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Lichen Bioindication of Biodiversity, Air Quality, and Climate: Baseline Results From Monitoring in Washington, Oregon, and California

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Abstract

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Lichens are highly valued ecological indicators known for their sensitivity to a wide variety of environmental stressors like air quality and climate change. This report summarizes baseline results from the U.S. Department of Agriculture, Forest Service, Forest Inventory and Analysis (FIA) Lichen Community Indicator covering the first full cycle of data collection (1998–2001, 2003) for Washington, Oregon, and California. During this period, FIA conducted 972 surveys of epiphytic macrolichen communities for monitoring both spatial and long-term temporal trends in forest health. Major research findings are presented with emphasis on lichen biodiversity as well as bioindication of air quality and climate. Considerable effort is devoted to mapping geographic patterns and defining lichen indicator species suitable for estimating air quality and climate.

Keywords: Acidophytes, air quality, California, climate change, cyanolichens, forest health, gradient analysis, indicator species, neutrophytes, nitrophytes, nonmetric multidimensional scaling, ordination, Pacific Northwest, pollution.

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Roseann Barnhill

Sticta fuliginosa (spotted felt lichen) found on Mount Hood National Forest in Oregon.

Chapter 1: Introduction and Methods

Introduction

Although appearing to be a single organism, a lichen (fig. 1) is actually a symbiotic partnership between a fungus and one or more photosynthetic organisms, an alga or cyanobacterium. Their intimate coexistence inspired the analogy (originally conceived by Canadian lichenologist Trevor Goward) that lichens are fungi that discovered agriculture (fig. 2). Typically the fungal partner provides most of the composite organism's structure and mass, thus trading physical protection for carbohydrates manufactured by the photosynthetic partner (fig. 3). Together the fungus and its partner(s) can inhabit a much wider variety of habitats and conditions than any could on their own.

Lichens play many essential functional roles in these forested ecosystems.

The mountainous landscapes of Washington, Oregon, and California support a very diverse and conspicuous lichen flora. This region is home to several rare, endemic, old-growth-associated species such as *Pseudocyphellaria rainierensis* (fig. 4) and *Nephroma occultum* (fig. 5) as well as species that often achieve impressively high biomass in western forests, like *Bryoria fremontii* (fig. 6). Lichens play many essential functional roles in these forested ecosystems. For instance, species of *Bryoria* and *Alectoria* are important forage for elk, caribou, deer, and flying squirrels (Maser et al. 1985, McCune 1993, Stevenson 1978). Birds, rodents, and invertebrates also use these pendulous, hair-like species for nesting materials and shelter (Hayward and Rosentreter 1994, Pettersson et al. 1995).


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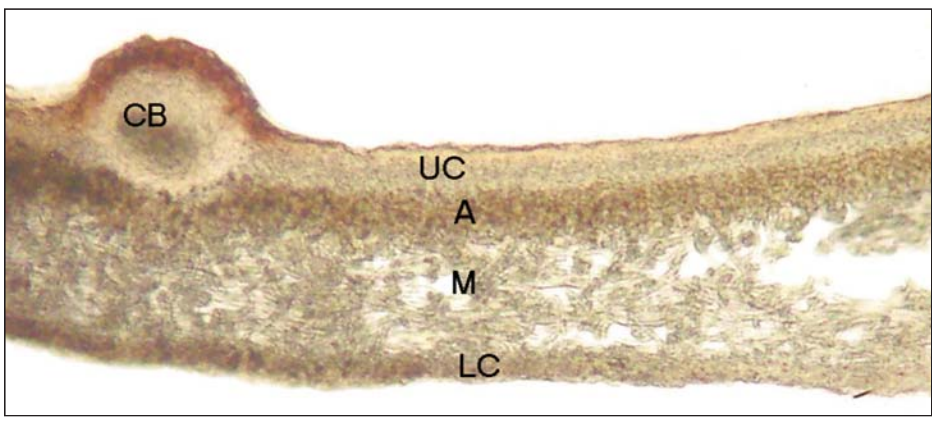
Figure 1—*Hypogymnia physodes* (tube lichen), one of several *Hypogymnia* species occurring in the Pacific Western States.

Daphne Stone

Figure 2—*Lobaria pulmonaria* (lung lichen), a large species found in wet forests of the Pacific Northwest.



Eric Peterson from www.crustose.net

Figure 3—Cross section of the lichen *Lobaria pulmonaria*, a three-way symbiosis between a fungus, algae, and cyanobacteria. Fungal cells are located in the upper cortex (UC), medulla (M), and lower cortex (LC). Photosynthesis occurs in the green algal layer (A) and nodules containing cyanobacteria (CB). The cyanobacteria also fix atmospheric nitrogen into a form that is useable to plants.

Jim Riley

Figure 4—*Pseudocyphellaria rainierensis* (Rainier *pseudocyphellaria* lichen). Provided courtesy of OSU Lichen Group. 1999. Photographs of Pacific Northwest Lichens. Oregon State University, Department of Botany and Plant Pathology, Lichen Research Group.

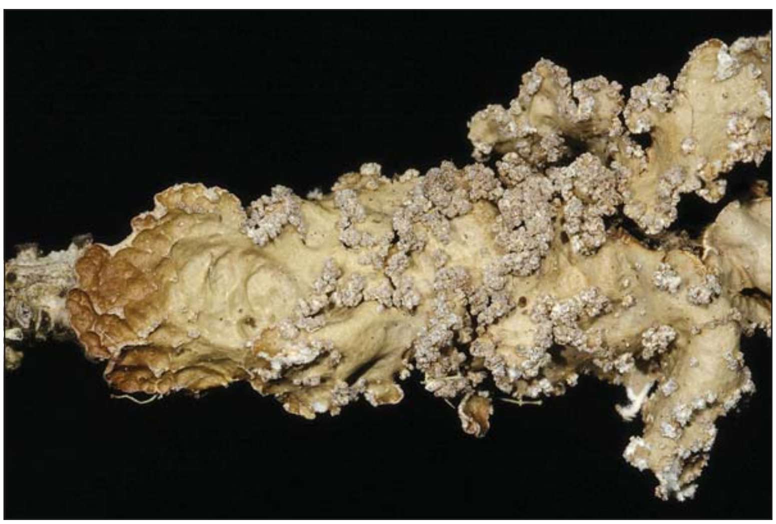


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Figure 5—*Nephroma occultum* (kidney lichen), a rare lichen species inhabiting old-growth forests in the Pacific Northwest.

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Figure 6—Conifers laden with *Bryoria fremontii* (Freemont's horsehair lichen) in Starkey Experimental Forest, eastern Oregon.

Cyanolichens such as *Pseudocyphellaria anthraspis*, *P. crocata* (fig. 7), and *Lobaria oregana* (fig. 8) make important contributions to nutrient cycling in Pacific Northwest forests as their cyanobacteria partners fix atmospheric nitrogen (N_2) into a form that is useable by plants. Nitrogen inputs from cyanolichens may be quite substantial, especially in moist, old-growth forests. It is estimated that *L. oregana* alone fixes as much as 16.5 kg $N_2 \cdot ha^{-1} \cdot yr^{-1}$ at some high biomass sites in the western Cascades of Oregon (Antoine 2004). These lichens, like many others, are critical components of western ecosystems and directly influence forest health.

Lichens as Biological Indicators

Lichens are often likened to canaries in a coal mine because some species are extremely sensitive to environmental change, a major reason for their popularity as bioindicators for natural resource assessment (e.g., Nimis et al. 2002). The Forest Inventory and Analysis (FIA) Program of the U.S. Department of Agriculture, Forest Service (USFS), includes lichens among a suite of forest health indicators (Stolte et al. 2002) that are monitored nationwide on a permanent sampling grid (Will-Wolf 2005). Formally known as the FIA Lichen Community Indicator, these

Tim Wheeler

Figure 7—*Pseudocyphellaria crocata* (*Pseudocyphellaria* lichen); its bright yellow soredia (powdery clusters of algal cells and fungal strands erupting from the surface) are diagnostic.

Eric Straley

Figure 8—*Lobaria oregana* (Oregon lung lichen), an important nitrogen-fixer in western forests.

The structure of a lichen community in a forest intrinsically provides a wealth of information about forest health, function, and local climatic conditions.

data are periodic surveys of epiphytic ("tree-dwelling") lichen communities conducted by specially trained field crews (fig. 9).

The structure of a lichen community in a forest (i.e., species presence and abundance) intrinsically provides a wealth of information about forest health, function, and local climatic conditions (fig. 10). Analysts can extract particular properties of the community data, such as indices of indicator species and community gradients, to address a wide variety of monitoring questions (See sidebar 1).
At present, the three primary objectives of the Lichen Community Indicator are to

Figure 9—The Alaskan Forest Inventory and Analysis crew training for the 2006 lichen certification exam. This was the second year of lichen surveying in coastal Alaska.

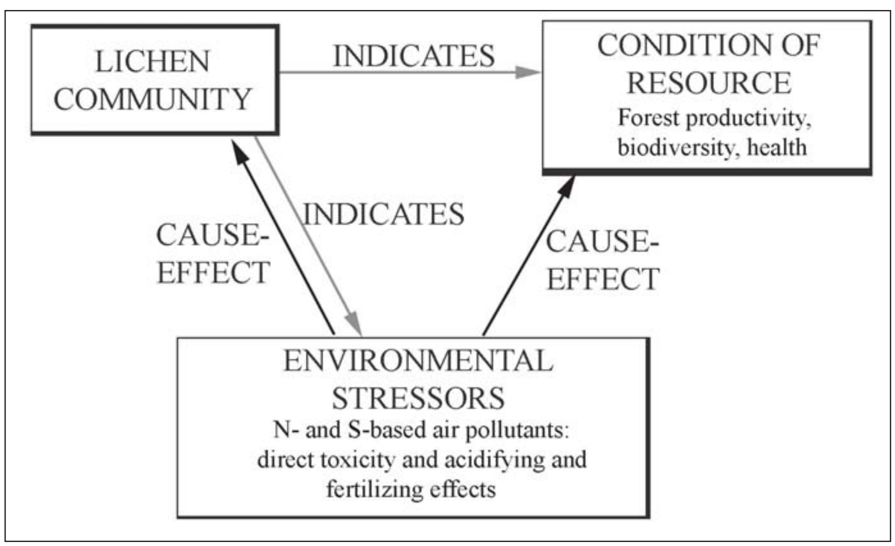

Figure 10—Concept behind the Lichen Community Indicator. N = nitrogen, S = sulfur.

Sidebar 1: Why use bioindicators?
What is the rationale for biomonitoring when we are technologically capable of directly measuring forest conditions? Perhaps the most immediate benefit is the ability to map conditions at a sampling intensity that is prohibitively expensive with active monitors. Moreover, bioindicators are intimately tied to local conditions. Their responses to stressors are often more representative of cumulative impact on the function and diversity of the surrounding ecosystem than are active monitors.

evaluate and monitor biodiversity, air quality, and climate. Survey data may be directly applied for biodiversity monitoring, whereas the latter two applications involve multivariate gradient models.

Report Objectives

Four gradient models that use FIA lichen data to estimate air quality and climate have been implemented in the study region, and three to four additional models are scheduled for completion within the next few years (fig. 11 and table 1). The main objective of this report is to summarize lichen biodiversity and major research findings from the four completed gradient models. Summaries typically include both original analysis and review of previously published articles. Air quality results are mapped to indicate forests at greatest risk of ecological degradation, and modeled climate estimates likewise signify current conditions affecting forests. Lichen indicator species are examined to help link air quality estimates to specific pollutants and also to illustrate the biological underpinnings of each gradient model. These baseline results are of great interest to forest and air managers, serving as the first large-scale comprehensive assessments of forest health for the study region.

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Methods

This section covers the survey protocol for the Lichen Community Indicator (USDA FS 2005) as well as analytical methods used to build gradient models for air quality and climate bioindication. These general overviews are critical to understanding the basis for results presented in the following chapters. Less essential but more technical explanations are presented in sidebars. Any model-specific methods are described in their respective chapters.

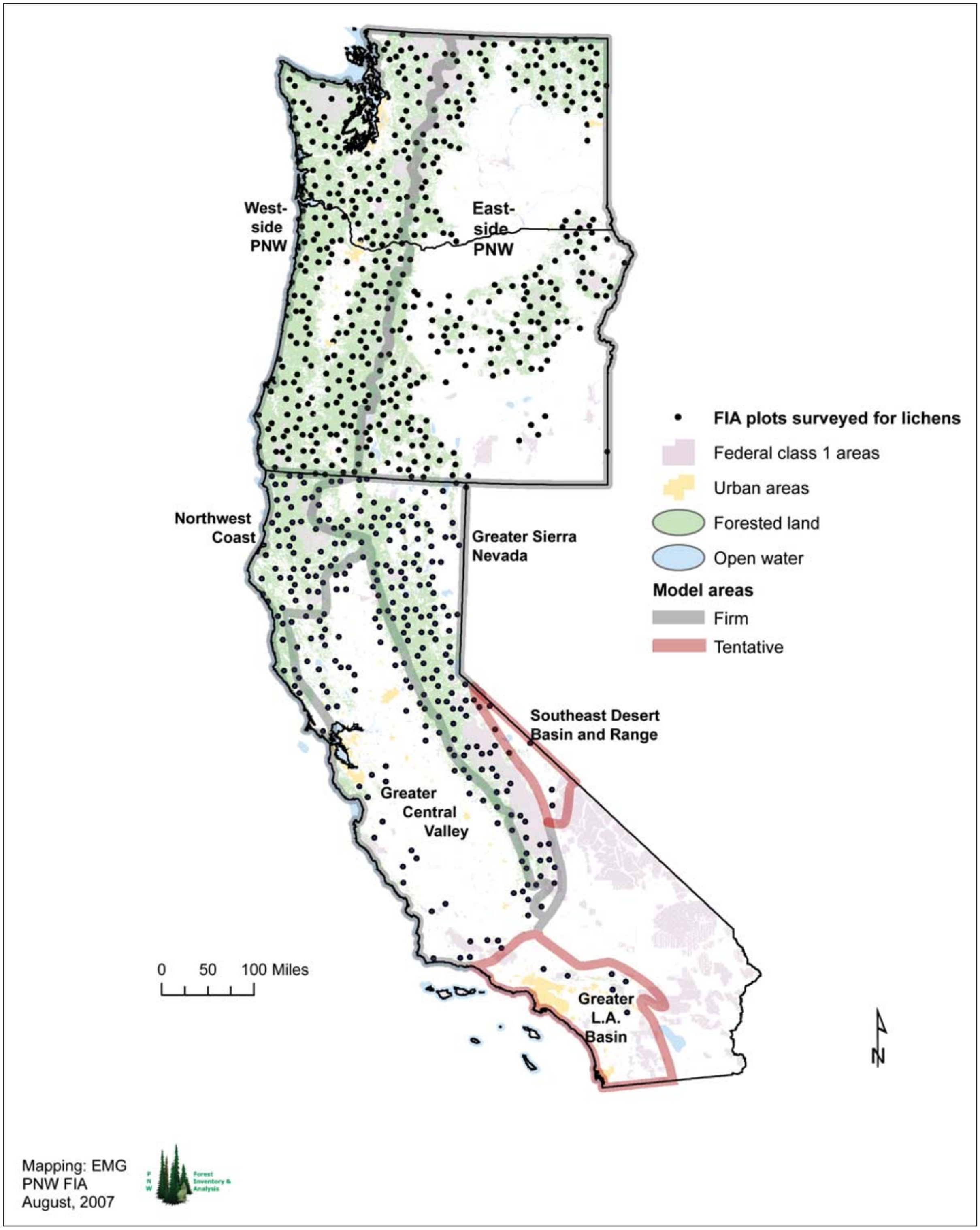

Figure 11—Map of all sites in Washington, Oregon, and California surveyed for lichen communities. Plots are grouped in model areas as described in table 1. Federal class 1 areas are shown because they receive special air quality protection under the Clean Air Act (Section 162(a)). These include national parks, national wilderness areas, and national monuments. Plot locations are approximate.

Table 1—Implementation of the Forest Inventory and Analysis Lichen Indicator in Washington, Oregon, and California[a]

Model region	Estimated parameters	Progress	Citation	Anticipated completion	Notes
Pacific Northwest, west-side	Air quality, climate	Complete	Geiser and Neitlich 2007	Done	See chapters 3 and 6
Pacific Northwest, east-side	Air quality, climate	In progress		Fall 2007	May include plots from Montana and Idaho
California, Northwest Coast	Air quality	In progress		Summer 2007	Region may be merged with the west-side Pacific Northwest Model
California, Greater Central Valley	Air quality	Complete	Jovan and McCune 2005	Done	See chapter 4
California, Greater Sierra Nevada	Air quality	Complete	Jovan and McCune 2006	Done	See chapter 5
California, Northern and Central	Climate	Complete	Jovan and McCune 2004	Done	Encompasses greater Central Valley, greater Sierra Nevada, and Northwest coast models; See chapter 7
California, Greater Los Angeles Basin	Air quality, climate	Study plan under development		2008 or 2009	Model boundaries in figure 11 are preliminary
California, Southeast Desert Basin and Range	Air quality, climate	Study plan in discussion		Not yet scheduled	May be merged with a model for the Southwest (Arizona, New Mexico, and Nevada)

[a] Model boundaries are shown in figure 11.

The FIA crews have completed lichen surveys at a full cycle of plots for California and Oregon and Washington.

The FIA crews have completed lichen surveys at a full cycle of plots for Forest Service Regions 5 (California) and 6 (Oregon and Washington; fig. 11). Five panels of plots were surveyed in 1998, 1999, 2000, 2001, and 2003, and resurveys are tentatively scheduled to begin in 2010. Extensive measurements of forest stand structure, history, and productivity are systematically collected nationwide at one plot for every 2430 ha on the FIA phase 2 (P2) grid. Every 16th plot is also a phase 3 (P3) plot where additional data are collected for all Forest Health Indicators, which includes the Lichen Community Indicator (Stolte et al. 2002).

Lichen Survey Protocol

Lichen community surveys are conducted on a circular, 0.378-ha plot centered on subplot 1 in the standard FIA plot design (fig. 12). Surveys last a minimum of 30 minutes and a maximum of 2 hours during which the crew member collects a voucher specimen of every epiphytic macrolichen species encountered. Although data are not a complete inventory of all macrolichen species on a plot, this cost-effective survey protocol generates representative and repeatable plot data that are comparable across the country. Abundance is estimated for each species by using broad abundance codes (table 2). Surveyors collect from the surface of all standing woody substrates, above 0.5 m and within arm's reach, and also freshly fallen lichens in the litter. Vouchers are sent to professional lichenologists for identification in the lab.

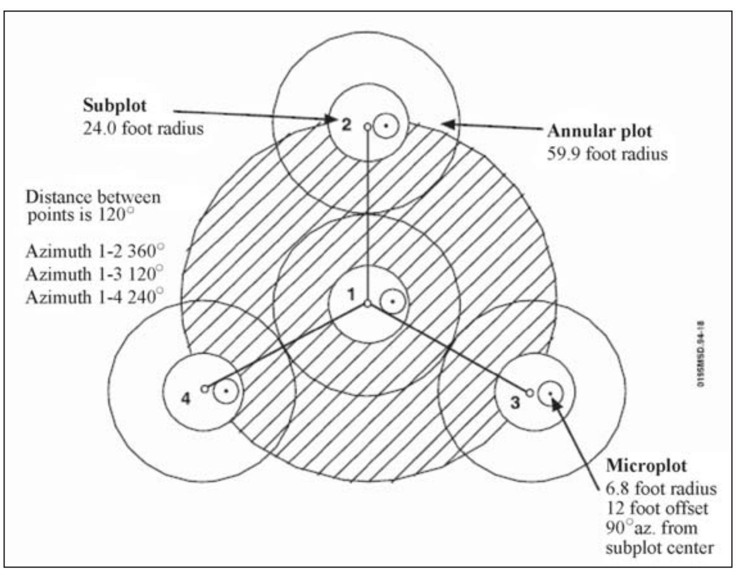

Figure 12—Forest Inventory and Analysis plot design. Lichen communities are surveyed in the shaded area.

Table 2—Abundance codes used during lichen community surveys

Code	Abundance
1	**Infrequent** (1 to 3 thalli)
2	**Uncommon** (4 to 10 thalli)
3	**Common** (>10 thalli; species occurring on less than 50 percent of all boles and branches in plot)
4	**Abundant** (>10 thalli; species occurring on greater than 50 percent of boles and branches in the plot)

Surveyors are nonspecialists specially trained to differentiate between lichen species. Every year surveyors must pass a certification exam administered by a professional lichenologist (fig. 13). At a practice FIA plot, the number of species the trainee collects must be 65 percent or more of the number found by the lichenologist in order to certify. The lichenologist then periodically audits crews during the field season with hot and blind checks to ensure that species capture continues to meet the 65 percent measurement tolerance. Hot checks are mainly instructive, where crew members and the lichenologist survey a plot simultaneously. Blind-checked plots are usually surveyed by a lichenologist within 1 month of the crew, without knowledge of the crew's data, and provide a measure of data quality. Air quality estimates from FIA gradient models have been found to be highly repeatable as long as the 65 percent criterion is met (McCune et al. 1997).

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Figure 13—The Alaskan Forest Inventory and Analysis crew prepares for the 2006 lichen certification exam.

To help build gradient models for air quality or climate bioindication, additional lichen surveys may be conducted at temporary plots off the regular FIA grid (i.e., off-frame plots). These plots are strategically located in areas of special interest or significance (e.g., wilderness areas and national parks) or in places expected to be highly polluted (e.g., in cities, near industry) in order to capture the entire regional pollution gradient. Off-frame plots are often co-located with air quality monitors.

Data Analysis Overview: Gradient Models Demystified

A model built with gradient analysis (see McCune and Grace 2002) is required to apply the lichen community data for air quality and climate monitoring. Gradient analysis helps the investigator detect the strongest patterns (i.e., gradients) in lichen community composition and determine how they relate to environmental variables. Gradient models are typically developed by using either nonmetric multidimensional scaling ordination (NMS) (Kruskal 1964) or regression techniques (or some combination of the two). Usually at least two strong gradients can be extracted from the FIA lichen data: one gradient in community composition relating to air quality and a second gradient relating to macroclimate.

Usually at least two strong gradients can be extracted from the FIA lichen data: one gradient in community composition relating to air quality and a second gradient relating to macroclimate.

Analysts tailor these gradient models to meet the management objectives and research needs of their respective coverage areas. Thus no two models are exactly alike. Attempts are made to integrate lichen data with outside sources of information, such as measurements of pollutant concentrations or deposition at off-frame plots, modeled climate estimates, and FIA forest mensuration data collected from the P2 and P3 grids, as well as lichen survey data from other landscape-scale sampling grids.

Nonmetric multidimensional scaling—
Nonmetric multidimensional scaling is a powerful tool for gradient analysis of complex ecological data (McCune and Grace 2002) and provides the foundation for three of the four models discussed in this report. Basically NMS simultaneously considers the abundance of all lichen species in all plots by using a "distance measure" (e.g., Sørensen or Euclidean distance; McCune and Grace 2002). This measure is a mathematical expression that quantifies how community composition differs between each and every plot in the data. NMS uses these differences to

detect gradients in community composition and score plots along them (see sidebar 2). All reported NMS analyses were conducted using the PC-ORD software package[1] (McCune and Mefford 1999).

Tools including scatterplots, regression, and overlays are used to determine how these lichen community gradients relate to environmental factors. For example, if a gradient detected by NMS is strongly correlated with pollution variables (e.g., nitrogen deposition or sulfur dioxide concentration), the score of a plot on that gradient serves as a relative estimate of local air quality. The FIA lichen surveys contain an enormous amount of information as lichens respond to many

Sidebar 2: Technical aspects of nonmetric multidimensional scaling (NMS)

The data set used to build an NMS model with PC-ORD (McCune and Mefford 1999) is an *n x p* matrix of Forest Inventory and Analysis plots (rows) by species (columns), with each cell containing a lichen abundance code (table 2). NMS is indirect ordination, meaning that detected gradients are based solely on the ecological information given by the distributions of species among plots. This process is technically a transformation of the plots as points in *p*-dimensional species space to a lower dimensional space, which is accomplished through hundreds of iterations. Each detected gradient is, functionally, an independent response of lichen communities to one or more environmental conditions (i.e., an environmental gradient). The analyst must discover the identity of these environmental conditions by looking at ancillary environmental data.

Because NMS generates major community gradients without consideration of environmental variables (unlike the other popular techniques, canonical correspondence analysis and redundancy analysis) (Økland 1996), it is statistically valid to correlate environmental variables with community gradients to make predictions. It is also statistically valid to make predictions for new plots, which can be easily fit to the NMS axes. For further technical detail, an excellent introduction to NMS is given by McCune and Grace (2002, chapter 16).

[1] Use of trade of firm names in this publication is for information and does not imply endorsement of any product or service by the U.S. Department of Agriculture.

Once community gradients are linked to the environmental gradient(s) they reflect, indicator species for that environmental factor can be identified.

aspects of their local environment. In essence, NMS is a distillation of that information into the strongest patterns. Once community gradients are linked to the environmental gradient(s) they reflect, indicator species for that environmental factor can be identified.

Identifying indicator species with species scores—
Species scores were used in chapters 3 and 4 to identify pollution indicator species. Basically each species used to build an NMS model is scored on each of the detected lichen community gradients. The calculation involves simple weighted averaging that considers how the species' abundance was distributed among plots and how those plots scored on the gradient. The species' score is technically its average position on the gradient and a representation of the species' optimum (i.e., for air

Sidebar 3: Calculating species scores

Species scores are calculated by using PC-ORD (McCune and Mefford 1999) in a single weighted-averaging step, whereby species abundance is weighted by plot scores from the nonmetric multidimensional scale air quality gradient:

$$v_j = \frac{\sum_{i=1}^{n} a_{ij} w_i}{\sum_{i=1}^{n} a_{ij}}$$

where v_j = score for species j, a_{ij} = abundance of species j in plot i, w_i is the plot score of plot i, and n is the number of species on the plot. A few important caveats are (1) scores for infrequent species are based on less data and so their scores are less reliable, (2) this analysis is susceptible to bias at extremes of the air quality gradient as species scores are restricted to the range of the data even if the species' true optimum lies beyond the data extremes (McCune and Grace 2002), and (3) a score can be calculated for every species even if the species does not actually respond to air quality. Species scores suggest pollution sensitivity or intolerance but should be supported by multiple lines of evidence.

quality or climate) (McCune and Grace 2002). For a gradient linked to air quality, species scores serve as rough estimates of how species respond individually to pollution in the study area, given a few caveats (see sidebar 3). Species are scored along the same gradient as plots. This means that any categorization of air quality scores that the analyst uses to summarize plots (e.g., best, fair, worst) can be used to gauge the implications of species scores and vice versa.

