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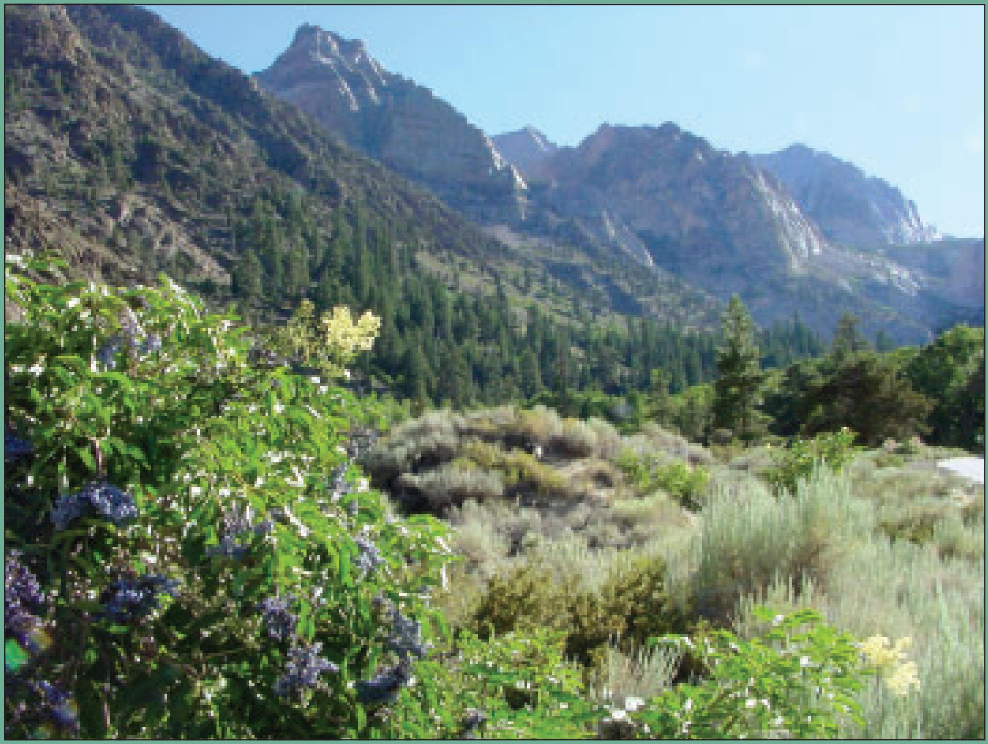
Ozone Injury in West Coast Forests: 6 Years of Monitoring

Sally J. Campbell, Ron Wanek, and John W. Coulston



Authors

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Abstract

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Six years of monitoring for ozone injury by the Pacific Northwest Research Station Forest Inventory and Analysis Program are reported. The methods used to evaluate injury, compute an injury index, and estimate risk are described. Extensive injury was detected on ozone biomonitoring sites for all years in California, with ponderosa and Jeffrey pines, mugwort, skunkbush, and blue elderberry showing injury. Little or no injury was detected in Oregon and Washington. The relation of observed injury to ambient ozone levels is discussed. The areas with the highest modeled risk of ozone injury are the areas east of Los Angeles, the southern Sierra Nevada, and portions of the central coast.

Keywords: Ozone, biomonitoring, indicator species, California, Oregon, Washington, forest health monitoring.

Summary

Key results of ozone biomonitoring from 2000 through 2005 in California, Oregon, and Washington by the Pacific Northwest Research Station Forest Inventory and Analysis (FIA) Program are as follows:

- Ozone injury occurs frequently (25 to 37 percent of sampled biosites) in California forested ecosystems demonstrating that ozone is present at phytotoxic levels.
- The California air basins having the highest percentage of biosites with injury were the South Coast, San Joaquin Valley, and San Diego County.
- The group of biosites in the areas with the highest ozone exposures (SUM60[1] ≥25,000 parts per billion) had corresponding highest mean percentage of injured biosites (52 percent) and highest mean biosite index (16.4).
- In 2005, new areas (previously unreported) of ozone injury were detected in northern California (Trinity, Plumas, and Lassen Counties) as well as in the Mojave Desert area (San Bernadino County).
- Although ozone exposure is moderate to high over much of California, forested areas with the highest risk were estimated (via our plant response

[1] SUM60 is the sum of all hourly ozone concentrations equal to or exceeding 60 parts per billion between 8 am and 8 pm for a certain period—in our case between June 1 and August 31.

model) for the area east of Los Angeles, the southern Sierra Nevada, and portions of the central coast.
- In California, an estimated 1.3 million acres of forest land and 596 million cubic feet of wood are at moderate to high risk to impacts from ozone.
- Despite reports of increasing ozone production and exposure in Oregon and Washington, ozone injury was observed only in the Columbia Gorge.
- Air quality as indicated by the FIA ozone bioindicator shows no consistent pattern of increases or decreases in any of the three states between 2000 and 2005. More years of data are needed to discern any trends.

Contents

Introduction

Tropospheric ozone and other air contaminants are stressors that affect long-term sustainability of temperate forests throughout the world (Chappelka and Chevone 1992, Smith 1985, USDA Forest Service 1997, US EPA 1996b). Ozone has such critical effects that it is included as one of the air quality indicators under the Forest Ecosystem Health and Vitality criterion in the Montreal Process Criteria and Indicators for the Conservation and Management of Temperate and Boreal Forests (Montreal Process 1995). In the United States, ozone is the only regional gaseous air pollutant that has been measured at known phytotoxic levels at numerous remote locations across the continent (Cleveland and Graedel 1979, Lefohn and Pinkerton 1988, Miller et al. 1997). Ozone injury to forest species in the United States has been observed and documented since the 1950s. Although high ozone concentrations (and injury) have been more widespread in the East (Chapellka and Samuelson 1998, Cleveland and Graedel 1979), portions of California have had some of the highest recorded concentrations of ozone in the United States (Bytnerowicz et al. 2003, Carroll et al. 2003) (fig. 1).

Ozone and Forest Health in the Western United States

The adverse effects of ozone on forest health was first reported in the West in California in the 1950s (Parmeter et al. 1962). A peculiar discoloration of the needles of ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.) was observed on the west-facing slopes and ridges of the San Bernardino Mountains east of Los Angeles (figs. 2 and 3). Needles of these pines developed yellow (chlorotic) mottling, becoming necrotic and abscising prematurely. Subsequent experimentation confirmed that the causal agent of the foliar injury to pines and other vegetation was exposure to high concentrations of ambient ozone originating in the urban Los Angeles area (Miller et al. 1963). Later, in the 1970s, ozone injury was reported on ponderosa, Jeffrey (*Pinus jeffreyi* Grev. & Balf.) and other pines on the western slopes of the southern Sierra Nevada and the south coast, southeast desert, San Joaquin, north central coast, San Francisco Bay, and San Diego air basins (Miller and Millecan 1971, Pronos et al. 1978) (fig. 4).

The response of western trees to ozone pollution is dependent both on the tree species and atmospheric ozone concentrations (Miller and Millecan 1971; Miller et al. 1983, 1997). Certain forest species, such as ponderosa pine, are sensitive to ozone at concentrations that normally occur over wide areas of the western landscape (Miller 1996, US EPA 1996b). Because of the long lifespan of trees, there is

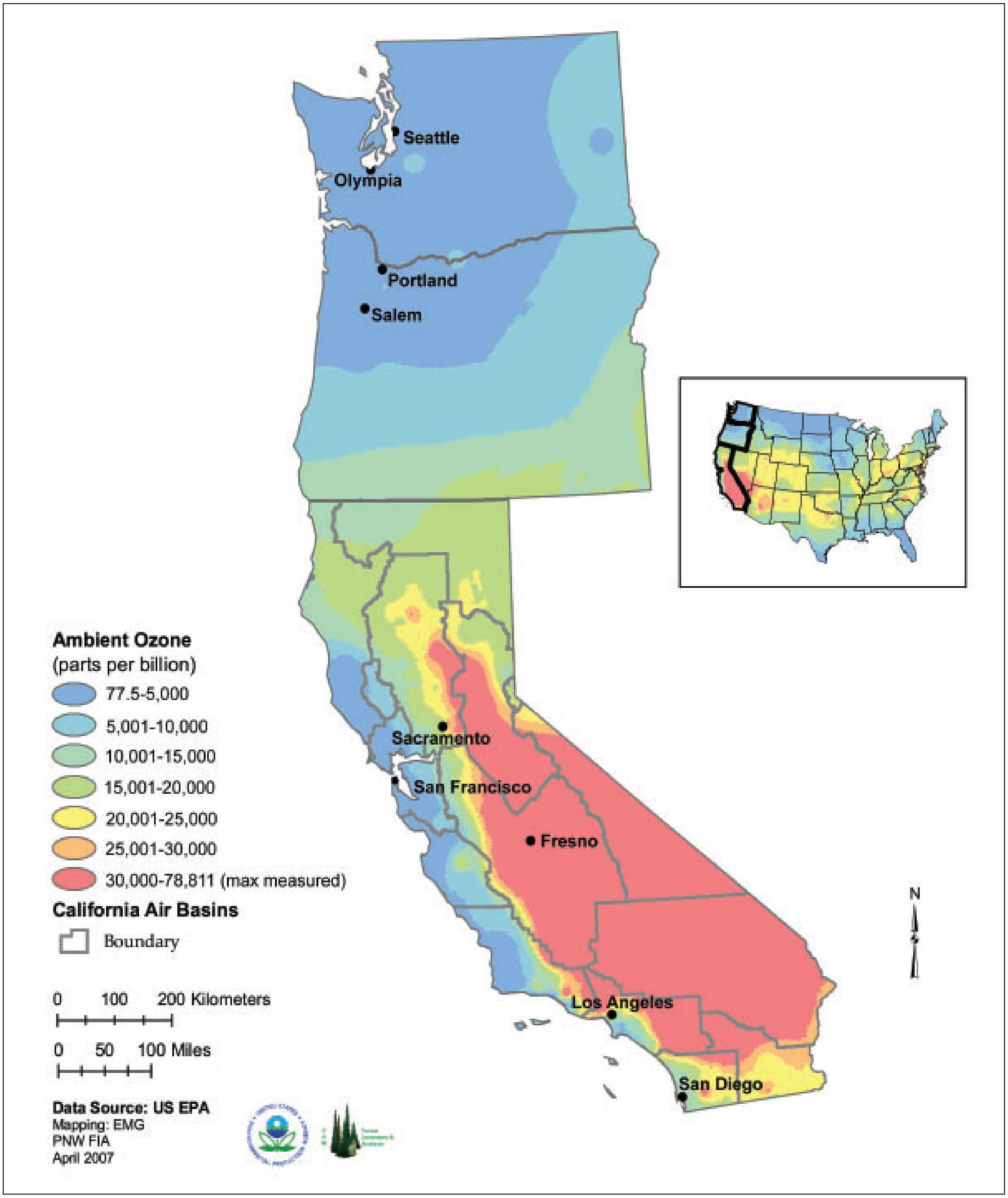

Figure 1—Cumulative hourly ozone concentrations exceeding 60 parts per billion (SUM60), June 1–August 31, 8 a.m. to 8 p.m., 2001 through 2005 average. For more information on exposure estimation, see appendix 2.

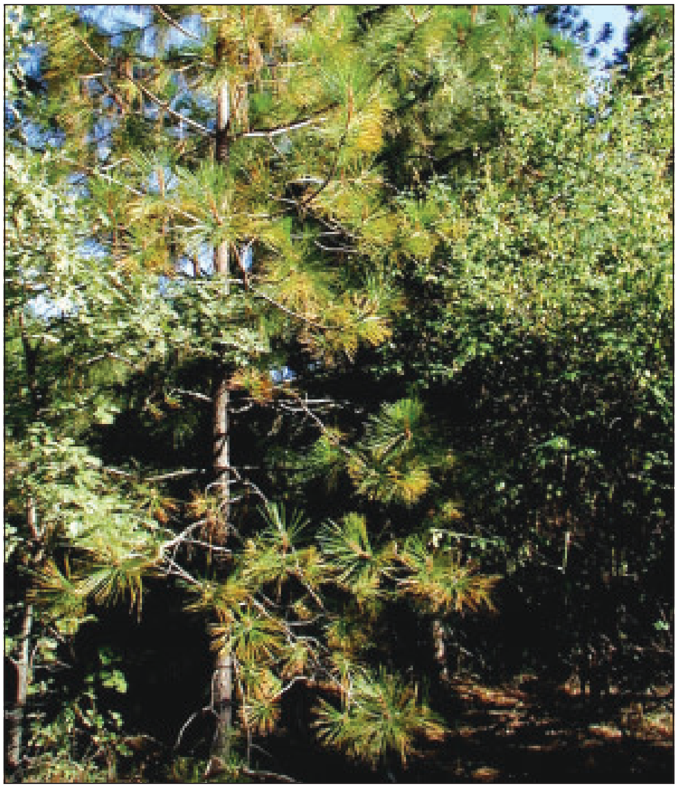
Dan Duriscoe

Figure 2—Ponderosa pine with ozone-induced needle loss and discoloration.


John Pronos

Figure 3—Ponderosa pine with severe ozone injury symptoms (chlortic mottle), California.

