LEAFVCHR
INJVALID	Injury validation	INJVALID
O3_STATCD	Ozone status code	O3_STATCD
MEASYEAR	Measurement year	MEASYEAR

[1]In the FIADB, FIELD_ID is a system generated number used to replace the sensitive field identification number stored in NIMS. SPLIT_PLOTID is a number used to identify the distinct locations sampled for a particular biosite. O3PLOT is a concatenation of FIELD_ID and SPLIT_PLOTID and a unique identifier used in combination with INVYR to identify a biomonitoring site.

OZONE_BIOSITE_SUMMARY		
NIMS		FIADB Version 3.0
Column Name		Column Name
INVYR	Inventory year	INVYR
STATECD	State code	STATECD
COUNTYCD	County code	COUNTYCD
FIELD_ID	Field identification number	FIELD_ID[1]
O3PLOT	Ozone plot number	O3PLOT
LOCATION_CNT	Location count	LOCATION_CNT
GROUND_LOC_CD	Ground location code	GROUND_LOC_CD
MEASYEAR	Measurement year	MEASYEAR
PLANT_INJ_CNT	Plant injury count	PLANT_INJ_CNT
PLANT_EVAL_CNT	Plant evaluation count	PLANT_EVAL_CNT
PLANT_RATIO	Plant ratio	PLANT_RATIO
SPECIES_EVAL_CNT	Species evaluation count	SPECIES_EVAL_CNT
BIOSITE_INDEX	Biosite index	BIOSITE_INDEX
BIOSITE_INDEX_MULTIPLIER	Biosite index multiplier	BIOSITE_INDEX_MULTIPLIER
SVRTY_CLASS_ZERO	Severity class zero	SVRTY_CLASS_ZERO
SVRTY_CLASS_ONE	Severity class one	SVRTY_CLASS_ONE
SVRTY_CLASS_TWO	Severity class one	SVRTY_CLASS_TWO
SVRTY_CLASS_THREE	Severity class one	SVRTY_CLASS_THREE
SVRTY_CLASS_FOUR	Severity class one	SVRTY_CLASS_FOUR
SVRTY_CLASS_FIVE	Severity class one	SVRTY_CLASS_FIVE

[1]In the FIADB, FIELD_ID is a system generated number used to replace the sensitive field identification number stored in NIMS. O3PLOT is a unique identifier used in combination with INVYR to identify a biosite. The last digit of O3PLOT = 1 when the biosite consists of one location or 2 when the biosite consists of two locations.

OZONE_PLOT_SUMMARY		
NIMS		FIADB Version 3.0
Column Name		Column Name
INVYR	Inventory year	INVYR
STATECD	State code	STATECD
COUNTYCD	County code	COUNTYCD
FIELD_ID	Field identification number	FIELD_ID[1]
SPLIT_PLOTID	Split plot identification number	SPLIT_PLOTID
O3PLOT	Ozone plot number	O3PLOT
MEASYEAR	Measurement year	MEASYEAR
SPECIES_EVAL_CNT	Species evaluated count	SPECIES_EVAL_CNT
BIOSITE_INDEX	Biosite index	BIOSITE_INDEX
BIOSITE_INDEX_MULTIPLIER	Biosite index multiplier	BIOSITE_INDEX_MULTIPLIER
ELEV	Elevation	ELEV
PLTSIZE	Plot size	PLTSIZE
ASPECT	Aspect	ASPECT
TERRPOS	Terrain position	TERRPOS
SOILDPTH	Soil depth	SOILDPTH
SOILDRN	Soil drainage	SOILDRN
PLOTWET	Plot wetness	PLOTWET
PLTDSTRB	Plot disturbance	PLTDSTRB
GPS_LAT	Latitude[2]	LAT
GPS_LON	Longitude[2]	LON

[1]In the FIADB, FIELD_ID is a system generated number used to replace the sensitive field identification number stored in NIMS. SPLIT_PLOTID is a number used to identify the distinct locations sampled for a particular biosite. O3PLOT is a concatenation of FIELD_ID and SPLIT_PLOTID and a unique identifier used in combination with INVYR to identify a biomonitoring site.

[2]Ozone biosite coordinates are fuzzed in the FIADB to protect landowner privacy.