Indicator species analysis—

A second tool for identification of indicator species, Indicator Species Analysis (ISA) (Dufrêne and Legendre 1997), is used in chapters 3, 6, and 7 to determine air quality and climate indicators. The ISA is a nonparametric analysis available in PC-ORD (McCune and Mefford 1999) that evaluates the faithfulness and exclusivity of each species to predefined groups of plots (McCune and Grace 2002), which are both fundamental characteristics of a reliable indicator. The analyst chooses how to best divide plots into a priori groups, which often involves segmentation of the air quality or climate gradient into useful categories (e.g., low, medium, and high pollution). To assess statistical significance of indicator species, a randomization test is used whereby plots are randomly reassigned to the groups 1,000 times (McCune and Grace 2002).

Part II: Lichen Diversity Biomonitoring

Evaluation of lichen species richness (i.e., a count of species encountered) is the main, formalized application of the Forest Inventory and Analysis (FIA), U.S. Department of Agriculture, Forest Service, Lichen Community Indicator in regions awaiting air quality and climate bioindication models. Because lichen surveys are timed, these species counts are technically a richness index rather than an unbiased estimator for plot species richness. Lichen diversity is commonly used as a general indicator of forest health and "ecological function" (Will-Wolf et al. 2002), as lichens are key primary producers with important linkages to nutrient cycling and forest food webs (see chapter 1 "Introduction"). High or low lichen diversity can result from certain types of air pollution, changes to forest management or stand structure, diversity of plant substrates available for colonization, favorability of climate, return interval of disturbances like fire, and so on. As such, species richness is a simple parameter with a complex origin and interpretation. To answer more specific questions about the local forest environment, analysts often parse out richness indices by using lichen indicator species. Richness or abundance of pollution indicators, for instance, is commonly used in the FIA lichen-air quality models (see chapters 3 to 5).

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Over 20 species of lichens inhabit this small oak in Walnut Park, Corvallis, Oregon.

Chapter 2: Epiphytic Lichen Diversity and Forest Habitats in Washington, Oregon, and California

Key Findings

1. In total, 263 epiphytic lichen species were found among 779 plots
2. Zero to 45 species occurred per plot. Plot-level species richness was highly heterogeneous within most ecoregions.
3. Prominent hotspots of diversity include the Klamath-Siskiyou region shared by Oregon and California, the Oregon-side western Cascades, and the Washington-side eastern Cascades.
4. Highest diversity was found in the Okanogan highlands of eastern Washington, where plots supported an average richness of 21.8 species. The eastern Blue Mountains farther south likewise supported a considerable density of species-rich plots.
5. Plots were sparsely distributed over dry, shrubby ecoregions that lack substantial forest cover like the Columbia Basin, Northwestern Basin and Range, Owyhee uplands, and the agricultural Central Valley. Species richness estimates are least reliable from these poorly sampled areas.

The diversity of conditions is reflected by a remarkable diversity of lichens.

Summary of Lichen Species Richness

Washington, Oregon, and California are home to a wide array of forested ecosystems (fig. 14, table 3). The terrain is highly mountainous and along these steep elevation gradients, climate and forest composition change drastically (fig. 15). The diversity of conditions is reflected by a remarkable diversity of lichens (fig. 16). An impressive total of 263 epiphytic lichen species were found in the region from a full cycle of survey data (n = 779, 1998-2001, 2003) collected by the Forest Inventory and Analysis (FIA) Program, U.S. Department of Agriculture. Among all plots surveyed in Washington (n = 199), Oregon (n = 292), and California (n = 288), plot-level species richness ranged from 0 to 45 species (tables 4 and 5). The study region supports several sizeable clusters of moderate- (≥ 16 species) to high-diversity (> 25 species) plots although richness is, overall, fairly heterogeneous within ecoregions (fig. 17).

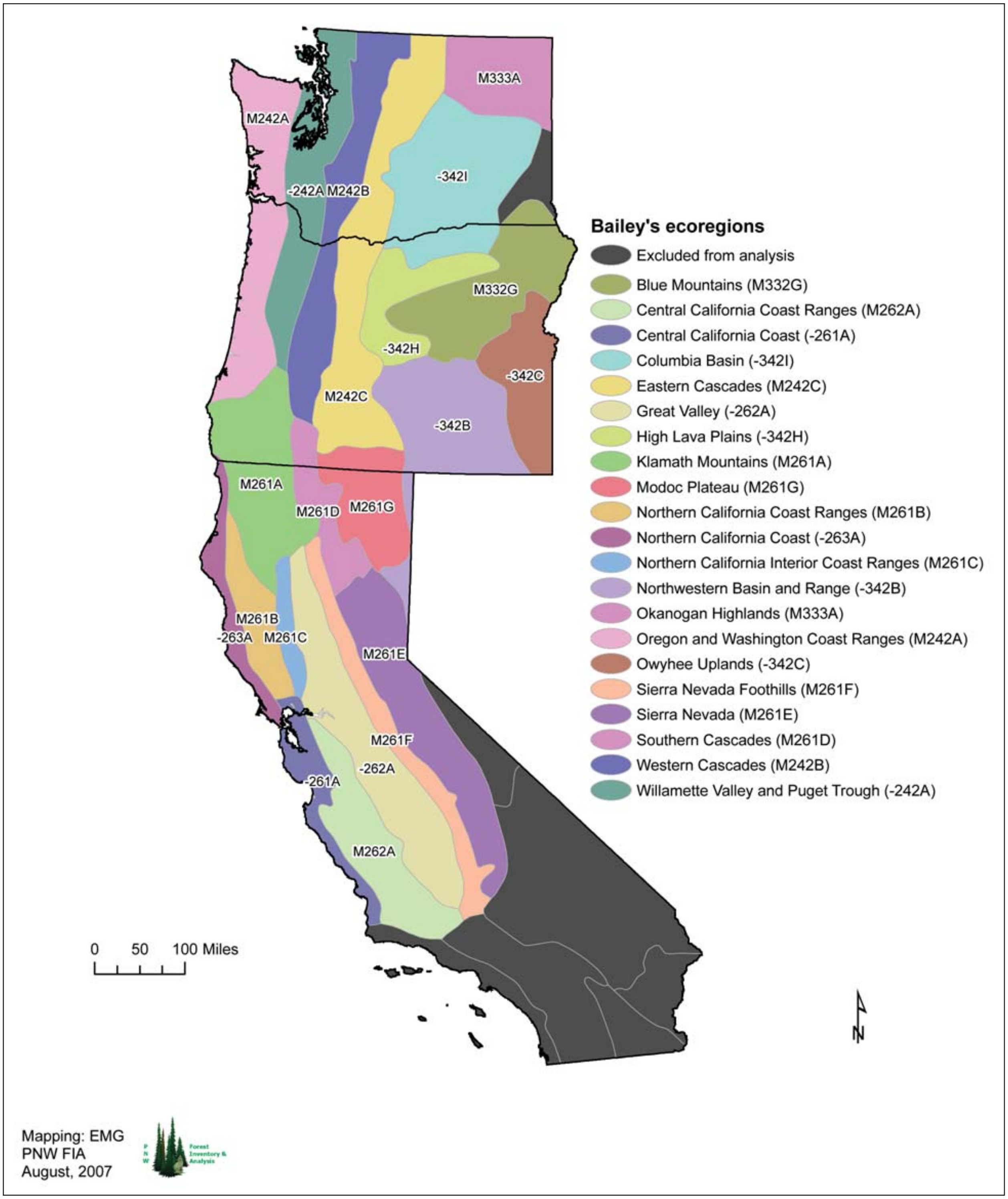


Figure 14—Study area for lichen diversity assessment coded by Bailey's ecoregion sections (1983).

Table 3— Basic parameters of the species richness index summarized by Bailey's ecoregions (1983; see fig. 14)[a]

Ecoregion section	Mean	Min	Max	n	SD	Median
Blue Mountains (M332G)	15.3	1	31	63	7.0	15
Central California Coast (261A)	16.5	12	26	4	6.5	14
Central California Coast Ranges (M262A)	12.1	2	22	13	5.6	13
Columbia Basin (342I)	19.3	13	27	6	5.7	18
Eastern Cascades (M242C)	13.8	0	34	97	7.3	12
Great Valley (i.e., Central Valley) (262A)	13.2	7	23	5	6.3	12
High Lava Plains (342H)	10.1	1	29	15	6.8	9
Klamath Mountains (M261A)	18.6	0	45	84	9.4	19
Modoc Plateau (M261G)	10.7	0	22	37	5.5	10
Northern California Coast (263A)	10.8	1	29	14	6.5	10
Northern California Coast Ranges (M261B)	19.2	7	39	26	8.0	19
Northern California Interior Coast Ranges (M261C)	15.5	7	26	8	7.3	14.5
Northwestern Basin and Range (342B)	8.0	1	17	11	4.3	6.5
Okanogan Highlands (M333A)	21.8	5	34	42	6.2	23
Oregon and Washington Coast Ranges (M242A)	14.3	0	32	73	8.2	15
Owyhee Uplands (342C)	7.9	5	13	7	3.0	7
Sierra Nevada (M261E)	8.9	0	34	79	7.4	8
Sierra Nevada Foothills (M261F)	13.0	2	29	30	6.4	12.5
Southern Cascades (M261D)	16	4	36	30	7.6	15
Western Cascades (M242B)	18.8	0	34	68	6.7	19
Willamette Valley and Puget Trough (242A)	15.7	0	43	54	8.1	15

[a] Ecoregion sections with fewer than four plots were excluded from the analysis.


Daphne Stone

Figure 15—Three Sisters Wilderness, Oregon.

Daphne Stone

Figure 16—Some hardwood forests in the Willamette Valley and Coast Ranges support a high biomass of *Ramalina menziesii* (Menzies' cartilage lichen) and several other green, hair-like species.

Table 4—Lichen species richness in the Pacific Northwest (1998-2001, 2003)[a]

Parameter	Pacific Northwest	Oregon	Washington	W-PNW	E-PNW
Number of plots	491	292	199	247	244
Number of plots by lichen species richness category					
1: 0 to 6 species	60	44	16	26	34
2: 7 to 15 species	186	118	68	81	105
3: 16 to 25 species	188	94	94	105	83
4: >25 species	57	36	21	35	22
Median	15	14	17	17	14
Range of species richness per plot (low to high)	0 to 45	0 to 45	0 to 34	0 to 45	0 to 34
Average species richness per plot (alpha diversity)	15.85	15.00	17.10	16.94	14.75
Standard deviation of lichen species richness per plot	7.99	8.45	7.10	8.20	7.63
Species turnover rate (beta diversity)	13.12	12.13	9.82	11.26	8.27
Total number of species per area (gamma diversity)	208	182	168	191	122

[a] The Pacific Northwest region is broken down into two areas used for air quality and climate biomonitoring (see table 1, fig. 11): the west-side (W-PNW) and the east-side (E-PNW).

Table 5—Lichen species richness in California (1998-2001, 2003)[a]

Parameter	California	GCV	GSN	NWC	SoCal	DBR
Number of plots	288	76	133	68	8	3
Number of plots by lichen species richness category						
1: 0-6 species	61	7	43	3	5	3
2: 7-15 species	141	41	67	31	2	0
3: 16-25 species	62	19	18	24	1	0
4: >25 species	24	9	5	10	0	0
Median	12	13	9	16	2.5	0
Range of species richness per plot (low to high)	0 to 39	2 to 31	0 to 34	1 to 39	0 to 16	0 to 0
Average lichen species richness per plot (alpha diversity)	12.59	14.38	9.87	17.21	4.88	0
Standard deviation of species richness per plot	7.97	6.82	7.06	8.05	6.10	0
Species turnover rate (beta diversity)	16.52	9.11	16.92	9.36	5.12	0
Total number of species per area (gamma diversity)	208	131	118	161	25	0

[a] Plots are broken down into model areas used for air quality biomonitoring (see table 1, fig. 11): greater Central Valley (GCV), greater Sierra Nevada (GSN), Northwest Coast (NWC), greater Los Angeles Basin (SoCal), and the Southeast Desert Basin and Range (DBR).

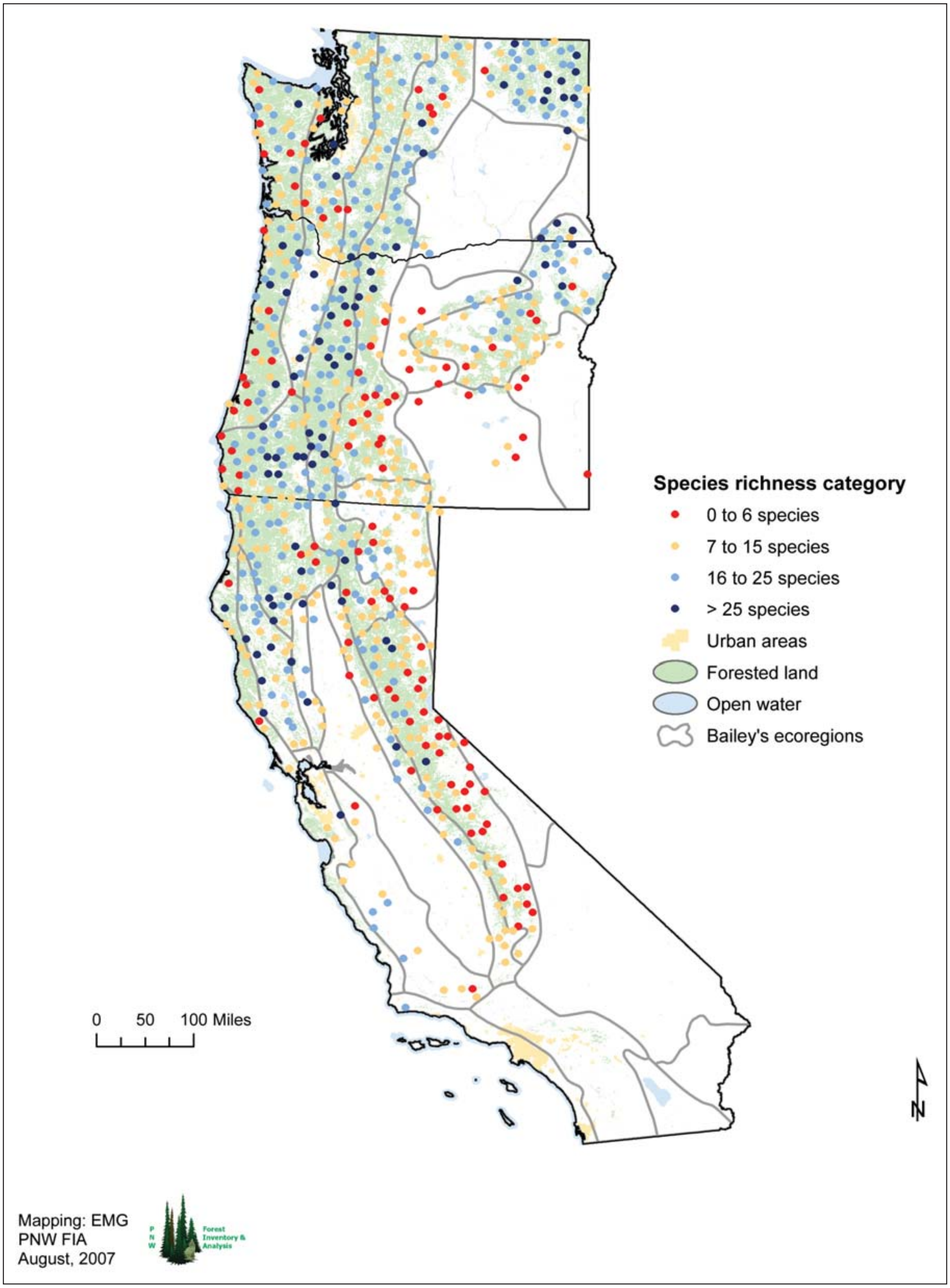


Figure 17—Lichen species richness index for plots.

Coast Ranges (ecoregion section codes: 261A, M262A, M261A, 263A, M261B, M261C, and M242A)

The Pacific Ocean has a strong influence on climate patterns, tending to moderate temperature fluctuation. The western border of the tri-state study region is lined by warm coastal mountains (fig.14) with lush evergreen forests to the north (i.e., *Pinus contorta* [Dougl. ex Loud.], *Picea sitchensis* [(Bong.) Carr.], *Tsuga heterophylla* [(Raf.) Sarg.] , *Pseudotsuga menziesii* [(Mirb.) Franco], *Thuja plicata* [Donn ex D. Don]), giving way to oak communities and chapparal in the drier south. Lichen diversity across these habitats is quite variable (range: 0 to 45 species) with average plot richness ranging from 10.8 to 19.2 species depending on ecoregion (table 3). The most prominent diversity hotspot in California spans the wet forests of the northern California Coast Ranges (M261B) and the Klamath-Siskiyou region (M261A; fig. 17). Lichen communities of the Oregon part of the Klamath Mountains are likewise species-rich and include the highest diversity site in the data set (45 species) at a remote forest stand about 30 km north of Medford, Oregon (see sidebar 4; fig. 18).

The most prominent diversity hotspot in California spans the wet forests of the northern California Coast Ranges and the Klamath-Siskiyou region.

Large Agricultural Valleys (262A, 242A)

Just east of the Coast Ranges in Oregon and central California lie the broad, flat Willamette Valley (Oregon half of 242A, fig. 14) and Central Valley (i.e., Great Valley 262A), where drier and hotter conditions support oak-savanna, prairies, and chaparral. These valleys are important agricultural foci and also include large cities and industry: the Willamette and Central Valleys are home to about 70 percent and 10 percent of the population in their respective states. Owing to intense development and low tree density, too few on-frame plots were surveyed to reliably characterize Central Valley diversity (table 3). Diversity of the Willamette Valley and Puget Trough ecoregion (average: 15.7 species) is comparable to the adjacent Coast Ranges (M242A; 14.3 species) although species dominance is fairly different owing to differences in climate and air quality (see chapters 3 and 6).

Cascades Range and Modoc Plateau (M242C, M261D, M242B, M261G)

Farther east lies a major landform that transects the study region, the volcanic Cascades Range (fig. 14). This rugged network of peaks extends from the Fraser River in British Columbia, Canada, to Lassen Peak in northern California. The wetter west-side supports several mixed-conifer and hardwood forest types where

Pseudotsuga menziesii, Tsuga heterophylla, and *Abies amabilis* (Dougl. ex Forbes) are common components. The Western Cascades is a lichen diversity hotspot (average: 18.8 species; table 3), especially in Oregon where field crews detected 16 or more species at well over half of plots. Diversity is unmatched on the west slope of the Washington Cascades for reasons unknown (fig. 17). East of the crest, precipitation declines abruptly. Open stands of *Pinus ponderosa* (Dougl. ex Laws.) and *P. contorta* predominate in the Cascades rainshadow, which supports less diverse lichen communities (13.8 species) comprising many drought-tolerant (e.g., xerophytic) lichens. Diversity is noticeably higher, overall, on the Washington side of the eastern Cascades.

A similar pattern is observed in the southern Cascades ecoregion in California (M261D). Fairly species-rich west-side communities (average: 16 species) give way to substantially lower diversity (10.7 species) in rainshadow forests of the

Sidebar 4: Klamath Region

The Klamath-Siskiyou region is heralded by the World Conservation Union as a global center of biodiversity. Botanical diversity is exceptional for a temperate coniferous ecosystem (reviewed by DellaSala et al. 1999), and forests are widely considered a conservation priority owing to a high incidence of plant and animal endemism.

Daphne Stone

Figure 18—Serpentine soils, like those found in the Klamath Range, often support endemic and endangered plants.

Modoc Plateau (M261G). This cool desert landscape consists of open *Juniperus occidentalis* (Hook.) stands alongside vast sagebrush-steppe and pockets of mixed-conifer forest. Dry, open-canopied forests are unfavorable for the growth of many lichen species (fig. 19). Thus, relatively low diversity in the eastern Cascades and Modoc forests is not necessarily unnatural.

Sierra Nevada (M261E, M261F)

South of the Cascades lies the granitic Sierra Nevada Range in California (fig. 14), where climate is more profoundly Mediterranean with hot dry summers and cool, wet winters. Resident ecosystems include sequoia groves (*Sequoiadendron giganteum* [(Lindl.) Buchholz]) at southern mid elevations, chaparral and dry oak scrub in the dry foothills, and a broad range of mixed-conifer stands occurring throughout (fig. 20). Tourism is especially prolific in the famous Yosemite, Sequoia, and Kings Canyon National Parks (see chapter 5). Excepting some communities in the foothills, diversity of Sierra sites averaged low at 8.9 species (table 3). Many of the most species-poor sites (<6 species) in the southern two-thirds of the ecoregion are alpine where harsh climatic conditions persist for much of the year (fig. 17).

Eastern Oregon and Washington (342I, 342H, 342B, 342C, M332G, M333A)

Further east in Oregon and Washington are four sparsely-sampled ecoregions (figs. 14 and 17): the Northwestern Basin and Range (average: 8 species), High Lava Plains (10.1 species), Owyhee Uplands (7.9 species), and the Columbia Basin

Tim Wheeler

Figure 19—*Melanelia subolivacea* (*Melanelia* lichen) is widespread across dry forests in eastern Washington, Oregon, and the Modoc Plateau.

Figure 20—*Letharia columbiana* (wolf lichen), a chartreuse species common in high-elevation forests of the Cascades and Sierra Nevada.

Low lichen richness is not surprising for the nominal forests, grasslands, and sagebrush-steppe typical of this arid landscape.

sections (19.3 species; table 3). Minus a few peripheral sites in the Columbia Basin that raise the average, low diversity is comparable to neighboring forests in Oregon's Eastern Cascades. Low lichen richness is not surprising for the nominal forests, grasslands, and sagebrush-steppe typical of this arid landscape.

Nearer to the Idaho border in the Blue Mountain Range (M332G; 15.3 species) and Okanogan Highlands (M333A; 21.8 species), lichen diversity abruptly increases along with forest cover and rainfall. Climate varies widely depending on topographic position, but winters are generally cold and long with extensive snowfal; summers are cool, dry, and brief. Both ecoregion sections support sagebrush-dominated ecosystems as well as conifer stands with *Pinus ponderosa* and *P. menziesii* at higher elevations (fig. 21).

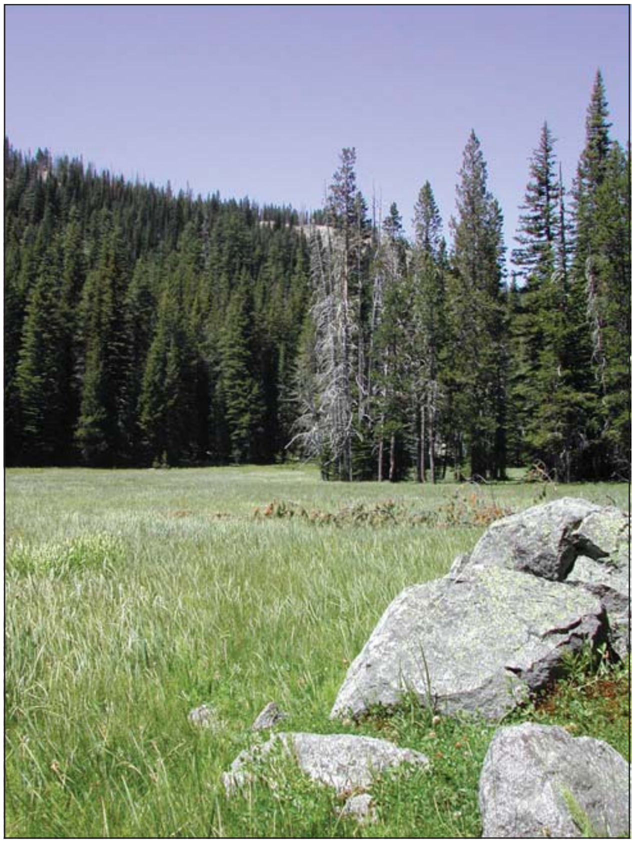


Figure 21—Conifer forest on the Umatilla National Forest in the Blue Mountains.

Lichens are important components of all forest habitats in the study region although species composition, ecological role, and connections to forest health differ substantially across ecosystems.

Conclusions

The biodiversity data presented here serve as the baseline for continued monitoring of forest health and function. Lichens are important components of all forest habitats in the study region although species composition, ecological role, and connections to forest health differ substantially across ecosystems. Environmental gradients in climate and forest stand characteristics are steep enough that two neighboring ecoregion sections may exhibit comparable diversity but possess totally incongruent lichen communities. Species composition of the various floras of Washington, Oregon, and California are explored more deeply in the following chapters for all regions except the eastern Pacific Northwest, which is currently under formal study.

Part III: Air Quality Biomonitoring

Lichens are best known for their utility in monitoring air quality, a practice dating back to the pioneering work of Nylander (1866). Since then, modern community-based approaches, like that of the Lichen Community Indicator, have benefited greatly from a profusion of research concerning which species are reliable indicators of what pollutants (e.g., Gilbert 1986; Hawksworth and Rose 1970; Sigal and Nash 1983; van Herk 1999, 2001) and modern computer technology that permits complex statistical analyses. Through the effective use of indicator species, community-based lichen models can often be tied to the deposition of a specific type of pollution. Several common compounds affect lichens, although relationships to sulfur dioxide, nitrogen-containing pollutants, and acidic deposition, are the best understood.

The three chapters in part III cover recent air quality bioindication results from the west-side Pacific Northwest, the greater Central Valley of California, and the nearby greater Sierra Nevada. Detected air quality patterns are mapped and summarized for each study area. Each chapter also discusses indicator species to illustrate the ecological underpinnings of the bioindication models. An attempt is made to define and utilize two promising groups of indicator species, the acidophytes and neutrophytes, which are not yet widely recognized by the North American lichen biomonitoring community.