Figure 4—California air basins.

ample opportunity for a long-term, cumulative effect on tree growth. Ozone has been implicated in the growth decline of pollution-sensitive tree species in the Eastern United States (Benoit et al. 1982, Chappelka and Samuelson 1998, Karnosky 1981) and in pines in California (McBride et al. 1975, Miller et al. 1997, Peterson et al. 1991). The amount of injury expressed by individuals of ozone-susceptible species is a function of more than atmospheric ozone concentrations; it is also related to tree age and size; site factors such as elevation, aspect, topography, temperature, and soil moisture; and genotypic and phenotypic characteristics that influence ozone uptake by the plant (Arbaugh et al. 1998, Miller et al. 1997, Musselman and Massman 1999, US EPA 2006).

Ozone also has a variety of ecological effects on forested landscapes, with the potential to alter species composition, soil moisture, and fire regimes and influence pest interactions (McBride and Laven 1999; Miller et al. 1982; Smith 1974; Treshow and Stewart 1973; US EPA 1996b, 2006). Ozone predisposes trees to bark beetle (*Dendroctonus* spp.) attacks, especially where ozone exposure is high (Pronos et al. 1999). In the highly impacted San Bernadino Mountain forests, reduction of fine-root mass and carbon cycling at both the tree and ecosystem levels has been attributed to ozone exposure (Fenn et al. 2003, Grulke et al. 1998). Arbaugh et al. (2003) reported shifts in mixed-conifer stand composition in the San Bernadino Mountains from predominantly ponderosa pine to predominantly white fir (*Abies concolor* (Gord. & Glend.) Lindley ex Hildebr.). Similarly, simulations of the physiological and ecological responses of ponderosa pine and white fir to elevated ozone exposure in conifer forests in California showed a decrease in individual tree carbon budgets as well as a subsequent decrease in abundance of ponderosa pine (Weinstein et al. 2005).

Monitoring for ozone-induced plant injury (biomonitoring) has been carried out for almost 30 years in California forests, primarily on pines (Dale 1996, Dursicoe 1990, Guthry et al. 1993, Miller 1996, Miller et al. 1989, Pronos and Vogler 1981, Pronos et al. 1978) and to a limited extent on other vegetation (Duriscoe and Temple 1996; Temple 1989, 1999). Consistent with ambient ozone levels (fig. 1), the greatest amount of ozone injury to western forests continues to be observed in the mountains east of Los Angeles, California, with foliar injury, premature defoliation, and growth loss commonly observed on ponderosa and Jeffrey pines. Injury also has been reported in this area on other tree species such as bigcone Douglas-fir (*Pseudotsuga macrocarpa* (Vasey) Mayr) (Peterson et al. 1995) and California black oak (*Quercus kelloggii* Newb.) (Miller 1996) and on understory plants such as blue elderberry (*Sambucus mexicana* Presl.), artemisia species (*Artemisia* spp.), evening primrose (*Oenothera elata* Kunth.), and others (Temple 1999). In the Sierra Nevada, ozone injury has been reported on ponderosa and Jeffrey pines since the 1970s and continues to be common on these species (Arbaugh et al. 1998, Carroll et al. 2003, Duriscoe 1990, Miller 1996, Pronos et al. 1978).

Elevated ozone concentrations also occur downwind of Pacific Northwest urban areas such as Vancouver, British Columbia; Seattle, Tacoma, and Vancouver, Washington; and Portland, Oregon (Bohm 1989, Brace and Peterson 1998, Cooper and Peterson 2000, Edmonds and Basabe 1989, Fenn et al. 2005). Visible injury or other effects on tree health have not been observed, however, in forests in these areas (Campbell et al. 2000, Duriscoe and Temple 1996, USDI NPS 2006).

Ozone, Forest Health Monitoring, and Forest Inventory and Analysis

In the 1990s, the Forest Health Monitoring (FHM) Program, begun as a partnership between the U.S. Environmental Protection Agency and the USDA Forest Service, began measuring a number of forest health indicators in order to assess changes in the health of U.S. forests. One of the FHM indicators was ozone injury to indicator species. In 2000, measurement of forest health indicators, including ozone injury, was transitioned from the FHM Program to the Forest Inventory and Analysis[1] (FIA) Program. The FHM/FIA biomonitoring approach observes and documents injury to susceptible conifers, hardwoods, and understory perennials annually on a network of sites (biosites) distributed across the Nation—it is likely the most comprehensive ozone biomonitoring program worldwide.

Results from the first year of FHM/FIA ozone biomonitoring in west coast states, 1998, were reported in 2000 (Campbell et al. 2000). Plant injury was detected at only one biosite in Washington and at no biosites in Oregon or California. Injury was present, however, on other ozone injury monitoring plots in the Sierra and Sequoia National Forests in California in 1997 and 1998 (measured by the Forest Service Region 5 Forest Health Protection program and reported by Campbell

[1] The FIA Program is a national USDA Forest Service research program with four regions: North, South, Intermountain, and West Coast.

et al. 2000). Since 1998, many more FIA ozone biosites have been established in these three states (fig. 5), and injury has been observed frequently and consistently at many sites in California and at one site in Washington.

This publication addresses key assessment questions posed by Smith et al. (in press) for the FIA ozone indicator, including:

- Are phototoxic concentrations of ozone present in the forest ecosystems of California, Oregon, and Washington?
- Is the air quality (e.g., ozone pollution) of the west coast states changing over time?
- If so, is it improving or deteriorating?

Additional questions are also addressed:

- Where is ozone injury the highest and most frequent?
- What is the relation, over a broad landscape, between ozone injury and ozone exposure?
- What amount of forest land and timber volume is at risk and where is it?

Methods

Biosite Locations

Each year, 70 to 132 ozone biosites per year were visited in Washington, Oregon, and California between 2000 and 2005 (table 1, figs. 5 through 9). Beginning in 2001, an ozone biosite grid was developed (fig. 10), separate from the regular FIA plot grid; biosites were more closely spaced in areas of higher potential ozone exposure and higher density of sensitive species (Smith et al. 2001). The alternate grid, not tied to the regular FIA forested plots, also provided the flexibility to search for and establish ozone plots per the biosite criteria defined by the FIA Program (USDA Forest Service 2000-2005) for access, location, size of canopy opening, bioindicator species and plant counts, soil condition, and disturbance (table 2). In west coast states, biosites are located exclusively on public lands because there is adequate distribution of public forests and, with the exception of the National Park Service, it saves the need each year to acquire landowner permission to visit each site. By 2003, almost all polygons of the new grid were populated with at least one biosite. The primary reason for not populating a polygon was not finding a biosite on public land that met the criteria in table 2.

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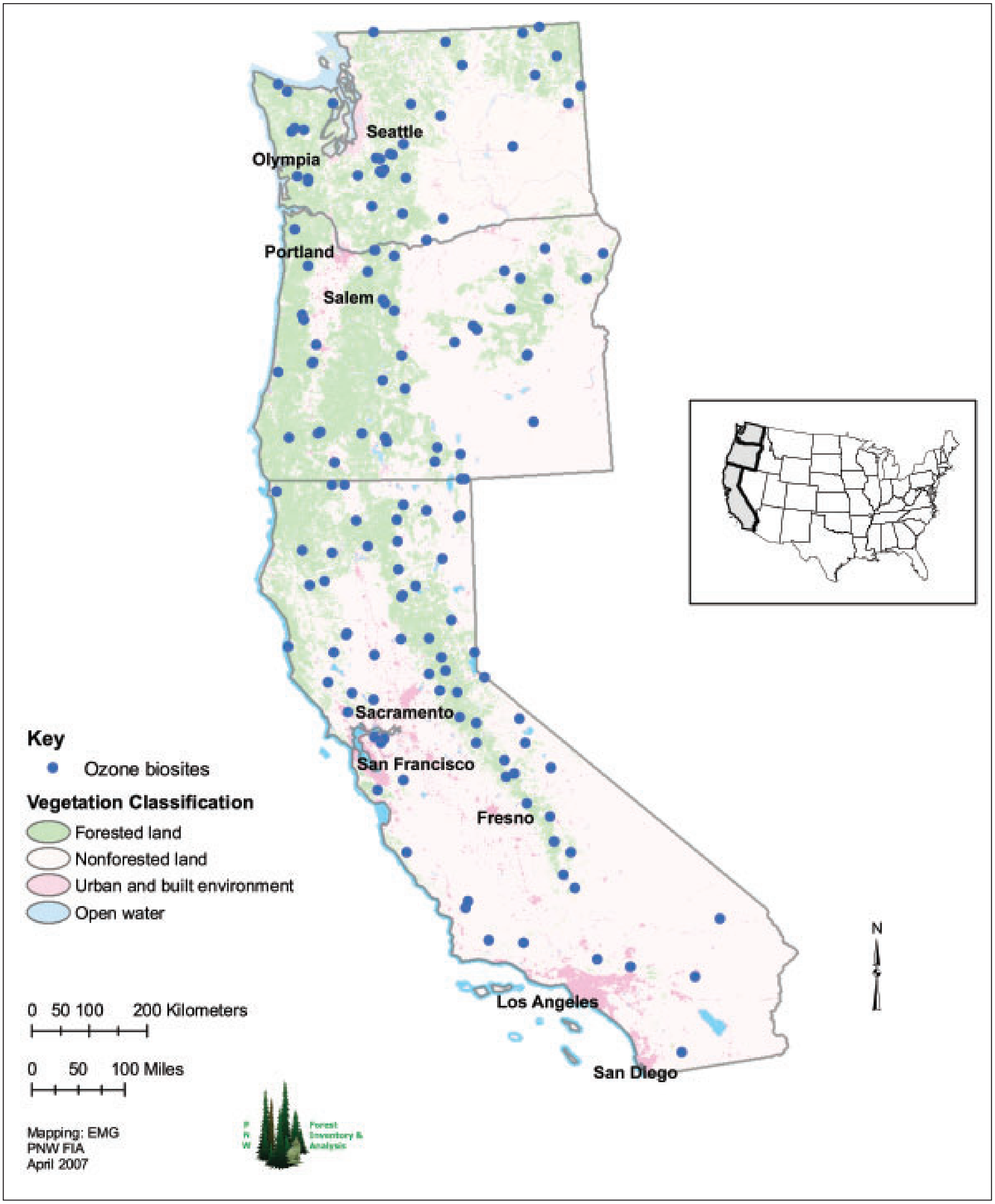

Figure 5—West Coast Forest Inventory and Analysis ozone biomonitoring sites, 2000-2005.

Table 1—Number of Forest Inventory Analysis ozone biosites by state and year

	2000	2001	2002	2003	2004	2005
California	22	29	61	65	65	65
Oregon	20	22	34	35	35	35
Washington	28	27	30	32	27	32

Dan Duriscoe

Figure 6—Central Sierra Nevada ozone biosite with trembling aspen and ponderosa pine as two of the indicator species, California.

Alan Kanaskie

Figure 7—High-elevation ozone biosite with thin-leaf huckleberry as one of the indicator species, Oregon.

Dan Duriscoe

Figure 8—Southern Sierra Nevada ozone biosite with blue elderberry as one of the indicator species (plant in foreground).

Sally Campbell

Figure 9—Ozone biosite in public park with Jeffrey pine as the indicator species, Washington.

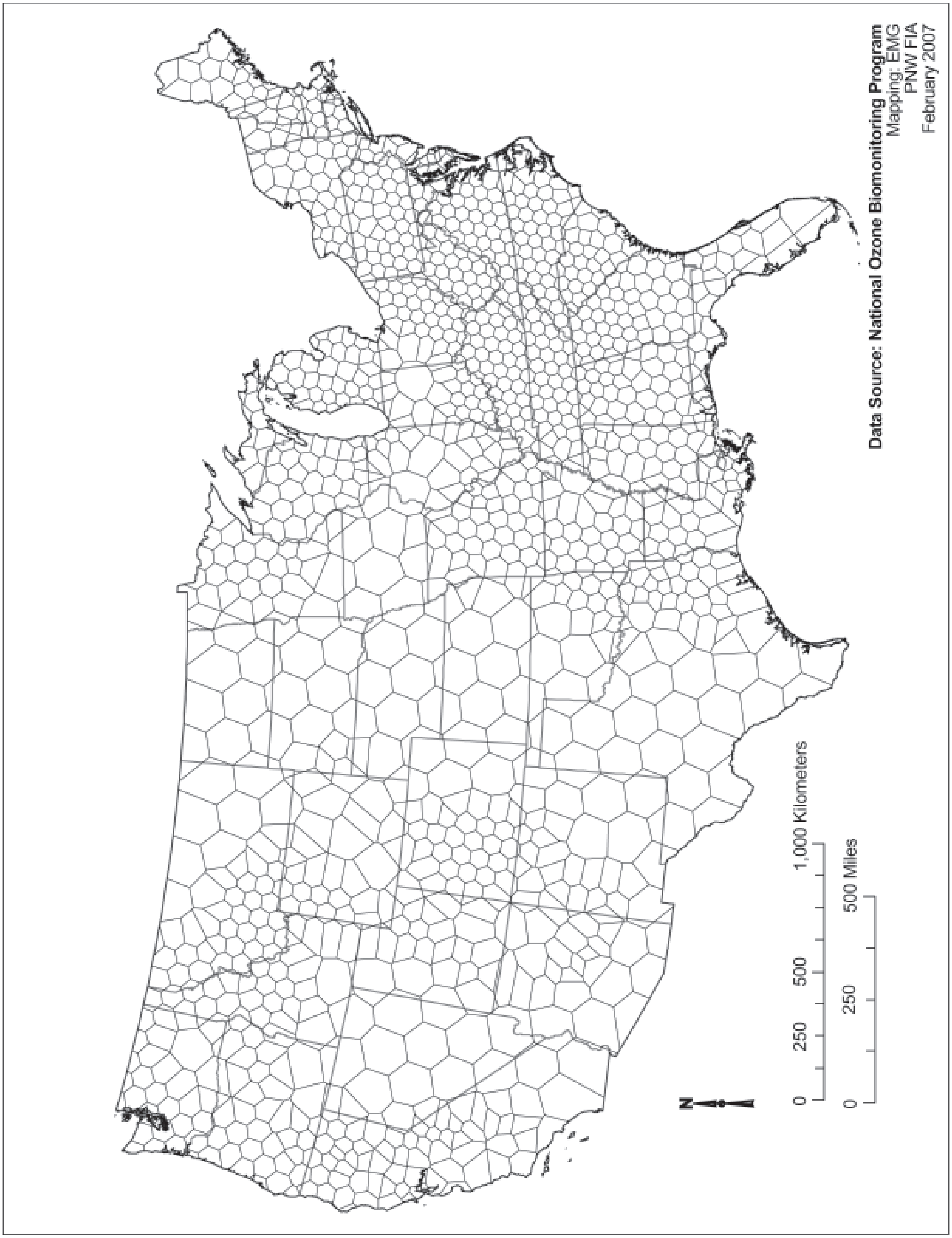

Figure 10—Forest Inventory and Analysis ozone biomonitoring grid.

