A NATIONAL OZONE BIOMONITORING PROGRAM – RESULTS FROM FIELD SURVEYS OF OZONE SENSITIVE PLANTS IN NORTHEASTERN FORESTS (1994 – 2000)

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Abstract. Ozone biomonitoring is a detection and monitoring technique that involves documenting ozone-induced visible injury to known ozone-sensitive species under conditions of ambient exposure. The USDA Forest Service administers a long-term, nationwide ozone biomonitoring program to address public and scientific concerns about ozone impacts on forest health. A systematic grid is used as the basis for biomonitoring site locations. At each site, trained field crews evaluate a maximum of thirty plants of up to six species and record the amount and severity of leaf-injury on individual plants. Injury from ozone was found more often on biomonitoring sites in the eastern Unites States than in the interior or west-coast areas. Further results from the northeast reveal that in any year, there is a higher percentage of ozone-injured plants with more severe symptoms in areas with relatively high ozone concentrations than in areas with relatively low ozone. In very dry years (e.g.,

1999) the percentage of injured plants and injury severity estimates are both sharply reduced even though ambient ozone exposures are high. These findings demonstrate that biomonitoring data provide meaningful evidence of when high ozone concentrations during the growing season have biological significance. Any assessment of ozone stress in the forest environment must include both biomonitoring (i.e., plant response) and air quality data to be complete.

Keywords: bioindicator, forest health, air quality, ozone exposure, SUM06 exposure index, kriging, sensitive species, Palmer drought severity index, seasonal precipitation.

1. Introduction

The land area of the United States currently includes 302 million hectares of forestland (USDA Forest Service 2001). These forests are essential to our public welfare and to the wellbeing of the biosphere. Today’s forests are, in part, a legacy of this continent’s history of European settlement and the industry-driven development that continues to shape the landscape and influence public interest in forest-resource protection. The responsibility to protect and maintain the health and vitality of our nation’s forests lies mainly with our federal and state land management agencies. To this end, the USDA Forest Service (USFS) has joined an international initiative to develop and implement internationally agreed upon criteria and indicators for sustainable forest management (USFS 1997). This initiative includes a commitment to monitor the area and percent of forestland subjected to levels of specific air pollutants, including ozone, that may cause negative impacts on forest ecosystems (Anon. 1995).

Ozone is the most pervasive phytotoxic air pollutant affecting natural ecosystems, both in the United States and elsewhere (US EPA 1996b). In the U.S., ecological studies have established that ambient ozone concentrations can change certain forest ecosystems and stress sensitive individuals and genotypes beyond normal bounds (Bennett et al. 1994, Berrang et al. 1991, Chappelka and Samuelson 1998, Hakkarienen 1997, Miller et al. 1996, Peterson et al. 1991, Taylor 1994). Documented ozone effects range from acute foliar injury and premature leaf loss to variable impacts on tree physiology and growth. Because forests are complex and natural stresses are numerous, it is difficult to assess the specific impact of anthropogenic ozone stress on any given forested landscape. This is particularly true given the absence of air quality monitoring stations in remote areas where most of our forestland is located.

Air quality monitoring stations operated by the United States Environmental Protection Agency (EPA) or state environmental agencies tend to be located near population centers where air-quality effects on human health are paramount (NARSTO 2000). Monitors are scarce in remote areas due to the expense of running electrical lines to air-conditioned instrument shelters and providing the required calibration services for EPA-approved data collection. One alternative to traditional instrumentation is the use of biological systems (i.e., tree and plant species) to monitor the effects of elevated ozone levels. Biological systems, by definition, depend on the ability of ozone-sensitive individuals within a species to exhibit typical foliar injury symptoms when exposed to ambient ozone concentrations under appropriate conditions (Krupa et al. 1998). Advantages of biological indicators are that they can be utilized anywhere, even in the most remote forest, and they have obvious biological relevance. Unlike physical monitors, biological indicators provide evidence of plant stress. They tell us not only that ozone concentrations were elevated for a particular time and place, but also that other necessary conditions for ozone uptake and injury (e.g., adequate light, nutrition, and moisture) were also present. This type of integrated response information is critical to a meaningful assessment of ozone exposure and injury in forested areas.

The need for more extensive ozone monitoring using both physical and biological systems received particular emphasis during the most recent EPA-sponsored review of our national ambient air quality standards for ozone (Heck and Cowling 1997, Heck et al. 1998). Numerous studies have demonstrated that ozone-sensitive plants can act as detectors of ozone pollution (Chappelka et al. 1997, Duriscoe 1990, Kohut et al. 1997, Neufeld et al. 1992, Skelly 2000, Temple 1989). Detection is based on a visible foliar response that is produced as ozone enters plant leaves through open stomates during the normal process of gas exchange. Once inside the leaf, ozone changes membrane permeability leading to cell death and the appearance of characteristic symptoms on the leaf surface. In this study, visible foliar response to ambient ozone exposure was used to detect and monitor ozone stress in the forest environment. This approach is known as biomonitoring and the plant species used are known as bioindicators.

The USFS Forest Health Monitoring program (FHM) administers a long-term, nationwide biomonitoring program in partnership with EPA, U.S. Department of the Interior Bureau of Land Management, and the National Association of State Foresters. The goal of the FHM biomonitoring program is to address public and scientific concerns about ozone impacts on forest health. The specific function of the existing biomonitoring network is to detect evidence of ozone-induced foliar injury on ozone-sensitive bioindicator species in a nationally consistent fashion under conditions of ambient exposure with suitable verification and quality assurance procedures (USFS 2000). The biomonitoring program was developed with support from the scientific research community and depends on a cooperative effort between federal and state employees as well as university cooperators (Lewis and Conkling 1994, Smith 1995). Currently, thirty-three states participate in the biomonitoring program with the majority of field sites concentrated in the east, where large portions of the landscape typically experience high ambient ozone concentrations during the growing season (Cleveland and Graedel 1979, Lefohn and Pinkerton 1988).