Sarah Jovan

Tufted *Usnea* (beard lichen) hangs from a hawthorn branch. Walnut Park, Corvallis, Oregon.

Chapter 3: Air Quality in the West-Side Pacific Northwest

Key Findings

1. There is strong evidence that one or more nitrogen (N) pollutants are impacting forests in the western Pacific Northwest.
2. Geiser and Neitlich (2007) found high N accumulations in lichens collected from polluted sites.
3. Lichen communities at polluted sites are also characterized by species promoted by or tolerant of N, whereas communities at clean sites are more heavily dominated by species known to be N-intolerant or generally pollution-sensitive.
4. Lichen communities and N content of lichens collected from forests near urban and agricultural areas reflect high N deposition. Air quality impacts are estimated to be most extensive in forests of the Willamette Valley and Puget Trough ecoregion section.
5. Remote forests at mid to high elevations in the Cascades, near national parks, and in the coast and Olympic Ranges, appear the most pristine.

Introduction to the Model

The gradient model for the west-side Pacific Northwest was designed for monitoring air quality and climate change in western Oregon and Washington forests (figs. 22 and 23). This model was developed by Geiser and Neitlich (2007) in a partnership between Forest Inventory and Analysis (FIA) and the Forest Service (FS) Region 6 Air Resource Management Program. They used nonmetric multidimensional scaling ordination (NMS) (see chapter 1 “Methods” section) to build the gradient model from 293 plots. These calibration plots were strategically drawn from a pool of over 1,400 plots surveyed for lichens between 1994 and 2001 (see sidebar 5). Calibration data included FIA plots (n = 19), plots on the FS Region 6 Current Vegetation Survey grid (CVS; n = 155; Max et al. 1996), and supplementary off-frame plots installed in both urban and remote areas (n = 119). Additional plots surveyed in the west-side Pacific Northwest study area can be easily fit to the model and scored for both air quality and climate.

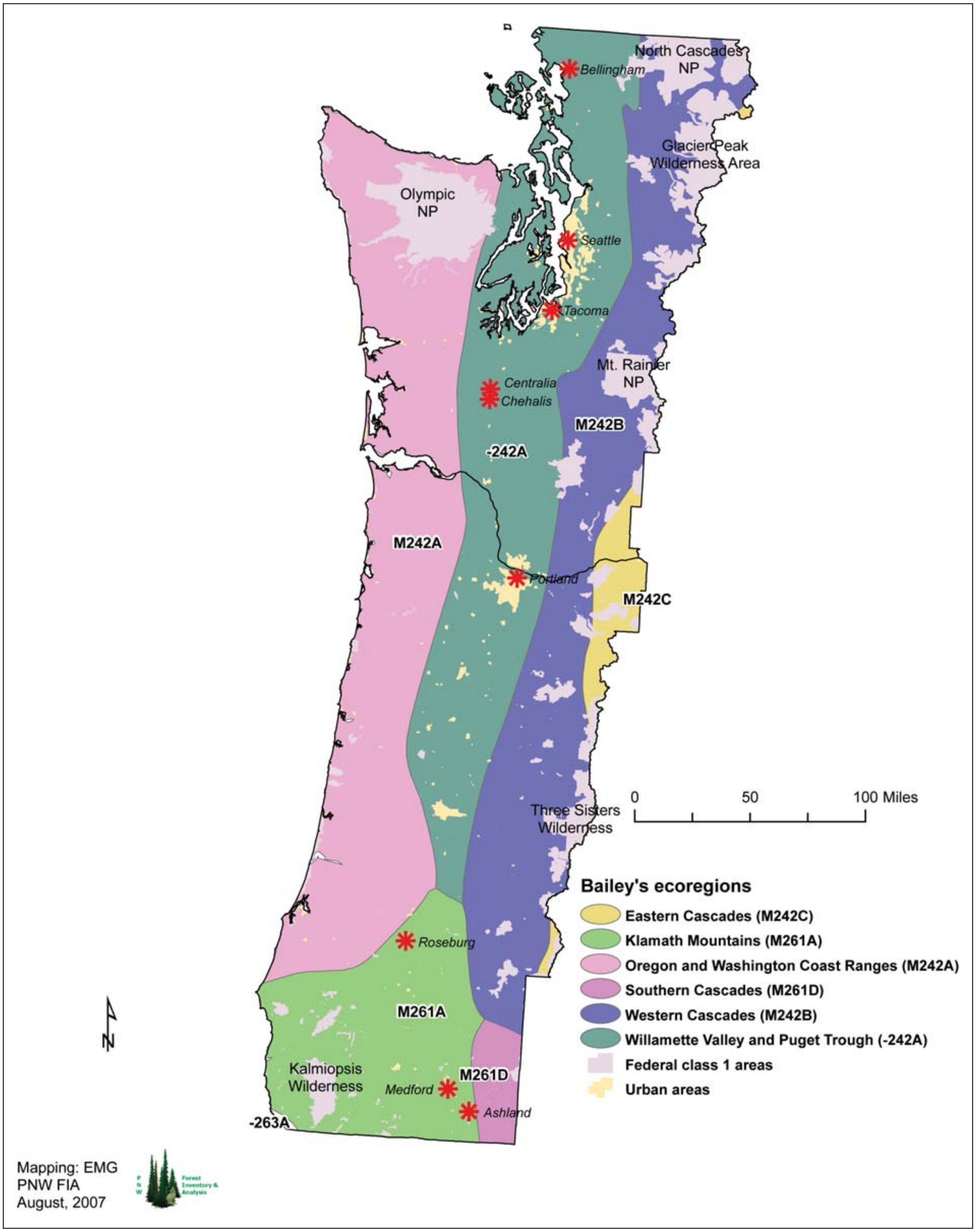


Figure 22—West-side Pacific Northwest model area. The eastern-most boundary is delineated by county lines, for the most part coinciding with the Cascades crest. Major cities are indicated by red asterisks.

Sarah Jovan

Figure 23—Riparian forest in Columbia River Gorge Scenic Area, Oregon.

Sidebar 5: Selection of calibration plots

For bioindication models that cover mountainous landscapes, it is not uncommon for elevation and precipitation to confound air quality estimates. Pollution emissions are often concentrated at low elevations, which are also drier than higher elevation forests (Jovan and McCune 2006, McCune et al. 1998). Among the 1,416 plots surveyed in the west-side Pacific Northwest, Geiser and Neitlich (2007) were able to select a calibration data set with equivalent numbers of polluted and clean sites spanning the elevation and precipitation gradient. (By definition, “polluted” sites possessed lichens with relatively high accumulations of N). This extra step reassured effective isolation of air quality versus elevation-related effects in the bioindication model. A second strategy for dealing with confounded environmental variables is presented in chapter 5.

Ancillary Data: Lichen Nitrogen and Sulfur Content

To provide independent verification of air quality patterns detected by the gradient model, common epiphytic lichens, like *Platismatia glauca* and *Hypogymnia imshaugii* (figs. 24 and 25), were collected from more than half of all surveyed plots (n = 886; Geiser and Neitlich 2007). Lichen samples were analyzed for N and sulfur (S) content by using protocols described in Blett et al. (2003). Both elements are key components of several major west-side pollutants. Chemical analysis is a

Roseann Barnhill, http://redskystudio.org

Figure 24—*Platismatia glauca* (ragged lichen).

Tim Wheeler

Figure 25—*Hypogymnia imshaugii* (Imshaug's tube lichen).

very practical biomonitoring tool because lichens accumulate both airborne and waterborne chemicals in concentrations that mirror the local pollution environment (Blett et al. 2003, Bruteig 1993, Geiser 2004, Jovan and Carlberg 2007, Søchting 1995).

N compounds are a key component of the air quality degradation detected by the model.

Interpretation of Air Quality Estimates: Nitrogen Pollutants Are Key Stressors

NMS uncovered two prominent gradients in lichen community composition; one relating to air quality and the other relating to forest climate (chapter 6). Several lines of evidence suggest that N compounds are a key component of the air quality degradation detected by the model although other types of pollution may certainly contribute. As reported by Geiser and Neitlich (2007), plots receiving high (poor) air quality scores were associated with (1) forests near urban or agricultural areas, (2) lichen samples with elevated N (r = 0.73) and S concentrations (r = 0.68), (3) regionally high wet deposition of ammonium (NH_4^+) measured by nearby National Atmospheric Deposition Program monitors (NADP; r = 0.74), and (4) lichen species known to be tolerant of or promoted by N (see "Discussion" below). Air quality scores are relative (i.e., the higher a plot scores on the air quality gradient, the poorer the air quality) but could be calibrated with direct pollutant measurements if more were available.

Discussion of Indicator Species

Two analyses of lichen indicator species are used to demonstrate how air quality in the west-side Pacific Northwest manifests as a lichen community response detectable with gradient analysis. First, Geiser and Neitlich (2007) defined indicator species of "polluted" vs. "clean" plots in the calibration data set using Indicator Species Analysis (ISA) (Dufrêne and Legendre 1997); (see sidebar 6). The ISA is reviewed below but results are reconceptualized in terms of four groups of lichens known to respond differently to N: nitrophytes, acidophytes, neutrophytes, and stratified cyanolichens. Linkages of the air quality gradient to N provided an excellent opportunity in this report to further develop our understanding of the N indicator groups. So as a followup, the same data set was used to score each lichen species along the air quality gradient to estimate how each responds individually to N (see "Indicator Synthesis" below). These species scores will help researchers determine which North American species belong to the understudied acidophytic and neutrophytic groups.

Sidebar 6: Defining a priori groups for Indicator Species Analysis

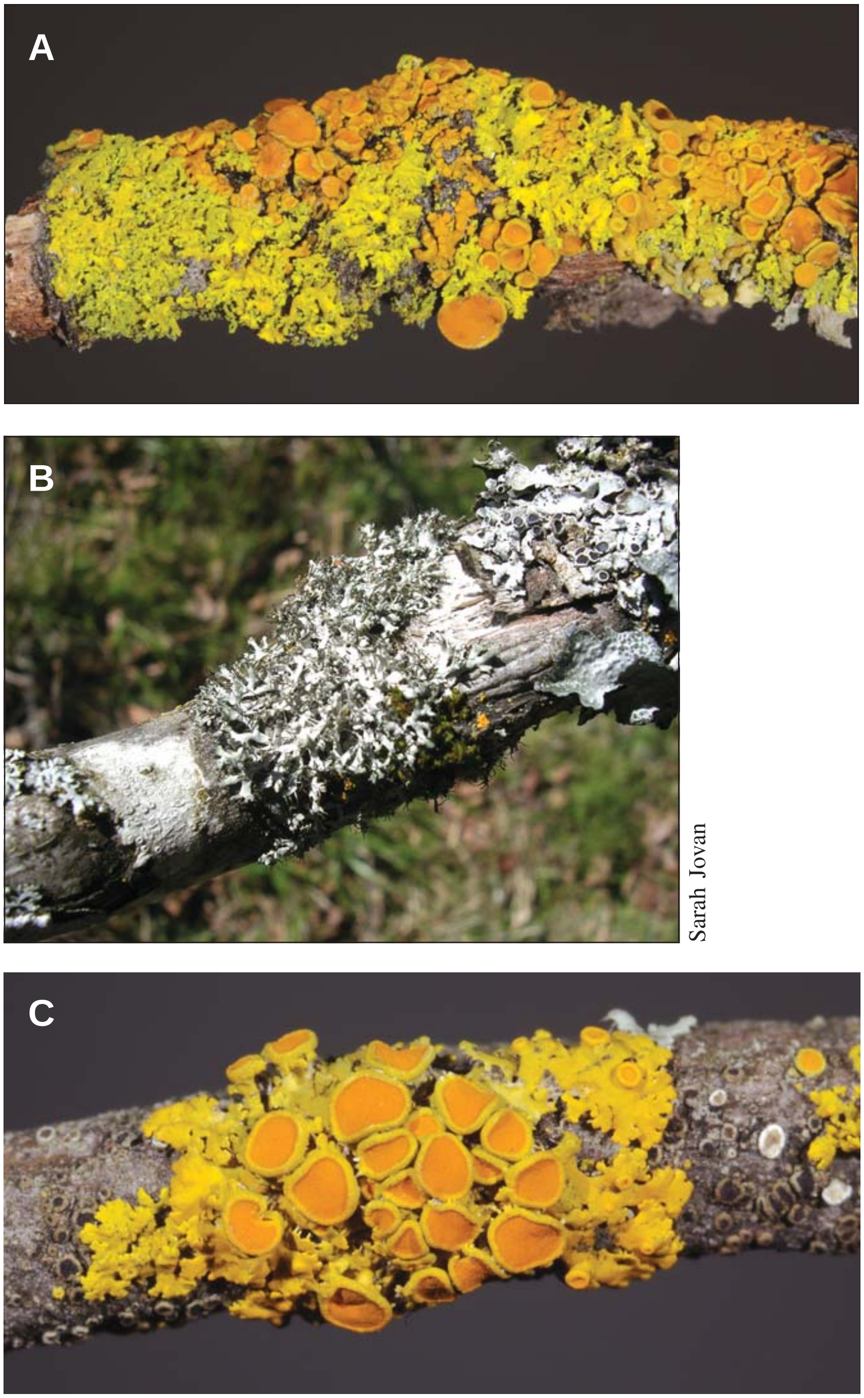
As described in chapter 1 “Indicator Species Analysis,” ISA is used to define statistically significant indicator species for groups of plots defined by the analyst. In this case, Geiser and Neitlich (2007) defined two groups, “polluted” and “clean.” Plots assigned to the “polluted” group had the highest air quality scores, spanning the range in which 90 percent of plots either occurred in an urban area or supported *Platismatia glauca* with enhanced N (N > 0.59 percent). Conversely, only 10 percent of plots in the “clean” group, scoring at the other extreme of the air quality gradient, had *P. glauca* with enhanced N.

Direct and Indirect Nitrogen Effects on Lichens

Nitrogen potentially affects lichens in two ways, directly by fertilization or other physiological effect, and indirectly by altering bark pH. Definitive research that clearly distinguishes between these two modes of action is lacking, in large part because substrate pH is often closely linked to deposition of certain N compounds. For instance, high ammonia (NH_3) deposition will raise bark pH while acidic forms of N, like nitric acid (HNO_3), may have the opposite effect. This confounding of direct N effects by substrate pH is not necessarily problematic unless other anthropogenic or natural agents are present that introduce significant variation in bark pH among sites. Alkaline dust is a common example of a natural agent that appears to affect at least some of the N indicators in dry climates (see next section). Because of potential interference like this, bioindication results for N are most reliable when supported by one or more sources of ancillary N data like those listed below.

Nitrophytes

Geiser and Neitlich’s (2007) ISA identified several statistically significant indicators of “polluted” plots that are widely considered nitrophytes, a well-known group of indicator species used already by FIA for N biomonitoring in California (Jovan and McCune 2004, 2005, 2006). Nitrophyte is a term commonly used to describe lichens that tolerate high N and high pH situations. Examples from the west-side Pacific Northwest include *Candelaria concolor*, *Physcia adscendens*, and *Xanthoria polycarpa* (fig. 26). Many studies have documented nitrophyte enhancement as a function of NH_3 (e.g., Frati et al. 2007; Ruoss 1999; van Dobben and de Bakker 1996; van Herk 1999, 2001) although a more generalized, positive response to N pollution is possible. In the absence of human-made pollution, these species tend



Tim Wheeler

Sarah Jovan

Tim Wheeler

Figure 26—Nitrophytic indicators of polluted plots in the west-side Pacific Northwest: (a) *Candelaria concolor* (concolor lemon lichen), (b) *Physcia adscendens* (rosette lichen), (c) *Xanthoria polycarpa* (orange wall lichen).

to inhabit eutrophicated substrates such as bark beneath bird perches, near tree wounds, or contacted at some point by urine (Barkman 1958, van Herk 1999). Nitrophytic blooms may sometimes occur in the absence of any obvious inputs of basic N compounds, such as near cement plants (Gilbert 1976) or in dry climates (Loppi and Pirintsos 2000) where alkaline dust is prevalent.

Acidophytes

***Bryoria fuscescens,* one of the strongest indicators of clean sites in the west-side Pacific Northwest, has been largely extirpated from its historical range in the Netherlands. High N is believed to play a critical role.**

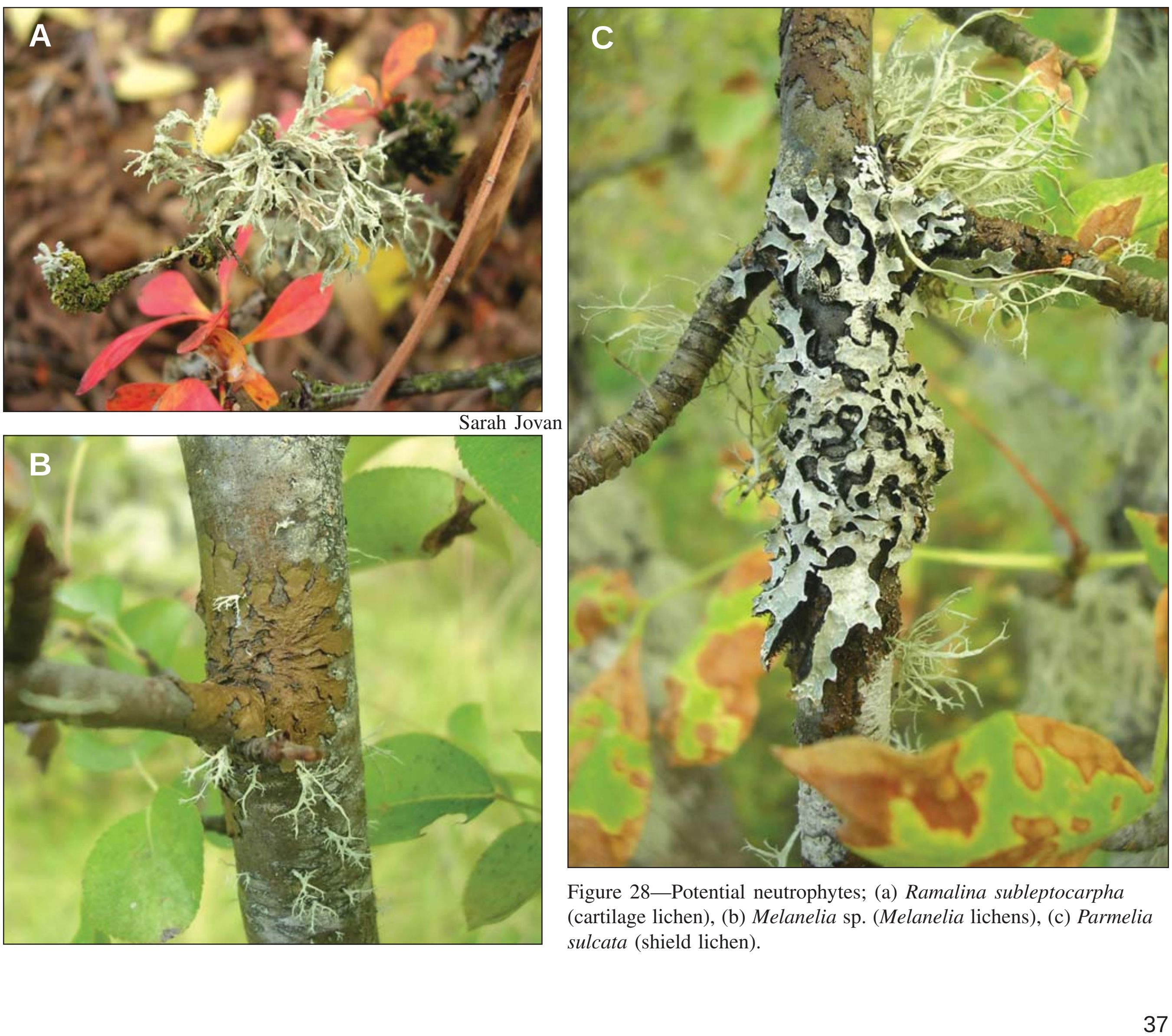
Conversely, many of the statistically significant indicators of “clean” plots are potentially acidophytic. Acidophyte technically describes species requiring an acidic substrate, which may explain why these indicators are characteristically intolerant of NH_3 (Sparrius 2007; van Herk 1999, 2001). Some acidophytes, however, show promise as more generalized N indicators. A recent study by van Herk et al. (2003) in the Netherlands suggests several acidophytes are also highly sensitive to both ammonium (NH_4^+) and nitrate (NO_3^-). This N indicator group is used primarily by the western European research community (Lambley and Wolseley 2004), and candidates have not yet been formally defined for the North American flora. However, several “clean” indicators identified by the ISA are congeners (e.g., species belonging to the same genus) of European acidophytes. These include multiple species of *Bryoria* (e.g., fig. 6, fig. 27), *Hypogymnia* (e.g., fig. 1, fig. 25), and *Usnea*. *Bryoria fuscescens* (fig. 27), one of the strongest indicators of clean sites in the west-side Pacific Northwest, has been largely extirpated from its historical range in the Netherlands. High N is believed to play a critical role (Van Herk et al. 2003).

Roger Rosentreter

Figure 27—Deer grazing on *Bryoria fuscescens* (horsehair lichen), an acidophyte and clean air indicator in west-side forests.

Neutrophytes

Nonnitrophytic indicators of polluted plots were mostly species of *Melanelia*, *Parmelia*, and *Ramalina* (fig. 28) (Geiser and Neitlich 2007). These genera are considered "neutrophytic" by Dutch lichenologists Sparrius (2007) and van Herk (1999) although the term is not yet widely applied in lichen biomonitoring research. Generally speaking, neutrophytes are considered intermediately sensitive to NH_3 (i.e., more sensitive than nitrophytes, less sensitive than acidophytes). According to Sparrius (2007), neutrophytes are actually promoted by NH_3 but have a lower critical threshold than nitrophytes (i.e., neutrophytes in a community will begin to die off while nitrophytes continue to prosper as NH_3 rises). The term



Sarah Jovan

Figure 28—Potential neutrophytes; (a) *Ramalina subleptocarpha* (cartilage lichen), (b) *Melanelia* sp. (*Melanelia* lichens), (c) *Parmelia sulcata* (shield lichen).

neutrophyte technically describes species preferring a substrate pH intermediate to nitrophytes and acidophytes. Conceivably, their response to N may be largely a function of substrate pH effects. The importance of direct stimulation or toxicity by N requires further study, however. Among the N indicator groups, pollution tolerances of the neutrophytes are least understood.

Stratified Cyanolichens

Other indicators identified by Geiser and Neitlich (2007) for clean sites included large, leafy cyanolichen species like *Lobaria oregana* (fig. 8) and *Nephroma bellum* (fig. 29; see chapter 1 "Introduction"). The result is unsurprising given the cyanolichen reputation for being especially "stress-sensitive" (Richardson and Cameron 2004). Compared to the nitrophytes and acidophytes, studies suggesting linkages between cyanolichen distributions and N are more anecdotal (but see mention of *Lobaria* in Farmer 1997, Lambley et al. 2004, Mitchell et al. 2005). Unlike the other N indicator groups, the term cyanolichen is biologically based and has no reference to specific pH or substrate preference, although this group is particularly well-known for high sensitivity to acidic deposition (i.e., Farmer et al. 1991, Gauslaa 1985, Gilbert 1986, Goward and Arnesault 2000, Richardson and Cameron 2004).

Jim Riley

Figure 29—*Nephroma bellum* (naked kidney lichen), a stratified cyanolichen and clean air indicator.

Indicator Synthesis

The ISA provides clear ecological evidence that one or more forms of N are affecting lichen community composition in the west-side Pacific Northwest and thus, entering the surrounding forest ecosystem. Figure 30 presents a more holistic view of how species relate individually to the N gradient detected by NMS. The gradient is divided into six air quality zones determined by Geiser and Neitlich (2007) (best, good, fair, degraded, poor, and worst; see sidebar 7). A species position along the x-axis in the diagram is determined by its score (i.e., optimum)

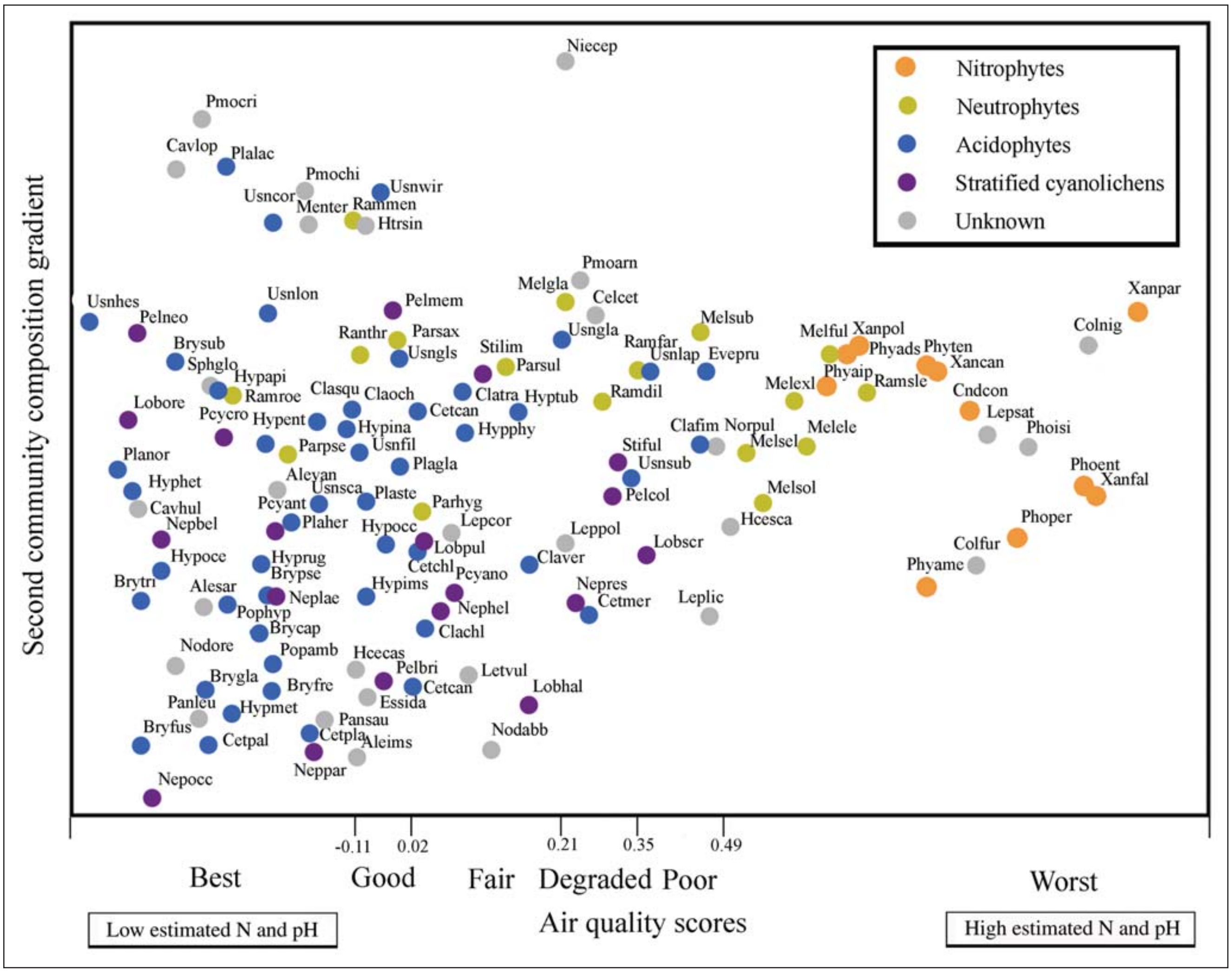


Figure 30—Distribution of species scores across the air quality gradient (x-axis). Scores are divided into the six air quality zones defined by Geiser and Neitlich (2007). The y-axis is included here for display purposes only; it is a second gradient in lichen community composition incidental to the discussion. Full species names are given in table 6.

on the air quality gradient (for methods see chapter 1 "Identifying Indicator Species"); a low species score suggests N sensitivity, whereas a high species score suggests tolerance or a stimulatory effect (table 6). It must be stressed, though, that the relative importance of direct N effects versus pH effects in determining species' responses is unknown at this juncture. Important caveats for interpretation of species scores are discussed in sidebar 3.