Table 2—Criteria[a] used by the Forest Inventory and Analysis Program to select ozone biomonitoring sites

	First choice = best site	Second choice
Access	Easy	Easy
Location	Single location	1 or 2 locations (split-plot)
Size of opening	>1.2 ha (3 ac); wide open area; <50% crown closure	0.405 to 0.2 ha (1 to 3 ac); long, narrow, or irregularly-sized opening
Species count	>3 species	>2 species
Plant count	30 plants of 3 species; 10 to 30 plants of additional species	30 plants of 2 species; 10 to 30 plants of additional species
Soil conditions	Low drought potential; good fertility	Moderately dry; moderate fertility
Site disturbance	No recent (1 to 3 years) disturbance; no obvious soil compaction	Little or no disturbance; no obvious soil compaction

[a] Criteria have changed slightly between 2000 and 2005; see FIA ozone field protocol, 2000 through 2005 (USDA Forest Service 2000, 2001, 2002, 2003, 2004, 2005)

Bioindicator Species

Based on controlled exposure studies and field observations (Brace et al. 1996, Duriscoe and Temple 1996, Mavity et al. 1995), a list of bioindicator species was developed for the west coast states (table 3). Ozone injury data were collected at biosites each year within a 4- to 6-week period (July 15–August 30) by contract, state, or Forest Service crews. Ten to thirty plants of up to three bioindicator species at each site were rated for amount of ozone injury and severity of symptoms (fig. 11, table 4). All ozone crews were trained to select ozone biosites, identify indicator species, and measure ozone injury. Each crew was audited at least once (usually twice) per field season during 2003-2005, with a blind remeasurement by a quality assurance crew.

Validation

The FIA ozone biomonitoring protocol requires that crews (both production and quality assurance) collect vouchers of every bioindicator species exhibiting suspected ozone injury at a biosite and send specimens to an ozone expert for validation of the injury. The voucher consists of three leaves that clearly show ozone injury (for broadleaved plant species) or two small branches containing a full complement of needles showing chlorotic mottle (for pine species). For the west

Table 3—Ozone-sensitive plant species used as bioindicators for Forest Inventory and Analysis ozone biomonitoring in California, Oregon, and Washington

Common name	Scientific name
Blue elderberry	*Sambucus mexicana* Presl
California black oak[a]	*Quercus kelloggii* Newberry
Evening primrose	*Oenothera elata* Kunth.
Jeffrey pine	*Pinus jeffreyi* Grev. & Balf.
Mugwort	*Artemisia douglasiana* Bess. ex Hook.
Ninebark	*Physocarpus malvaceus* (Greene) Kuntze
Pacific ninebark[b]	*Physocarpus capitatus* (Pursh) Kuntze
Ponderosa pine	*Pinus ponderosa* P. & C. Lawson var. *ponderosa*
Quaking aspen	*Populus tremuloides* Michx.
Red alder	*Alnus rubra* Bong.
Red elderberry	*Sambucus racemosa* L.
Scouler's willow	*Salix scouleriana* Barratt ex. Hook.
Skunkbush	*Rhus trilobata* Nutt.
Snowberry	*Symphoricarpos* spp.
Western wormwood	*Artemisia ludoviciana* Nutt.
Thinleaf huckleberry	*Vaccinium membranaceum* Dougl.

[a] Dropped as bioindicator plant in 2002.

[b] This species found west of Cascades only.

Tom Iraci

Figure 11—Examination of thin-leaf huckleberry for ozone injury, Oregon.

Table 4—Ozone injury rating system for amount and for severity

Injury rating	Range	Midrange values used in calculations
	Percent	
0	0	0
1	1-6	.03
2	7-25	.16
3	26-50	.38
4	51-75	.63
5	>75	.875

Note: A rating applies to **each** of amount (percentage of the plant's leaves or needles that have ozone symptoms) and severity (average percentage of leaf or needle area with symptoms for injured foliage). Scale from USDA FS 2005.

coast states of California, Oregon, and Washington, the same expert provided validation services for vouchers from all years reported here (2000 to 2005). All positive injury results presented in this report are for validated injury as reported by production crews.

Biosite Index

A biosite index (BI) is calculated from the amount and severity of injury (table 4) recorded for each evaluated plant. The BI is a value that reflects local air quality and bioindicator response and therefore the potential risk of ozone impact in the area represented by that biosite. A BI value—the midrange values for amount times the midrange values for severity averaged for each species and then averaged across all species on the biosite—is calculated for each biosite. The BIs were then classified into four risk categories (table 5) used in the risk assessment described below. See appendix 1 for the BI formula and an example of a calculated BI for one biosite.

Exposure Analysis

The relationships between average ambient ozone and various measures of injury (BI and percentage of plots with injury) were examined. We used the 2001-2005 average ozone exposure, SUM60 (US EPA 2006), interpolated across the landscape to provide a continuous surface, which was then grouped into several different classes of exposure (fig. 1). The metric, SUM60, a common metric for ozone exposure, is the sum of all hourly ozone concentrations equal to or exceeding 60 parts per billion (ppb) between 8 a.m. and 8 p.m. for a certain period—in our case

Table 5—Biosite index categories (risk categories) and risk assumptions[a]

Biosite index	Biosite index category	Risk assumption
0 to 4.9	1 = little or no foliar injury	None. Tree-level response. Visible injury to leaves and needles.
5 to 14.9	2 = low foliar injury	Low. Tree-level response. Visible and invisible injury.
15 to 24.9	3 = moderate foliar injury	Moderate. Tree-level response. Visible and invisible injury.
≥25	4 = severe foliar injury	High. Structural and functional changes. Visible and invisible injury.

[a] Coulston et al. 2003.

between June 1 and August 31. Overlaying the exposure map with biosite locations allowed us to look at the level of exposure to which each biosite was subjected.

The FIA ozone biomonitoring program has developed an application that calculates ozone exposures by using data from the U.S. Environmental Protection Agency (EPA) Aerometric Information Retrieval System database by month and over a standard growing season (May 1-Sept. 31) and a user-defined growing season for a daylight (12-hour) and 24-hour period for a wide variety of common indices. See appendix 2 for the exposure analysis methods.

Risk Assessment

One goal of the FIA ozone biomonitoring program is to appraise the likelihood of an undesirable response of forests to ambient ozone conditions. We use a risk assessment approach that was suggested by Smith et al. (in press), demonstrated by Coulston et al. (2003), and consistent with the ecological risk assessment paradigm described by Regens (1995). Table 5 provides a quantitative description of observed plant response to ambient ozone conditions (biosite index), and a qualitative description of risk and possible impacts. However, plant injury to bioindicator species from ozone is recorded on biosites, which are generally open areas that may or may not meet the FIA requirements of forest land and use bioindicator species that may or may not be forest tree species. Therefore, to evaluate the likelihood of ozone injury to forest trees, we use spatial interpolation to extend the information collected at biosites to the forest population (Coulston et al. 2003; Smith et al., in press).

We interpolated gridded maps of the BI for each year, 2000-2005, via gradient inverse distance weighting (GIDS). The GIDS was first proposed as a way to interpolate climatic data on a broad spatial scale as input for plant growth models (Nalder and Wein 1998). The GIDS technique combines multiple linear regressions with inverse distance weighting interpolation and, like other recently developed interpolation techniques, incorporates elevation as a covariate. See appendix 3 for further details.

The six interpolated BI maps were averaged to create the final risk map (average 2000-2005 BI) (fig. 12). We then overlaid the final risk map with FIA plots. This variable (2000-2005 BI) could then be used to summarize the FIA survey data. At this point, we used the methods suggested by Bechtold and Patterson (2005) to estimate the acres of forest land and the volume of susceptible tree species in each BI risk category.

Results

With the exception of one site in Washington, ozone injury occurred only in California. The percentage of biosites with injury was relatively stable between 2000 and 2005, varying between about 25 percent in 2003 and almost 37 percent in 2001 and 2005 in California and between 0 and 4 percent in Washington (table 6). The number of plants evaluated increased each year as more biosites were added and as crews located additional species on the biosite or replaced existing biosites that had low species or plant counts with ones that had more species or plants (table 7). The Washington biosite with positive injury is located within the Columbia Gorge, east and downwind of Portland, Oregon, and Vancouver, Washington. The injured species is offsite (planted) Jeffrey pine in an irrigated setting. In California, five species exhibited validated ozone injury: blue elderberry, Jeffrey pine, mugwort (*Artemisia douglasiana* Bess. ex Hook.), ponderosa pine, and skunkbush (*Rhus trilobata* Nutt.) (figs. 13a through 17). The species that showed the greatest proportion of injured to sampled plants, across all years, was ponderosa pine (table 8, fig. 18).

Although the number of sites or species with injury is informative, the average biosite injury index (which takes into account both severity and amount of injury on multiple species at a site) provides a more meaningful measure of injury on biosites across the state that can be compared from year to year. In California, the average biosite injury index was highest in 2000 and 2005, indicating that injury, where it occurred, was more severe (higher level of injury on individual plants) than in other years (table 9). However, more meaningful trend analyses will be those that focus on comparisons between mean values for different sets of years such as comparing

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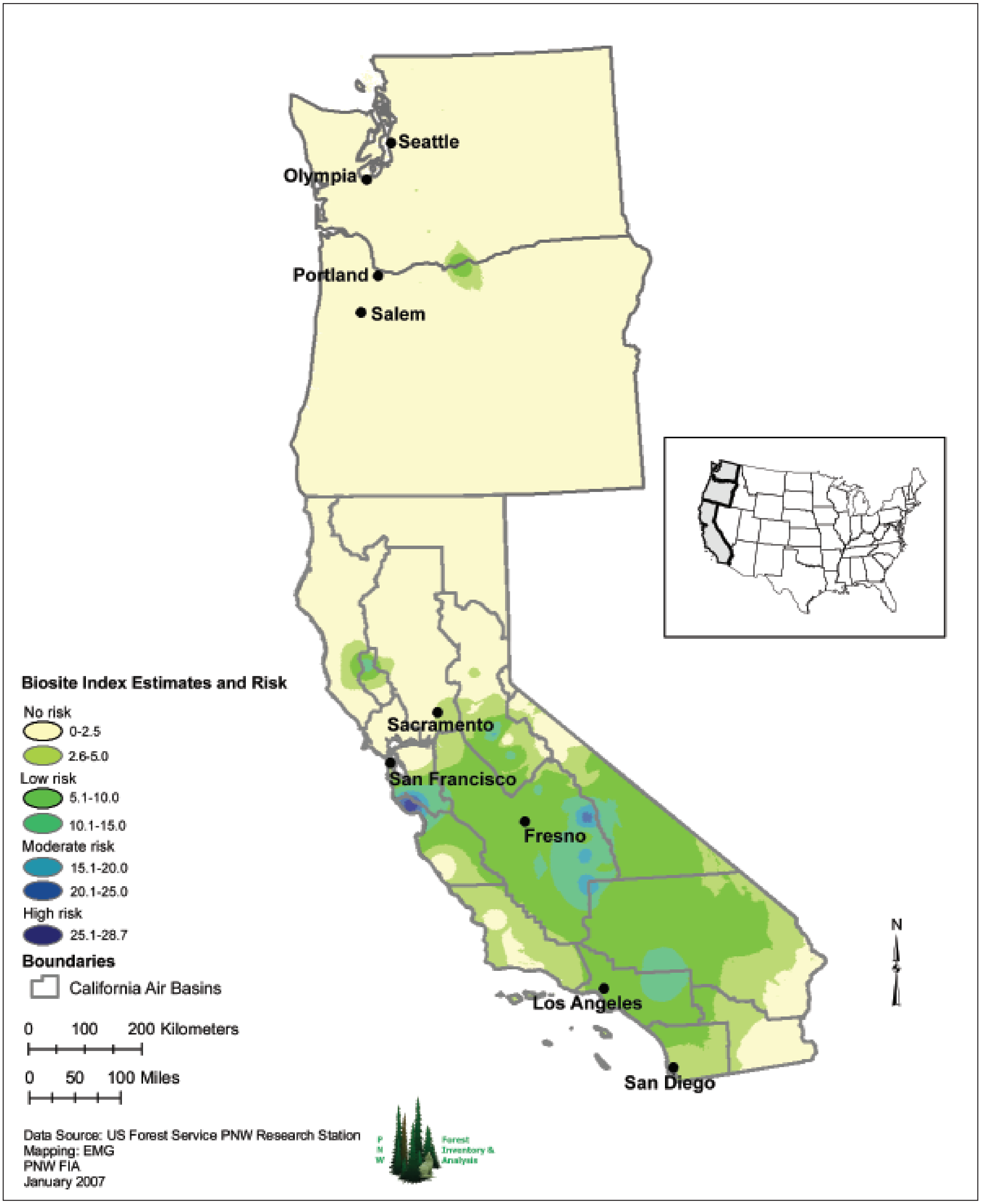

Figure 12—Biosite index estimates and risk to forests of injury from ozone exposure, 2000–2005 average. For more information on ozone risk assessment, see appendix 3.