There are two objectives of this report. The primary objective is to provide a description of the scope and methods of the FHM biomonitoring program. The second objective is to highlight the interpretive value of the FHM biomonitoring data, as distinct from traditional air quality statistics from physical monitors, and thereby encourage inclusion of this type of data in air quality and forest health assessment models.

2. Materials and Methods

2.1 National Protocol

A systematic sampling grid, based on a global sampling design, is used as the basis for determining FHM field plot and biomonitoring site locations (White et al. 1992). The sampling intensity is approximately 1 plot per 65,000 hectares. FHM field measurements are collected at forested sites on the sampling grid and biomonitoring sites are generally located in close proximity to these locations. The national map of biomonitoring sites (Figure 1) displays the geographic distribution and sampling intensity of the FHM biomonitoring program for the year 2000. Additional sites are added each year as new states enter the program.

Basic procedures for biomonitoring are standardized nationally and updated annually in a detailed peer-reviewed field manual (Smith 1995). These updates allow biomonitoring to keep progress with research and programmatic changes in field implementation. The most recent version of the manual is available online at http://www.fhmozone.net. The manual details the sampling grid, training and quality assurance requirements for field crews, the criteria for selection of biomonitoring sites and plant species, and the injury evaluation procedures. While procedures are standardized nationally, regional adjustments are allowed to account for differences in ozone exposures, growing season, topography, and forest type.

The national list of ozone bioindicator species selected for use in this study (Tables I and II) 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 work. Selected species 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 of field evidence and causative fumigation experiments. The majority of eastern bioindicator species have a long history of application in ozone field studies and easily meet the stated criteria (Krupa et al. 1998, Skelly et al. 1987, Skelly 2000). The western bioindicator species are not as well tested under natural conditions of ozone exposure, but have all received enough testing to justify inclusion in the FHM program (Brace et al. 1999, Campbell et al. 2000, Duriscoe and Temple 1996, Mavity et al. 1995, Temple 2000).

2.2 The Northeast Regional Approach

In the Northeast region, field protocol requires the crews to establish an ozone biomonitoring site (biosite) close to or at some distance from the FHM forested ground plots depending on the availability of open areas with ozone bioindicator plants (USFS 2000). Ozone site selection was determined by ease of access, species and plant counts, and general site conditions such as soil moisture and disturbance. Once a site was selected, the field crew recorded the size of the opening, elevation, terrain position, aspect, soil drainage, soil depth, and disturbance using a standardized coding system.

At each biosite, crews equipped with a 10X hand lens, evaluated between ten and thirty individual plants of up to six known ozone-sensitive species using a prioritized list (Table I). All foliar evaluations were conducted between the last week in July and the third week in

August. Each plant was evaluated for ozone injury by recording the percent of the leaves with ozone injury symptoms (Amount) and the average severity of injury on leaves that showed ozone injury symptoms (Severity). Amount and severity were recorded separately using a modified Horsfall-Barrett (HB) scale with breakpoints at 6, 25, 50, 75, and 100 percent (Horsfall and Barrett 1945, Horsfall and Cowling 1978).

Each crew collected a voucher sample for each injured species evaluated at the site using a forester-grade plant press. The voucher consisted of three pressed leaves that clearly showed the ozone injury symptom. For each voucher, injury type and location codes were recorded to fully describe the injury observed in the field. Each voucher sample was mailed with an identifying data sheet to a regional ozone expert for validation of the ozone injury symptom.

All crews received training in bioindicator species identification and site selection procedures at the start of the field season and a second training in ozone injury evaluations just prior to the opening of the foliar evaluation window in July. Crews were audited twice during the field season, one training audit and one remeasurement audit by a quality assurance crew. Additional quality assurance activities included validation of the leaf vouchers, debriefing sessions, and final data assessment.

Field data were collected electronically on a portable data recorder or on paper and subjected to a computerized editing and validation process. Field data were zeroed out for any species with a voucher that was either missing or not validated. Validated data from the ozone field sites were used to generate national and regional maps and summary statistics for status and trend analyses. Data are stored with FHM information management staff at the University of Nevada at Las Vegas (UNLV), where access is available to any individual or user group (http://www.na.fs.fed.us/spfo/fhm/index.htm).

2.3 Regional analysis

Validated data from the ozone field sites were used to generate plot and state level summary statistics for this report. For comparative analyses, states were assigned to different subregions within the Northeast based on usual geographical groupings within FHM and general similarities in ozone air quality regimes as described in Table III. Subregions included the Lake States (Minnesota, Wisconsin, Michigan) with relatively clean air quality, the New England states (Maine, New Hampshire, Vermont, Massachusetts, Rhode Island, Connecticut) with intermediate air quality, and the North-Central (Missouri, Illinois, Indiana) and Mid-Atlantic (Ohio, Pennsylvania, New Jersey, Delaware, Maryland, West Virginia) states with relatively poor air quality. Average growing season (June, July, August), 12 hour (8am to 8pm) SUM06 (the sum of all hourly average concentrations $\geq$0.06 ppm) exposures were determined using hourly averaged concentration data obtained from the US EPA Aerometric Information Retrieval System (AIRS). The SUM06 values were spatially interpolated across the landscape using inverse distance squared weighting to estimate the global mean by state and year for each subregion (Isaaks and Srivastava 1989). Regional summaries of ozone air quality data compiled by NESCAUM (Northeast States for Coordinated Air Use Management) were also consulted.