Many species were classified a priori to one of the four N indicator groups. Cyanolichens and nitrophytes are already well-defined from the literature, whereas acidophyte and neutrophyte classifications are intended as a starting point for determination of North American candidates (table 6). Tentative designations were given to west-side Pacific Northwest species belonging to a genus exhibiting acidophytic or neutrophytic behavior in the Netherlands (Sparrius 2007; van Herk 1999, 2001) or United Kingdom (Sutton et al. 2004). Some misclassifications are likely given this coarse system but species scores will help steer refinements in future studies of the N indicators (table 6).

Figure 30 shows a distinct progression from conditions favoring cyanolichens and potential acidophytes (low estimated N and pH) towards conditions favoring nitrophytes (relatively high estimated N and pH) along the west-side Pacific Northwest air quality gradient. Overall, 42 percent of cyanolichens and 59 percent of

Sidebar 7: Air quality zones

Geiser and Neitlich (2007) used results of the ISA to define six biologically-based air quality zones: best, good, fair, degraded, poor, and worst. Each zone is based on the distribution of air quality scores for plots inhabited by either the "polluted" or the "clean" air indicator species. Upper bounds for the best, good, and fair zones are based on the 75th, 90th, and 97.5th percentiles of plot scores associated with the clean air indicators. For example, 75 percent of plots hosting the clean air indicators had air quality scores < -0.11, which serves as the upper bound of the "best" zone (as well as the lower bound of the "good" zone). The upper bound of the "degraded" zone is the 25th percentile of air quality scores for plots hosting the polluted air indicators while the upper bound of the "poor" zone corresponds to the 100th percentile for clean air indicators. Thus, by definition, none of these sensitive species were present in "worst" plots.

Table 6—Species list for the west-side Pacific Northwest calibration data set[a]

N indicator group	Species	Acronym	Frequency	Species score	Air quality zone
			Percent		
Nitrophytes					
	Candelaria concolor	Cndcon	8.19	0.89	Worst
	Physcia adscendens	Phyads	25.94	0.69	Worst
	Physcia aipolia	Phyaip	17.75	0.66	Worst
	Physcia americana	Phyame	3.41	0.82	Worst
	Physcia tenella	Phyten	8.53	0.82	Worst
	Physconia enteroxantha	Phoent	4.44	1.07	Worst
	Physconia perisidiosa	Phoper	7.51	0.97	Worst
	Xanthomendoza fallax	Xanfal	3.75	1.09	Worst
	Xanthoria candelaria	Xancan	3.41	0.83	Worst
	Xanthoria parietina	Xanpar	1.71	1.15	Worst
	Xanthoria polycarpa	Xanpol	25.60	0.71	Worst
Potential acidophytes					
	Bryoria capillaris	Brycap	26.62	-0.27	Best
	Bryoria fremontii	Bryfre	2.39	-0.25	Best
	Bryoria friabilis	Bryfri	6.48	-0.30	Best
	Bryoria fuscescens	Bryfus	8.19	-0.46	Best
	Bryoria glabra	Brygla	9.22	-0.36	Best
	Bryoria pseudofuscescens	Brypse	5.46	-0.25	Best
	Bryoria subcana	Brysub	1.71	-0.41	Best
	Bryoria trichodes	Brytri	4.44	-0.46	Best
	Cetraria canadensis	Cetcan	7.85	-0.02	Good
	Cetraria chlorophylla	Cetchl	51.88	-0.01	Fair
	Cetraria merrillii	Cetmer	3.41	0.27	Degraded
	Cetraria orbata	Cetorb	61.09	-0.01	Fair
	Cetraria pallidula	Cetpal	7.85	-0.35	Best
	Cetraria platyphylla	Cetpla	16.04	-0.18	Best
	Cladonia chlorophaea	Clachl	2.05	0.00	Fair
	Cladonia fimbriata	Clafim	8.87	0.45	Poor
	Cladonia ochrochlora	Claoch	20.48	-0.11	Best
	Cladonia squamosa	Clasqu	18.09	-0.18	Best
	Cladonia transcendens	Clatra	14.68	0.07	Fair
	Cladonia verruculosa	Claver	2.05	0.17	Fair
	Evernia prunastri [b]	Evepru	52.90	0.46	Poor
	Hypogymnia apinnata	Hypapi	37.88	-0.33	Best
	Hypogymnia enteromorpha	Hypent	61.77	-0.26	Best
	Hypogymnia heterophylla	Hyphet	2.05	-0.48	Best
	Hypogymnia imshaugii	Hypims	41.30	-0.09	Good

Table 6—Species list for the west-side Pacific Northwest calibration data set[a] (continued)

N indicator group	Species	Acronym	Frequency	Species score	Air quality zone
			Percent		
	Hypogymnia inactiva	Hypina	67.92	-0.13	Best
	Hypogymnia metaphysodes	Hypmet	11.26	-0.31	Best
	Hypogymnia occidentalis	Hypocc	13.65	-0.06	Good
	Hypogymnia oceanica	Hypoce	4.10	-0.43	Best
	Hypogymnia physodes	Hypphy	72.01	0.07	Fair
	Hypogymnia rugosa	Hyprug	2.05	-0.27	Best
	Hypogymnia tubulosa	Hyptub	61.77	0.15	Fair
	Parmeliopsis ambigua	Popamb	5.80	-0.25	Best
	Parmeliopsis hyperopta	Pophyp	33.79	-0.32	Best
	Platismatia glauca	Plagla	82.94	-0.04	Good
	Platismatia herrei	Plaher	51.88	-0.21	Best
	Platismatia lacunosa	Plalac	5.12	-0.32	Best
	Platismatia norvegica	Planor	10.92	-0.50	Best
	Platismatia stenophylla	Plaste	42.32	-0.09	Good
	Usnea cornuta	Usncor	21.16	-0.25	Best
	Usnea filipendula	Usnfil	48.46	-0.11	Best
	Usnea glabrata	Usngla	24.57	0.22	Degraded
	Usnea glabrescens	Usngls	8.53	-0.04	Good
	Usnea hesperina	Usnhes	1.71	-0.54	Best
	Usnea lapponica	Usnlap	5.12	0.36	Poor
	Usnea longissima	Usnlon	7.51	-0.26	Best
	Usnea scabrata	Usnsca	23.21	-0.17	Best
	Usnea subfloridana	Usnsub	14.33	0.34	Degraded
	Usnea wirthii	Usnwir	37.20	-0.06	Good
Potential neutrophytes					
	Melanelia elegantula	Melele	1.37	0.63	Worst
	Melanelia exasperatula	Melexl	16.38	0.60	Worst
	Melanelia fuliginosa	Melful	13.31	0.66	Worst
	Melanelia glabra	Melgla	1.02	0.23	Degraded
	Melanelia subaurifera	Melsub	20.14	0.45	Poor
	Melanelia subelegantula	Melsel	8.19	0.53	Worst
	Melanelia subolivacea	Melsol	5.80	0.55	Worst
	Parmelia hygrophila[b]	Parhyg	41.30	0.00	Fair
	Parmelia pseudosulcata	Parpse	5.80	-0.22	Best
	Parmelia saxatilis[b]	Parsax	4.78	-0.04	Fair
	Parmelia sulcata	Parsul	87.71	0.13	Fair
	Ramalina dilacerata	Ramdil	18.09	0.29	Degraded
	Ramalina farinacea	Ramfar	60.41	0.36	Poor
	Ramalina menziesii	Rammen	1.71	-0.11	Best
	Ramalina roesleri	Ramroe	1.37	-0.31	Best
	Ramalina subleptocarpha[b]	Ramsle	5.46	0.72	Worst
	Ramalina thrausta	Ramthr	2.39	-0.10	Good

Table 6—Species list for the west-side Pacific Northwest calibration data set[a] (continued)

N indicator group	Species	Acronym	Frequency	Species score	Air quality zone
			Percent		
Stratified cyanolichens					
	Lobaria hallii	Lobhal	2.05	0.17	Fair
	Lobaria oregana	Lobore	22.18	-0.48	Best
	Lobaria pulmonaria	Lobpul	33.11	0.00	Fair
	Lobaria scrobiculata	Lobscr	12.29	0.36	Poor
	Nephroma bellum	Nepbel	8.19	-0.42	Best
	Nephroma helveticum	Nephel	11.95	0.03	Fair
	Nephroma laevigatum	Neplae	5.80	-0.25	Best
	Nephroma occultum	Nepocc	1.71	-0.44	Best
	Nephroma parile	Neppar	1.37	-0.18	Best
	Nephroma resupinatum	Nepres	10.24	0.25	Degraded
	Peltigera britannica	Pelbri	1.37	-0.07	Good
	Peltigera collina	Pelcol	28.33	0.31	Degraded
	Peltigera membranacea	Pelmem	4.44	-0.05	Good
	Peltigera neopolydactyla	Pelneo	2.39	-0.47	Best
	Pseudocyphellaria anomala	Pcyano	20.14	0.05	Fair
	Pseudocyphellaria anthraspis	Pcyant	19.11	-0.24	Best
	Pseudocyphellaria crocata	Pcycro	11.60	-0.33	Best
	Sticta fuliginosa	Stiful	14.33	0.32	Degraded
	Sticta limbata	Stilim	15.36	0.09	Fair
Unknown					
	Alectoria imshaugii	Aleims	6.48	-0.11	Best
	Alectoria sarmentosa	Alesar	35.49	-0.36	Best
	Alectoria vancouverensis	Alevan	4.78	-0.24	Best
	Cavernularia hultenii	Cavhul	8.53	-0.46	Best
	Cavernularia lophyrea	Cavlop	13.31	-0.40	Best
	Cetrelia cetrarioides	Celcet	7.17	0.28	Degraded
	Collema furfuraceum	Colfur	1.71	0.90	Worst
	Collema nigrescens	Colnig	1.37	1.08	Worst
	Esslingeriana idahoensis	Essida	10.58	-0.09	Good
	Fuscopannaria leucostictoides	Panleu	1.71	-0.36	Best
	Fuscopannaria saubinetii	Pansau	3.75	-0.17	Best
	Hypocenomyce castaneocinerea	Hcecas	2.73	-0.11	Best
	Hypocenomyce scalaris	Hcesca	2.73	0.50	Worst
	Hypotrachyna sinuosa	Htrsin	32.08	-0.10	Good
	Leptogium corniculatum	Lepcor	1.37	0.04	Fair
	Leptogium lichenoides	Leplic	1.71	0.47	Poor
	Leptogium polycarpum	Leppol	5.46	0.23	Degraded
	Leptogium saturninum	Lepsat	2.39	0.92	Worst
	Letharia vulpina	Letvul	14.33	0.07	Fair
	Menegazzia terebrata	Menter	25.26	-0.19	Best

Table 6—Species list for the west-side Pacific Northwest calibration data set[a] (continued)

N indicator group	Species	Acronym	Frequency	Species score	Air quality zone
			Percent		
	Niebla cephalota	Niecep	1.37	0.23	Degraded
	Nodobryoria abbreviata	Nodabb	1.71	0.11	Fair
	Nodobryoria oregana	Nodore	19.45	-0.41	Best
	Normandina pulchella	Norpul	4.78	0.47	Poor
	Parmotrema arnoldii	Pmoarn	8.87	0.25	Degraded
	Parmotrema chinense	Pmochi	9.22	-0.19	Best
	Parmotrema crinitum	Pmocri	1.37	-0.36	Best
	Physconia isidiigera	Phoisi	4.44	0.98	Poor
	Sphaerophorus globosus	Sphglo	55.29	-0.35	Best

[a] A low species score suggests nitrogen (N) sensitivity and an association with low pH substrates. A high score suggests tolerance or stimulation by N and an association with high pH. Species scores are divided into the six air quality zones developed by Geiser and Neitlich (2007): best, good, fair, degraded, poor, and worst.

[b] Species assigned to different indicator groups in the literature. Neutrophyte designations are consistent with the concept of Sparrius (2007). *Evernia prunastri* is considered a neutrophyte by Gombert et al. 2005. Van Herk (1999) considers *Parmelia saxatilis* acidophytic, and Jovan and McCune (2005, 2006) classified *Parmelia hygrophila* and *Ramalina subleptocarpha* as nitrophytes.

potential acidophytes were most closely associated with forests classified as having the "Best" air quality (table 7, fig. 31). Quite the opposite, nitrophyte scores were exclusively associated with a narrow range of the highest ("Worst") scores along with a few hardy neutrophytes like *Ramalina subleptocarpha* and *Melanelia* species (tables 6 and 7). Species scores range widely among neutrophytes, although as posited by Sparrius (2007), optimal N and substrate pH for the group appears to be, on average, intermediate between the acidophytes and nitrophytes (figs. 30 and 31).

A major shift in the chemical composition of N deposition could cause considerable departure from this trajectory.

In summary, air quality appears to be influencing lichen communities of the west-side Pacific Northwest in two key ways (1) a negative impact on the acidophytic and cyanolichen floras and (2) a positive effect on nitrophytes and at least some neutrophytes. Accordingly, results suggest that increased deposition of N and substrate alkalinization would favor shifts in communities from low-scoring to high-scoring species, and vice-versa, should deposition improve. A major shift in the chemical composition of N deposition affecting the study area could cause considerable departure from this trajectory as different forms of N have different effects on substrate pH. Chemical composition of detected N in the

Table 7—Species scores summarized by nitrogen (N) indicator group and Geiser and Neitlich's (2007) air quality zones

N indicator group	Mean	Min	Max	n	Air quality zones					
					Best	Good	Fair	Degraded	Poor	Worst
					Percent					
Nitrophytes	0.88	0.66	1.15	11	0.0	0.0	0.0	0.0	0.0	100.0
Acidophytes	-0.13	-0.54	0.46	49	59.2	14.3	14.3	6.1	6.1	0.0
Neutrophytes	0.26	-0.31	0.72	17	17.6	5.9	17.6	11.8	11.8	35.3
Cyanolichens	-0.07	-0.48	0.36	19	42.1	10.5	26.3	15.8	5.3	0.0
Unknown	0.09	-0.46	1.08	29	44.8	6.9	10.3	13.8	10.3	13.8

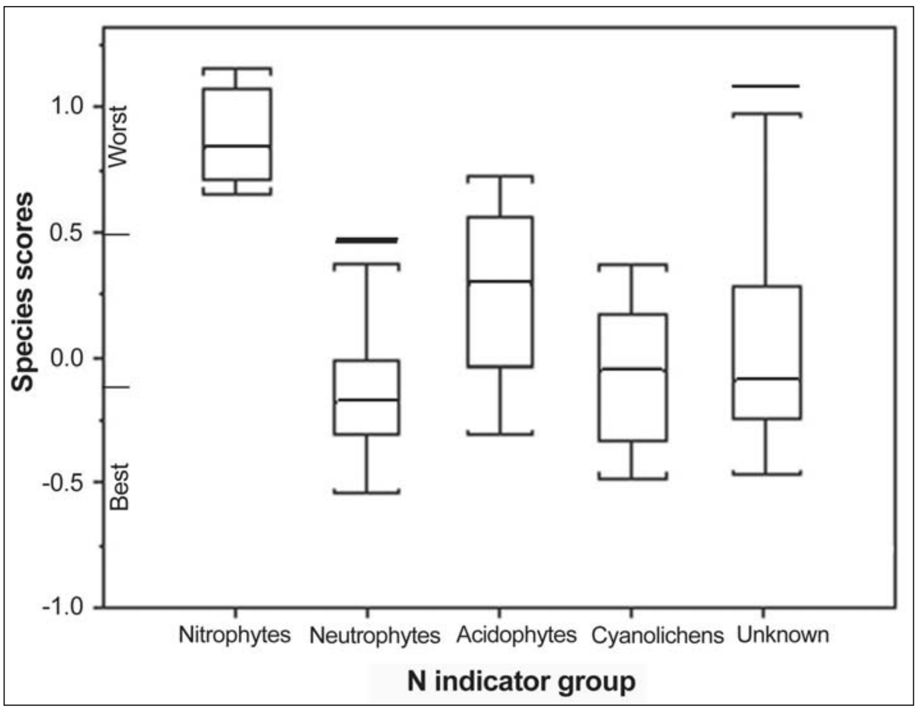


Figure 31—Distribution of species scores according to N indicator group. Box plots are divided into quartiles with outliers indicated by lines. Ranges of the "Best" and "Worst" air quality zones (depicted on the x-axis in figure 30) are indicated on the y-axis.

NMS model is ultimately unknown, although NH_3 and its reaction product, NH_4^+, seem likely to be major components. Besides correlation of the air quality gradient to NH_4^+ (see "Interpretation of Air Quality Estimates"), the distribution of acidophytes, neutrophytes, and nitrophytes along the air quality gradient is analogous to the NH_3-dependent optimum curves published by Sparrius (2007).

Summary of Air Quality Patterns

The gradient model was used to estimate air quality at a full cycle of FIA data (n = 243; 1998-2001, 2003) to describe baseline conditions affecting west-side Pacific Northwest forests. About 75 percent of these plots were included in the extensive air quality summary published by Geiser and Neitlich (2007). Air quality zones used to categorize plot scores are the same as those used in the previous section for discussing species scores (see sidebar 7). The spread of plot scores among air quality zones (table 8) was similar for Oregon and Washington, as was average score (-0.05 and -0.07, respectively).

Valley and low-elevation foothill forests of the Willamette Valley and Puget Trough ecoregion seem proportionally the most affected by poor air quality.

Consistent with Geiser and Neitlich's (2007) observations, nitrophyte-rich sites receiving high (poor) air quality scores were prevalent near urban and agricultural areas (fig. 32). It follows that valley and low-elevation foothill forests of the Willamette Valley and Puget Trough ecoregion (covering about 38 600 km^2) seem proportionally the most affected by poor air quality (fig. 32). Air quality scores for this ecoregion were varied (SD = 0.49), spanning nearly the full range of the data (-1.08 to 1.59; table 9), but the majority of sites scored as "Degraded" or worse. This region included 8 of the 12 plots receiving the worst 5 percent of air quality scores (fig. 33).

Concentration of human activity and its infrastructure generate high pollution emissions in this ecoregion compared to elsewhere in the study area. A large proportion of the human population in Washington and Oregon (> 65 percent) inhabits the cities of the Willamette Valley and Puget Trough (Oregon Department of Fish and Wildlife 2006, Washington Department of Fish and Wildlife 2005). Urban density is greatest along the oftentimes congested Interstate-5 corridor (fig. 22), which serves as the main conduit of north-south motor vehicle travel. The ecoregion possesses abundant productive farmland that supports a diversified agricultural-based economy, as well as forestry, manufacturing, and tourism (Oregon Department of Fish and Wildlife 2006, Washington Department of Fish and Wildlife 2005). Correspondingly, agricultural, industrial, and motor vehicle pollutant N sources are locally plentiful.

Table 8—Air quality scores from the west-side Pacific Northwest (PNW) model by state (1998–2001, 2003)[a]

Parameter	West-side PNW	West-side Oregon	West-side Washington
Number of plots surveyed	243	140	103
Number of plots by air quality zone:			
Best: -1.4 to -0.11	111	65	46
Good: -0.11 to 0.02	26	14	12
Fair: 0.02 to 0.21	40	25	15
Degraded: 0.21 to 0.35	21	13	8
Poor: 0.35 to 0.49	13	8	5
Worst: 0.49 to 2.00	32	15	17
Air quality score extremes	-1.28 to 1.59	-1.28 to 1.02	-1.22 to 1.59
Average air quality score	-0.062	-0.05	-0.07
Standard deviation of air quality scores	0.49	0.43	0.56

[a] Plot scores are divided into Geiser and Neitlich's air quality zones (2007). Plots were excluded from analysis if they lacked species, had no species in common with the calibration plots, or were duplicate surveys used for quality assurance purposes.

Table 9—Air quality scores by Bailey's ecoregions (1983)

Ecoregion section	Min	Max	Mean	n	SD	Median
Eastern Cascades (M242C)	-0.57	0.32	-0.34	11	0.27	-0.44
Klamath Mountains (M261A)	-1.28	1.02	-0.11	39	0.43	-0.06
Oregon and Washington Coast Ranges (M242A)	-1.22	0.91	-0.16	70	0.40	-0.11
Southern Cascades (M261D)	-0.65	0.79	0.13	6	0.58	0.13
Western Cascades (M242B)	-1.07	0.97	-0.25	64	0.42	-0.33
Willamette Valley and Puget Trough (242A)	-1.08	1.59	0.36	53	0.49	0.38

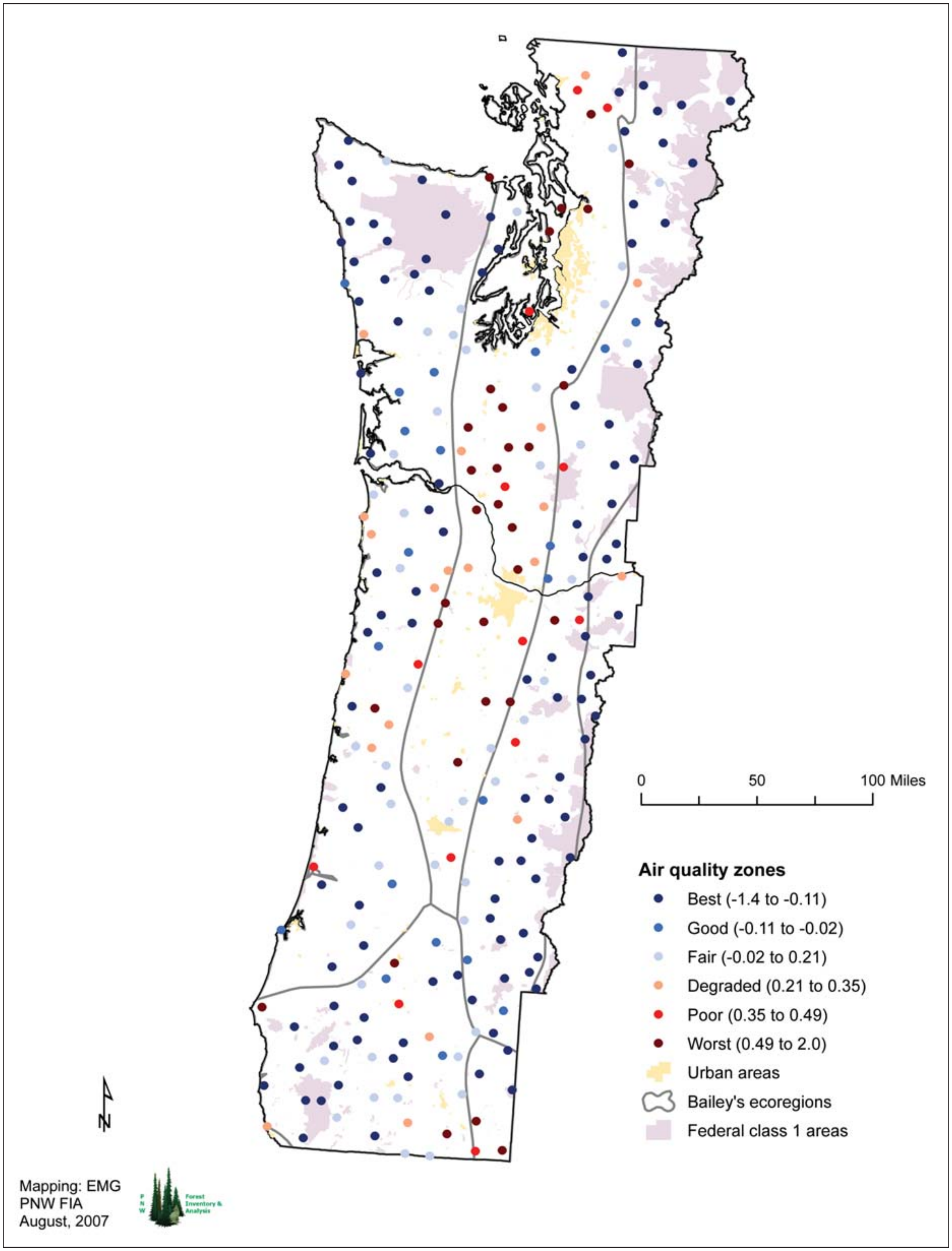


Figure 32—Air quality scores for the west-side Pacific Northwest divided into Geiser and Neitlich's air quality zones (2007). Scores are unitless until calibrated with pollutant measurements. See figure 22 for ecoregion codes.