Table 6—Number and percentage of Forest Inventory and Analysis biosites with validated ozone injury, by year

	2000	2001	2002	2003	2004	2005
California						
Number	6	11	20	16	22	24
Percent	27.3	36.7	30.8	24.6	33.8	36.9
Oregon						
Number	0	0	0	0	0	0
Percent	0	0	0	0	0	0
Washington						
Number	1	1	0	1	1	1
Percent	3.8	3.7	0	3.1	3.7	3.1

Table 7—Number of plants evaluated and injured[a] on Forest Inventory and Analysis biosites, by year

	2000	2001	2002	2003	2004	2005
California						
Evaluated	1,078	1,492	3,865	4,295	4,370	4,177
Injured	98	114	207	119	165	254
Oregon						
Evaluated	964	963	2,764	2,909	2,901	2,845
Injured	0	0	0	0	0	0
Washington						
Evaluated	1,281	1,250	2,072	2,693	2,497	2,490
Injured	7	6	0	4	4	5

[a] Injury validated by expert.

Dan Duriscoe

Figure 13a—Blue elderberry with light ozone injury symptoms (interveinal necrosis), California.

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Figure 13b—Blue elderberry with moderate ozone injury symptoms (interveinal necrosis), California.

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Figure 13c—Blue elderberry with severe ozone injury symptoms (interveinal necrosis), California.

Figure 14—Jeffrey pine needles with light ozone injury symptoms (chlorotic mottle), California.

Figure 15—Mugwort with artificially induced ozone injury symptoms (chlorosis and premature senescence).

Dan Duriscoe

Figure 16a—Ponderosa pine with moderate severity of ozone injury symptoms (chlorotic mottle), California.

Dan Duriscoe

Figure 16b—Ponderosa pine with severe ozone injury (chlorotic mottle), California.

Pat Temple

Figure 17—Skunkbush with artificially induced ozone injury symptoms (necrotic stippling).

Table 8—Plants evaluated and injured[a] on Forest Inventory and Analysis biosites, by species, by year, California

	2000	2001	2002	2003	2004	2005
Blue elderberry						
Evaluated	100	133	452	499	407	304
Injured	31	31	41	7	17	7
California black oak[b]						
Evaluated	43	13	—	—	—	—
Injured	0	0	—	—	—	—
Jeffrey pine						
Evaluated	161	330	410	480	566	563
Injured	2	28	60	15	57	58
Mugwort						
Evaluated	120	187	599	600	632	684
Injured	13	3	0	5	0	0
Pacific ninebark						
Evaluated	0	0	30	30	22	30
Injured	0	0	0	0	0	0
Ponderosa pine						
Evaluated	325	434	984	1,016	1,112	1,075
Injured	52	52	106	92	97	181
Quaking aspen						
Evaluated	159	166	237	288	322	313
Injured	0	0	0	0	0	0
Red alder						
Evaluated	0	0	112	120	120	90
Injured	0	0	0	0	0	0
Red elderberry						
Evaluated	0	0	30	30	47	30
Injured	0	0	0	0	0	0
Scouler's willow						
Evaluated	0	25	100	96	60	90
Injured	0	0	0	0	0	0
Skunk bush						
Evaluated	0	0	254	270	328	262
Injured	0	0	0	0	0	8
Snowberry						
Evaluated	170	204	627	776	724	706
Injured	0	0	0	0	0	0
Western wormwood						
Evaluated	0	0	30	90	30	30
Injured	0	0	0	0	0	0

[a] Injury validated by expert.

[b] No data 2002 through 2005 because dropped as bioindicator plant in 2002.

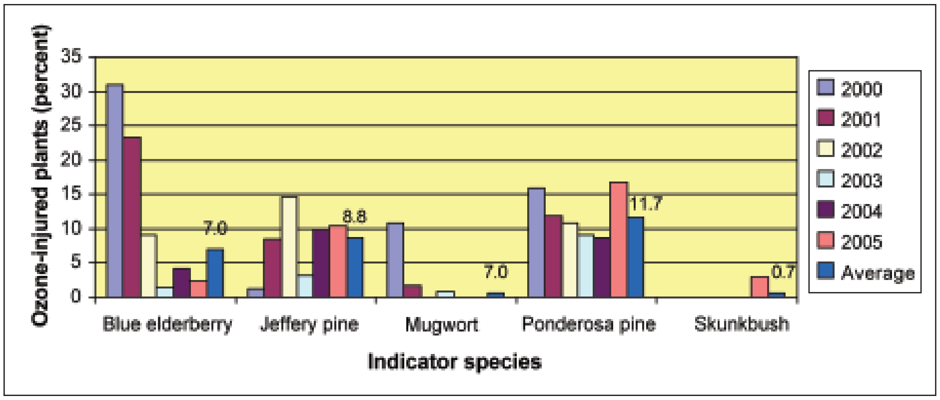

Figure 17—Percentage of evaluated plants with ozone injury, California, 2000-2005.

Table 9—Number and percentage of biosites by biosite index category[a] in California, by year

Biosite index	2000	2001	2002	2003	2004	2005
0 to 4.9 (least injured)						
Number	18	24	52	56	57	48
Percent	81.8	82.8	85.2	86.2	87.7	73.8
5.0 to 14.9						
Number	1	2	7	7	3	2
Percent	4.5	6.9	11.5	10.8	4.6	3.1
15.0 to 24.9						
Number	0	1	1	1	3	5
Percent	0.0	3.4	1.6	1.5	4.6	7.7
≥25.0 (most injured)						
Number	3	2	1	1	2	10
Percent	13.6	6.9	1.6	1.5	3.1	15.4
Average biosite index	6.7	3.4	2.2	2.1	2.5	9.3

[a] See appendix 1 for calculation of biosite index.

the mean for 2000-2004 to that for 2005-2009 or a comparison of 2000-2004 to 2001-2005 to 2002-2006 and so on. We will make these types of trend analyses as we collect additional years of data.

In California, the distribution of biosites with injury was fairly constant from year to year, with injury detected in the following key areas: south central and south coast (north and east of Los Angeles), San Diego County, the Sierra Nevada (with more injury in the southern portion), and San Francisco Bay (figs. 19 through 24). In 2005, injury was detected for the first time farther north in the north coast area

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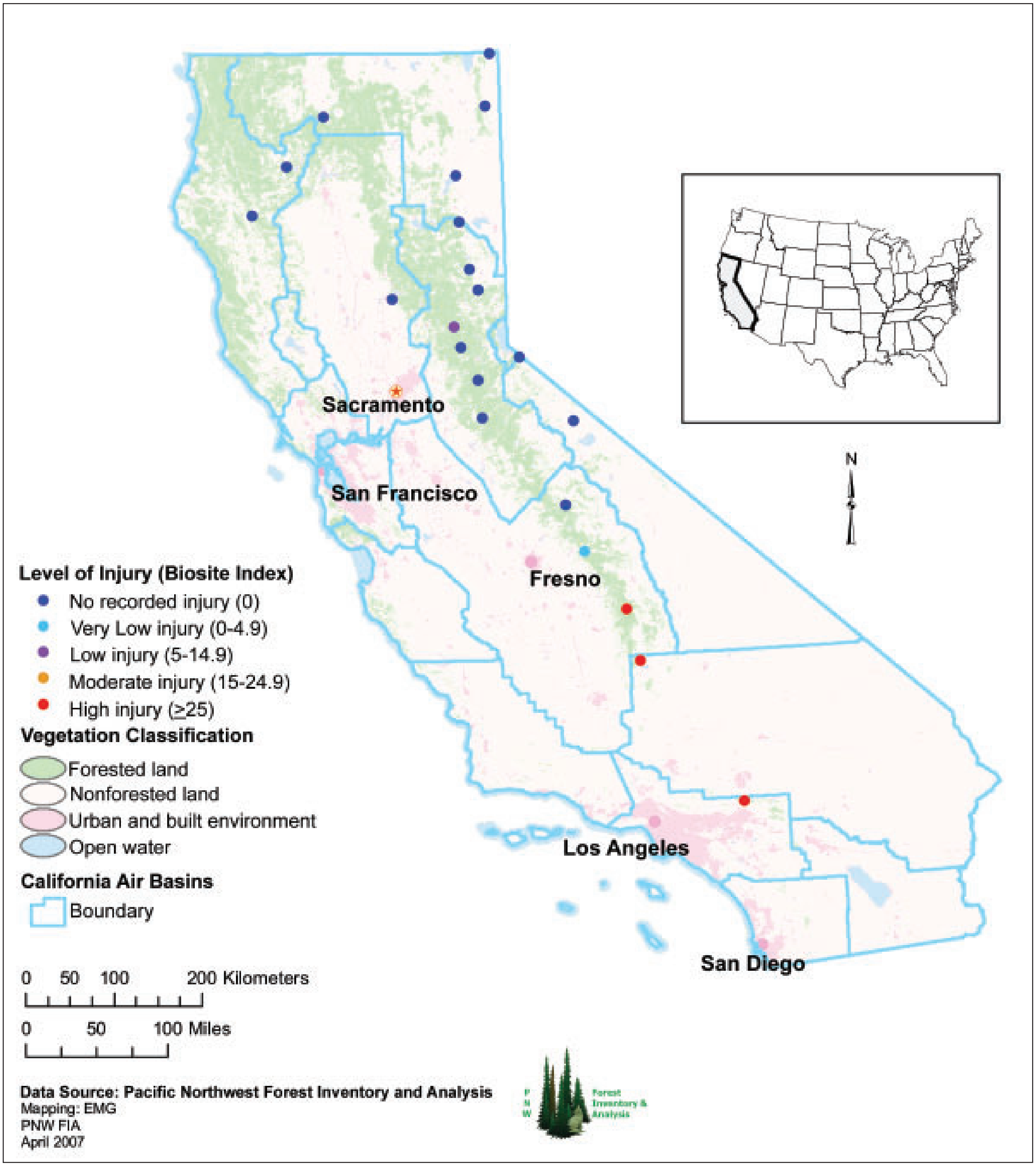

Figure 19—Forest Inventory and Analysis ozone biosites and biosite index, California, 2000.

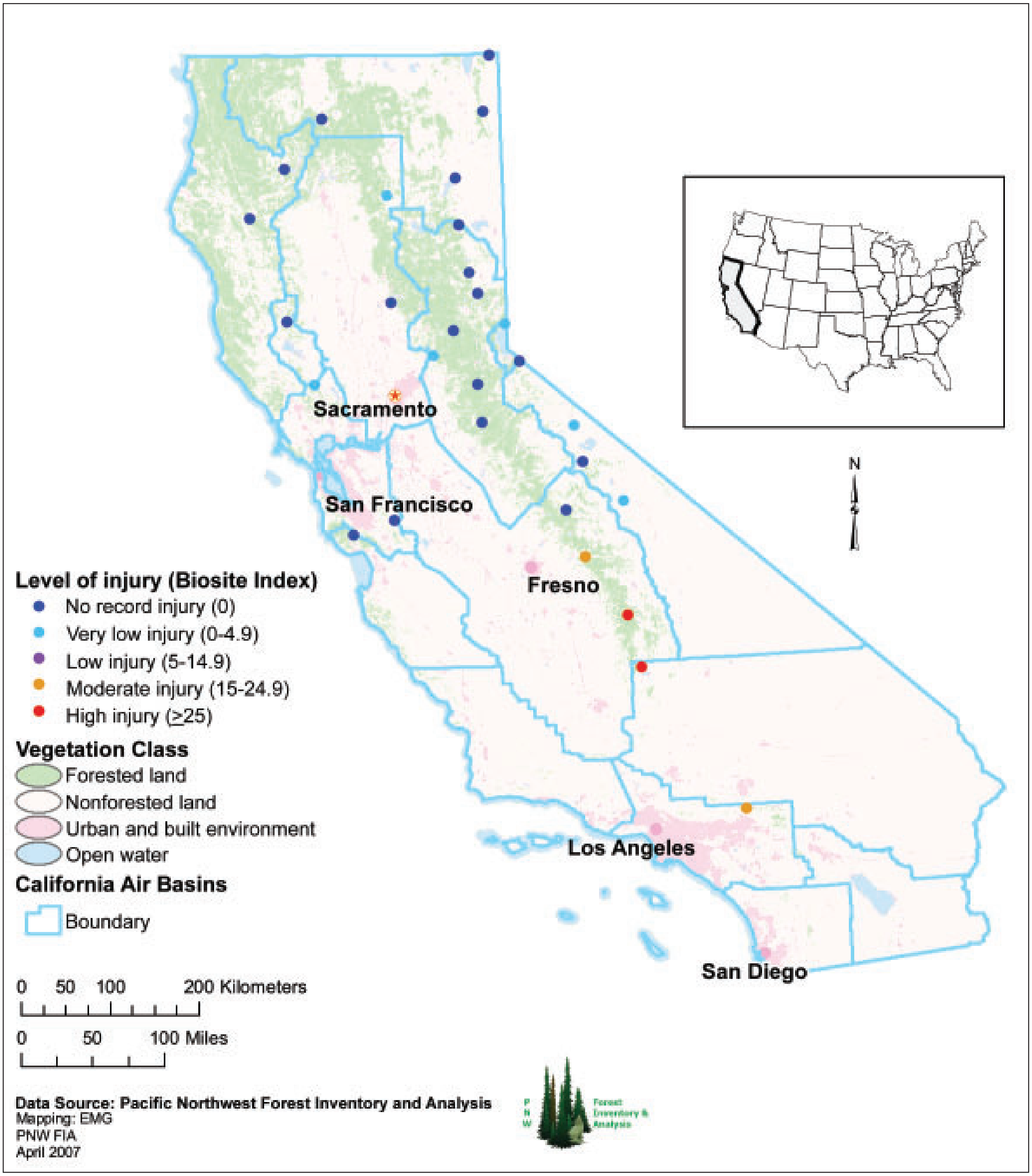

Figure 20—Forest Inventory and Analysis ozone biosites and biosite index, California, 2001.