Subregional differences in ozone injury response were examined in terms of numbers of plots evaluated for ozone injury, numbers of plants sampled, and the percent of the sampled plants in each HB injury severity category. In addition, a plot-level foliar injury index (<u>biosite index</u> [BI]) was formulated from the injury amount and severity ratings recorded for each plant and the numbers of plants and species evaluated at each site.

$$BI = m^{-1} \sum_{j=1}^{m} n_j^{-1} \sum_{i=10}^{n_j} a_{ij} s_{ij} \quad \text{[Equation 1]}$$

where,

BI = biosite index

m = number of species evaluated

n_j =number of plants of the jth species evaluated

a_{ij} =amount of injury on the ith plant of the jth species

s_{ij} =severity of injury on the ith plant of the jth species

Mean growing season BI were examined alongside corresponding subregional data on ozone air quality (as described above), precipitation norms, and soil moisture availability. Seasonal precipitation averages and precipitation norms were obtained from the Northeast Regional Climate Center at Cornell University (NRCC) and the Midwestern Regional Climate Center in Champaign, Illinois. Palmer Drought Severity Indices (PDSI) obtained from National Oceanic and Atmospheric Administration (NOAA) were used as an indication of soil moisture availability and the relative severity of wet or dry spells (NCDC 1994). Average growing season (June, July, August) indices were calculated by state and year along with subregional indications of normality for the precipitation averages.

A linear model relating BI to the SUM06 and PDSI explanatory variables was developed using regression analysis. The average annual BI for each state and subregion (1996 to 1999) was used along with corresponding annual mean values for the SUM06 and PDSI indices. The explanatory variables (SUM06 and PDSI) were examined for significance and partial standardized regression coefficients were examined to quantify the relative importance of each explanatory variable. The overall goodness of fit was also calculated.

For additional interpretive analyses, the biosite index was classified into four response categories representing (1) little or no injury to bioindicator plant species [BI = 0 to <5], (2) light to moderate injury [BI = 5 to <15], (3) moderate to severe injury [BI = 15 to <25], and (4) severe foliar injury [BI = ≥25]. These four bioindicator response categories were then used to define and describe possible impact (i.e., risk) to the forest resource from ambient ozone exposure, <u>and</u> to provide an indication of ozone relative air quality with respect to a plant rather than a human interface. The average 1994-1999 biosite index was calculated for each plot (equation 1) in the Northeast. An interpolated bioindicator response surface was then created based on average plot values using kriging. The interpolated map was then classified into the 4 response categories listed above.

3. Results and Discussion

3.1 National Program Summary

As of the 2000 field season, there were a total of 918 ozone biomonitoring sites in the thirty-three states participating in the FHM Program (Figure 1). Biomonitoring sites are located across the landscape in most states, with the majority of sites established on forest land at some distance from developed areas. Numbers of sites vary by state depending on the availability of bioindicator species in certain forest types and, in a few cases, the intensity of the sampling grid for ozone. 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 in Rhode Island and Pennsylvania the numbers of ozone sites are relatively high due to increased sampling activity on the part of the State Cooperator. In some western states, like California, the biomonitoring sampling grid is still under development and there are, as yet, few sites. In contrast to the FHM forest-based biomonitoring network, traditional monitors of ambient ozone (http:/www.epa.gov/airnow) tend to be clustered near metropolitan areas and are noticeably lacking in forested areas, particularly across the western interior landscape.

The national map also shows the number and distribution of biosites where ozone injury was detected on ozone-sensitive bioindicator plants in 2000 (Figure 1). Clearly, more biosites and more sites where ozone injury was detected were located in eastern than in western states. The greater number of sites in the East was largely a function of where FHM was implemented in 2000. The greater number of sites with ozone injury reflects the fact that most of the eastern United States experiences high ambient ozone during the growing season (Skelly 2000) in a relatively moist environment that is conducive to the uptake of ozone by plants. Except for the Los Angeles basin area, less is know about the largely unmonitored western landscape. FHM findings provide important baseline data that tend to confirm the assumption that ozone air quality is relatively good across wide areas of the West (U.S. EPA 1996a, Lee and Hogsett 2000). In 1999, ozone injury was detected on only one biomonitoring site in California due to a lack of biomonitoring sites in areas of high ambient ozone. In 2000, FHM field crews detected injury at six sites in California, one site in Washington, and one site in Utah. Although ozone injury in some areas of California was not unexpected, the detection of injury symptoms in Washington and Utah was a new finding and should alert environmental agencies to the possibility of growing air quality problems in these states.

The most common species found on eastern biomonitoring sites is common milkweed, followed by black cherry, blackberry, spreading dogbane, and white ash (Table I). A few of the less commonly evaluated species, like yellow poplar, are at the limit of their natural range in the heavily sampled northeastern states, or, like pin cherry, tend to occupy highly disturbed sites that do not meet FHM site selection criteria for biomonitoring. Over the years, we have learned that certain species are more responsive and useful as ozone detectors in wet years (e.g., milkweed), others (e.g., black cherry) are more useful in dry years. Field crews have observed ozone-like injury symptoms on species like wild plum (Prunus americana) that have never been tested for ozone sensitivity. FHM has also built a significant library of symptomology and mimicking symptoms that will prove valuable to other programs or researchers interested in ozone field studies (http://www.fhmozone.net).

Ponderosa pine and quaking aspen are the most common tree species on western biomonitoring sites followed by Scouler's willow, red alder, and Jeffrey pine (Table II). Associated shrub species that are widely sampled include snowberry, ninebark, huckleberry, and elderberry. A few of the species, like California black oak and Pacific ninebark, are limited in their range and not sampled very often, while others like skunk bush and evening primrose may not be useful as bioindicators either because they are scarce or difficult to identify under field conditions. Recent fumigation studies funded by FHM confirmed ozone specific foliar injury symptoms on Scouler's willow, trembling aspen, red alder, Pacific ninebark, skunk bush, snowberry, and blue elderberry (Temple 2000). In this same study, ozone specific injury symptoms were not confirmed on Rubus parviflorus and Prunus virginiana, two species thought to be potentially useful bioindicators based on earlier reports (Brace 1996, Mavity et al. 1995). Unlike the eastern selection of bioindicators, only a portion of the western species are well tested under natural conditions of ozone exposure. FHM biomonitoring provides a significant contribution to this research need as both field crews and regional experts cooperating with FHM gain experience with the western bioindicator species.