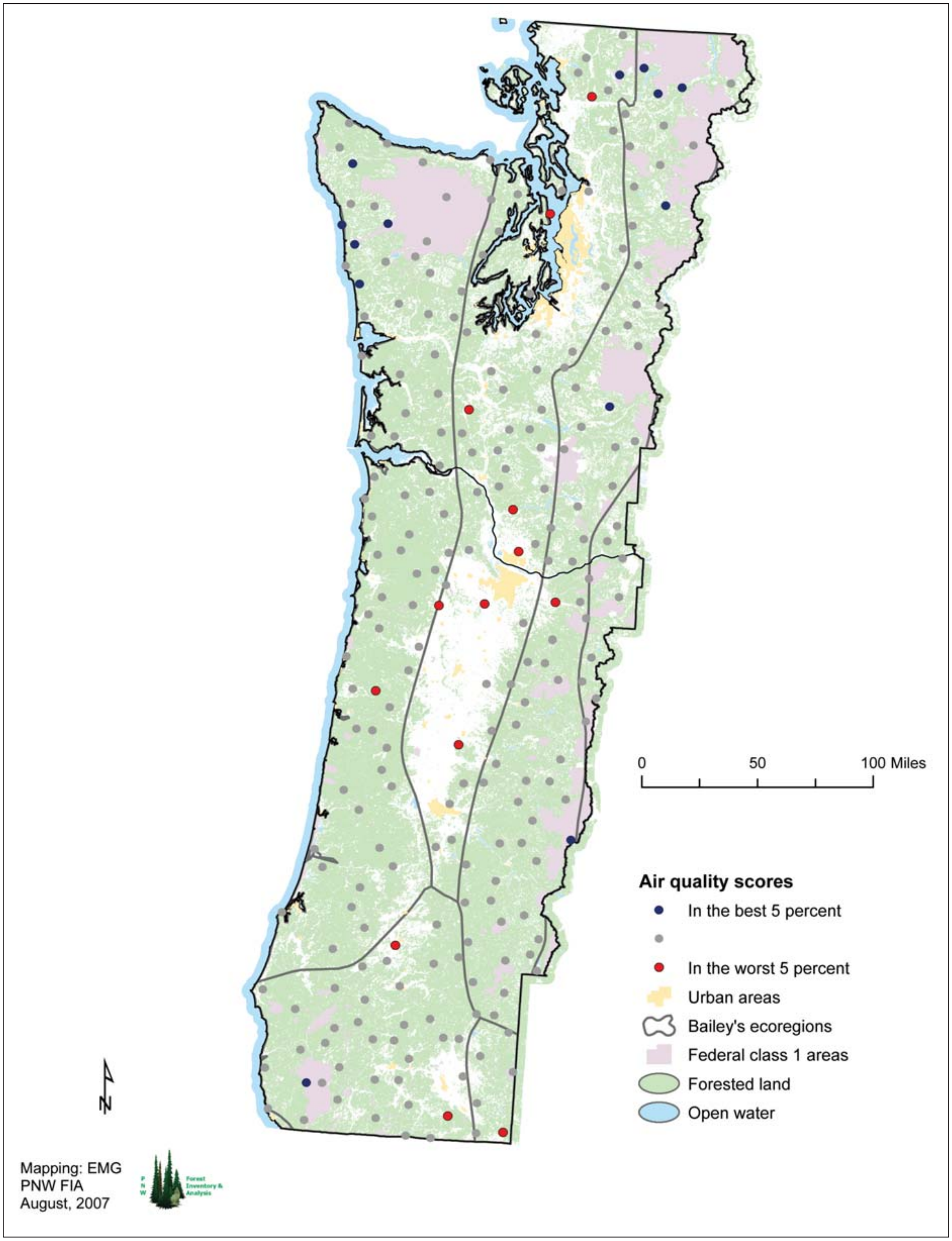


Figure 33—Extreme best and worst 5 percent of air quality scores. All other plots are indicated in gray. See fig. 22 for ecoregion codes.

The model suggested that plots on the Willamette Valley fringe in the foothills of the Cascades and Coast Ranges tend to experience worse air quality than more remote forests (fig. 32). Regardless, most air quality scores in both the Cascades and Coast Ranges fall in the "best" category. Some air quality degradation was detected in the Klamath ecoregion, primarily in association with cities on or near Interstate-5. Air quality at a few coastal plots is classified as "poor" or "worst," although such sites were widely distributed with no discernable clustering.

The importance of N as an ecological stressor in some west-side Pacific Northwest forests is unmistakable.

Most plots receiving the lowest (best) 5 percent of scores were near national parks and on the immediate coast in Washington (fig. 33). Overall, lichen communities suggested relatively good air quality for forests in the northern Olympic peninsula and mid to high Cascades. Ostensibly, these forests benefit from their distance from west-side urban, industrial, and agricultural centers.

Conclusions

The importance of N as an ecological stressor in some west-side Pacific Northwest forests is unmistakable given the clear association of N/pH lichen indicator groups with the air quality gradient. Forests near cities and agriculture are potentially the most impacted by poor air quality, as suggested by the spatial distribution of air scores and verified by enhanced accumulations of N and S in collected lichens (Geiser and Neitlich 2007). Estimated pollution hotspots are somewhat localized as compared to parts of the Northeastern United States where pollution is more a regional issue (Fenn et al. 2003a, 2003b). If emissions intensify, the geographic scope of pollution impacts may, of course, extend in tandem.

Excessive N is a growing problem in many developed nations as documented in many studies (Driscoll et al. 2003**,** Fenn et al. 1998, Holland et al. 2005, Vitousek et al. 1997). But in the bigger picture, how dire is the status of forest air quality in the west-side Pacific Northwest? A direct comparison to other regions is precluded by the lack of comprehensive instrumented pollutant measurements, which means that we hardly know how much N is actually getting into the system. As reviewed by Fenn et al. (2003a), N deposition patterns are unknown for most of the Western United States, which underscores the importance of lichen-air quality bioindication. Comparison is likewise difficult because large-scale characterizations of dry N deposition, potentially a major component of total N loading, are highly uncertain (Holland et al. 2005). Given these caveats, the best available information does suggest that N deposition to the Pacific Northwest is milder than that for much of western Europe and the Eastern United States (Holland et al. 2005), although in some localized instances deposition may be just as high.

The story as told from the lichen perspective is that many sensitive species remain widespread and altogether make for a "largely intact flora (Geiser and Neitlich 2007)." Still, air quality in the west-side Pacific Northwest has much room for improvement, most especially conditions affecting the lowland oak and mixed-conifer forests in the Willamette and Puget Trough ecoregion. About 24 percent of land area in the western Pacific Northwest is estimated to experience air quality that is classified as "degraded" or worse (Geiser and Neitlich 2007). Spatial patterns in lichen community composition as seen in these baseline data illustrate how communities might change should air quality, and N/bark pH effects in particular, worsen. To reiterate from Geiser and Neitlich (2007), acidophytes and cyanolichens tend to be our ecologically important and endemic lichen species. To their detriment, we expect to see enhancement of nitrophytes (and perhaps also neutrophytes) with increased N and alkalinization of substrates. Resampling lichen communities at FIA plots will help us continually evaluate risks to forest health. In the meanwhile, we hope these results will serve as a catalyst for investigation into N impacts to other components of the forest ecosystem.

Chapter 4: Air Quality in the Greater Central Valley, California

Key Findings

1. As in the west-side Pacific Northwest, the model suggests nitrogen (N) is a major stressor shaping lichen communities in the greater Central Valley.
2. Jovan and McCune (2005) found that air quality scores from the model were correlated with estimates of ammonia (NH_3) and the dominance of nitrophytes (e.g., lichen species commonly associated with high NH_3 habitats and high bark pH).
3. Lichen species expected to be N intolerant were rare in the greater Central Valley, most especially at plots where the model indicated high N impact. The regional rarity of N-sensitive species, however, may be partly due to the hot and dry climate.
4. Poor air quality was estimated for most forests in urban and agricultural areas where lichen communities consisted of up to 100 percent nitrophytes.
5. Small hotspots of poor air quality were scattered across the study area, with the largest hotpots detected in the Central Valley and San Francisco Bay area.

Introduction to the Model

The greater Central Valley (fig. 34) is a climatically and floristically distinct region of northern and central California (Jovan and McCune 2004; see also chapter 7). The study area includes the broad, agricultural Central Valley (fig. 35), the low-elevation Sierra Nevada foothills, the San Francisco Bay area, and a strip of coastal ranges stretching from Willits, California, south to the Santa Clara River. Jovan and McCune (2005) developed a gradient model for air quality bioindication using nonmetric multidimensional scaling (NMS; for methods see chapter 1) and the integration of various sources of land use and pollution data (table 10).

Lichen community surveys used to build the model came from 66 plots on the Forest Inventory and Analysis (FIA), U.S. Department of Agriculture, sampling grid visited between 1998 and 2001. These calibration data included 32 supplemental off-frame plots surveyed in 2002. Off-frame sites were placed in forests near urban and agricultural areas, intentionally near key pollution emission sources like high motor vehicle traffic, fertilizers, and animal husbandry, as well as various industrial and domestic point sources (fig. 34).

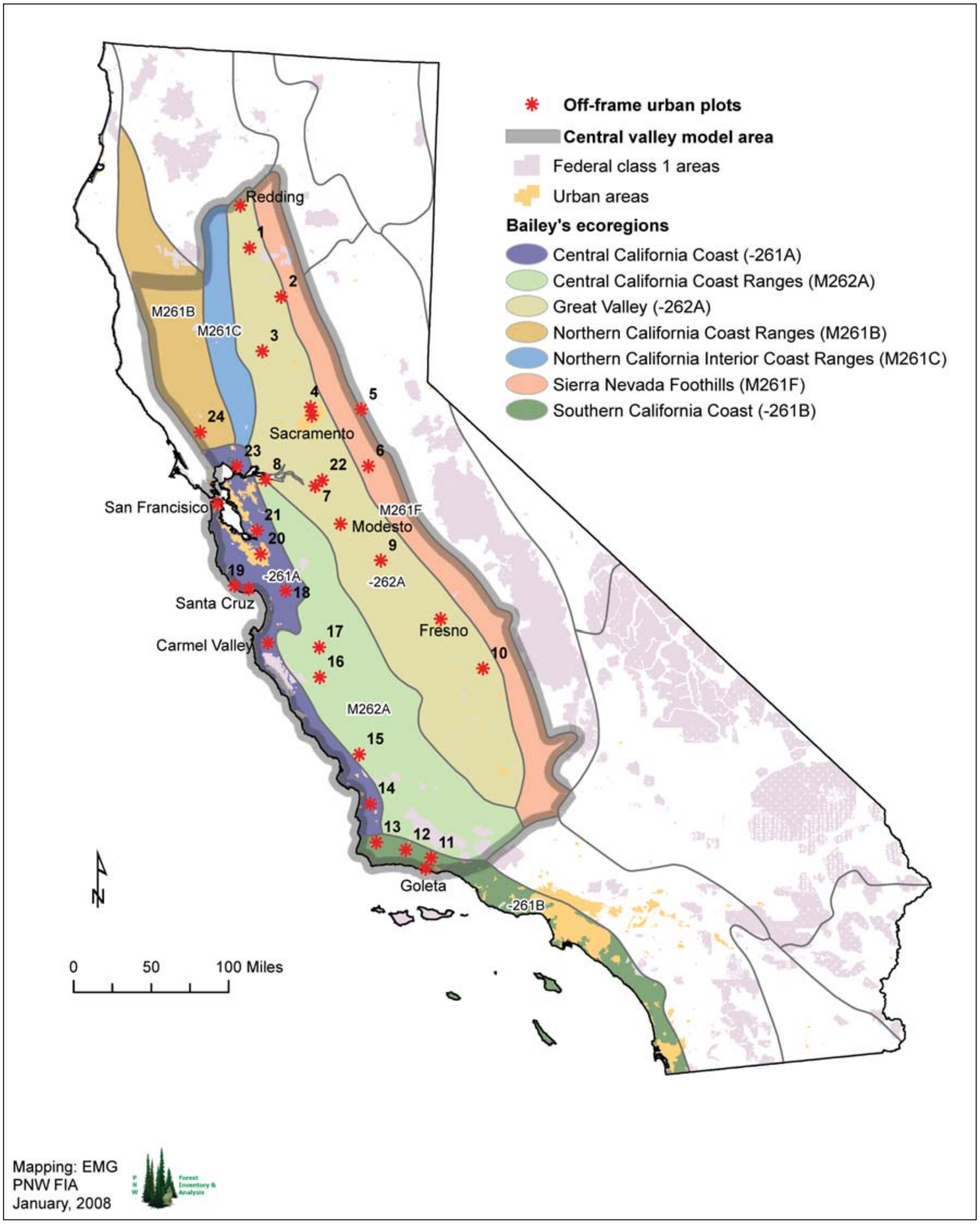


Figure 34—Greater Central Valley model area. Off-frame plots are indicated by red asterisks and named after the city or park in which they were located. Off-frame plots not named on the map are numbered as follows: 1 = Red Bluff, 2 = Chico, 3 = Colusa, 4 = North Highland, 5 = Placerville, 6 = San Andreas, 7 = Stockton, 8 = Pittsburg, 9 = Merced, 10 = Visalia, 11 = Los Padres National Forest, 12 = Santa Ynez, 13 = Lompoc, 14 = Nipomo, 15 = Atascadero, 16 = King City, 17 = Pinnacles National Monument, 18 = Gilroy, 19 = Davenport, 20 = San Jose, 21 = Fremont, 22 = Crockett, 23 = Vallejo, 24 = Santa Rosa. The plot surveyed in Bakersfield was excluded from all analyses because no lichens were present.

Dr. Christopher Bochna

Figure 35—Aerial view of Central Valley landscape, taken somewhere between Patterson and Merced. Griffin McKinney (pilot).

Table 10—Pollution data for the greater Central Valley used to interpret the air quality gradient detected by NMS[a]

Variable	n	Measurement type	Data source
SO_2	14	Annual arithmetic mean	CARB; Data averaged over 1999 to 2002
NO_2	22	Annual arithmetic mean	CARB; Data averaged over 1999 to 2002
O_3	30	Maximum 1-hour value	CARB; Data averaged over 1999 to 2002
Kriged O_3	All sites	estimate; SUM60 index[b]	Unpublished data provided by T. Pritchard. Interpolation across study area based on O_3 measurements from CARB monitors.
NH_3 Emissions	All sites	Estimate of emissions; tons per year	California Gridded Ammonia Inventory Modeling System; ENVIRON International Corporation 2002
Land use-NH_3	All sites	Estimate; proportion	Index calculated with land use data from the California Gap Analysis Project; Davis et al. 1998

[a] All California Air Resources Board (CARB) data are publicly accessible at: http://www.arb.ca.gov/aqd/aqdpage.htm. SO_2 = sulfur dioxide, NO_2 = nitrogen dioxide, O_3 = ozone, and NH_3 = ammonia.

[b] SUM60: the sum of all hourly O_3 concentrations ≥60 parts per billion from June 1 to August 31, 2002.

Ancillary Data: Air Quality Measurements

Each off-frame plot was co-located with an air quality monitor operated by the California Air Resources Board that measures at least one major anthropogenic pollutant (table 10): sulfur dioxide (SO_2; range = 1 to 5 parts per billion [ppb]), nitrogen dioxide (NO_2; range = 3 to 25 ppb), and ozone (O_3; range = 68 to 139

One or more N compounds are impacting lichens in the greater Central Valley.

ppb). Ozone monitor data were kriged to calculate an index of O_3 exposure (range = 21-7.81 x 10^4 ppb hrs). Ammonia, for which measurements were not available, was estimated for all on- and off-frame sites by using two independently derived variables: (1) modeled NH_3 emissions provided by ENVIRON International Corporation (2002), and (2) NH_3 estimated by using a land use index of urban and agricultural development in the plot vicinity (table 10).

Interpretation of Air Quality Estimates: Nitrogen Is Shaping Lichen Community Structure

Much like results from the west-side Pacific Northwest (chapter 3), NMS detected an air quality gradient suggesting that one or more N compounds are impacting lichens in the greater Central Valley (Jovan and McCune 2005). Air quality scores determined for plots were linearly related to the proportion of nitrophyte abundance (PNA; r = -0.78; fig. 36), a simple measure of nitrophyte dominance in the community (see sidebar 8; fig. 37). Nitrophytes are a well-studied group of lichen indicator species known to react positively to N and the alkalinization of substrates (see chapter 3 “Nitrophytes” section). Plot scores were also substantially correlated to NH_3 estimates from the emissions model and the land use index (r = -0.51 and -0.63, respectively) but less so with NO_2 (r = -0.33). In the literature, nitrophytes are often linked specifically to NH_3, which is expected to be a

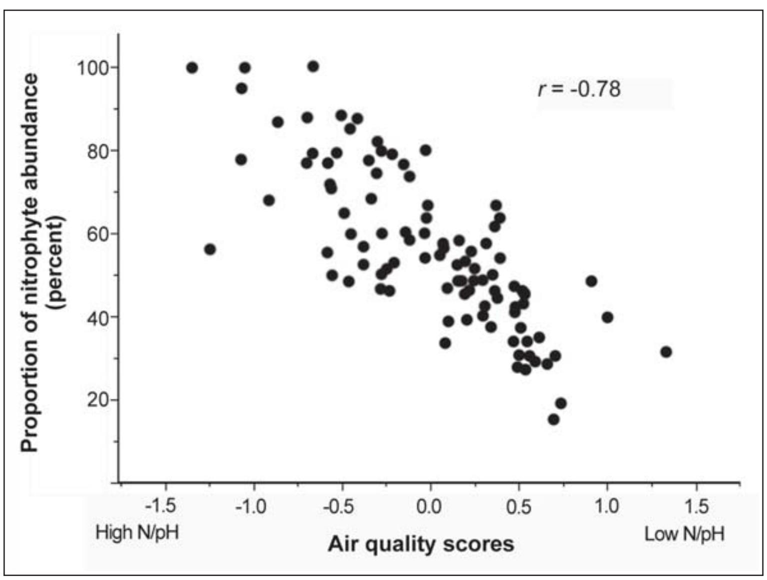


Figure 36—Scatterplot of the greater Central Valley calibration data showing the relationship between air quality score and the proportion of nitrophyte abundance at each plot.

Sidebar 8: Calculating the PNA

The proportion of nitrophyte abundance (PNA) is a semiquantitative measure of nitrophyte dominance in a lichen community. The index is a variation on the popular Nitrofiele Indicatie Waarde of van Herk (1999, 2001), which has been implemented for estimating NH_3 in the Netherlands and elsewhere in Europe. The PNA is calculated by (1) summing the abundance codes of all nitrophytes recorded during the lichen survey and (2) dividing by the summed abundance of all lichens found. The formula is as follows:

$$PNA_i = \frac{\sum_{j=1}^{s} a_{ij} n_j}{\sum_{j=1}^{s} a_{ij}}$$

where s is number of species in plot i, a_{ij} is the abundance of species j in plot i, and n_j indicates whether each species is a nitrophyte ($n_j = 1$) or not ($n_j = 0$).

Judy Robertson

Figure 37—Colorful nitrophytes on a twig in Pinnacles National Monument, California.

major component of total N deposition in the study area owing to the density of agriculture. Altogether these results suggest that plots receiving low (poor) air quality scores are the most impacted, wherein N is relatively high and lichen communities are dominated by weedy nitrophytic species (fig. 36).

Discussion of Indicator Species

Although the PNA only distinguishes nitrophyte from nonnitrophyte, the abundance of acidophytes (species sensitive to N and high pH) and neutrophytes (a more nebulous group of species that prefer or tolerate moderate N and circumneutral pH) does influence the PNA denominator (see chapter 3 "Acidophytes" and "Neutrophytes" sections). The pollution-sensitive cyanolichens are uncommon in the greater Central Valley and so contribute little information to the PNA and the gradient model. As in the section "Indicator Synthesis," in chapter 3, weighted averaging was used to calculate a score for each species in the calibration data set to serve as a rough estimate of the species' response to N and associated pH effects (table 11; for methods see chapter 1 "Identifying indicator species with species scores" section). The distribution of these species scores across the detected air quality gradient illustrates the ecological patterns NMS uses to derive air quality scores for plots.

The most obvious pattern emerging from species scores is the nitrophyte-acidophyte dichotomy along the air quality gradient.

Four air quality categories ranging from "best" to "worst" are used to give species scores context. Each category corresponds with a quartile calculated from the air quality scores determined for all plots in the calibration data set. A low species score suggests tolerance or promotion by N, whereas a high score suggests N sensitivity, given the caveat that bark pH (as influenced by N deposition or otherwise) probably plays an important role in determining species' responses (see chapter 3 "Direct and Indirect Nitrogen Effects on Lichens"). Many species were classified a priori to one of the four N indicator groups: nitrophytes, cyanolichens, acidophytes, and neutrophytes (table 11). Species classified to the latter two groups belong to a genus considered acidophytic or neutrophytic in Europe. Species scores may be used to help refine these preliminary designations as North American candidates receive further study.

The most obvious pattern emerging from species scores is the nitrophyte-acidophyte dichotomy along the air quality gradient (fig. 38), as witnessed also with the west-side Pacific Northwest data set (fig. 30). Nitrophyte species richness was high (n = 22; table 12), and species scores for both nitrophytes and neutrophytes were spread widely across the lower three quartiles of air quality scores (fig. 38). Cyanolichens (n = 2) and acidophytes (n = 11) were scarce by

Table 11—Species list for the greater Central Valley calibration data set[a]

N indicator group	Species	Acronym	Frequency	Species score	Air quality category
Nitrophytes			***Percent***		
	Candelaria concolor	Cndcon	87.76	-0.01	2nd
	Flavoparmelia caperata[b]	Flacap	9.18	-0.02	2nd
	Flavopunctelia flaventior[b]	Fpufla	51.02	0.13	3rd
	Phaeophyscia hirsuta	Phahir	10.20	-0.44	1st (Worst)
	Phaeophyscia orbicularis	Phaorb	41.84	-0.30	2nd
	Physcia adscendens	Phyads	67.35	0.00	2nd
	Physcia aipolia	Phyaip	32.65	0.19	3rd
	Physcia dimidiata	Phydim	15.31	-0.11	2nd
	Physcia dubia	Phydub	4.08	-0.10	2nd
	Physcia stellaris	Physte	20.41	0.17	3rd
	Physcia tenella	Phyten	36.73	-0.13	2nd
	Physconia enteroxantha	Phoent	27.55	0.01	2nd
	Physconia perisidiosa	Phoper	56.12	0.11	3rd
	Punctelia perreticulata[b]	Punper	24.49	0.21	3rd
	Xanthomendoza fallax	Xanfal	23.47	-0.25	2nd
	Xanthomendoza fulva	Xanful	11.22	-0.13	2nd
	Xanthomendoza hasseana	Xanhas	36.73	0.01	2nd
	Xanthomendoza oregana	Xanore	44.90	-0.27	2nd
	Xanthoria candelaria	Xancan	9.18	0.29	3rd
	Xanthoria parietina	Xanpar	8.16	-0.26	2nd
	Xanthoria polycarpa	Xanpol	50.00	0.00	2nd
	Xanthoria tenax	Xanten	21.43	-0.51	1st (Worst)
Potential acidophytes					
	Cetraria merrillii	Cetmer	11.22	0.57	4th (Best)
	Cetraria orbata	Cetorb	6.12	0.37	3rd
	Evernia prunastri[b]	Evepru	56.12	0.26	3rd
	Hypogymnia imshaugii	Hypims	20.41	0.54	4th (Best)
	Hypogymnia tubulosa	Hyptub	4.08	0.40	4th (Best)
	Platismatia glauca	Plagla	4.08	0.64	4th (Best)
	Usnea arizonica	Usnari	4.08	0.27	3rd
	Usnea cornuta	Usncor	6.12	-0.15	2nd
	Usnea glabrata	Usngla	5.10	-0.05	2nd
	Usnea lapponica	Usnlap	6.12	0.14	3rd
	Usnea substerilis	Usnsst	6.12	-0.09	2nd
Potential neutrophytes					
	Melanelia elegantula	Melele	5.10	0.05	3rd
	Melanelia exasperatula	Melexl	4.08	0.10	3rd
	Melanelia fuliginosa	Melful	6.12	0.31	3rd
	Melanelia glabra	Melgla	61.22	0.26	3rd
	Melanelia subargentifera	Melsar	11.22	-0.09	2nd
	Melanelia subolivacea	Melsol	31.63	0.14	3rd
	Parmelia hygrophila[b]	Parhyg	4.08	0.40	4th (Best)
	Parmelia sulcata	Parsul	16.33	0.42	4th (Best)
	Ramalina farinacea	Ramfar	25.51	0.07	3rd
	Ramalina leptocarpha	Ramlep	18.37	-0.33	1st (Worst)

Table 11—Species list for the greater Central Valley calibration data set[a] (continued)

N indicator group	Species	Acronym	Frequency	Species score	Air quality category
			Percent		
	Ramalina menziesii	Rammen	14.29	-0.02	2nd
	Ramalina pollinaria	Rampol	5.10	-0.25	2nd
	Ramalina subleptocarpha[b]	Ramsle	21.43	-0.11	2nd
Stratified cyanolichens					
	Pseudocyphellaria anthraspis	Pcyant	7.14	0.61	4th (Best)
	Peltigera collina	Pelcol	8.16	0.62	4th (Best)
Unknown					
	Collema furfuraceum	Colfur	22.45	0.28	3rd
	Collema nigrescens	Colnig	15.31	0.07	3rd
	Heterodermia	Het	5.10	-0.10	2nd
	Leptogium lichenoides	Leplic	16.33	0.35	3rd
	Leptogium pseudofurfuraceum	Lepfur	14.29	0.45	4th (Best)
	Letharia columbiana	Letcol	7.14	0.10	3rd
	Letharia vulpina	Letvul	12.24	0.37	3rd
	Niebla cephalota	Niecep	6.12	-0.21	2nd
	Parmelina quercina	Pnaque	42.86	0.43	4th (Best)
	Parmotrema austrosinense	Pmoaus	4.08	0.03	2nd
	Parmotrema chinense	Pmochi	11.22	0.02	2nd
	Phaeophyscia ciliata	Phacil	4.08	-0.07	2nd
	Physcia biziana	Phybiz	30.61	0.12	3rd
	Physconia americana	Phoame	43.88	0.26	3rd
	Physconia isidiigera	Phoisi	60.20	0.01	2nd
	Teloschistes chrysophthalmus	Telchr	7.14	-0.29	2nd

[a] A low species score suggests tolerance or promotion by nitrogen (N) and an association with high pH substrates. A high score suggests N sensitivity and an association with low pH substrates. Species scores are divided into four air quality categories corresponding with quartiles of plot scores from the calibration data set: 1st (worst), 2nd, 3rd, and 4th (best).