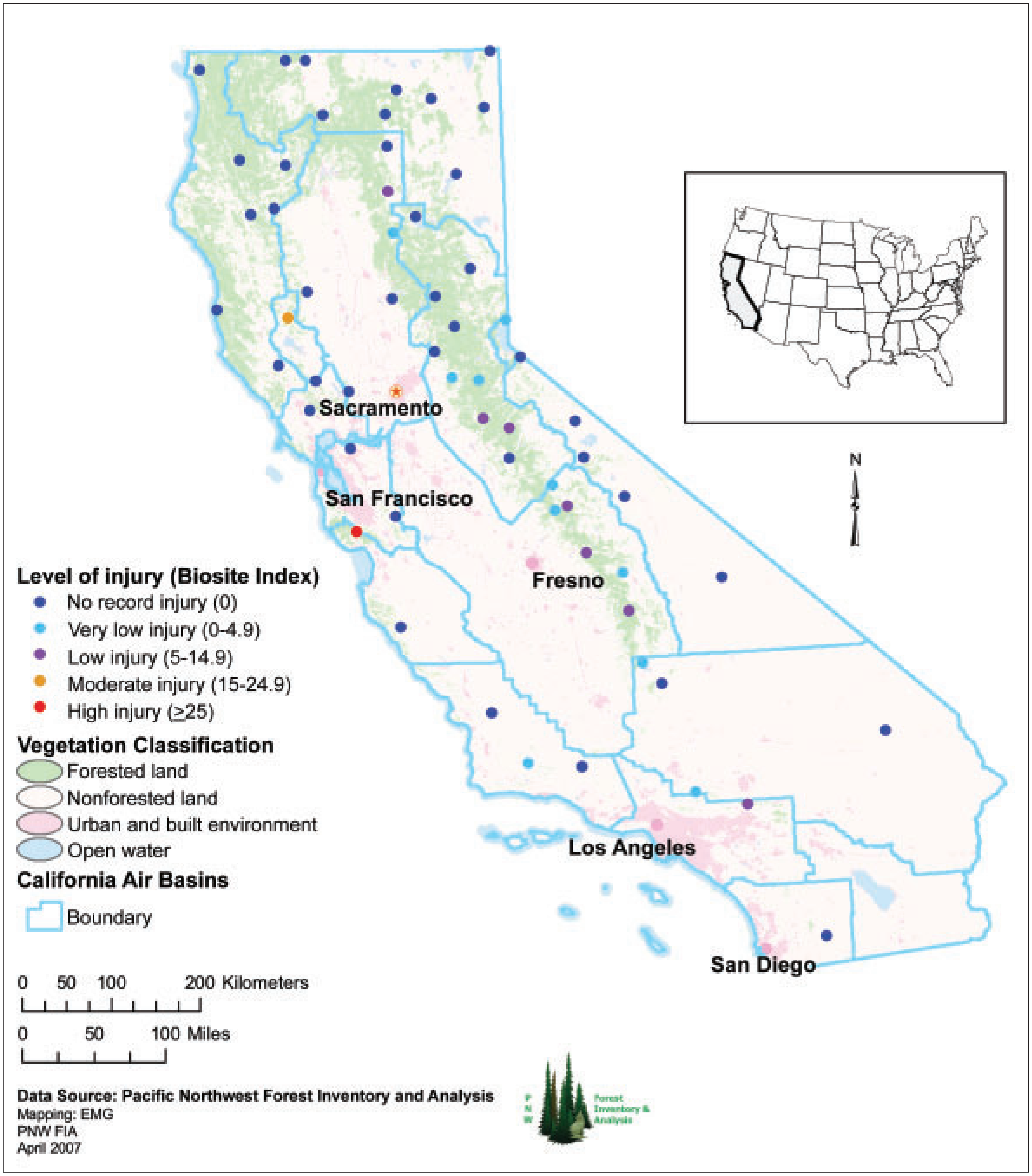

Figure 21—Forest Inventory and Analysis ozone biosites and biosite index, California, 2002.

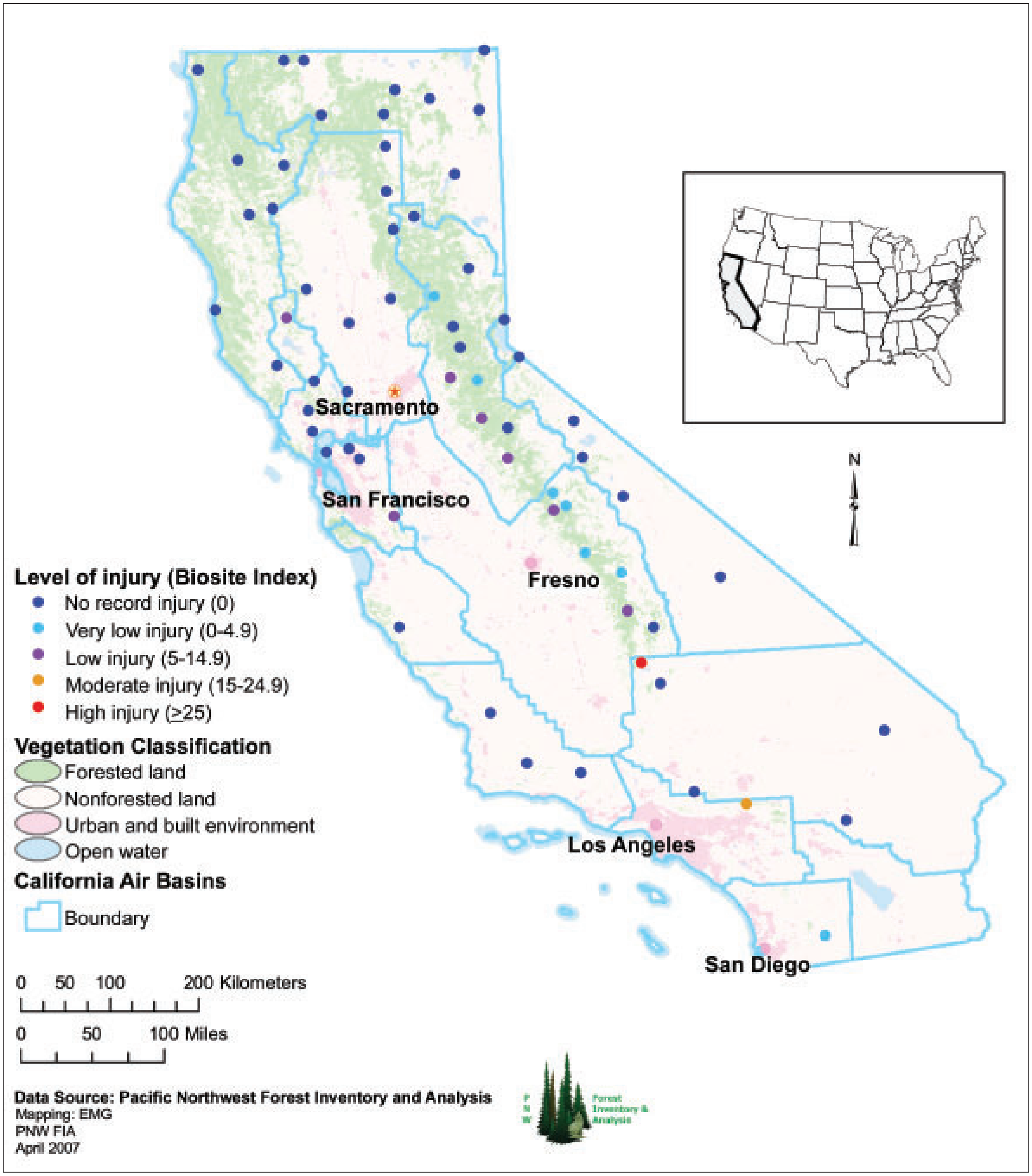

Figure 22—Forest Inventory and Analysis ozone biosites and biosite index, California, 2003.

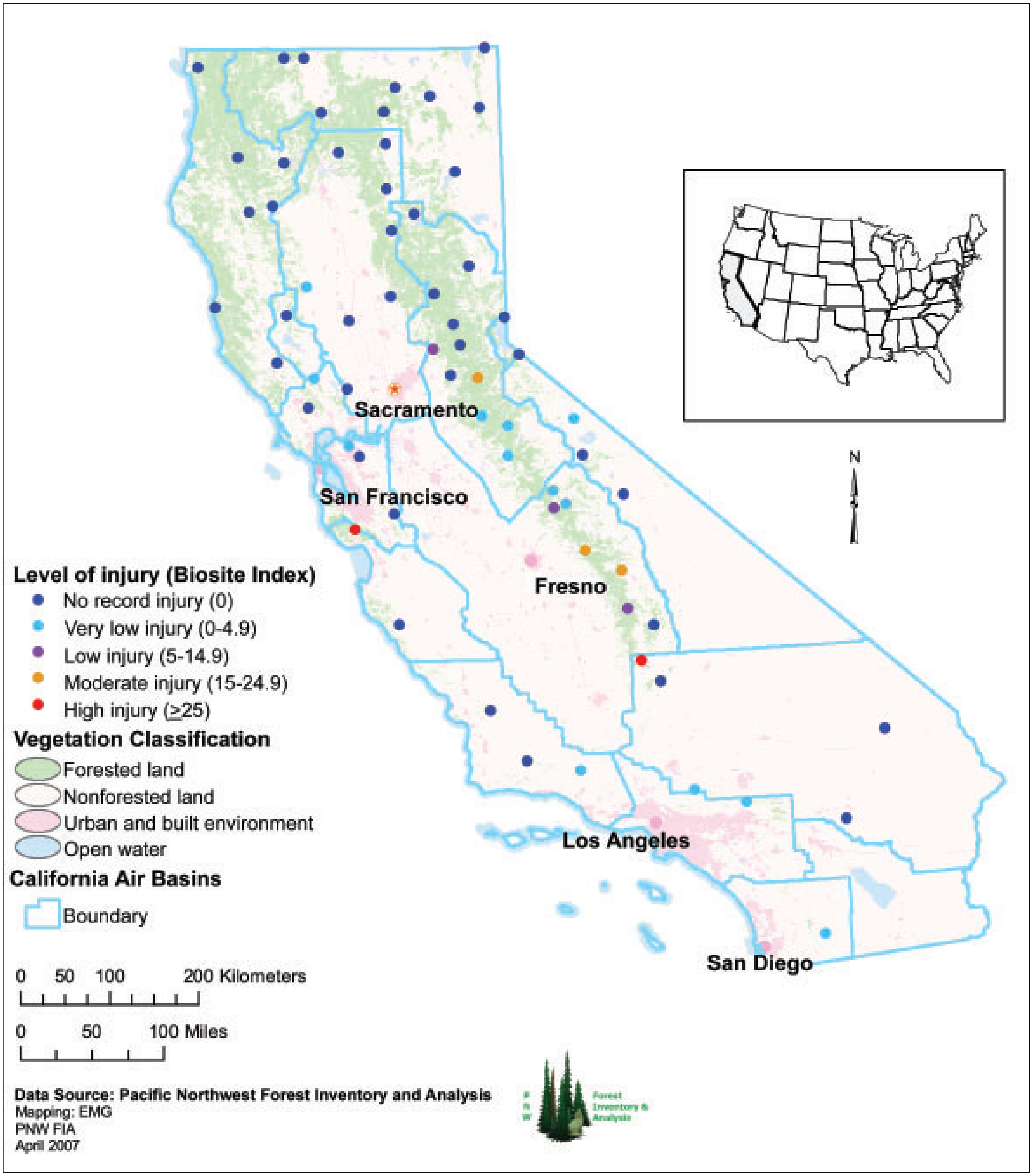

Figure 23—Forest Inventory and Analysis ozone biosites and biosite index, California, 2004.