3.2 Northeast Regional Findings

Summary values for ozone air quality for the years 1996 through 1999 indicate that the SUM06 ozone exposure values were highest in the Mid-Atlantic subregion followed by the North-Central, New England, and Lake States subregions (Table III). On a subregional basis there is no consistent pattern of increasing or decreasing Sum06 mean values over the four-year measurement period (data not shown). However, most states outside the relatively clean Lake States subregion did obtain maximum mean values in 1999, as is reflected in the range of maximum ozone exposure values reported for each subregion. According to NESCAUM (http://www.nescaum.org) and the EPA, exceptionally high ambient ozone concentrations were recorded during the 1999 growing season, particularly along the heavily urbanized Northeast corridor.

Summary findings from the FHM biomonitoring plots tend to correlate with the ambient air quality data. For example, over the five year period from 1996 to 2000, the percentage of plants with higher average severity ratings was greater in the high ozone zones of the Mid-Atlantic and North-Central states than in the intermediate ozone zone characteristic of the New England states, and low ozone zone characteristic of the Lake States (Table IV). Regardless of subregion, most plants of ozone sensitive species remained uninjured and only a very small percentage expressed severe foliar injury (category 5). This is in agreement with other field studies 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 (Skelly et al. 1987, Treshow and Stewart 1973). Large variation in visible injury response is also expected under natural conditions due to differences in ozone sensitivity controlled by genotype and micro-site conditions of growth, exposure, and ozone flux (Heck 1968, McCool 1998, Reich 1987).

Similar to the severity ratings, the biosite index for the years 1996, 1997, and 1998 mimicked the ambient air quality data as injury values were consistently highest in the Mid-

Atlantic and North-Central subregions and relatively low in the cleaner New England and Lake States subregions (Table V). In contrast, the 1999 biosite index for three of the four subregions dropped to the lowest value over the four year period despite the region-wide high ozone values. Growing season precipitation in 1999 was one of the lowest on record across much of the eastern region, except in the Lake States. Similarly, the Palmer Drought Severity Index fell into negative values over the same time period, indicating mild to severe drought conditions over much of the eastwide sampling area. The low bioindicator response values in 1999 suggest that even the most sensitive genotypes of known bioindicator plants will be protected from ozone stress under drought conditions. Similar results were reported from a two-year field survey on ozone foliar injury conducted in Ohio and Indiana (Showman 1991). Ozone levels were very high in 1988, but little injury was observed. In 1989, ozone concentrations were lower, but injury was much greater. Rainfall was much less in 1988 than in 1989 when drought conditions prevailed throughout most of the spring and summer.

Interpretation of the seasonal biosite index values within the context of corresponding regional data on ozone air quality and soil moisture availability revealed a complex relationship (Figure 2). Elevated ozone exposure, by itself, did not result in high levels of foliar injury. Only when PDSI was above normal (i.e., >0) did elevated ozone exposure result in an increase in the biosite index. Seventy percent of the variability in BI was explained by SUM06 and PDSI and the linear model was significant ($p<0.001$). Both explanatory variables were also significant in the model with SUM06 having a slightly greater contribution ($p<0.001$; std. coef.=0.73) than PDSI ($p=0.003$; std.coef.=0.549).

These findings demonstrate that FHM biomonitoring data can provide a biologically meaningful indication of the stress imposed on our forests by elevated ozone concentrations, as individual plants integrate and respond to the combination of environmental influences that determine ozone flux. One of the principle values of the biomonitoring data is that the foliar injury record reflects not how high ambient ozone levels are, but how significant those levels are to the exposed plants. Ozone cannot injure plants or affect physiological disruption in individual trees or whole ecosystems unless it can pass through the open stomates of an actively photosynthesizing plant (Krupa and Manning 1988). This is not the case during periods of prolonged drought when most plants reduce stomatal aperture and become physiologically inactive in an attempt to minimize water loss. Although plants may develop fewer ozone injury symptoms under drought stress, experimental evidence suggests that some plants may be even more susceptible to ozone when that drought stress has been relieved (Greitner et al. 1994), an observation that needs testing under field conditions.

Clearly, the FHM biosite index for ozone stress is highly responsive to ozone flux. Although the relationship between ozone uptake and stomatal aperture has been demonstrated repeatedly under controlled conditions, this is the first large-scale field study where the influence of moisture on ozone flux has been clearly demonstrated. This type of information must be integrated into scientific models of ozone air quality and forest health if ecological impacts are to be fully described and understood. By the same token, the FHM biomonitoring program provides a unique resource of plant response data from the natural environment that should prove invaluable to the development of biologically meaningful air quality standards to protect the forest resource.

3.3 Formative Analyses

FHM biomonitoring data also provides informative regional statistics. A region-wide assessment of ozone <u>relative</u> air quality using the FHM biomonitoring data is presented in Figure 3. Plot-level biosite values were averaged over the six-year time period from 1994 through 1999. Kriging procedures were then used to interpolate a surface of biological response data across the northeast (Figure 3). The color-based interpretation of ozone relative air quality is based on categorizations used by EPA to convey cautionary messages of human health effects (http://www.eps.gov/airnow/factsht.html). In this case, the cautionary message in intended for a plant rather than a human interface (Table VI). A similar approach could be used to look at relative air quality across eco-regions or forest types. FHM intends to use consecutive five-year periods (e.g., 1994-1998; 1999-2003) with variable ozone levels, weather, wind flow, and precipitation patterns to examine regional trends in ozone air quality over the long-term.

FHM also has an interest in applying the ozone biomonitoring data to risk assessment analyses for ozone sensitive tree species like black cherry, or to examine impacts on species like milkweed that are closely linked to the welfare of the Monarch butterfly. Accordingly, the biosite data were categorized into four levels of risk defined here in terms of the relative risk of tree-level or ecosystem-level disturbance to the forest resource from ambient ozone exposure (Table VI). The same kriging procedures described above were used in risk-based analyses to interpolate a surface of probable ozone injury to plants. A geographic analysis was then used to locate where ozone sensitive species were likely to be at risk. A comprehensive study of the Mid-Atlantic region using this approach has been completed and will be reported in a separate publication (Coulston et al. 2002). These types of analyses can identify localized areas where ozone effects on specific tree species require a more intensive evaluation of injury and growth response.