OZONE_SPECIES_SUMMARY		
NIMS		FIADB Version 3.0
Column Name		Column Name
INVYR	Inventory year	INVYR
STATECD	State code	STATECD
COUNTYCD	County code	COUNTYCD
FIELD_ID	Field identification number	FIELD_ID[1]
SPLIT_PLOTID	Split plot identification number	SPLIT_PLOTID
O3PLOT	Ozone plot number	O3PLOT
GROUND_LOC_CD	Ground location code	GROUND_LOC_CD
MEASYEAR	Measurement year	MEASYEAR
BIOSPCD	Bioindicator species code	BIOSPCD
AMNT_MAX	Amount maximum	AMNT_MAX
AMNT_MIN	Amount minimum	AMNT_MIN
AMNT_MEAN	Amount mean	AMNT_MEAN
SVRTY_MAX	Severity maximum	SVRTY_MAX
SVRTY_MIN	Severity minimum	SVRTY_MIN
SVRTY_MEAN	Severity mean	SVRTY_MEAN
PLANT_INJ_CNT	Plant injury count	PLANT_INJ_CNT
PLANT_EVAL_CNT	Plant evaluation count	PLANT_EVAL_CNT
PLANT_RATIO	Plant ratio	PLANT_RATIO
BIOSPCD_SUM	Biospecies sum	BIOSPCD_SUM
BIOSPCD_INDEX	Biospecies index	BIOSPCD_INDEX
ELEV	Elevation	ELEV
PLTSIZE	Plot size	PLTSIZE
ASPECT	Aspect	ASPECT
TERRPOS	Terrain position	TERRPOS
SOILDPTH	Soil depth	SOILDPTH
SOILDRN	Soil drainage	SOILDRN
PLOTWET	Plot wetness	PLOTWET
PLTDSTRB	Plot disturbance	PLTDSTRB

[1]In the FIADB, FIELD_ID is a system generated number used to replace the sensitive field identification number stored in NIMS. SPLIT_PLOTID is a number used to identify the distinct locations sampled for a particular biosite. O3PLOT is a concatenation of FIELD_ID and SPLIT_PLOTID and a unique identifier used in combination with INVYR to identify a biomonitoring site.

APPENDIX 7.—CORE TABLES FOR STATE AND REGIONAL REPORTS

Core summary tables for state reports provide information to address the following forest health assessment questions:

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 the 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 is the relationship between ambient ozone concentrations and the injury data?
9. What amount of forest land is subject to levels of ozone pollution that may cause negative impacts?
10. What volume of ozone-sensitive species is at risk, and where is it?

A template for the ozone bioindicator core summary table is provided here along with several examples of state-level core tables (MA, MD, WI, and VA). Refer to Campbell et al. (2007) for more examples from Western States. Refer to the main text of this report (pages 28-30) for more information on tables and map products for the ozone indicator.

CORE TEMPLATE	Summary of ozone biomonitoring statistics by state, region, and year									
Parameter	ABC region	State1	State2	State3	State4	State5	State6	State7	State8	State9
Number of biosites evaluated										
Number of biosites with injury										
Average biosite index score[1]										
Percent biosites with BI = 0 to 4.9[2]										
Percent biosites with BI = 5 to 14.9										
Percent biosites with BI = 15 to 24.9										
Percent biosites with BI >= 25										
Percent forest land with BI = 0 to 4.9[3]										
Percent forest land with BI = 5 to 14.9										
Percent forest land with BI = 15 to 24.9										
Percent forest land with BI >= 25										
Average number of species per biosite										
Percent sample plants by HB category:[4]										
0 = no injury										
1 = 1 to 6 %										
2 = 7 to 25 %										
3 = 26 to 50 %										
4 = 51 to 75 %										
5 = >75 %										
Number of plants evaluated										
Number of plants injured										
Number of plants evaluated (injured) by species:										
Species 1 (number injured in parentheses)										
Species 2										
Species 3, etc.										

[1]The biosite index is based on the average injury score (amount*severity) for each species averaged across all species on the biosite. Smith et al. (2007).
[2]Biosite categories represent a relative measure of tree-level response (least injured to most injured) to ambient ozone exposure. See Table 3 in this report.
[3]Percent forest land is estimated after spatial interpolation of the BI values across the landscape. Estimation methods are described in Smith et al. (2007).
[4]HB values are an estimate of the mean severity of symptoms on injured foliage. See Field Methods in this report.