[b] Species assigned to different indicator groups in the literature. *Flavoparmelia caperata*, *Flavopunctelia flaventior*, and *Punctelia perriticulata* are not widely defined as nitrophytes in the literature. Neutrophyte designations are consistent with the concept of Sparrius (2007). *Evernia prunastri* is considered a neutrophyte by Gombert et al. 2005. Jovan and McCune (2005, 2006) classified *Parmelia hygrophila* and *Ramalina subleptocarpha* as nitrophytes.

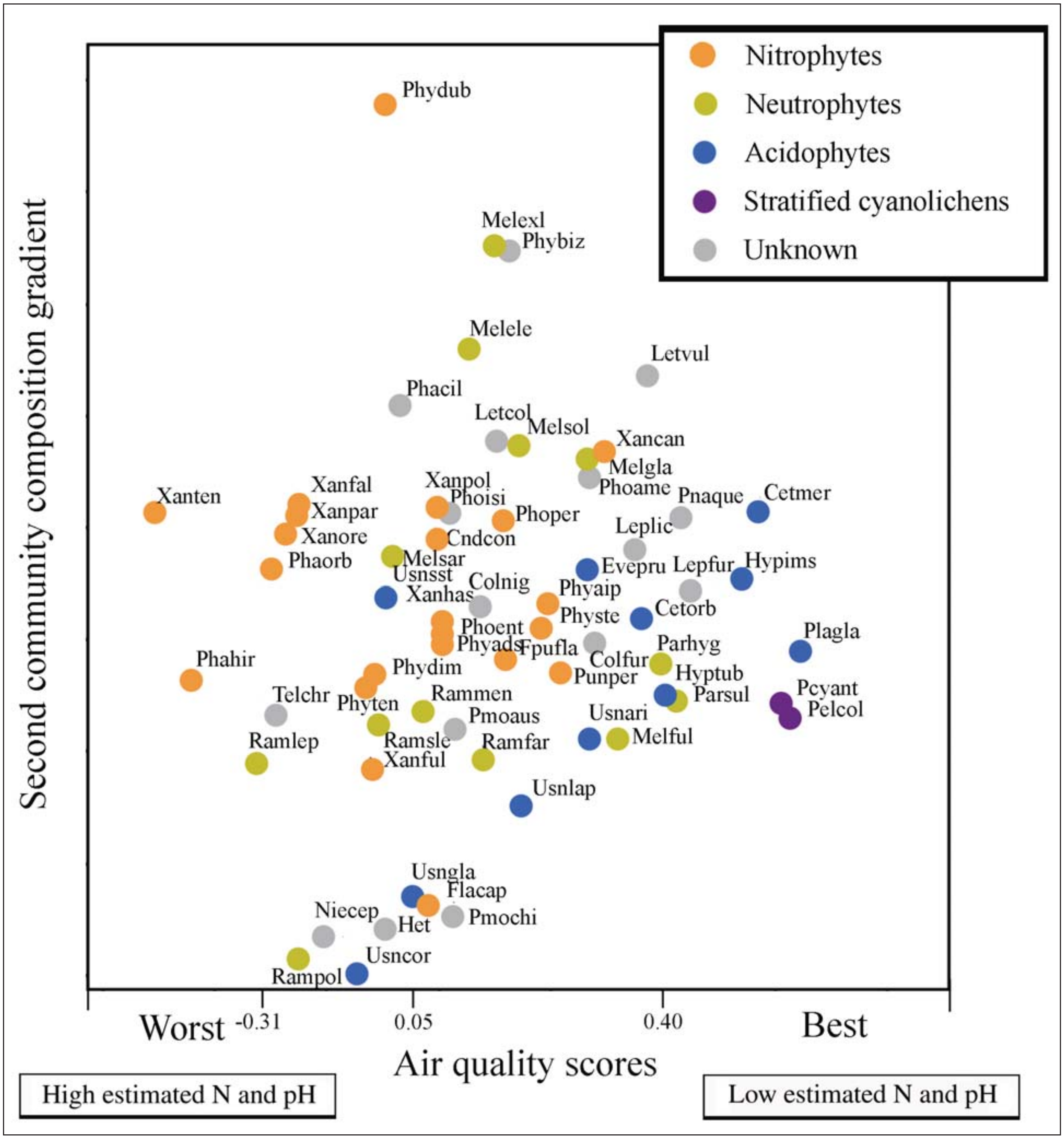


Figure 38—Display of species scores along the air quality gradient (x-axis), which is divided into four air quality categories based on data quartiles. The y-axis is included here for display purposes only; it is a second gradient in lichen community composition incidental to the discussion. Full species names are given in table 11.

Table 12—Species scores summarized by nitrogen (N) indicator group and air quality category

N indicator group	Mean	Min	Max	n	Air quality categories: 1 (worst)	2	3	4 (best)
					Percent			
Nitrophytes	-0.06	-0.51	0.29	22	9.1	63.6	27.3	0.0
Acidophytes	0.26	-0.15	0.64	11	0.0	27.3	45.5	27.3
Neutrophytes	0.07	-0.33	0.42	13	7.7	30.8	53.8	7.7
Cyanolichens	0.62	0.61	0.62	2	0.0	0.0	0.0	100.0
Unknown	0.11	-0.29	0.45	16	0.0	41.2	43.8	11.8

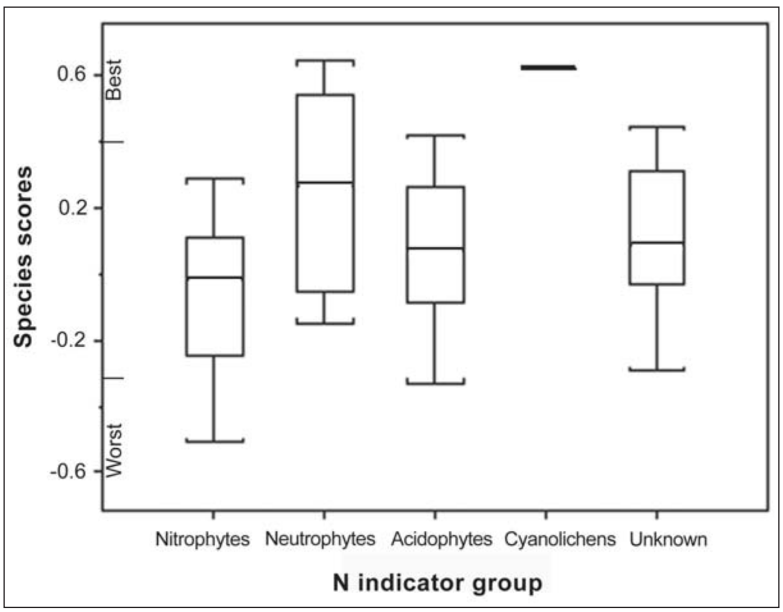


Figure 39—Distribution of species scores according to nitrogen (N) indicator group. Box plots are divided into quartiles with outliers indicated by lines. Ranges of the "best" and "worst" air quality zones (depicted on the x-axis in fig. 38) are indicated on the y-axis.

It is likely that N deposition has already marginalized some sensitive species from these groups.

comparison. It is likely that N deposition has already marginalized some sensitive species from these groups although low diversity may partly be a natural consequence of the hot, dry valley climate, as discussed further in chapter 4. Among the cyanolichens and potential acidophytes found in the study area, however, most did score within the better two air quality categories suggesting an association with low to moderate N and substrate pH (table 12, fig. 39). *Usnea* species were an exception, scoring low compared to other acidophytic candidates (table 11). Because the genus is so large and ecologically diverse, some species may well have neutrophytic or nitrophytic tendencies.

Summary of Air Quality Patterns

The following summary is based on air quality scores for most plots in the greater Central Valley calibration data set (Jovan and McCune 2005; n = 94) plus an additional 14 sites surveyed for lichens in 2003. Air quality scores are categorized into zones based on quartiles from the on-frame data only; off-frame plots are excluded as they will not be resampled. About a quarter of on-frame sites are thus in the "worst" zone. This particular representation of on-frame data will become more informative when used for assessment of air quality trends. Air quality zones can be redefined with more biologically meaningful thresholds once N critical loads for lichen communities are established. In this case, a "critical load" is the deposition of one or more forms of N that, if exceeded, has a harmful effect on lichen communities.

Differences in the distribution of air quality scores estimated for on-frame versus off-frame plots are dramatic (table 13). Scores from off-frame plots had a very poor average (-0.27), and 26 of these plots (81 percent) scored in the worst air quality zone. Scores differed widely within ecoregions, with the highest N impacts typically estimated for off-frame sites near urban and agricultural areas (fig. 40). The variable spatial pattern of scores may be a reflection of high NH_3 levels. In contrast to most other major N pollutants, like nitrogen oxides (NO_x), nitrates (NO_3^-), and ammonium (NH_4^+)-containing aerosols (see sidebar 9), a high proportion of gaseous NH_3 is dry deposited near the emission source. This makes a

Table 13—Air quality scores from the greater Central Valley (GCV) model (1998–2001, 2003)[a]

Parameter	GCV	On-frame	Off-frame
Number of plots surveyed	108	76	32
Number of plots by air quality zone:			
1: (Worst) -0.99 to 0.13	45	19	26
2: 0.13 to 0.55	23	19	4
3: 0.55 to 0.85	22	20	2
4: (Best) 0.85 to 1.58	18	18	0
Air quality score extremes	-0.99 to 1.58	-0.86 to 1.58	-0.99 to 0.70
Average air quality score	0.28	0.52	-0.27
Standard deviation of air quality scores	0.61	0.50	0.46

[a] Plots were excluded from analysis if they lacked species, had no species in common with the calibration plots, or were duplicate surveys used for quality assurance purposes.

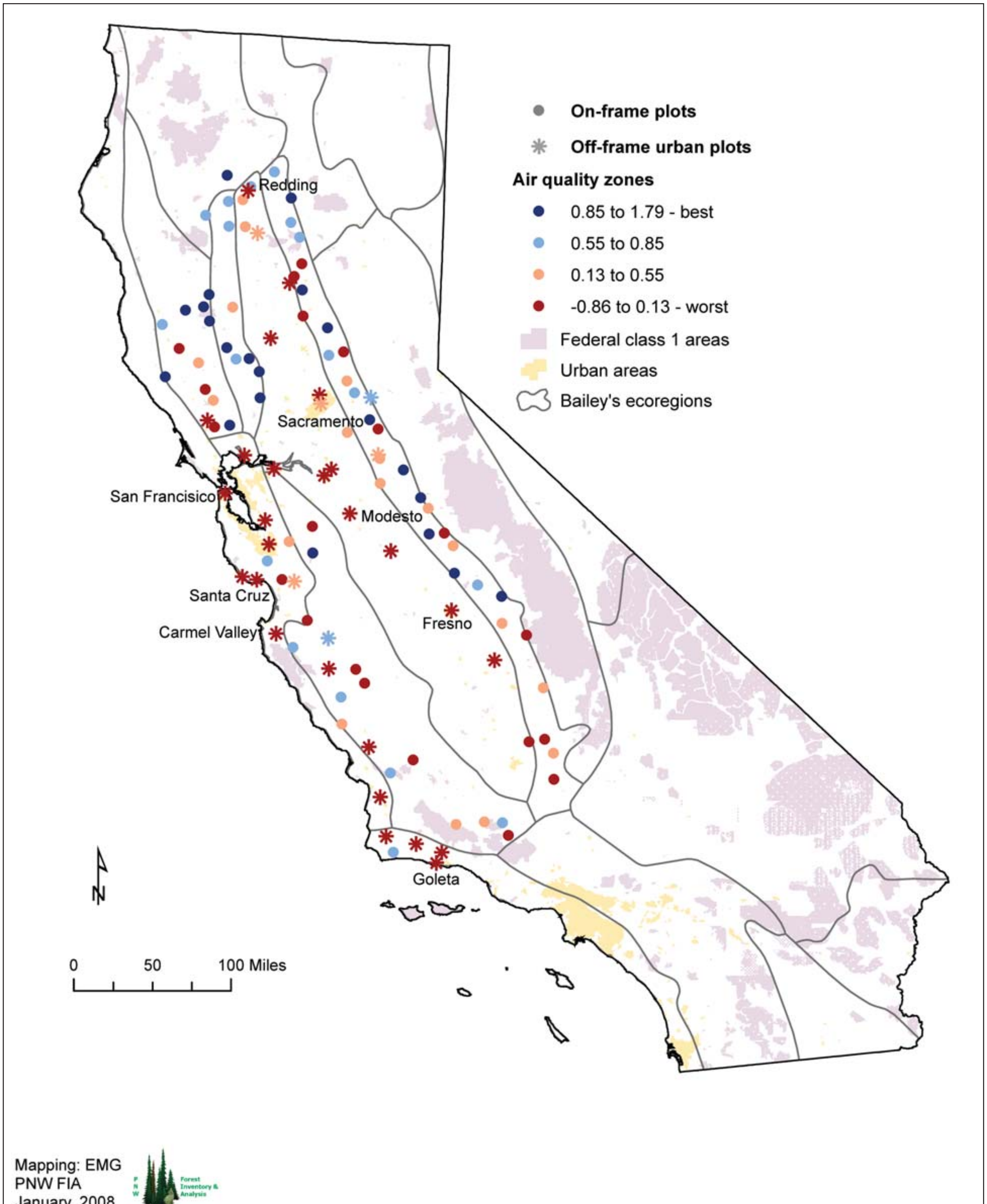


Figure 40—Air quality scores for the greater Central Valley divided into air quality zones. Scores are unitless until calibrated with pollutant measurements. On-frame (circles) and off-frame plots (asterisks) are indicated by a common color scheme. See figure 34 for ecoregion codes.

Sidebar 9: ***Particulate pollution***

Ammonia and NO_x combine to form ammonium nitrate (NH_3NO_3), a major component of haze-inducing particulate pollution in California (California Environmental Protection Agency 2005, Fenn et al. 2003b). In this form, the N from NH_3 emissions can be transported over hundreds of miles. Besides reducing visibility, these particulates irritate the lungs and are considered a serious human health concern. Levels are especially high in the San Joaquin Valley Air Basin, which is in nonattainment of the national standard (California Environmental Protection Agency 2005).

heterogeneous distribution of NH_3 across the landscape that is difficult to accurately capture with networks of air quality monitors (Erisman et al. 2005).

Hotspots of Degraded Air Quality

Plots sampled in the Central Valley (Great Valley section -262A) appear heavily impacted by N (figs. 40 and 41) although it is important to note how air quality in this ecoregion is primarily represented by lichen communities sampled at off-frame plots (fig. 34), which were intentionally installed in high pollution areas. Most on-frame plots fell on nonforest land and so were not surveyed for lichens. Despite the biased sample, other regional deposition and emissions studies recognize the valley as a major N hotspot in California (ENVIRON 2002, Fenn et al. 2003b, Potter et al. 2000, Weiss 2006).

For instance, according to the Community Multiscale Air Quality Model (CMAQ) (Buyn and Ching 1999, Tonnesen et al. 2002[1]), the San Joaquin valley receives the highest N in California excepting the Los Angeles Basin (reviewed by Weiss 2006; resolution of model estimates = 36 km^2). Maximum deposition is estimated at 13 to 14 kg $N \cdot ha^{-1} \cdot year^{-1}$ at Modesto, with the San Francisco Bay area following as the second worst hotspot in the greater Central Valley (8 to 9 kg $N \cdot ha^{-1} \cdot year^{-1}$; see sidebar 10). Arguably, the lichen bioindication model detects N on

[1] Tonnesen, G.S.; Wang, Z.S.; Omary, M.; Chien, C.J.; Wang, B. 2002. Regional aerosol and visibility modeling using the Community Multiscale Air Quality Model for the Western U.S.: Results and model evaluation for the 1996 annual simulation. Paper presented at the WESTAR Technical Conference on Regional Haze Modeling; 12-14 February 2002, Riverside, California.

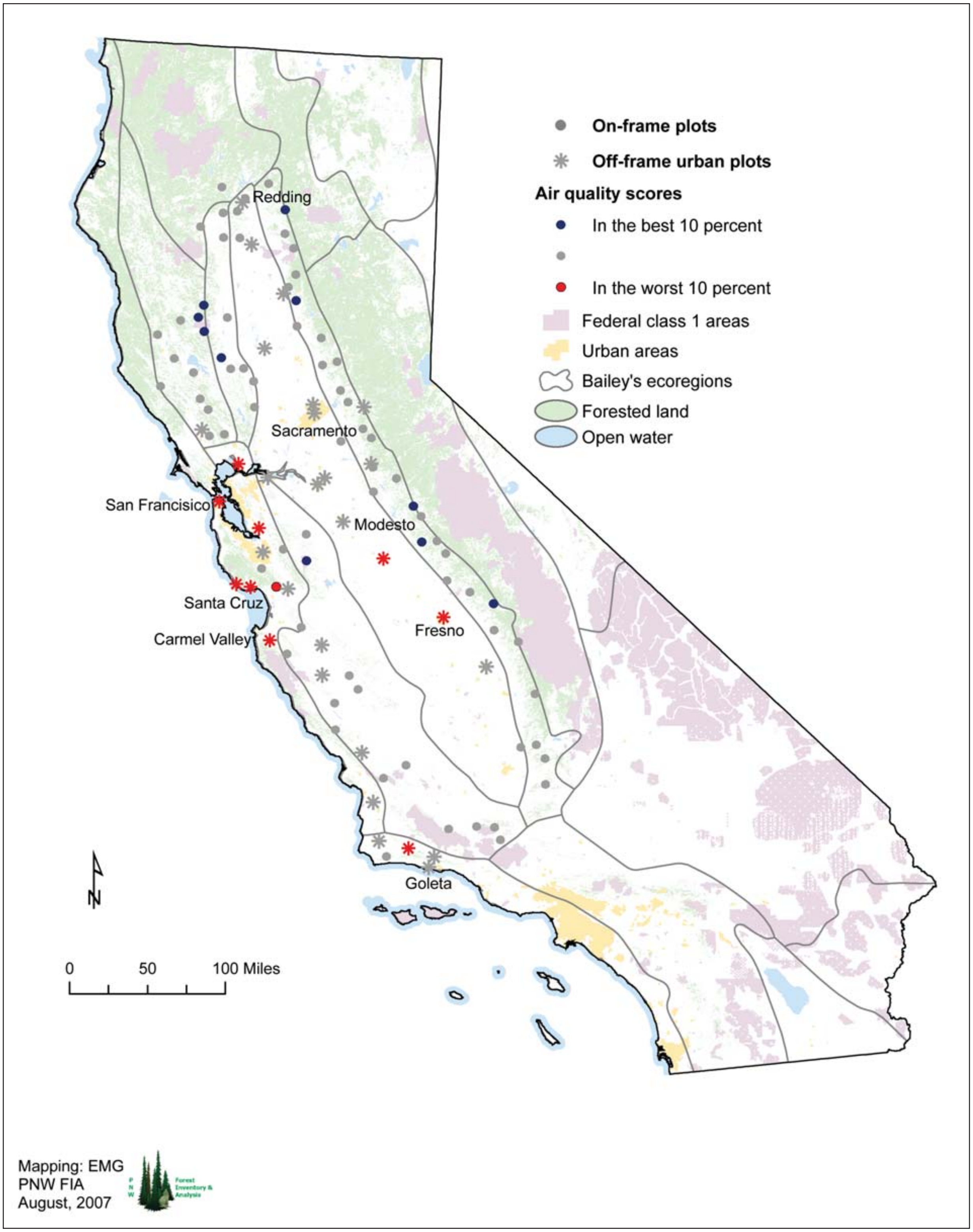


Figure 41—Extreme best and worst 10 percent of air quality scores. Off-frame plots are symbolized by asterisks. See figure 34 for ecoregion codes.

a finer spatial scale, and moreover, lichens may not respond equally to all forms of N (see chapter 3 “Direct and Indirect Nitrogen Effects on Lichens” section). Regardless, both hotspots were detected with the lichen gradient model (fig. 40). Several FIA sites scoring among the worst 10 percent were from the San Joaquin and Bay area (fig. 41). Lichen abundance in communities from the worst 10 percent was, on average, 72 percent nitrophytic (including two plots that are 100 percent nitrophytic).

Smaller hotspots of N impacts to lichen communities were scattered across the study area, including forests near cities and agricultural parts of the Sacramento Valley and downwind in forests of the southern Sierra Nevada foothills (fig. 40). Many of the best-scoring sites (fig. 41) occurred in the northern and central Sierra foothills and in the northern California Coast Ranges at sites more remote from human habitation and industry (average abundance in nitrophytes at the best 10 percent of sites was 31 percent). Similar patterns were detected in the statewide N analysis by Weiss (2006).

Many of the best-scoring sites occurred in the northern and central Sierra foothills and in the northern California Coast Ranges.

Sidebar 10: ***Nitrogen deposition estimates***
For perspective, the community multiscale air quality model estimates maximum nitrogen (N) in the Los Angeles Basin at 21 kg (Weiss 2006), although deposition levels in excess of 45 kg have been measured in that region (Fenn et al. 2003b). The Los Angeles Basin is believed to receive the highest N deposition in the Nation (Fenn et al. 2003b). Conversely, background N deposition in the Western United States is commonly estimated at 0.5 kg (Baron 2006, Holland et al. 1999).

Conclusions

Nitrogen, probably mostly in the form of NH_3 and the reaction product NH_4^+, is an important driver of lichen community composition in the greater Central Valley. Air quality scores were substantially correlated to modeled NH_3 estimates (Jovan and McCune 2005), and geographic distribution also broadly matched the regional N analysis by Weiss (2006). Moreover, complementary ecological evidence lies in the distribution of N indicator species along the air quality gradient detected by

NMS. Variation among current lichen communities lends insight into how composition is likely to shift in response to ameliorating or worsening N influence. To echo the forecast presented for the west-side Pacific Northwest, increased N loading and alkalinization of bark are anticipated to stimulate nitrophytes and neutrophytes while marginalizing cyanolichens and acidophytic species.

The scarcity of cyanolichens and prospective acidophytes begs the question: Is regional deposition advanced enough that some N-sensitive species have already been lost from the greater Central Valley flora? Nitrogen-driven local extinction is possible, although without a historical inventory it is impossible to know just how much the current flora is actually a deviation from normalcy. Assuming immaculate air quality, it is highly unlikely that the same abundance of cyanolichens and acidophytes found in the western Pacific Northwest could naturally occur in the greater Central Valley for strictly climatic reasons. Nitrophytes generally can better tolerate the hot and dry habitats characteristic of a Mediterranean climate regime (Loppi 2004, Loppi and De Dominicis 1996; see also van Herk et al. 2002) like those of the study area (see chapter 7). Also, dry conditions may promote alkaline dust that stimulates nitrophytes while excluding acidophytes and perhaps other species from local forests. The prevalence of this phenomenon in the Pacific coastal states is unknown and needs further investigation. Regardless, the establishment of baseline conditions as presented here will allow tracking of sensitive species as well as air quality trends.

Chapter 5: Air Quality in the Greater Sierra Nevada, California

Key Findings

1. The lichen bioindication model suggested that nitrogen (N) compounds are impacting some forests of the greater Sierra Nevada.
2. Plots with high estimated N impact were (by definition) more dominated by indicator species of N-enriched environments and high bark pH than low-impact sites.
3. Lichens collected from high-impact sites likewise tended to have relatively high N content (Jovan and Carlberg 2007).
4. Lichen community composition and N content of lichens both suggest that forests of the southern Sierra Nevada lie in a large N hotspot, as further evidenced by other air quality studies.
5. Areas of relatively low N influence were substantial in the northern half of the study area.

Introduction to the Model

The greater Sierra Nevada is a mountainous region in California spanning most of the Sierra Nevada Range, the Southern Cascades, the Modoc Plateau, and high-elevation sites (>1500 m) in the eastern Klamath Mountains (fig. 42). The majority of the western boundary lies along the highly agricultural Central Valley (chapter 4), which is widely recognized as an important source of pollutants carried into Sierran forests (Bytnerowicz and Fenn 1996; Bytnerowicz et al. 2002; Cahill et al. 1996; Fenn et al. 2003b, 2003c). By comparison, the greater Sierra Nevada is considerably less populated and less developed for agriculture and industry (Momsen 2001). Much of the landscape is managed in national forests, parks, and monuments that support an economy based on recreational tourism (figs. 43 and 44).