4. Summary and Conclusions

FHM has made a commitment to monitoring indicators of forest heath and air quality in order to accurately report on the condition of our nation's forests and possible threats to sustainable forest management. The ozone biomonitoring program allows FHM to quantify regional trends in ozone stress in terms of significant changes in the number and distribution of plots with ozone injury and increases or decreases in the biosite index. The biomonitoring approach has been used repeatedly and successfully in other smaller scale field studies (Chappelka 1997, Hildebrand et al. 1996, Kohut et al. 1997, Neufeld et al. 1992, Pronos and Vogler 1981) to assess pollutant stress. What is new and significant about the FHM network is its national scope and the successful implementation of national standards for training, field procedures, and quality assurance (Lewis and Conkling 1994).

The findings reported in this paper focus on the field measurements collected across the northeast from 1996 through 2000. The results show a strong regional correlation between biomonitoring data and air quality data from physical ozone monitors. In any year, there is a higher percentage of ozone injured plants with more severe symptoms in areas with relatively high ozone concentrations than in areas with relatively low ozone. The findings also demonstrate a marked disparity between biomonitoring data and air quality data during dry years. This suggests that biomonitoring data provide a more accurate indication of ozone stress, or the lack of it, than air quality data alone. The FHM biosite index fluctuates from one year to the next in response to very real differences in ozone injury conditions on the biomonitoring plots. In this sense, the biomonitoring data provide meaningful evidence of when periods of high ozone concentration, during the growing season, have potential biological significance.

The response of bioindicator plants to ozone depends on a combination of environmental factors, plant properties, and exposure characteristics that foster ozone uptake and foliar injury (Krupa and Manning 1988). In this context, the FHM plot data from this national program may be used to characterize the percent of our nation's forests subjected to phytotoxic levels of ozone pollution across a region or forest type. However, just as data from physical monitors has obvious limitations to our scientific understanding of air quality and forest health, so too does the biomonitoring data. FHM data cannot be used to quantitatively assess air quality or be used alone to make definitive statements about forest health. As emphasized by Chappelka and Samuleson (1998), natural systems are highly variable and any attempt to assess ozone impacts on forests must account for this variability as well as the relative influences of insect pests, biotic pathogens, and a multitude of edaphic and climatic factors. Taken together with genetic and environmental factors, the biomonitoring data is an additional important database for modelers to use to improve ozone exposure/tree response information in forest growth, productivity, and biodiversity models.

Finally, the biomonitoring program also has value in that priorities for establishing air quality monitoring sites can be rationalized and better account for biological factors. Federal and state air quality planners and policy makers responsible for establishing ambient air quality standards will have information from a coherent, national, quality-assured database that was entirely lacking in previous deliberations. The scientific research community will have a better database for assessing assumptions about ecosystem response to ambient ozone exposure and will be able to more tightly focus on critical modeling questions. Hopefully, this information will also be used to direct funding to basic and applied research efforts needed to answer basic questions raised by the findings of the FHM program.

Acknowledgements

Dr Smith wishes to acknowledge Dr Robert Brooks, USDA Forest Service, for his support and encouragement during the writing of this manuscript and his help with data analysis. The authors wish to thank the many State Forest Health Specialists who work in partnership with the USDA Forest Health Monitoring program to produce a quality, nationwide biomonitoring program. This work is funded wholly or in part by the USDA Forest Service,

the US Environmental Protection Agency, the US Department of the Interior Bureau of Land Management, and the National Association of State Foresters. As of the 2001 field season, the USDA Forest Service, Forest Inventory and Analysis program (FIA) has assumed primary responsibility for administration of the ozone biomonitoring program. A new national grid has been developed and may be reviewed at http://fia.fs.fed.us. Data archives may be accessed at http://www.na.fs.fed.us/spfo/fhm/index.htm.

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Title: A national ozone biomonitoring program – results from field surveys of ozone sensitive plants in northeastern forests (1994 – 2000)

Figure Captions – EMAS 1210

Fig.1. The national distribution of ozone biomonitoring sites in the Forest Health Monitoring program in 2000. Red circles indicate sites where ozone-induced foliar injury was detected on sensitive plants. Green circles indicate no injury and open circles indicate sites that were not measured in 2000.

Fig.2. The relationship among ozone-induced foliar injury to bioindicator species (Biosite Index), ambient ozone exposures (SUM06) and soil moisture availability (PDSI) in the Northeast.

Fig.3. Plant health risk from ozone exposure in the Northeast and North Central states. Categories represent (1) relatively good ozone air quality, (2) moderate air quality, (3) air quality that is unhealthy for the most ozone-sensitive species, and (4) air quality that is unhealthy for all or most ozone-sensitive species. In terms of bioindicator response, green areas represent little or no injury to bioindicator plant species, yellow areas represent light to moderate foliar injury, orange areas represent moderate to severe injury, and red areas represent severe foliar injury to ozone-sensitive species. See text for details on spatial interpolation techniques.

TABLE I

List of eastern bioindicator species and numbers of evaluated plants by species for the 2000 field season.

Scientific name	Common name	Plants evaluated
Asclepias spp.	common and tall milkweed	10,211
Prunus serotina	black cherry	7,275
Rubus allegheniensis	blackberry	7,084
Apocynum androsaemifolium	spreading dogbane	5,212
Fraxinus americana	white ash	4,720
Sassafras albidum	sassafras	2,657
Liriodendron tulipifera	yellow poplar	1,743
Aster macrophylum	big-leaf aster	1,159
Liquidambar styraciflua	sweetgum	1,115
Prunus pensylvanica	pin cherry	530

TABLE II

List of western bioindicator species and numbers of evaluated plants by species for the 2000 field season.