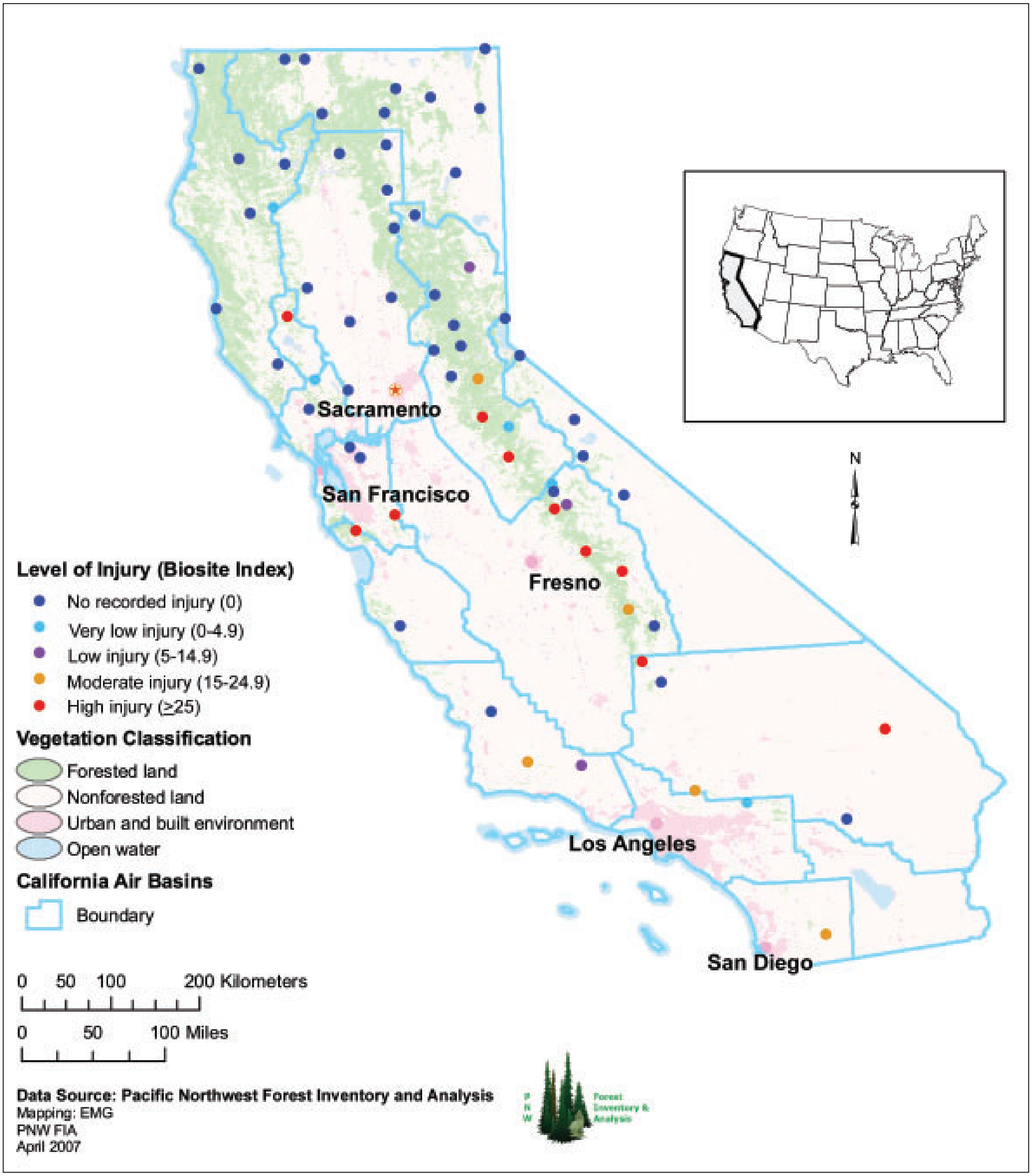

Figure 24—Forest Inventory and Analysis ozone biosites and biosite index, California, 2005.

(Trinity County) and in the northeastern portion of the Sierra Nevada (Plumas and Lassen Counties) as well as in the Mojave Desert area (San Bernadino County). Summaries of injury are depicted as average BI, by biosite (fig. 25) and as percentage of biosites with validated injury, by air basin (figs. 26 and 4).

California FIA biosite data were also summarized by ozone exposure levels depicted in figure 1. Areas where the average ozone exposure exceeded a SUM60 of 25,000 ppb had a higher percentage of biosites with injury (fig. 27) and higher average BI (fig. 28). Averages across all years for both percentage injured and BI are more comparable to exposure class than year-to-year values, as the SUM60 exposure map is an average across several years as well. A scatter graph of each biosite's average BI and the average exposure there further illustrates that, when looking at individual biosites, relatively high levels of injury can occur in areas where the 5-year average of ozone exposure is low or alternatively, low levels of injury can occur in areas of high exposure (fig. 29).

Using the gradient plus inverse distance weighting risk model described in "Methods" (p. 6) to predict risk, the areas at greatest risk from ozone injury in California are the southern Sierra Nevada, portions of the central coast, and much of the area east of Los Angeles (fig. 12). The majority of ozone-susceptible trees in California are not at risk; about 25 million acres (76 percent) of forest land area with 87 percent of the tree volume of susceptible species is classified in the lowest BI risk category (BI<5, no risk, tables 5, 10, and 11). However, more than 8 million acres with 5.5 billion cubic feet (13 percent) of susceptible tree species are at low, moderate, or high risk (BI ≥5). About 18 percent of ponderosa pine volume and 29 percent of Jeffrey pine volume, two species that consistently show injury in the field, are estimated to be at low or moderate risk (table 11). About 1.2 percent of the volume of Douglas-fir (*Pseudotsuga menzesii* (Mirb.) Franco), although not a species on which ozone injury has been observed in the field, is estimated to be at moderate or high risk (table 11). In Oregon and Washington, all forest land area and all susceptible species in Oregon and Washington are classified in the lowest BI/risk category (BI <5, no risk) (table 10). The area showing higher risk in the Columbia Gorge is not forested so there are no forested acres or volume of susceptible species at risk.

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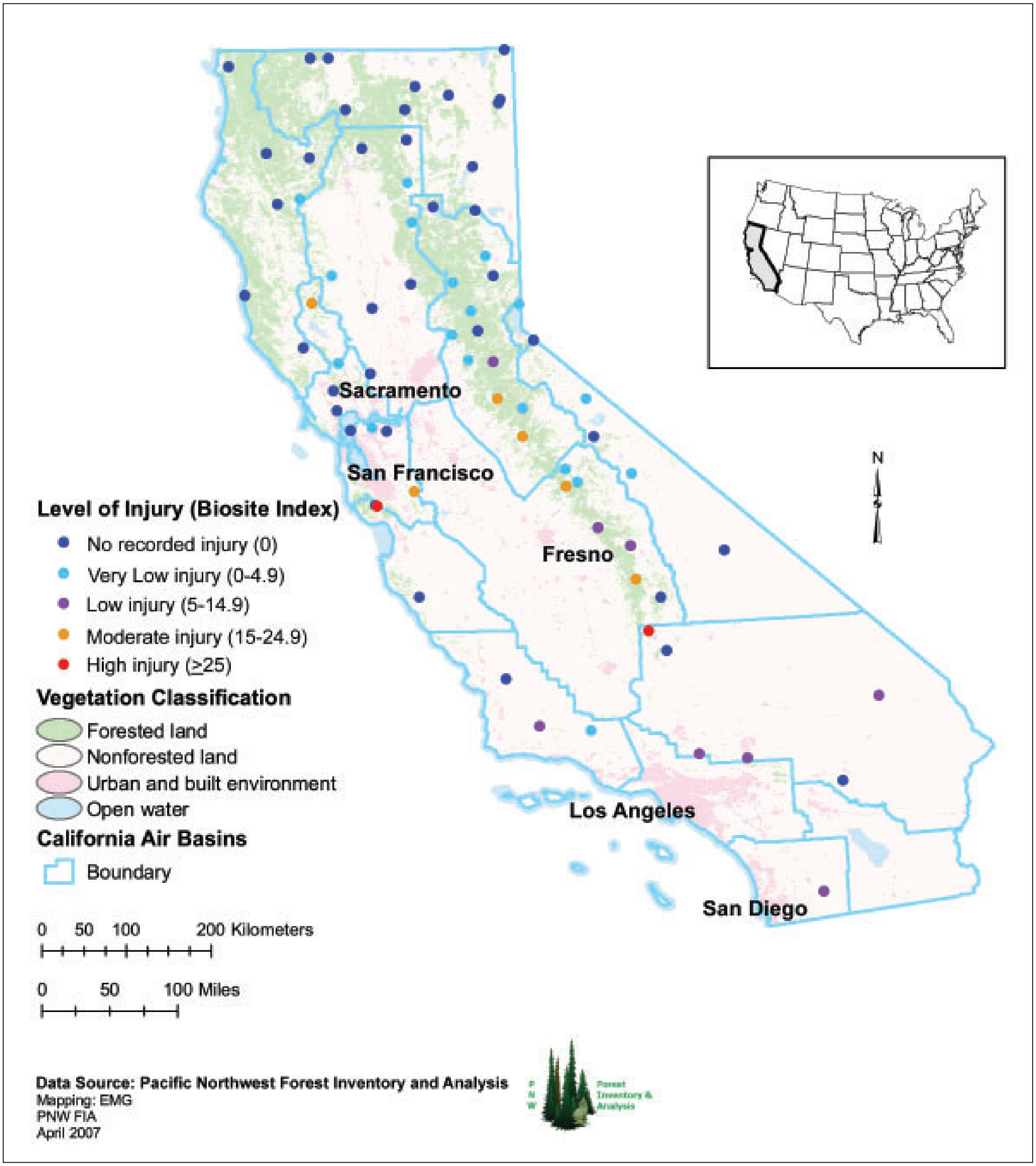

Figure 25—Forest Inventory and Analysis ozone biosites and average biosite index, California, 2000-2005.

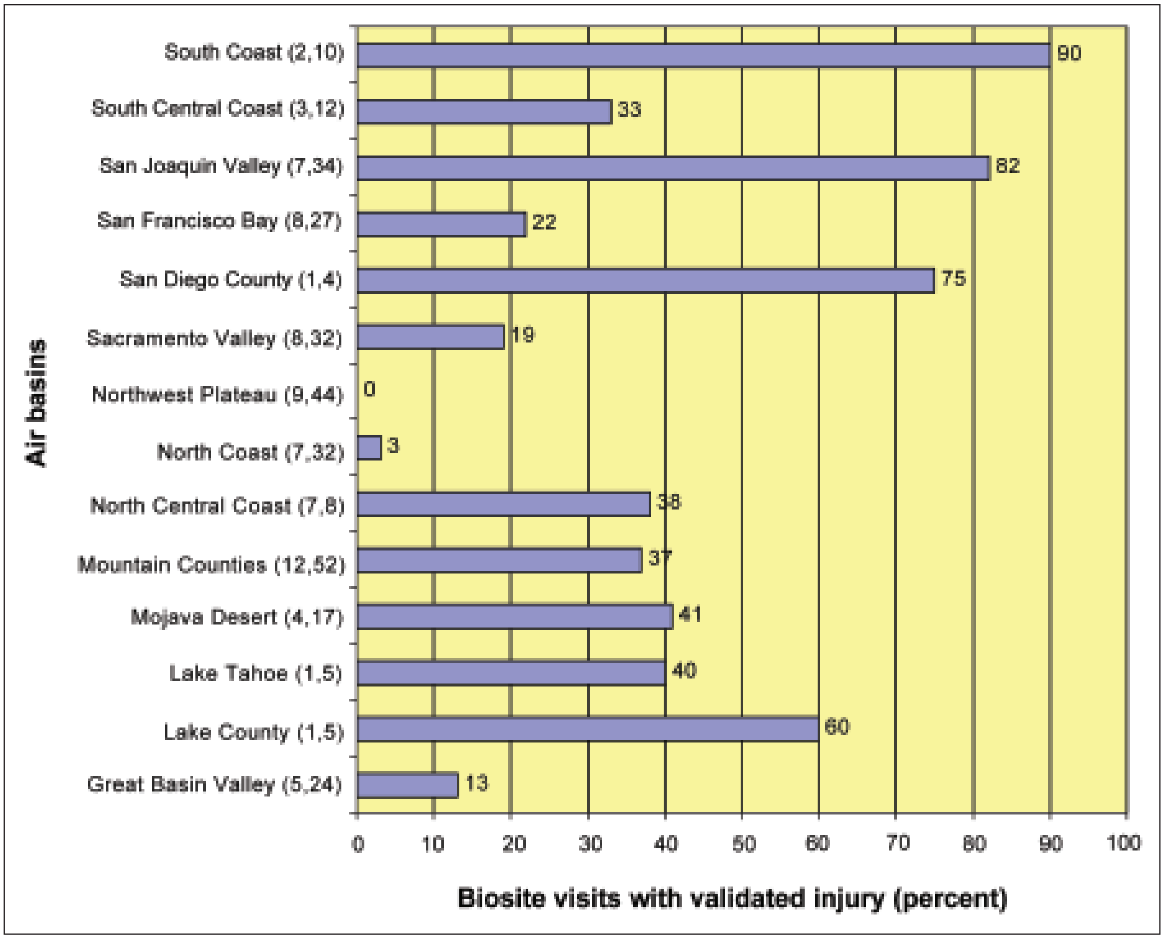

Figure 26—Percentage of biosite visits recording injury, by California air basin, 2000-2005. Numbers in parentheses after air basin label are the number of biosites in the basin followed by the total number of visits to those biosites between 2000 and 2005.