Overall, long-term air quality data are limited although various short-term monitoring campaigns help characterize conditions in the Sierra Nevada Range (reviewed by Fenn et al. 2003c). It is well established that nitrogen (N) pollutants can reach high levels in some Sierran forests, most especially at sites in the southwestern foothills (~15 kg $N˜ha^{-1}·year^{-1}$) (Fenn et al. 2003c, Weiss 2006). Deposition is apparently high enough in some cases to provoke classic ecological symptoms of

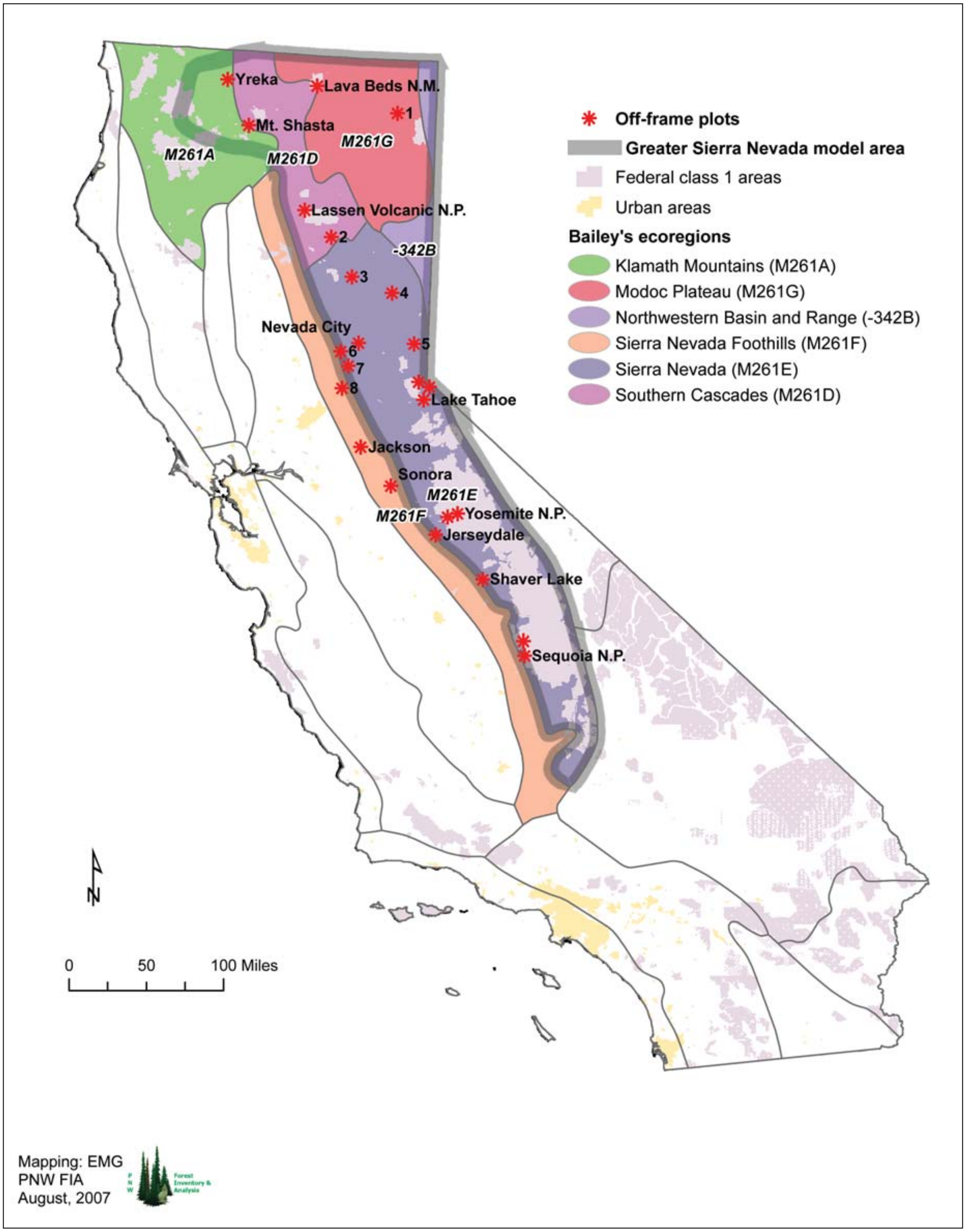


Figure 42—Greater Sierra Nevada model area. Off-frame plots are indicated by red asterisks and named after the city or park in which they were located. Off-frame plots not named on the map are numbered as follows: 1 = Alturas, 2 = Chester, 3 = Quincy, 4 = Portola, 5 = Truckee, 6 = Grass Valley, 7 = Colfax, 8 = Cool.

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Figure 43—Yosemite National Park, California.

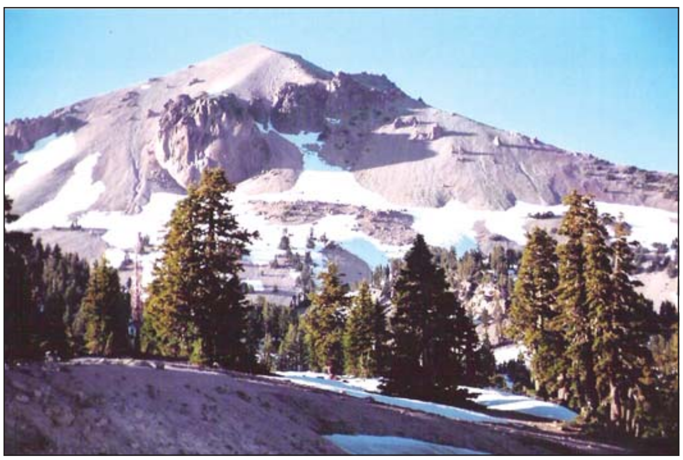

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Figure 44—Lassen Volcanic National Park.

Elevated nitrate in stream water, has been detected in Sequoia National Park and Mountain Home State Park.

N enrichment. Elevated nitrate in stream water, for instance, has been detected in Sequoia National Park and Mountain Home State Park (Fenn et al. 2003c). During development of the air quality model for the Forest Inventory and Analysis (FIA) Program, U.S. Department of Agriculture, it quickly became apparent that lichen communities too were showing signs of N pollution (Jovan and McCune 2006).

Model Adjustment for Elevation Effects

Calibration data used to build the greater Sierra Nevada model included 91 on-frame plots surveyed between 1998 and 2001 (for methods see chapter 1 “Lichen Survey Protocol” section) and 24 off-frame plots surveyed in 2003. Off-frame plots were located in urban, agricultural, or recreation areas including Yosemite, Sequoia, and Lassen Volcanic National Parks (figs. 43 and 44). Extra steps were needed to ensure that the greater Sierra Nevada model isolates air quality effects from the strong influence elevation naturally exerts on lichen communities (Jovan and McCune 2006). The problem arises because air quality and elevation are at least somewhat correlated with each other in the study area (Fenn et al. 2003c). Higher elevation sites tend to be less N polluted than the foothills (fig. 42) since there are fewer local emission sources and forests are farther from the Central Valley with its high density of N sources (Jovan and McCune 2006).

The greater Sierra Nevada model is built around a simple index of indicator species used for N bioindication in the greater Central Valley, the proportion of nitrophyte abundance (PNA; see chapter 4 "Interpretation of Air Quality Estimates: Nitrogen is Shaping Lichen Community Structure" section). The PNA is the summed abundance codes for all nitrophytes (table 14) divided by the summed abundance of all lichen species found in the survey. Nitrophytes are most frequently linked to ammonia (NH_3), but it is unclear to what degree species are responding to the N versus the increase in bark pH that NH_3 causes (see chapter 3 sections "Direct and Indirect Nitrogen Effects on Lichens" and "Nitrophytes"). To isolate the lichen response to air quality, elevation was regressed on the PNA using nonlinear regression with a generalized sigmoid curve (Jovan and McCune 2006; see sidebar 11). The unstandardized residuals from the nonlinear regression serve as the air quality scores for the greater Sierra Nevada.

Ancillary Data: Lichen Nitrogen Content

To complement air quality scores, *Letharia vulpina* (fig. 45) was collected from 38 on-frame sites intentionally selected to encompass a wide range of air quality scores (Jovan and Carlberg 2007). Kjeldahl analysis was used to determine how much N, as a percentage of dry weight, had accumulated in the lichen. Elemental analysis of lichen collections is a widely practiced bioindication tool sometimes employed to estimate N levels in air and precipitation (Bruteig 1993, Geiser and Neitlich 2007, Søchting 1995. Collection and processing of *L. vulpina* samples followed the protocols used by Geiser and Neitlich (2007) as documented in Blett et al. (2003).

Table 14—Species list for the greater Sierra Nevada[a]

Nitrogen indicator group	Species	Acronym	Frequency
Nitrophytes			*Percent*
	Candelaria concolor	Cndcon	43.31
	Flavopunctelia flaventior[b]	Flafla	3.82
	Phaeophyscia orbicularis	Phaorb	7.01
	Physcia adscendens	Phyads	14.65
	Physcia aipolia	Phyaip	13.38
	Physcia dimidiata	Phydim	4.46
	Physcia stellaris	Physte	11.46
	Physcia tenella	Phyten	18.47
	Physconia enteroxantha	Phoent	15.92
	Physconia perisidiosa	Phoper	21.66
	Xanthomendoza fallax	Xanfal	11.46
	Xanthomendoza fulva	Xanful	14.01
	Xanthomendoza hasseana	Xanhas	17.2
	Xanthomendoza oregana	Xanore	22.29
	Xanthoria candelaria	Xancan	12.74
	Xanthoria polycarpa	Xanpol	18.47
Potential acidophytes			
	Bryoria fremontii	Bryfre	17.83
	Cetraria canadensis	Cetcan	5.1
	Cetraria chlorophylla	Cetchl	8.92
	Cetraria merrillii	Cetmer	45.22
	Cetraria orbata	Cetorb	19.75
	Cetraria pallidula	Cetpal	3.82
	Cetraria platyphylla	Cetpla	28.03
	Evernia prunastri[b]	Evepru	22.93
	Hypogymnia imshaugii	Hypims	66.24
	Hypogymnia occidentalis	Hypocc	3.82
	Parmeliopsis ambigua	Paramb	3.18
	Platismatia glauca	Plagla	17.83
	Usnea filipendula	Usnfil	8.92
Potential neutrophytes			
	Melanelia elegantula	Melele	31.21
	Melanelia exasperatula	Melexl	19.11
	Melanelia glabra	Melgla	14.01
	Melanelia subargentifera	Melsar	3.18
	Melanelia subelegantula	Melsel	10.19
	Melanelia subolivacea	Melsol	51.59
	Parmelia hygrophila[b]	Parhyg	10.19
	Parmelia sulcata	Parsul	25.48
	Ramalina subleptocarpha[b]	Ramsle	4.46
Stratified cyanolichens			
	Lobaria hallii	Lobhal	0.64
	Nephroma helveticum	Nephel	0.64
	Nephroma resupinatum	Nepres	0.64
	Peltigera collina	Pelcol	5.73

Table 14—Species list for the greater Sierra Nevada[a] (continued)

Nitrogen indicator group	Species	Acronym	Frequency
			Percent
	Pseudocyphellaria anomala	Pcyano	2.55
	Pseudocyphellaria anthraspis	Pcyant	3.18
Unknown			
	Ahtiana sphaerosporella	Ahtsph	22.29
	Alectoria sarmentosa	Alesar	3.82
	Collema furfuraceum	Colfur	7.01
	Esslingeriana idahoensis	Essida	10.19
	Leptogium lichenoides	Leplic	6.37
	Letharia columbiana	Letcol	59.87
	Letharia vulpina	Letvul	75.16
	Nodobryoria	Nod	6.37
	Nodobryoria abbreviata	Nodabb	43.31
	Nodobryoria oregana	Nodore	23.57
	Parmelina quercina	Pnaque	9.55
	Physcia biziana	Phybiz	5.73
	Physconia americana	Phoame	16.56
	Physconia isidiigera	Phoisi	15.29

[a] Tentative designations of acidophytes and neutrophytes are based on whether the species belongs to a genus exhibiting acidophytic or neutrophytic behavior in the Netherlands (van Herk 1999, 2001; Sparrius 2007) or United Kingdom (Sutton et al. 2004).

[b] Species assigned to different indicator groups in the literature. *Flavopunctelia flaventior* is not widely defined as nitrophytic. *Evernia prunastri* is considered a neutrophyte by Gombert et al. 2005. Jovan and McCune (2005, 2006) classified *Parmelia hygrophila* and *Ramalina subleptocarpha* as nitrophytes.

Sidebar 11: *Calculating Greater Sierra Nevada air scores*

Air quality scores for plots in the greater Sierra Nevada are derived as follows:

- Calculate the proportion of nitrophyte abundance (PNA) in the lichen community (see sidebar 8).
- Plug elevation (in meters) into the nonlinear regression equation to get *Y*.

$$Y = \frac{0.48}{1 + \left(\frac{Elevation}{1689}\right)^{5.91}}$$

- Subtract *Y* from the actual PNA and multiply by 100.

$$\text{Air quality score} = 100(PNA - Y).$$

- The resulting air quality score is a measure of how much the PNA is above or below what is expected given the plot elevation. A higher score suggests higher N influence.

Figure 45—*Letharia vulpina* (wolf lichen) was collected for analysis of accumulated nitrogen.

Interpretation of Air Quality Estimates: Nitrogen Impacts Are Apparent

High (poor) air quality scores from the greater Sierra Nevada model are equated with high N impact, of which NH_3 is likely a major component (Jovan and McCune 2006). Because scores are derived from the PNA, nitrophytes were abundant at high-impact sites by definition. *Letharia vulpina* collected from these poorly scoring plots tended to have higher N content (lichen N ranged from 0.6 percent to 2.11 percent). When mapped, air quality scores and N content of lichens resolved the same major N deposition patterns (Jovan and Carlberg 2007) as discussed further in the following section.

Summary of Air Quality Patterns in the Greater Sierra Nevada

Air quality scores are summarized for a full cycle of FIA data (n = 146; 1998-2001, 2003) including the 24 off-frame plots. Most of these plots were included in the published summary found in Jovan and McCune (2006) excepting 25 additional sites surveyed in 2003. Most off-frame plots were purposefully installed in forests expected to be pollution-stressed and so are included here to provide a basis for

Table 15—Air quality scores from the greater Sierra Nevada (GSN) model (1998–2001, 2003)[a]

Parameter	GSN	On-frame	Off-frame
Number of plots surveyed	146	122	24
Number of plots by air quality zone:			
1: (Best) -43.36 to -15.88	35	31	4
2: -15.88 to -8.22	31	30	1
3: -8.22 to 4.35	33	30	3
4: (Worst) 4.35 to 66.49	47	31	16
Air quality score extremes	-43.36 to 66.49	-43.36 to 66.49	-32.38 to 41.61
Average air quality score	-2.77	-5.13	10.27
Standard deviation of air quality scores	19.28	18.32	19.60

[a] Plots were excluded from analysis if they lacked species or were duplicate surveys used for quality assurance purposes.

The highest N impacts are estimated for several plots located within or near Kings Canyon, Sequoia, and Yosemite National Parks.

comparison. Unsurprisingly, greater N impacts are estimated for off-frame sites. The average off-frame air quality score was poor at 10.27 (range: -32.38 to 41.61) compared to the on-frame average of -5.13 (range: -43.4 to 66.5; table 15). More than two-thirds of off-frame plots were more nitrophyte-dominated than would be expected given plot elevation. Even so, the worst air quality score was found for an on-frame plot lying just outside Kings Canyon National Park where 66.5 percent of lichen abundance was from nitrophytic lichen species.

Major Deposition Patterns

The highest N impacts are estimated for several plots located within or near Kings Canyon, Sequoia, and Yosemite National Parks (fig. 46). Both on- and off-frame sites indicate that a large deposition hotspot extends from Yosemite to the southernmost model boundary (figs. 46 and 47). Likewise, the most N-enriched *Letharia vulpina* found in the greater Sierra Nevada (n = 38) came from six of the seven collection sites in this region (range: 1.38 to 2.11 percent N; Jovan and Carlberg 2007).

Instances of high N-loading are well-documented for the southern Sierras (reviewed in Fenn et al. 2003c). These mixed-conifer forests lie downwind of the San Joaquin Valley where the FIA Lichen Indicator (see chapter 4) and the Community Multiscale Air Quality Model (CMAQ) (Buyn and Ching 1999, Tonnesen et al. 2002, Weiss 2006) both suggest high N concentrations. Climate patterns in the San Joaquin Valley are reminiscent of the Los Angeles Basin: frequent temperature inversions cause air to stagnate, in effect trapping emissions near leeward forests.

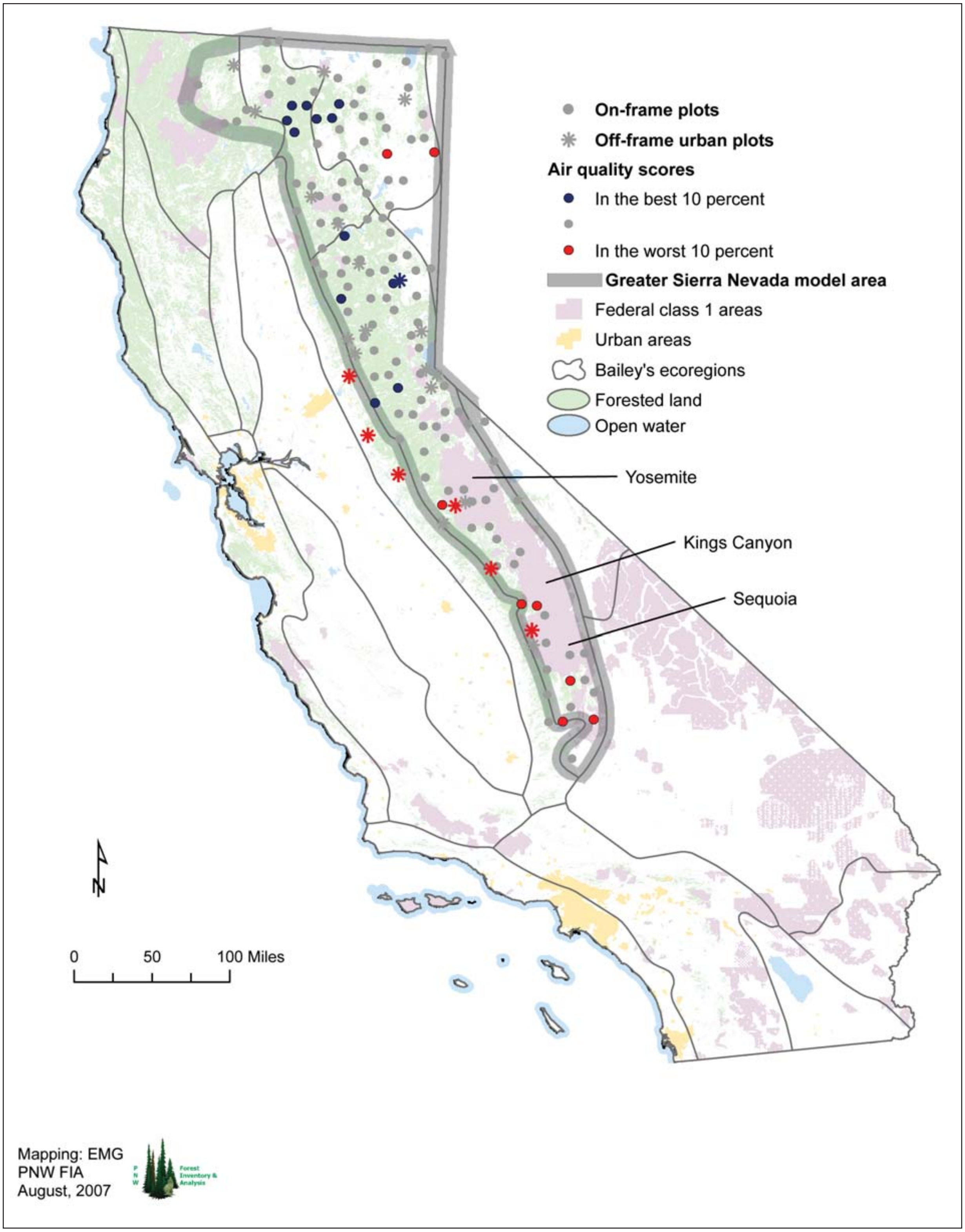

Figure 46—Extreme best and worst 10 percent of air quality scores. Off-frame plots are symbolized by asterisks. See figure 42 for ecoregion codes.

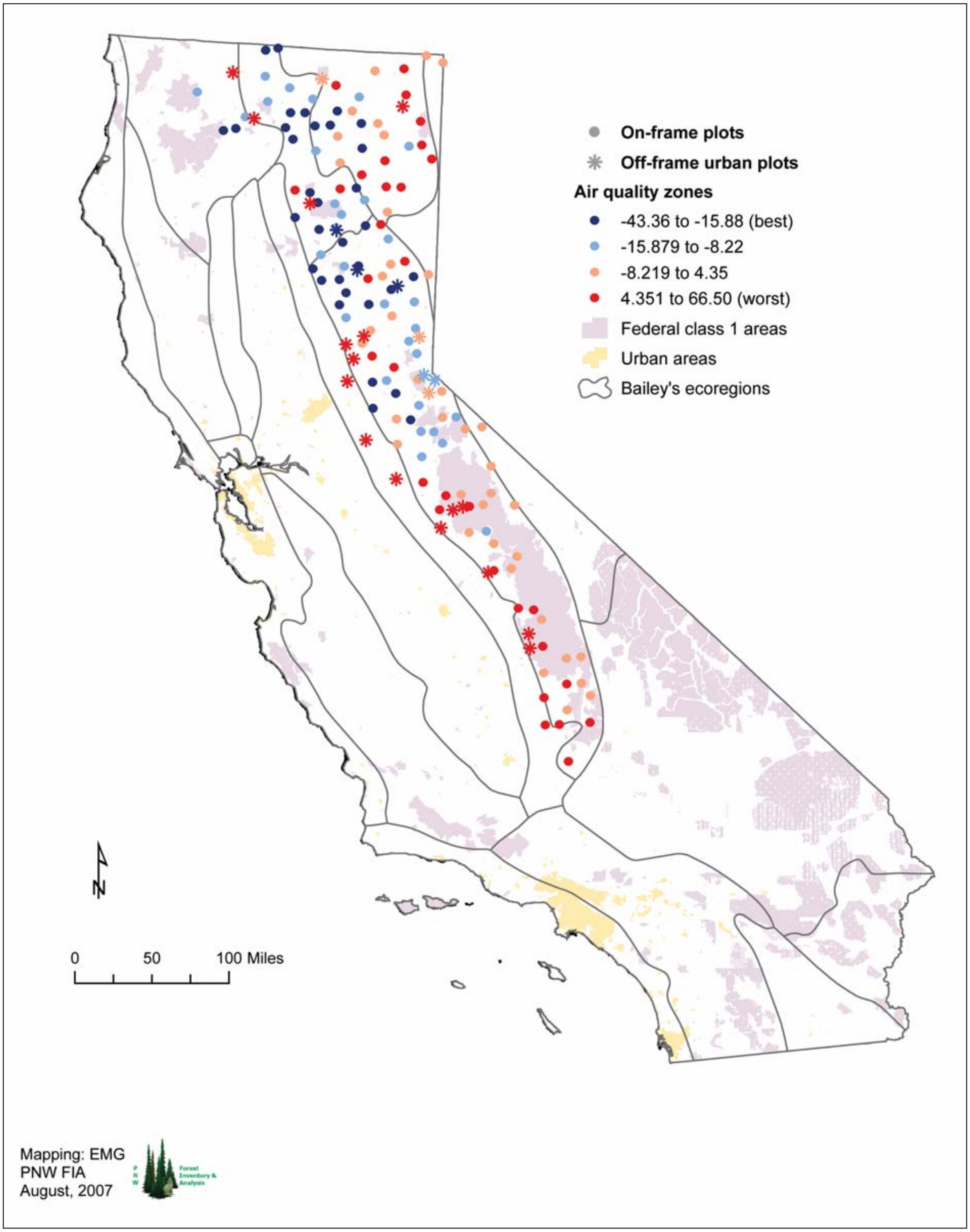

Figure 47—Air quality scores for the greater Sierra Nevada model area divided into air quality zones. Scores are unitless until calibrated with pollutant measurements. Scores for on-frame (circles) and off-frame plots (asterisks) are indicated by a common color scheme. See figure 42 for ecoregion codes.

Preliminary high-resolution results (4 km^2) from the CMAQ model estimate deposition in the southern Sierra hotspot reaches up to 8.7 kg $N \cdot ha^{-1} \cdot year^{-1}$, especially at lower elevations and more southerly sites.[1]

A smaller deposition hotspot may occur on the eastern Modoc Plateau as indicated by poor air quality scores (figs. 46 and 47) and high N accumulation (up to 1.32 percent) in some *Letharia vulpina* collections (Jovan and Carlberg 2007, Jovan and McCune 2006). There are not, however, any local N measurements to corroborate lichenological evidence of N impact. There are indeed agricultural N sources in the Modoc although the area is fairly remote and sparsely populated. Closer investigation would be needed before drawing any firm conclusions. Alkaline dust may contribute to the high abundance of nitrophytes in the dry landscape of the plateau (see chapter 3 “Direct and Indirect Nitrogen Effects on Lichens” section).

Relatively low N influence was estimated for many forests in the northern half of the study area.

Relatively low N influence was otherwise estimated for many forests in the northern half of the study area, which includes all plots scoring in the best 10 percent (figs. 46 and 47). Lichen communities from the southern Cascades and northern Sierra Nevada were frequently rich in acidophytes, neutrophytes, as well as a variety of species of “unknown” N indicator value (table 14; see chapter 3 “Discussion of Indicator Species” section). Some of these forests likely receive N from the Sacramento Valley, although there are few in situ N measurements to help quantify exposure.

Conclusions

Nitrogen compounds are important constituents of air quality in the greater Sierra Nevada, as evidenced by (1) the distribution of nitrophytes in the FIA Lichen Community Indicator data (2) accumulation of N in *Letharia vulpina* collections, (3) N estimates from the CMAQ model, and (4) various short-term N monitoring campaigns (Fenn et al. 2003b, 2003c). Altogether these varied data sources make a clear case for high N impact to forests in the southwestern Sierra Nevada, a scenic region lavish with over 1.2 million ha of land in 17 federally protected class I areas. Ozone is also a major stressor in these forests as evidenced by the FIA Ozone Indicator, where 82 percent of ozone biosites in the San Joaquin Valley air basin (all located in the southern Sierra Nevada) and 27 percent of biosites in the Mountain Counties air basin (central and northern Sierra Nevada) exhibited foliar damage between 2000 and 2005 (Campbell et al. 2007).

[1] Tonnesen. 2007. Unpublished data. On file with: R. Johnson, Center for Conservation Biology, 2415A Boyce Hall, University of California Riverside, Riverside, CA 92521.

Part IV: Climate Mapping and Tracking

Although lesser known, the Lichen Community Indicator data may also be applied for mapping and monitoring climate change. Lichens, like many other sedentary organisms, often arrange themselves predictably along climatic gradients (Insarov and Schroeter 2002, Jovan and McCune 2004). Temperature is usually of central importance to lichen distributions because it influences the rate of photosynthesis and basic metabolic processes. Lichens are also intimately tied to moisture regime because, as they lack a vascular system, they absorb water passively. (This passive uptake is in fact a physiological reason why lichens are so sensitive to pollutants, which dissolve in the water and then are transferred directly into the thallus.) A dry lichen becomes metabolically inactive and may be able to persevere through long periods of drought. But much like plants, some lichen species are drought-tolerant, whereas some require mesic and hydric habitats to survive. Conversely, lichens continuously hydrated will suffer, some species sooner than others, particularly under low light levels. In the same way, lichen tolerances to heat and cold differ widely across species.