Scientific name	Common name	Plants evaluated
Symphoricarpos oreaphilus[1]	mountain snowberry	2,104
Populus tremuloides	quaking aspen	1,541
Pinus ponderosa[2]	ponderosa pine	1,339
Salix scouleriana	Scouler's willow	465
Physocarpus malvaceus	ninebark	327
Vaccinium membranaceum	huckleberry	322
Sambucus racemosa	red elderberry	309
Alnus rubra	red alder	292
Sambucus mexicana	blue elderberry	266
Pinus jeffrey	Jeffrey pine	247
Artemesia ludoviciana	western wormwood	120
Artemesia douglasiana	mugwort	120
Physocarpus capitatus	pacific ninebark	90
Rhus trilobata	skunk bush	47
Quercus kellogii[3]	California black oak	43
Oenothera elata	evening primrose	0

[1] Symphoricarpos spp. also included.
[2] Pinus ponderosa var. scopulorum in interior states; var.ponderosa in coastal states.
[3] Quercus kellogi is no longer on the western bioindicator species list.

TABLE III

Summary ozone air quality statistics for the different subregions in the FHM sampling area.

Subregion[1]	Range of maximum ozone exposure values (SUM06)[2] 1996	1997	1998	1999	Mean value[3] 1996-1999
Lake States	7.39 – 33.56	11.30 – 33.76	5.09 – 29.58	9.12 – 28.13	8.82
New England	11.89 – 20.71	14.26 – 29.85	11.87 – 27.42	16.50 – 31.86	12.17
North Central	36.19 – 44.35	28.34 – 31.96	31.22 – 36.05	37.74 – 46.33	20.44
Mid-Atlantic	29.30 – 41.56	30.95 – 45.58	36.53 – 50.34	41.14 – 48.55	29.49

[1] Subregions are defined as follows: Lake States = MI, MN, WI; New England = CT, ME, MA, NH, RI, VT; North Central = IL, IN, IA, MO; Mid-Atlantic = DE, MD, OH, NJ, PA, WV.

[2] SUM06 = Sum of the hourly ozone concentrations ≥ 0.06 ppm. Maximum values were calculated by state and year for each subregion.

[3] Mean values were calculated for each subregion based on spatially interpolated SUM06 exposures. See text for details.

TABLE IV

Number of biomonitoring sites evaluated for ozone-induced foliar symptoms, number of plants sampled, and percent of sampled plants in each injury severity category by year and subregion in the northeastern area.

Subregion and year[1]	No. of plots evaluated	No. of plants sampled	Injury Severity Categories[2]					
			0	1	2	3	4	5
			Percent of sampled plants					
Lake States								
1996	95	3,880	99	1	<1	<1	0	0
1997	104	4,584	99	1	<1	<1	0	<1
1998	160	9,012	97	2	1	<1	<1	<1
1999	143	10,949	97	2	1	<1	<1	<1
2000	160	12,647	97	2	1	<1	<1	<1
New England								
1996	92	4,245	89	5	4	2	<1	<1
1997	91	4,248	93	3	3	1	<1	<1
1998	98	5,460	90	4	4	2	<1	<1
1999	96	5,057	97	1	1	<1	<1	<1
2000	87	4,850	96	2	2	<1	<1	0
North Central								
1996	8	589	67	6	7	4	7	9
1997	19	1,180	77	3	9	6	4	<1
1998	36	1,580	72	5	10	9	4	<1
1999	45	3,387	90	4	3	2	1	<1
2000	131	8,688	92	4	3	1	<1	<1
Mid-Atlantic								
1996	34	1,244	82	5	5	5	2	1
1997	60	2,908	93	2	2	2	1	<1
1998	170	6,384	78	5	7	5	3	2
1999	191	10,941	97	1	1	1	<1	<1
2000	182	12,762	93	2	2	1	1	<1

[1] Subregions are defined as follows: Lake States = MI, MN, WI; New England = CT, ME, MA, NH, RI, VT; North Central = IL, IN, IA, MO; Mid-Atlantic = DE, MD, NJ, OH, PA, WV.

[2] 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.

TABLE V

Indices of ozone air quality, bioindicator response, seasonal precipitation, and soil moisture by subregion and year.

Subregion[1] and Year	Ozone SUM06 (ppm-hrs)[2]	Biosite index[3]	Seasonal precipitation (% normal)	PDSI[4]
Lake States				
1996	7.72	0.05	98	1.69
1997	10.62	0.02	103	0.92
1998	7.60	0.14	94	-0.20
1999	9.33	0.12	119	1.29
New England				
1996	9.83	0.94	105	2.69
1997	11.72	0.69	94	0.54
1998	11.22	1.32	124	1.79
1999	14.54	0.50	65	-1.97
North Central				
1996	29.98	8.11	102	2.58
1997	19.65	3.22	99	0.93
1998	20.37	3.91	139	2.15
1999	21.91	0.72	85	-0.58
Mid-Atlantic				
1996	26.34	3.49	132	3.05
1997	23.08	1.23	93	0.97
1998	29.80	3.21	96	0.26
1999	31.44	0.82	73	-2.83

[1] Subregions are defined as follows: Lake States = MI, MN, WI; New England = CT, ME, MA, NH, RI, VT; North Central = IL, IN, IA, MO; Mid-Atlantic = DE, MD, OH, NJ, PA, WV.

[2] SUM06 = Sum of the hourly ozone concentrations ≥ 0.06 ppm; seasonal mean values were calculated by state and year.

[3] See text for formulation of the biosite index; mean values were calculated by state and year.

[4] PDSI = Palmer drought severity index; seasonal mean values were calculated by state and year.