MASSACHUSETTS													
Parameter	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006
Number of biosites evaluated	14	15	13	16	18	18	14	8	8	8	8	8	8
Number of biosites with injury	11	6	3	11	14	10	9	1	2	3	2	4	8
Average biosite index score	7.70	2.15	2.60	3.61	3.74	3.15	2.07	2.20	0.42	0.12	0.03	0.51	4.74
Number of plants evaluated	469	492	528	424	1129	942	720	451	728	822	630	927	841
Number of plants injured	88	56	22	53	146	63	41	25	15	16	6	15	71
Number of plants by HB severity category:[1]													
0 = no injury	381	436	506	371	983	879	679	426	713	806	624	912	770
1 = 1 to 6 %	60	40	5	31	94	32	21	13	9	13	4	5	31
2 = 7 to 25 %	15	9	11	17	30	25	13	9	5	3	2	10	27
3 = 26 to 50 %	9	7	6	5	19	6	7	3	1	0	0	0	12
4 = 51 to 75 %	3	0	0	0	2	0	0	0	0	0	0	0	1
5 = >75 %	1	0	0	0	1	0	0	0	0	0	0	0	0
Maximum SUM06 value (ppm-hr)[2]	28.2	27.6	21.2	29.2	24.4	32.1	18.5	23.1	34.7	27.4	15.9	22.6	-
Most sampled bioindicator herb/shrub spp[3]	915	915	365	915	365	365	365	365	365	365	915	365	365
Most sampled bioindicator tree species	762	762	541	541	762	762	762	762	762	762	762	762	762

MARYLAND													
Parameter	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006
Number of biosites evaluated	9	9	5	4	12	10	7	27	8	8	8	8	8
Number of biosites with injury	9	9	5	3	12	3	2	16	3	2	3	8	5
Average biosite index score	76.50	21.62	66.83	30.59	48.06	24.78	0.40	9.54	11.03	4.63	1.07	14.77	1.15
Number of plants evaluated	392	316	248	207	414	338	261	1820	1109	762	833	671	844
Number of plants injured	202	79	76	37	86	29	27	143	49	31	35	94	18
Number of plants by HB severity category:[1]													
0 = no injury	190	237	172	170	328	309	234	1677	1060	731	798	577	826
1 = 1 to 6 %	33	20	19	6	28	15	24	23	2	6	24	33	
2 = 7 to 25 %	53	26	20	11	29	8	2	67	7	13	10	26	12
3 = 26 to 50 %	49	28	23	11	16	3	1	43	14	8	1	29	5
4 = 51 to 75 %	44	3	12	6	8	2	0	8	20	3	0	5	1
5 = >75 %	23	2	2	3	5	1	0	2	6	1	0	1	0
Maximum SUM06 value (ppm-hr)[2]	101.1	105.3	110.3	106.9	53.3	50.6	34.2	42.7	52.5	30.1	23.5	30.2	-
Most sampled bioindicator herb/shrub spp[3]	915	915	915	915	366	915	915	915	915	915	915	366	915
Most sampled bioindicator tree species	611	611	611	931	541	621	611	611	931	611	611	611	611

[1]See Field Methods in this report for details on the HB severity rating.
[2]See Ambient Concentrations and Exposure Patterns in this report for details on the SUM06 value.
[3]Species codes: 364 = bigleaf aster; 365 = milkweed; 366 = spreading dogbane; 541 = white ash; 611 = sweetgum; 621 = tulip poplar; 762 = black cherry; 915 = blackberry; 931 = sassafras.