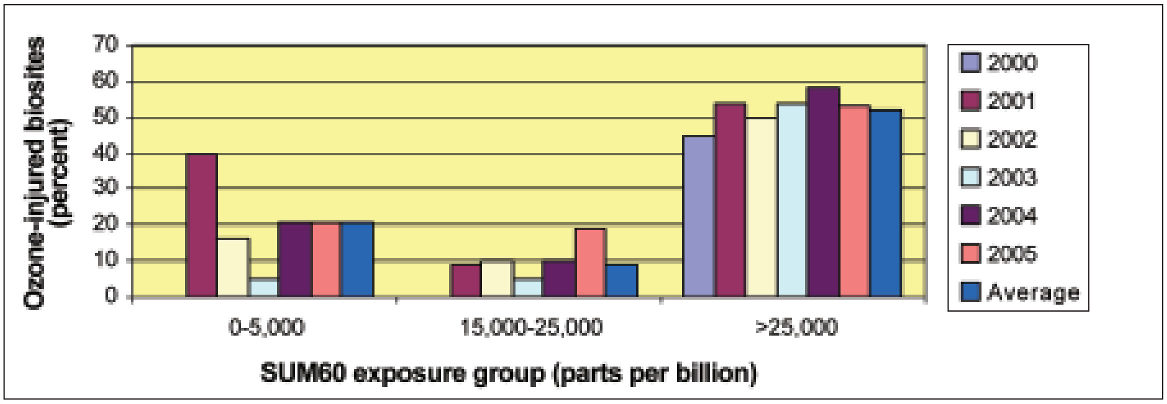

Figure 27—Percentage of biosites with injury, by ozone exposure class, by year, California.

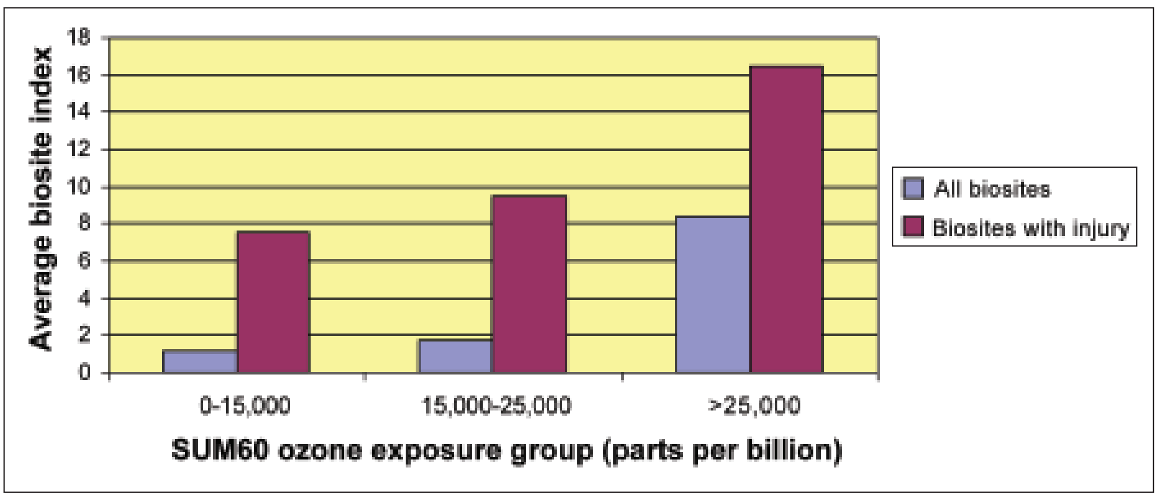

Figure 28—Average biosite index, by exposure class, 2000-2005, California. For more information on biosite index, see appendix 1.

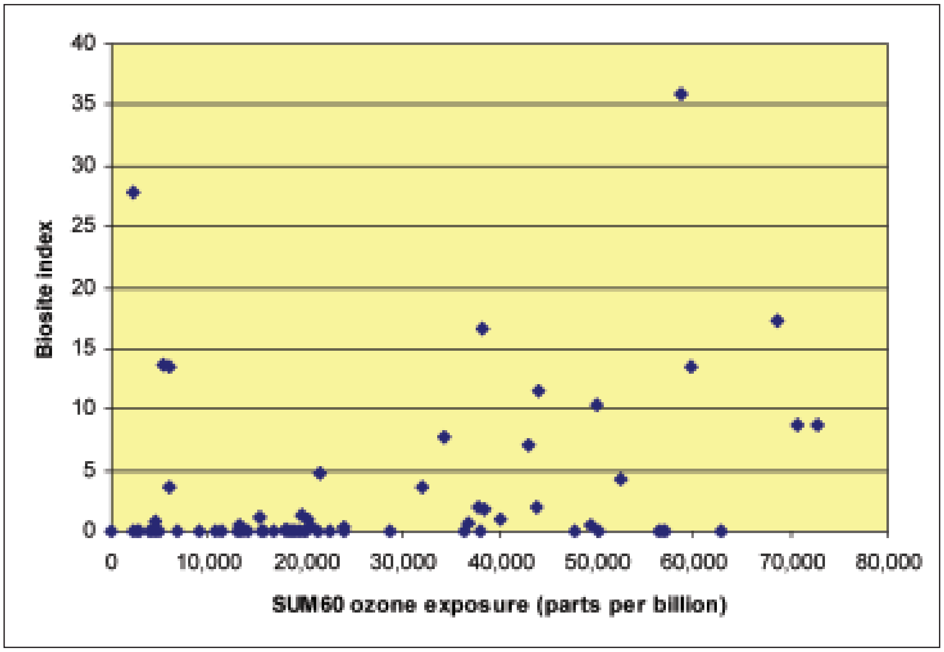

Figure 29—Relationship between average biosite index, 2000-2005, and average ozone exposure, 2001-2005, California. For more information on biosite index, see appendix 1.

Table 10—Estimated area of forest land and volume of ozone-susceptible tree species, by biosite index and risk category, by state

State and biosite index[a]	Area of forest land	Volume of susceptible species[b]
	Million acres	*Million cubic feet*
California:		
0 to 4.9, no risk	25.15	36,429.25
5 to 14.9, low risk	7.36	4,059.28
15 to 24.9, mod risk	.67	560.18
≥25, high risk	.63	36.11
Oregon:		
0 to 4.9, no risk	30.47	74,478.25
5 to 14.9, low risk	0	0
15 to 24.9, mod risk	0	0
≥25, high risk	0	0
Washington:		
0 to 4.9, no risk	22.12	65,035.59
5 to 14.9, low risk	0	0
15 to 24.9, mod risk	0	0
≥25, high risk	0	0

[a] Biosite index based on interpolated values for each Forest Inventory and Analysis plot; see appendix 3 for interpolation methods.

[b] Species susceptibility based on both field observations and fumigation trials.

Table 11—Estimated volume of ozone-susceptible tree species by species and biosite index (BI)[a] and risk category, California

	BI			
Species	0 to 4.9 (no risk)	5 to 14.9 (low risk)	15 to 24.9 (mod risk)	≥25 (high risk)
	Million cubic feet			
Red alder	430.51	4.61	0	0
Lodgepole pine	2,253.57	1,174.53	97.95	0
Jeffrey pine[b]	3,191.34	1,260.43	67.40	0
Ponderosa pine[b]	6,941.44	1,387.60	106.90	0
Monterey pine	0	0	14.59	0
Quaking aspen[b]	58.07	2.38	0	0
Black cottonwood	66.26	5.89	0	0
Douglas-fir	20,747.91	475.06	225.36	36.11
California black oak[b]	2,568.60	648.77	47.99	0
Western hemlock	171.55	0	0	0
All susceptible species	36,429.25	4,959.28	560.18	36.11

[a] Biosite index based on interpolated values for each Forest Inventoy and Analysis plot; see appendix 3 for interpolation methods.
[b] Ozone injury observed in the field on these species; other species demonstrated susceptibility following fumigation with ozone.

Discussion

California

Although ozone and its precursors have been decreasing throughout the state since 1975, several air basins in California still experience high levels of ozone (Cox et al. 2006). These include the South Coast Air Basin (the area around and east of Los Angeles with 43 percent of California's population) and the San Joaquin Valley Air Basin (the southern portion of the California Central Valley with 10 percent of California's population) (fig. 26). These two areas also contribute ozone and ozone precursors to a number of other downwind air basins including Great Basin Valleys, Mojave Desert, Mountain Counties, North and South Central Coast, Sacramento, and San Diego. Examination of up to the highest 10 FIA ozone BIs each year between 2000 and 2005 (n = 56, as year 2000 had only 6 biosites with any injury) shows that 88 percent of these occur in the South Coast and San Joaquin Valley or the downwind air basins mentioned above.

Air quality is a significant concern in national parks, with mandates to protect air quality via the 1916 Organic Act and the 1963 Clean Air Act (and its 1970 and 1990 amendments) with many elements (such as vegetation, visibility, water quality, and panoramas) of a park environment identified as being sensitive to air pollution (NAS 2004). The NPS has committed to managing their air resources through activities such as inventories of air-quality-related values, monitoring air quality in the parks, and evaluating air pollution effects and causes. In California, ambient ozone levels increased significantly in the Sequoia and Death Valley National Parks between 1995 and 2004, exceeding the EPA's national ambient air quality standard[2] (USDI NPS 2006). However, FIA biosites in these two parks (one each) showed consistent low injury (average BI = 13.2 for the Sequoia National Park and no detected injury for Death Valley National Park). For the five FIA ozone biosites located in national parks in California, including the above two, injury was detected 39 percent of the time between 2000 and 2005, with an average BI of 5.7, and maximum BI of 43.

The model we used to predict risk of ozone injury across the west coast is a plant response model, where the plants themselves integrate climatic (e.g., temperature and precipitation), site (e.g., moisture, elevation), and genetic factors to influence ozone uptake and their response to it. Other models such as those reported by Bytnerowicz et al. (2003: chapters 7 through 9) are exposure models that use ambient ozone data and climatic, topographic, and site factors to predict areas of high ozone exposure. These, like the SUM60 maps, will coincide generally but often not specifically, with our reported areas of injury and high BIs. Bytnerowiscz et al. (2003) found that patterns of ozone injury in the western Sierra Nevada generally followed patterns of ozone exposure risk predicted by several exposure models.

Oregon and Washington

Although California has monitored ozone for many years, Oregon and Washington have little or no pre-1980s data on ozone air quality (Bohm 1989, US EPA 1996a). Until recently, the forests in Oregon and Washington were assumed to be relatively clean with only occasional intrusions of above-background concentrations of ambient ozone (Brace and Peterson 1998, Cooper and Peterson 2000). However, increases in ambient ozone have been observed in a number of western Washington locations between 1999 and 2003, including Mount Rainier and North Cascades National Parks (Fenn et al. 2005, USDI NPS 2006).

[2] The national ozone standard: ozone levels not to exceed 0.08 parts per million for 8 hours, based on the 4th highest concentration averaged over 3 years. (www.epa.gov/ttn/naaqs/ozone/03imp8hr/finalrule.html.) "An area violates the federal 8-hour ozone standard if the calculated fourth highest 8-hour concentration averaged over a three-year period exceeds the level of the standard at any monitoring site in the region" (Cox et al. 2006).

The Columbia River Gorge, where ozone levels in the Gorge rise as distance from the Portland, Oregon/Vancouver, Washington, metropolitan area increases, levels as high as 0.079 parts per million (ppm) for 8 hours in 2001 were reported at Wishram, Washington (96 miles east of Portland). The injury detected in the Gorge by the FIA ozone biomonitoring program was at a biosite a little over 100 miles east of Portland in an irrigated area that is naturally nonforested. Although the presence of injury is atypical there, this site supports ambient data showing that ozone levels are high there and capable of causing injury to susceptible species, forest or nonforest, given favorable environmental conditions.

The FIA ozone data provide a baseline of no injury and no risk in Oregon and Washington forests against which future data can be compared. Climate change and population growth in these two states suggest that ground-level ozone generation and injury is more likely, rather than less, to increase in coming years. For all three states, analyses of trends will be more meaningful as more data are collected and, as mentioned on pages 15 and 22, comparisons can then be made between mean values for different sets of years.

Research and Monitoring Needs

Ozone research and monitoring needs for the Sierra Nevada in California are well described in Bytnerowicz et al. (2003) and are applicable to other parts of California as well as Oregon and Washington—refinement of ambient monitoring technologies, development of more sophisticated pollution distribution and biological response models, integrated monitoring networks, alternative ways to assess ozone uptake and injury, identification of additional bioindicator species, better linkage between air levels and visible injury, and integrated assessments of urban and wildland pollution. Additional research is needed to elucidate the role of other stressors such as insects, diseases, nitrogen deposition, and climate change in relation to ozone uptake and effects.[3] We also need to better understand the role and contribution of ozone and its precursors from out-of-country emittors such as Asia or Mexico (Fenn et al. 2005).

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[3] Arbaugh, M. 2006. Personal communication. Statistician. Air pollution and global change impacts on western forest ecosystems research unit, Pacific Southwest Research Station, Forest Fire Lab, 4955 Canyon Crest Drive, Riverside, CA 92507.