TABLE VI

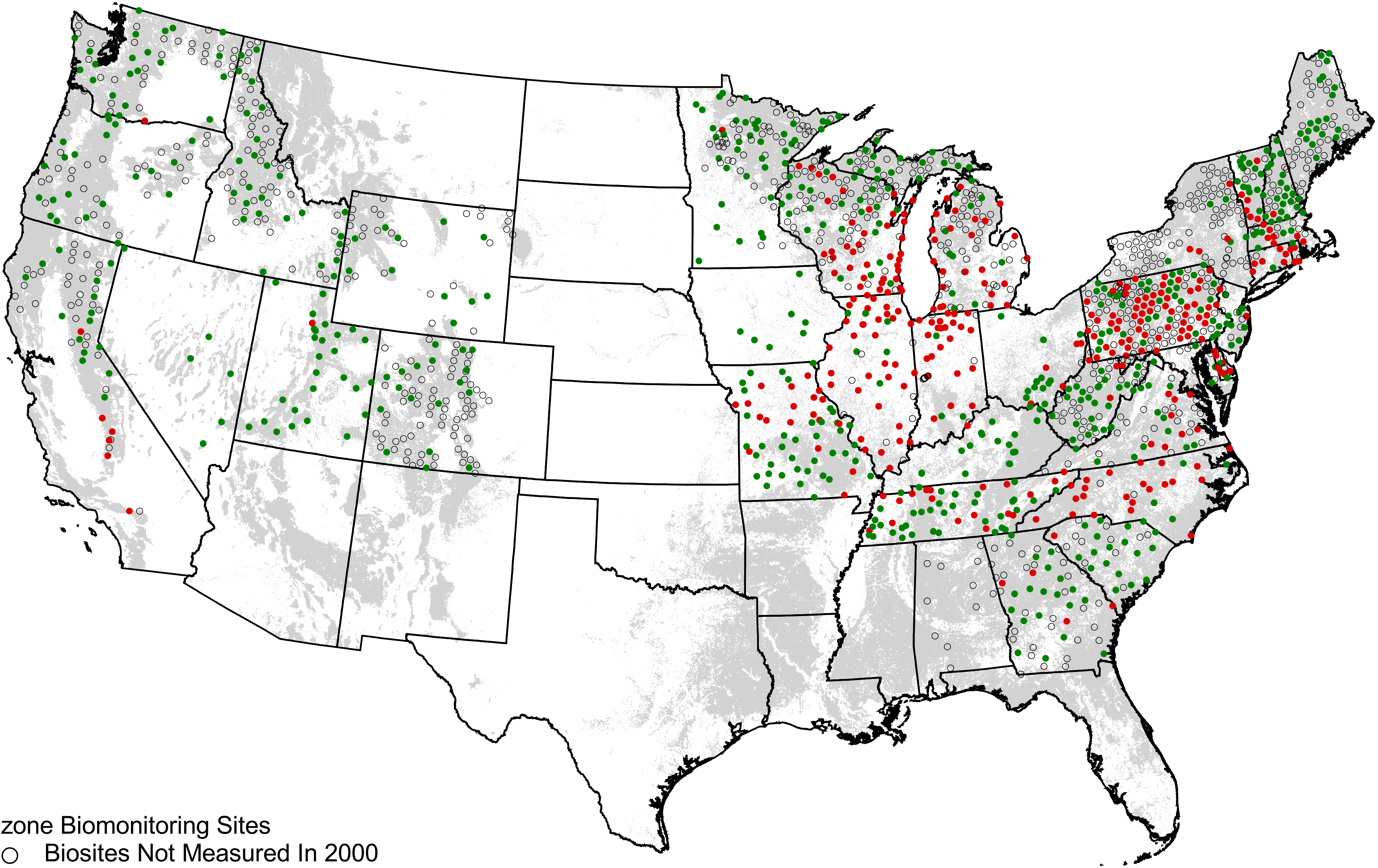
Classification scheme for the FHM biosite index[1].

Biosite value	Bioindicator response	Assumption of risk	Possible impact	Relative air quality[2]
0 to 4.9	Little or no foliar injury	None	Visible injury to highly sensitive species, e.g. black cherry	Good
5.0 to 14.9	Light to moderate foliar injury	Low	Visible injury to moderately sensitive species, e.g. tulip poplar	Moderate
15.0 to 24.9	Moderate to severe foliar injury	Moderate	Visible and invisible injury. Tree-level response.[3]	Unhealthy for sensitive species
≥ 25	Severe foliar injury	High	Visible and invisible injury. Ecosystem-level response.[3]	Unhealthy

[1] See text for formulation of the biosite index. The categorizations of the biosite index are subjective and based solely on the first author's opinion.

[2] Relative ozone air quality from a plant's perspective. See reference in text: www.eps.gov/airnow/factsht.html.

[3] According to the EPA's Proposed Guidelines for Ecological Risk Assessment (Federal Register 61 (175):47552-47631).