WISCONSIN													
Parameter	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006
Number of biosites evaluated	16	65	28	34	42	54	64	39	55	57	55	31	31
Number of biosites with injury	8	9	14	9	25	41	49	20	25	13	22	12	6
Average biosite index score	1.51	1.07	1.24	0.47	3.65	1.19	1.97	1.10	0.67	0.41	0.48	0.51	0.77
Number of plants evaluated	652	3210	1997	2287	4065	5540	6616	3751	4953	5392	5473	2933	2809
Number of plants injured	47	79	36	40	252	195	218	104	107	45	75	24	38
Number of plants by HB severity category:[1]													
0 = no injury	605	3131	1961	2247	3813	5345	6398	3647	4846	5347	5398	2909	2771
1 = 1 to 6 %	30	31	21	25	160	123	118	58	51	27	50	11	19
2 = 7 to 25 %	14	37	12	12	72	61	80	45	54	18	23	11	19
3 = 26 to 50 %	3	7	3	2	12	5	12	1	2	0	2	2	0
4 = 51 to 75 %	0	4	0	0	6	2	5	0	0	0	0	0	0
5 = >75 %	0	0	0	1	2	4	3	0	0	0	0	0	0
Maximum SUM06 value (ppm-hr)[2]	18.68	39.70	19.54	25.44	27.24	28.03	15.15	31.77	32.95	22.32	8.61	25.29	-
Most sampled bioindicator herb/shrub spp[3]	364	915	365	365	365	365	365	365	365	365	365	365	365
Most sampled bioindicator tree species	762	762	762	762	762	762	762	762	541	762	541	541	762

VIRGINIA													
Parameter	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006
Number of biosites evaluated	-	-	-	9	16	26	25	30	24	32	39	39	38
Number of biosites with injury	-	-	-	3	7	6	10	11	2	8	5	0	2
Average biosite index score	-	-	-	10.98	22.12	1.77	20.79	3.07	0.99	4.04	0.26	0	1.47
Number of plants evaluated	-	-	-	366	977	1268	1122	1936	1841	2436	3347	2780	3236
Number of plants injured	-	-	-	55	174	49	97	87	4	100	11	0	9
Number of plants by HB severity category:[1]													
0 = no injury	-	-	-	311	803	1219	1025	1849	1837	2336	3336	2780	3227
1 = 1 to 6 %	-	-	-	2	41	6	2	16	0	1	0	0	5
2 = 7 to 25 %	-	-	-	29	54	24	12	36	0	42	3	0	4
3 = 26 to 50 %	-	-	-	14	47	16	33	20	1	51	7	0	0
4 = 51 to 75 %	-	-	-	8	23	3	22	12	2	6	1	0	0
5 = >75 %	-	-	-	2	9	0	28	3	1	0	0	0	0
Maximum SUM06 value (ppm-hr)[2]	109.3	110.1	110.3	106.9	56.1	47.7	34.2	38.4	50.0	29.2	23.5	29.2	-
Most sampled bioindicator herb/shrub spp [3]	-	-	-	915	915	915	915	915	915	915	915	915	915
Most sampled bioindicator tree species	-	-	-	931	621	621	611	621	762	762	621	611	621

[1]See Field Methods in this report details on the HB severity rating.
[2]See Ambient Concentrations and Exposure Patterns in this report for details on the SUM06 value.
[3]Species codes: 364 = bigleaf aster; 365 = milkweed; 366 = spreading dogbane; 541 = white ash; 761 = pin cherry; 762 = black cherry; 915 = blackberry.

Smith, Gretchen C.; Coulston, John W.; O'Connell, Barbara M. 2008. **Ozone bioindicators and forest health: a guide to the evaluation, analysis, and interpretation of the ozone injury data in the Forest Inventory and Analysis Program**. Gen. Tech. Rep. NRS-34. Newtown Square, PA: U.S. Department of Agricluture, Forest Service, Northern Research Station. 100 p.

In 1994, the Forest Inventory and Analysis (FIA) and Forest Health Monitoring programs of the U.S. Forest Service implemented a national ozone (O_3) biomonitoring program designed to address specific questions about the area and percent of forest land subject to levels of O_3 pollution that may negatively affect the forest ecosystem. This is the first and only nationally consistent effort to monitor O_3 stress on the forests of the United States. This report provides background information on O_3 and its effects on trees and ecosystems, and describes the rationale behind using sensitive bioindicator plants to detect O_3 stress and assess the risk of probable O_3 impact. Also included are a description of field methods, analytic techniques, estimation procedures, and how to access, use and interpret the ozone bioindicator attributes and data outputs such as the national ozone risk map.

KEY WORDS: air quality, bioindicator species, biomonitoring, forest health, ozone, ozone sensitive, risk assessment, spatial interpolation

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