Conclusions

Although several important pieces of California legislation have been implemented for pollution abatement since the 1980s and per-car emissions have been reduced in the state from the very high levels of the 1970s and 1980s, ozone standards[4] are still being exceeded in several California air basins (Cox et al. 2006). With changes in global and regional climate, increases in populations and anthropogenic sources of pollution, and greater potential for disturbance events such as wildfires and insect and disease outbreaks, forests are increasingly vulnerable.

The FIA network of biosites is designed to detect the first visible sign of ozone stress and establish regional and national trends from a real baseline condition (Smith et al., n.d.). It has tremendous value as one of few large-scale biological networks of ozone air quality. This information can inform governments, the public, and industry in determining air pollution guidelines, regulations, and laws. The FIA ozone injury data serve as a source of information about the effects of ozone on forest plants that is complementary and enhances that provided by ambient ozone monitoring systems. The FIA ozone data can also serve as a resource to aid land managers in local forest management (species selection in high-exposure areas, tree improvement programs, etc.) and planning for future forest health and condition.

The FIA ozone biomonitoring from 2000 through 2005 in California, Oregon, and Washington tells us the following:

- Ozone injury occurs frequently (25 to 37 percent of sampled biosites) in California forested ecosystems demonstrating that ozone is present at phytotoxic levels.
- The California air basins with the highest percentge of biosites with injury were the South Coast, San Joaquin Valley, and San Diego County.
- The group of biosites in the areas with the highest ozone exposures (SUM60 ≥25,000 parts per billion) had corresponding highest mean percentage of injured biosites (52 percent) and highest mean biosite index (16.4).
- In 2005, new areas (previously unreported) of ozone injury were detected in northern California (Trinity, Plumas, and Lassen Counties) as well as in the Mojave Desert area (San Bernadino County).

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[4] The California ozone standard: ozone levels not to exceed 0.07 ppm averaged over 8 hours. This standard was implemented in January 2006; the previous standard was ozone levels not to exceed 0.09 ppm for 1 hour (Cox et al. 2006).

- Although ozone exposure is moderate to high over much of California, forested areas with the highest risk were estimated (via our plant response model) for the area east of Los Angeles, the southern Sierra Nevada, and portions of the central coast.
- In California, an estimated 1.3 million acres of forest land and 596 million cubic feet of wood are at moderate to high risk to impacts from ozone.
- Despite reports of increasing ozone production and exposure in Oregon and Washington, ozone injury was observed only in the Columbia Gorge.
- Air quality as indicated by the FIA ozone bioindicator shows no consistent pattern of increases or decreases in any of the three states between 2000 and 2005. More years of data are needed to discern any trends.

Acknowledgments

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Metric Equivalents

1 acre = 0.405 hectare
1 foot = 0.305 meter
1 cubic foot = 0.0283 cubic meter
1 mile = 1.609 kilometers

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Appendix 1: Biosite Index Calculation

The biosite index (BI) is the average score (amount x severity) for each species averaged across all species on the biosite.

$$BI = 1{,}000\left(m^{-1} \sum_{j=1}^{m} n_j^{-1} \sum_{p=1}^{n_j \geq 10} a_{pj} s_{pj} \right)$$

where:

BI = biosite index,
m = number of species evaluated,
n_j = number of plants of the j^{th} species evaluated,
a_{pj} = proportion of injured leaves on the p^{th} plant of the j^{th} species, and
s_{pj} = average severity of injury on the p^{th} plant of the j^{th} species.

Example: A BI is calculated for a biosite with 30 ponderosa pine trees, 30 mugwort plants, and 30 snowberry plants. Each plant of each species is evaluated for amount and severity of ozone injury, with the following results:

Ponderosa pine: 28 trees with no injury (amount = 0; severity = 0); 1 tree with amount = 2; severity = 2; 1 tree with amount = 2; severity = 5.

Mugwort: 29 plants with no injury (amount = 0; severity = 0); 1 plant with amount = 3; severity =3.

Snowberry: 30 plants with no injury (amount = 0; severity = 0).

The midpoint of the amount or severity category is used to calculate BI. For example, if the rating category is 2, then the value used is the midpoint of 0.07 to 0.25 = 0.16. The data, in tabular format, from the example biosite is listed below.

	Plant number	Ponderosa pine	Mugwort	Snowberry
amount =	1	0.16	0.38	0
	2	.16	0	0
	3	0	0	0
	⋮	⋮	⋮	⋮
	30	0	0	0

	Plant number	Ponderosa pine	Mugwort	Snowberry
	1	0.16	0.38	0
severity =	2	.875	0	0
	3	0	0	0
	⋮	⋮	⋮	⋮
	30	0	0	0

These data are then used to calculate BI as follows:

For each *j* species, the average amount x severity is calculated
Ponderosa pine: [(0.16 x 0.16) + (0.16 x 0.875) + (0 x 0) +…+ (0 x 0)] x 30^{-1} = 0.0055
Mugwort: [(0.38 x 0.38) + (0 x 0) +…+ (0 x 0)] x 30^{-1} = 0.0048
Snowberry: [(0 x 0)+…+(0 x 0)] x 30^{-1} = 0

The average amount x severity for each species is then averaged across species and multiplied by 1,000.
BI = 1,000(0.0055 + 0.0048 + 0.0) x 3^{-1} = 3.44

Appendix 2: Ambient Ozone Exposure Indices Calculation and Spatial Interpolation Methods[1]

Calculating Ambient Ozone Exposure Indices: Data Preparation

Ambient ozone data were downloaded from the U.S. Environmental Protection Agency Technology Transfer Network Air Quality System Web site: http://www.epa.gov/ttn/airs/airsaqs/archived%20data/downloadaqsdata.htm.

Ambient data were corrected for missing data by calculating a monthly average for each hour for each site. If there is a missing monthly hour average (usually because it is the hour that daily calibration checks are performed), it is estimated by averaging the hour before and after as follows:

$$\int_{Hour=2}^{Hour=23} MonthlyAverage_{Hour} = \sum_{Day=May1st}^{May30th} (OzoneValue_{Hour-1} + OzoneValue_{Hour+1}) \div 2$$

$$MonthlyAverage_{Hour1} = \sum_{Day=May1st}^{May30th} (OzoneValue_{Hour24} + OzoneValue_{Hour2}) \div 2$$

$$Monthly\ Average_{Hour24} = \sum_{Day=May1st}^{May30th} (Ozone\ Value_{Hour1} + Ozone\ Value_{Hour23}) \div 2$$

The monthly average for an hour was then added to the "corrected" table for missing hours. Thus, the corrected table has an ozone value for every hour from May 1 through September 30, unless an entire month of data was missing. In that case, a monthly average cannot be calculated, because no data exist.

Calculating Ambient Ozone Exposure Indices: SUM60 12-Hour Data Capture

The data capture (DC) is presented as a percentage of total hours between 08:00 and 20:00 in a month for which there are data. Data Capture = (number of values in table per month per site) / (number of days in month x 12 hours)

$$\int_{Month-May}^{Month-September} Monthly\ Data\ Capture_{Month} = \left(\sum_{Day=1}^{Last\ Day\ in\ Month} \sum_{Hour=8}^{Hour=20} Count(Ozone) \right) \div \left(\sum_{Day=1}^{Last\ Day\ in\ Month} 12 hours \right)$$

Excerpt from Prichard 2003.

Example:

If a site has 362 ozone values for May:
May DC = (362) / (31 x 12)
May DC = 97.3 percent

The data captures for each month per site are averaged to calculate the data capture for the 3-month and 5-month periods.

$$3Month\ Data\ Capture = \left(\sum_{Month=\text{June}}^{\text{August}} Monthly\ Data\ Capture_{Month} \right) \div 3$$

$$5Month\ Data\ Capture = \left(\sum_{Month=\text{May}}^{\text{September}} Monthly\ Data\ Capture_{Month} \right) \div 5$$

Only sites having 75 percent or greater original data capture have a SUM60 calculated. If the data capture is less than 75 percent, a null is reported for that site and 5-month period for both the original and corrected data.

Calculating Ambient Ozone Exposure Indices: SUM60 Exposure Index

The monthly, 3-month (June through August), and 5-month (May through September) sum of all hourly ozone concentrations equaling or exceeding 60 parts per billion (ppb) between 08:00 and 20:00 are calculated for each site in each of the original tables and the corrected tables.

$$\int_{Month=2}^{23} SUM\ 60_{Month} = \sum_{Day=1}^{Last\ Day\ in\ Month} \sum_{Hour=8}^{20} Ozone \geq 60$$

$$SUM\,60_{3Month} = \sum_{Day=\text{June 1st}}^{\text{August 30th}} \sum_{Hour=8}^{20} Ozone \geq 60$$

$$SUM\,60_{5Month} = \sum_{Day=\text{May 1st}}^{\text{September 30th}} \sum_{Hour=8}^{20} Ozone \geq 60$$

Spatial Interpolation of Ambient Ozone Exposure Indices

The inverse distance weighting scheme was selected based on previous experience with spatial interpolation of ozone exposures. The power of the function was set to 2, indicating a monitor's influence on a grid cell decreases with the square of distance. The variable scheme was used with each grid cell being the composite of the seven closest monitors. However, no monitor can be more than 500 kilometers (310 miles) from a grid cell. Please note that a lack of good data in the Southern United States led to having a restriction of no monitor farther than 700 kilometers (435 miles) in 2001. Each grid cell is 3 kilometers (5.6 miles) square.

Specifically, without the restriction on the distance, grid cells in data-sparse regions can have values higher than expected. With a low number of monitors versus the size of the region, it is not possible to interpolate based on a subset of data and then verify the process with the remaining data.

Appendix 3: Ozone Injury Risk Assessment Methods

We use a risk assessment approach that was suggested by Smith et al. (in press), demonstrated by Coulston et al. (2003), and consistent with the ecological risk assessment paradigm described by Regens (1995). Table 5 provides a quantitative description of observed plant response to ambient ozone conditions (biosite index [BI]), and a qualitative description of risk and possible impacts. However, plant injury to bioindicator species from ozone is recorded on biosites, which are generally open areas that may or may not meet the Forest Inventory and Analysis (FIA) requirements of forest land (land that is at least 10 percent stocked with live trees, not currently developed for nonforest use, and larger than 1 acre and at least 120 feet wide) and use bioindicator species that may or may not be forest tree species. Therefore to evaluate the likelihood of ozone injury to forest trees, we use spatial interpolation to extend the information collected at biosites to the forest population (Coulston et al. 2003; Smith et al., in press).

We interpolated gridded maps of the BI for each year 2000 through 2005 via gradient inverse distance weighting (GIDS). The GIDS technique was first proposed as a way to interpolate climatic data on a broad spatial scale as input for plant growth models (Nalder and Wein 1998). The GIDS technique combines multiple linear regression with inverse distance weighting interpolation and, like other recently developed interpolation techniques, incorporates elevation as a covariate.

For a given unmeasured location *k* and variable *Z*, an ordinary least squares regression is performed by using the *N* closest neighboring locations to calculate coefficients (C_x, C_y, and C_e) representing x, y, and elevation gradients: $Z = a + C_x X + C_y Y + C_e E + \tilde{\varepsilon}$, where *a* is the intercept and ε is error. Then, the basic GIDS formula is

$$Z_k = \frac{\sum_{i=1}^{N} \frac{Z_i + C_x(X_k - X_i) + C_y(Y_k - Y_i) + C_e(E_k - E_i)}{d_i^2}}{\sum_{i=1}^{N} \frac{1}{d_i^2}}$$

where Z_k = the predicted value at an unmeasured location *k*, Z_i = the measured value at location *i*, *X* = the x-coordinate for the specified location, *Y* = the y-coordinate, *E* = the elevation value, and *d* = the three-dimensional distance from measured location *i* to *k* (Nalder and Wein 1998).

For each location of interest, we fitted a generalized linear model, based on the 30 closest neighboring biosites. We acknowledged that all three gradient variables (x, y, and elevation) could prove insignificant for a given prediction location and its closest measured neighbors. As a result, we evaluated a sequence of the full and all possible reduced models for statistical significance:

1. $Z = a + C_x X + C_y Y + C_e E + \varepsilon,$
2. $Z = a + C_x X + C_e E + \varepsilon,$
3. $Z = a + C_y Y + C_e E + \varepsilon,$
4. $Z = a + C_x X + C_y Y + \varepsilon,$
5. $Z = a + C_x X + \varepsilon,$
6. $Z = a + C_y Y + \varepsilon,$
7. $Z = a + C_e E + \varepsilon.$

For each prediction location, we tested all seven regression models by using the 30 closest stations and identified those models in which all variables were significant. In cases where more than one of the models had all significant variables, we identified the one that yielded the smallest value for Akaike's Information Criterion. If the best-performing model was not the full model, then the coefficient(s) for any insignificant variable(s) were set to zero in the GIDS equation. If none of the tested models proved to have significant variables, then the GIDS interpolation reverted to inverse distance squared weighting (i.e., all variable coefficients were set to zero).

The six interpolated BI maps were averaged to create the final risk map (fig. 11, average 2000-2005 BI). We then overlaid the final risk map with FIA plots. This variable (the 2000-2005 BI for each FIA plot) could then be used to summarize the FIA survey data. At this point, we used the methods suggested by Bechtold and Patterson (2005) to summarize the FIA data. For example, we estimated the number of acres of forest land and the volume of susceptible tree species in each BI risk category (table 10).

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