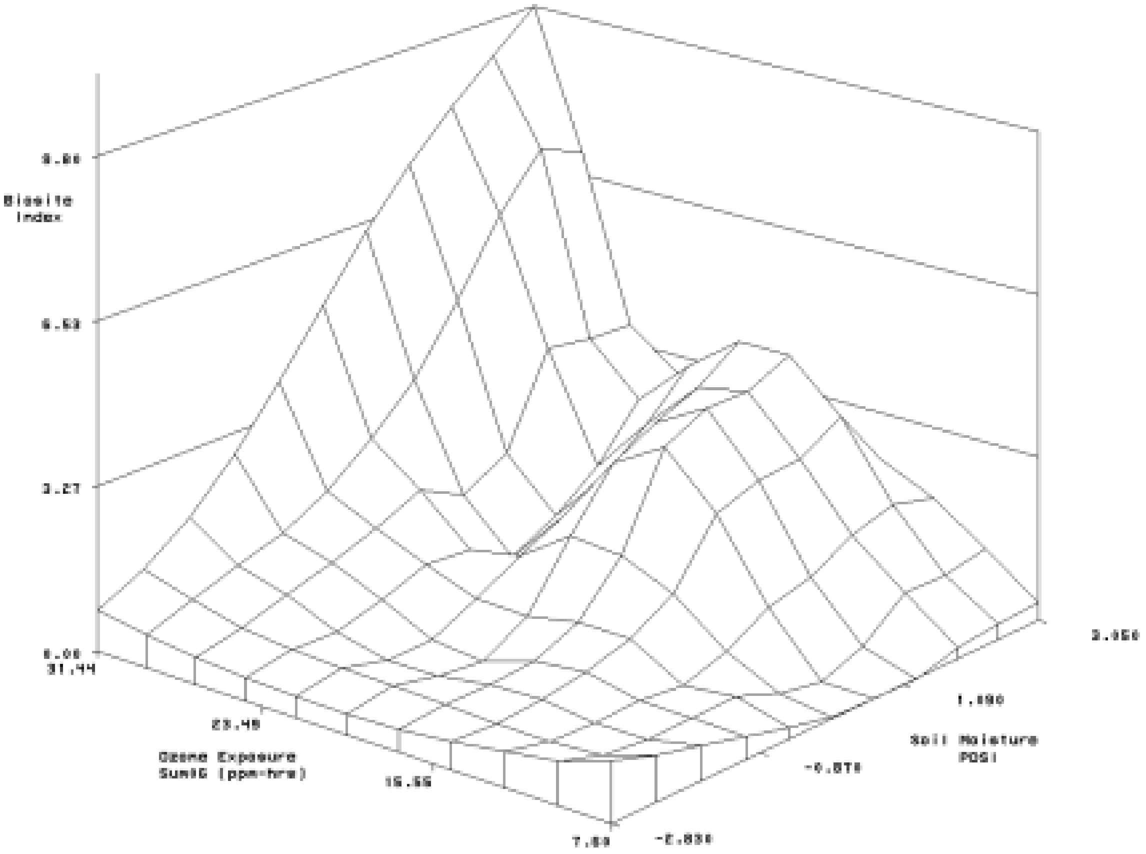


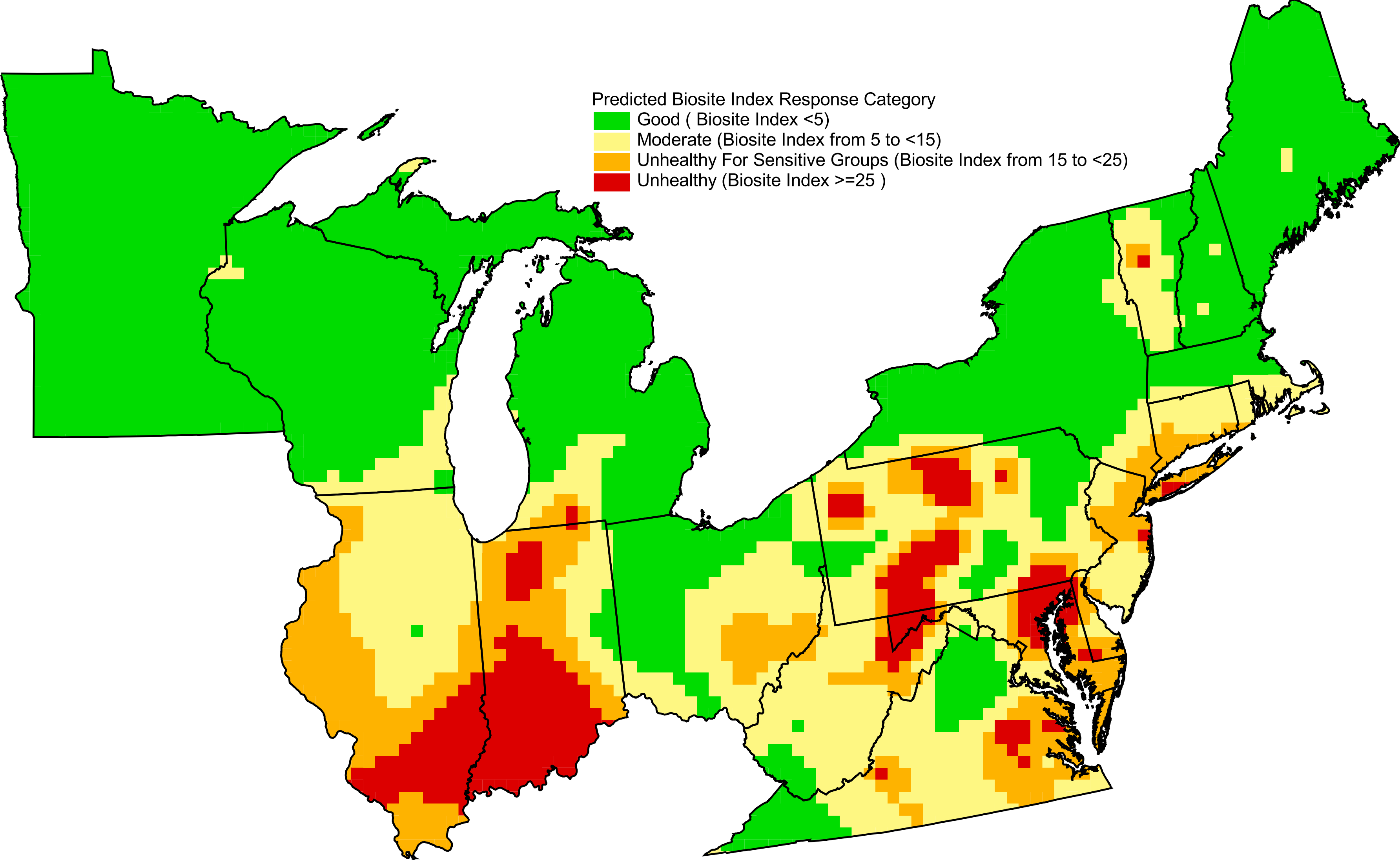
Ozone Biomonitoring Sites

○ Biosites Not Measured In 2000

● Biosites Measured In 2000 And No Ozone Injury Recorded

● Biosites Measured In 2000 And Ozone Injury Recorded


9.80
Biosite
Index
6.53
3.27
0.00
31.44
23.48
Ozone Exposure
SUM06 (ppm-hrs)
15.56
7.60
-2.834
-0.878
1.090
Soil Moisture
PDSI
3.056


Predicted Biosite Index Response Category
🟩 Good (Biosite Index <5)
🟨 Moderate (Biosite Index from 5 to <15)
🟧 Unhealthy For Sensitive Groups (Biosite Index from 15 to <25)
🟥 Unhealthy (Biosite Index >=25)