The two following chapters deal with application of the FIA lichen data for mapping baseline forest climate in the west-side Pacific Northwest and in northern and central California. In the long-term, it is expected that warming trends will initiate floristic shifts across forest ecosystems with temperature-sensitive species generally shifting to higher latitudes and higher elevations (Easterling et al. 2000, Parmesan and Yohe 2003, Walther et al. 2002). Lichenologists in Europe have already documented the incursion of tropical and subtropical lichen species into higher latitudes while also witnessing a net decrease in alpine species (van Herk et al. 2002). Similar trends and species shifts will be detectable with data from the Forest Inventory and Analysis (FIA) Lichen Community Indicator, U.S. Department of Agriculture.

Roseann Barnhill

Hypogymnia (tube lichen) found in Rhododendron, Oregon.

Chapter 6: Climate Biomonitoring in the West-Side Pacific Northwest

Key Findings

1. In the west-side Pacific Northwest, climate scores were most strongly patterned on temperature: forests at higher scoring plots experience, on average, more continental climate and lower minimum temperatures than low-scoring sites (Geiser and Neitlich 2007).
2. Based on climate scores, plots can be subdivided into four geographically cohesive climate zones: maritime (lowest scores), lowland, montane, and high elevation (highest scores; Geiser and Neitlich 2007).
3. The analysis by Geiser and Neitlich (2007) suggests predicted warming trends would push mean temperatures in the maritime zone (and potentially also the lowland zone) to levels unprecedented in the study area.
4. Warming may be especially troubling for lichen communities of the high-elevation zone, which have limited opportunity to migrate farther upwards in elevation to find cooler habitat conditions. Likewise, rare species are more likely to be extirpated than common species (Glavich and others 2005b)
5. As would be expected, the spatial distribution of climate scores based only on data collected by the Forest Inventory and Analysis (FIA) Program, U.S. Department of Agriculture, resembles the more extensive climate map produced by Geiser and Neitlich (2007).

Introduction to the Model

Details of the west-side Pacific Northwest gradient model are summarized in chapter 3. To review briefly, Geiser and Neitlich (2007) built the model with nonmetric multidimensional scaling (NMS) and applied it to estimate both air quality and climate at 1,416 plots in the study area. Each plot was surveyed for epiphytic lichen communities between 1994 and 2001 by using the standardized FIA field protocol (for methods see chapter 1 “Lichen Survey Protocol” section). About 211 plots in their study lie on the FIA sampling grid.

Ancillary Data: PRISM Model Climate Data

Geiser and Neitlich (2007) related climate scores from the gradient model to a series of climate variables extracted from the Parameter-elevation Regressions on

Independent Slopes Model (PRISM) (Daly and Taylor 2000). Variables were all long-term annual averages (1969 to 1990) at 2 km^2 resolution, and included dew point, maximum August temperature, minimum December temperature, continentality (e.g., the difference between the latter two variables), number of wet days, precipitation, and relative humidity. Mean annual days of marine fog and annual temperature were obtained from Lipow et al. (2004).

Interpretation of Climate Estimates

The lichen community response to climate, as captured in the NMS model, was strongly patterned on a temperature gradient (Geiser and Neitlich 2007). Climate scores were most correlated with minimum December temperature and continentality (r = - 0.79 and 0.73, respectively). In other words, high scores indicate forest habitats that endure lower minimum temperatures and a wider temperature range throughout the year. Despite this relation, these scores are not necessarily a pure reflection of temperature and are more appropriately regarded as an integrative lichen response to local climate. Predictably, other variables had substantial linear correlations to climate scores like relative humidity (r = 0.57) and geographic covariates such as elevation (r = 0.68), longitude (r = 0.68), and distance from the ocean (r = 0.67).

That lichen community composition could be used to classify forests into distinctive climate zones is itself a compelling indication that some species will be highly responsive to climate change.

Review of Climate Zones and Indicator Species From Geiser and Neitlich (2007)

Geiser and Neitlich (2007) used natural breaks (Jenks 1967) to divide climate scores from all 1,416 plots into four broad zones: maritime (lowest scores), lowland, montane, and high elevation (highest scores). A comparison of current mean temperatures per zone to temperatures projected for 2040 led them to the troubling observation that “even under the most conservative scenario [+1.5 °C for the Pacific Northwest, according to Mote et al. 2003] mean maritime temperatures would shift above any current climate zone range [in the study area]. The lowland mean would be shifted into the maritime range under the minimum change scenario and above any current zone under the maximum change [+3.2 °C; Mote et al. 2003] scenario” (Geiser and Neitlich 2007). That lichen community composition could be used to classify forests into distinctive climate zones is itself a compelling indication that some species will be highly responsive to climate change. Accordingly, Indicator Species Analysis (ISA) (Dufrêne and Legendre 1997) (for methods see chapter 1 "Indicator Species Analysis" section) was able to identify 17 to 23 lichen indicator species per zone, as reported in full by Geiser and Neitlich (2007) and highlighted below.

Large Stratified Cyanolichens

Statistically defined indicator species of the maritime zone include the large, stratified cyanolichen species *Lobaria oregana* (fig. 8), *Peltigera membranacea*, *Pseudocyphellaria anthraspis*, and *Pseudocyphellaria crocata* (fig. 7) (Geiser and Neitlich 2007). Rich cyanolichen assemblages are also a feature of moist, low- to mid-elevation forests in the montane zone; *Lobaria pulmonaria*, *Nephroma helveticum*, *N. resupinatum* (fig. 48), and *Pseudocyphellaria anomala* are all associated with the montane climate regime (Geiser and Neitlich 2007). Owing to their unique physiology, lichens in this group are renowned for their susceptibility to both thermal and moisture stress (Bjerke et al. 2003, Geiser and Neitlich 2007, Nash and Olafsen 1995, Richardson and Cameron 2004). Cyanolichens are intimately linked to forest health in the Pacific Northwest because of their contribution to nitrogen budgets and nutrient cycling.

Hypermaritime Communities

Another community of particular concern for the maritime zone is the suite of rare and endemic lichen species restricted to a thin band of forest hugging the coastline (Glavich et al. 2005b). These warm and wet hypermaritime forests are a bona fide

Karen Dillman

Figure 48—A large thallus of *Nephroma resupinatum* (kidney lichen).

Along with poor dispersal ability, rarity and narrow ecological amplitude are traits that probabilistically increase a species' risk of climate-driven extirpation.

special habitat for epiphytic lichens in the Pacific Northwest (Geiser et al. 2004; Glavich et al. 2005a, 2005b), supporting such rarities as *Bryoria pseudocapillaris*, *Erioderma sorediatum* (fig. 49), *Leptogium brebissonii*, *Pseudocyphellaria perpetua*, and *Usnea hesperina*. Habitat models built for these species do forecast a high sensitivity to climate fluctuation (Glavich et al. 2005b). For sedentary organisms, successful range migration to cooler habitats at higher latitudes and elevations will depend on many factors. Along with poor dispersal ability, rarity and narrow ecological amplitude are traits that probabilistically increase a species' risk of climate-driven extirpation (Thomas et al. 2004, Walther et al. 2002; sidebar 12).

High-Elevation Communities

At the extreme cool end of the west-side Pacific Northwest temperature gradient are lichen communities of the high-elevation zone. Indicator species of this zone include several hair-like forage species (see chapter 1 "Introduction") such as *Alectoria sarmentosa* (fig. 50), *Bryoria capillaris*, *B. fremontii*, *B. fuscesens*, *B. glabra*, and *Nodobryoria oregana* (Geiser and Neitlich 2007). All of these lichens rely, to varying extents, on thallus fragmentation for reproduction and colonization of new habitats. Perhaps to untold advantage, two of these species do regularly employ a second mode of asexual reproduction, soredia (small powder-like granules of a few algal cells wrapped in fungal hyphae). By virtue of small size and abundance, soredia are propagules that are better suited for long-distance dispersal.

Sarah Jovan

Figure 49—*Erioderma sorediatum* (mouse ear lichen), a very rare lichen species usually found in coastal forests of Oregon and Washington.

Sidebar 12: *Usnea longissima*

Karen Dillman

Usnea longissima (beard lichen).

The west-side Pacific Northwest has worldwide importance as a refuge for the charismatic lichen *Usnea longissima* (Keon and Muir 2002), an indicator species of the "lowland" zone (Geiser and Neitlich 2007). A notoriously poor dispersor, *U. longissima* relies entirely on fragmentation to reproduce: chunks of thallus break off in the wind and, if lucky, snag on a nearby tree and grow into clones. Current populations are patchy, and colonization of new forested habitats is slow (Keon and Muir 2002). A chief concern among ecologists is that dispersal-limited species like *U. longissima* will have difficulty "outrunning" climate change.

Jim Riley, Courtesy of OSU

Figure 50—Trees bearded with thick *Alectoria sarmentosa* (witch's hair lichen) in the western Cascades.

Table 16—Core table summarizing climate scores for the west-side Pacific Northwest (PNW) model area by state (1998-2001, 2003)[a]

Parameter	West-side PNW	West-side Oregon	West-side Washington
Number of plots surveyed	243	140	103
Number of plots by climate zone:			
Maritime/warmest (-1.41 to -0.25)	73	32	41
Lowland (-0.25 to 0.23)	54	29	25
Montane (0.23 to 0.66)	57	38	19
High elevation/coolest (0.66 to 1.73)	59	41	18
Climate score extremes	-1.41 to 1.73	-1.21 to 1.73	-1.41 to 1.15
Average climate score	0.14	0.27	-0.03
Standard deviation on climate scores	0.64	0.63	0.61

[a] Categories are based on climate zones defined by Geiser and Neitlich (2007). Plots were excluded from analysis if they lacked species, had no species in common with the calibration plots, or were duplicate surveys used for quality assurance purposes.

Good dispersal ability may become increasingly important for species associated with alpine and subalpine ecosystems as there is limited opportunity for upward migration.

Summary of Climate Patterns in the West-Side Pacific Northwest

The same plots summarized for air quality in chapter 3 are summarized here for climate and will be utilized by the FIA Program and the Forest Service Region 6 Air Resource Program to track effects of climate change on forest communities. Plots constitute a full cycle of FIA lichen data (n = 249; 1998 to 2003). About 75 percent of plots were included in Geiser and Neitlich's (2007) extensive summary.

Climate scores for west-side Oregon and Washington are summarized in table 16 using Geiser and Neitlich's (2007) climate zones. The spatial pattern of climate scores is analogous to the more extensive map of Geiser and Neitlich (2007), with geographically cohesive climate zones that coincide with sizeable portions of ecoregions (fig. 51). As expected, low scores characteristic of the maritime and lowland zones were predominantly assigned to low-elevation forests of the Oregon and Washington Coast Ranges and the Willamette and Puget Trough ecoregions (see fig. 14). Farther from the temperature-moderating effects of the ocean, the higher scoring, cooler forests of the montane and high-elevation climate zones predominate in the Cascades Range and Klamath Mountains.

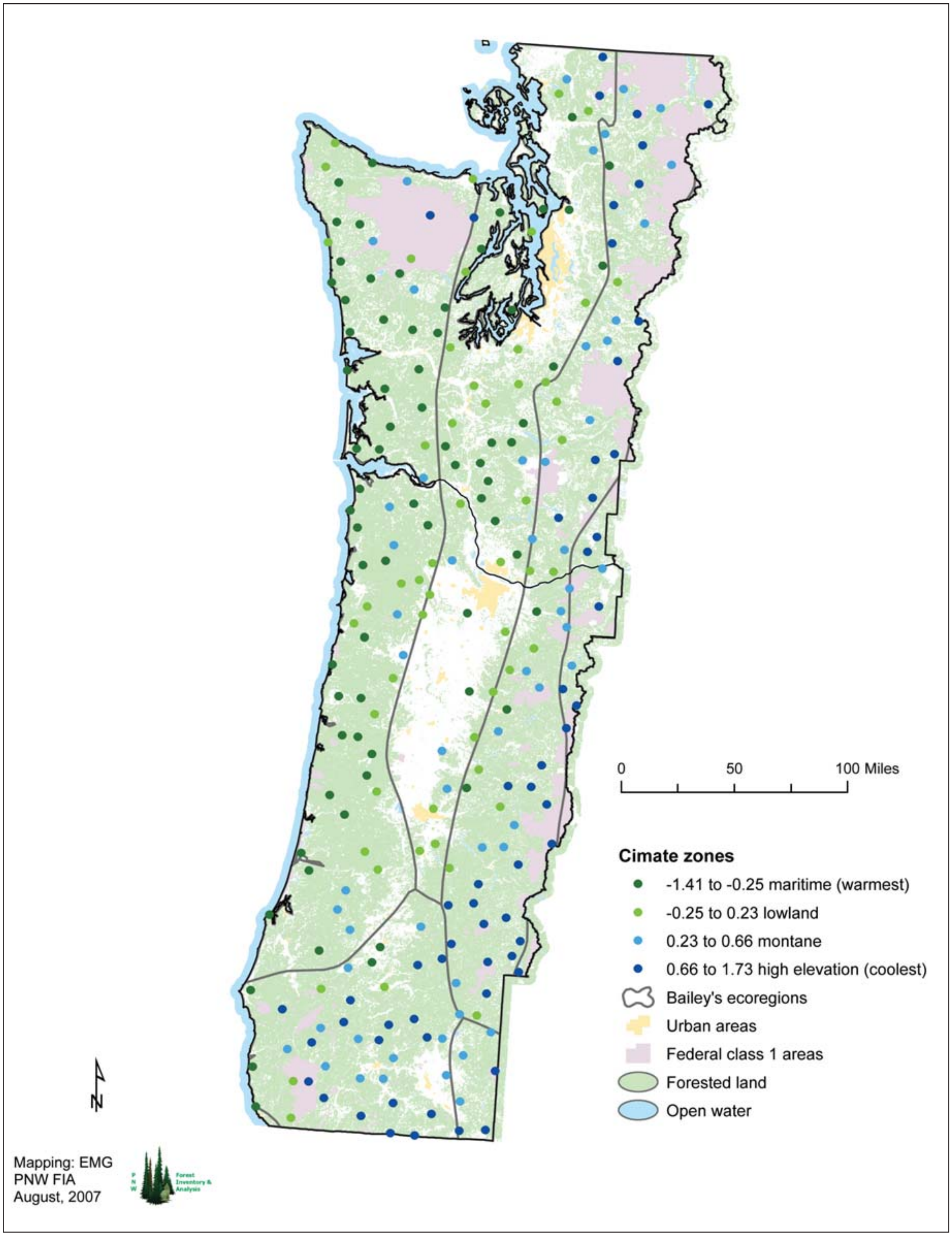

Figure 51—Climate scores for the west-side Pacific Northwest categorized by Geiser and Neitlich's (2007) four climate zones. See figure 22 for ecoregion codes.

Predicted warming trends have considerable potential to alter the lichen flora of the west-side Pacific Northwest.

Conclusions

Clearly, predicted warming trends have considerable potential to alter the lichen flora of the west-side Pacific Northwest. Changes to moisture regime are also likely to affect the composition of communities, although this relationship is not as strongly represented in the model. There is little agreement about how precipitation will change in the region, if at all. As temperature and moisture trends interactively drive range shifts, resulting patterns will be easily detectable with the FIA Lichen Community Indicator. It is uncertain at this point how much noise will be introduced into the model if certain species, like the poor dispersers, are unable to successfully migrate across the fragmented forest landscape. Many lichens are rare, poor dispersers, or have strict habitat requirements, which are all qualities that make species more susceptible to extirpation. All in all, climate change has considerable potential to depress lichen biodiversity.

Chapter 7: Climate Biomonitoring in Northern and Central California

Key Findings

1. Lichen community composition in northern and central California is closely patterned on two macroclimatic gradients: the first gradient appears strongly correlated with temperature and the second with moisture.
2. Following the analytical procedure of Geiser and Neitlich (2007) (chapter 5), plot scores along the first gradient were divided into four temperature zones differing in mean temperature and elevation. Scores on the second gradient were divided into four moisture zones differing in mean number of wet days and precipitation.
3. An Indicator Species Analysis (ISA) (Dufrêne and Legendre 1997) found multiple statistically significant lichen indicator species for each climate zone. Results provide a general framework suggesting how long-term temperature and moisture fluctuation may alter lichen community composition.
4. With the advent of rising temperatures, species restricted to cooler forests at mid to high elevations may face a regionally shrinking niche, whereas communities of warmer temperature zones may presumably migrate upwards in elevation.
5. Predictions of precipitation changes conflict among global climate models (California Climate Change Center 2006a, 2006b). Species associated with the wettest and the driest zones are most likely to endure range contractions in the study region depending on which way (if any) precipitation patterns swing.

Introduction to the Model

The U.S. Department of Agriculture Forest Inventory and Analysis (FIA) Program uses a single lichen bioindication model to assess climate across northern and central California forests (fig. 52) (Jovan and McCune 2004). Lichen communities in this region are strongly influenced by coast-to-inland macroclimatic gradients that are intensified by the diversity of landforms in the mountainous terrain. The FIA climate model was originally developed by Jovan and McCune (2004) as a tool to delineate three smaller, more climatically homogeneous model areas for air quality bioindication (fig. 52): the southernmost boundary of the climate study region

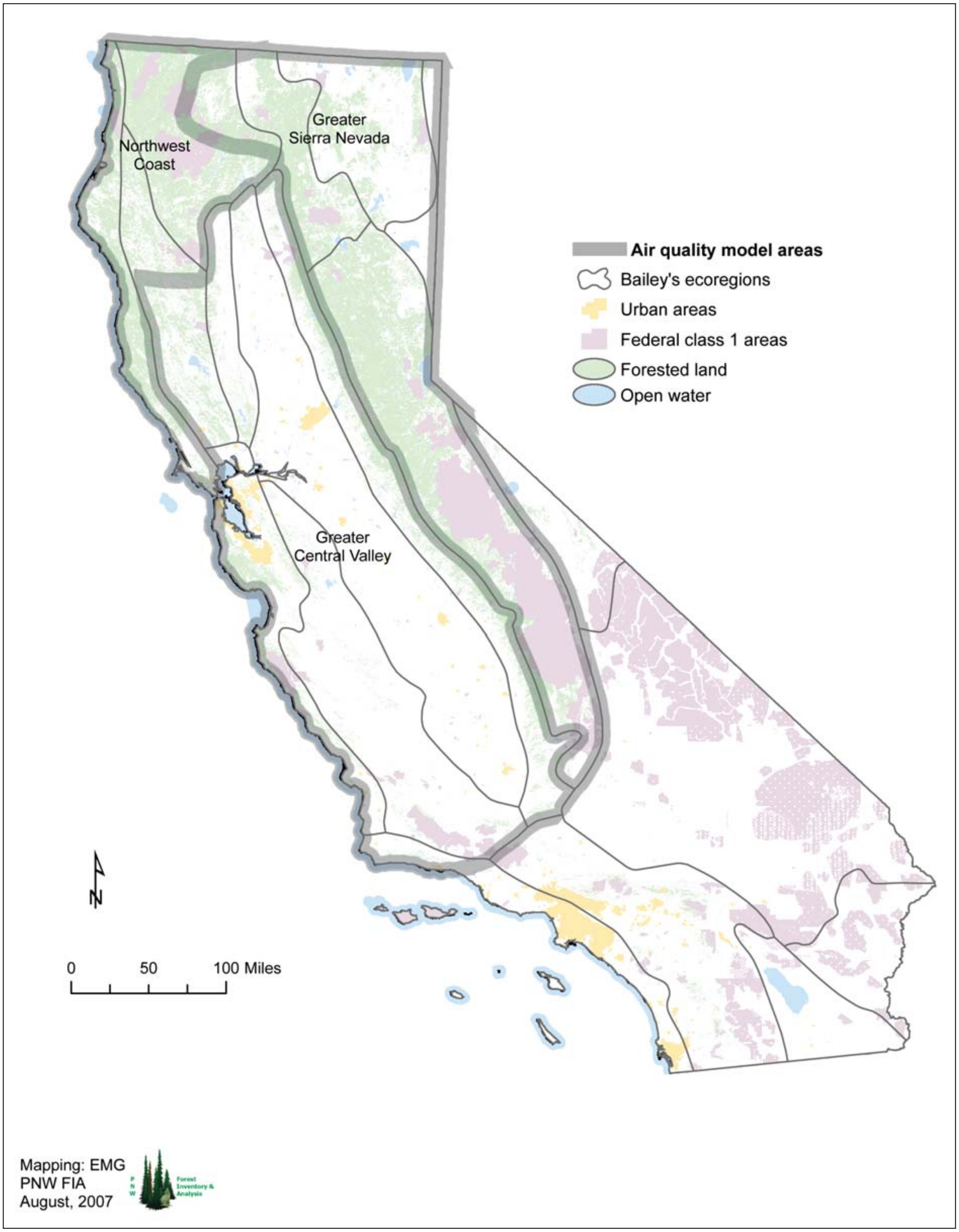

Figure 52—Northern and central California model area for climate bioindication showing the three nested air quality model areas. See figure 14 for ecoregion codes.

coincides with the greater Central Valley (chapter 4) and greater Sierra Nevada (chapter 5) model areas. Calibration data from 211 on-frame FIA plots were used to build the climate model with nonmetric multidimensional scaling (NMS) (see chapter 1 "Methods" section). All plots, visited once between 1998 and 2001, were surveyed using the standard FIA lichen community sampling protocol.

Ancillary Data: PRISM Model Climate Data

Plot scores from the NMS model, hereafter referred to as "climate scores," were compared to climate estimates from the high-resolution (2 km^2) Parameter-elevation Regressions on Independent Slopes Model (PRISM) (Daly et al. 2001). The PRISM estimates are long-term averages (1969 to 1990) and include dew temperature, temperature, maximum temperature, minimum temperature, precipitation, number of wet days, and relative humidity.

Interpretation of Climate Estimates

The model resolved two major gradients in lichen community composition, one relating primarily to temperature and a second gradient relating to moisture. Climate scores from the temperature gradient are most closely correlated with mean temperature (r = -0.78) and elevation (r = 0.79) such that low scores indicate warm, low-elevation forests, whereas higher scores typify colder forests at higher elevations. Climate scores derived from the moisture gradient are strongly correlated with annual number of wet days (r = -0.71) and precipitation (r = -0.66). Lichen communities at low-scoring sites reflect relatively wet forest conditions versus higher scoring dry forests. As mentioned briefly in chapter 6 ("Interpretation of Climate Estimates" section), however, climate scores are not necessarily a pure estimate of one particular element of climate. Results are discussed in the context of "temperature" and "moisture" because those are likely the primary determinants of climate scores although scores are, more precisely, an integrative reflection of local climate.

Discussion of Climate Zones and Indicator Species

Geiser and Neitlich (2007) were the first to use data collected with FIA protocols to assess potential impacts of climate change on lichen communities. Their analysis (see chapter 6) was used here as a guideline for the delineation of climate zones and lichen indicator species for northern and central California. Scores from the temperature and moisture gradients detected by NMS were each divided into four climate zones using natural breaks in the data (Geiser and Neitlich 2007, Jenks 1967). Lichen indicator species were defined for each climate zone with ISA (for methods see chapter 1 "Indicator Species Analysis" section); in this case the strongest possible indicator species is consistently present in its climate zone and absent everywhere else. It is important to note that rare species cannot be significant indicators because it is probable that all of the species' occurrences will fall within a particular climate zone simply by random chance.

Average temperature or moisture per zone was calculated from the PRISM data (Daly et al. 2001) to roughly represent current conditions. Because we are intersecting modeled climate data (from lichens) to modeled climate data (from PRISM), there is unavoidably some noise in their relationships to one another. Still, results provide a generalized, descriptive framework for forecasting community-based responses to climate change.

Predicted warming trends could potentially have a powerful impact on lichen assemblages.

Proposed Temperature Effects

Indicator species, mean temperature, and mean elevation per climate zone from the first gradient detected by NMS are displayed in table 17. Despite overlapping ranges, mean temperatures decrease by 1.2, 3.1, and 2.0 °C between consecutive zones. Predicted warming trends could potentially have a powerful impact on lichen assemblages given that average temperatures in California are expected to increase by 1.7 to 5.8 °C by 2100 (California Climate Change Center 2006a, 2006b). This wide temperature range was derived from multiple climate scenarios differing by anticipated magnitude of greenhouse gas emissions and assumed climatic sensitivity (California Climate Change Center 2006a, 2006b) (see sidebar 13). Depending on how quickly warming proceeds, shorter-term impacts to lichens and the surrounding forest ecosystem are indeed possible.

Migrations of temperature-sensitive lichen species are expected to proceed from lower to higher numbered climate zones as defined with the FIA Lichen Community Indicator data (table 17); how this trend might play out geographically is demonstrated in section 7.4 below. The warmer zones, 1 through 3, are each characterized by numerous indicator species spanning a variety of lichen genera and functional groups. The comparatively low diversity of zone 4 indicators is not surprising considering the harsh climatic conditions of high-elevation forests. *Ahtiana sphaerosporella* (fig. 53) and *Parmeliopsis ambigua* (fig. 54; table 17) are both hardy boreal species. Like high-elevation species in the west-side Pacific Northwest (see chapter 6 "High-Elevation Communities" section), these indicators

Table 17—Indicator species of temperature zones in northern and central California[a]

Zone 1: Warm, low elevation forests Temperature: 14.0 (2.0) Elevation: 584 (376)	***Candelaria concolor***, *Dendriscocaulon* sp., ***Flavopunctelia flaventior***, *Hypogymnia tubulosa, Leptogium lichenoides, Melanelia* fuliginosa, *Melanelia glabra, Melanelia subargentifera*, ***Phaeophyscia orbicularis***, *Physconia americana, Physconia isidiigera*, ***Physconia perisidiosa***, ***Physcia adscendens***, *Physcia biziana*, ***Physcia dimidiata***, ***Physcia stellaris***, *Parmotrema chinense, Parmelina quercina*, ***Punctelia perriticulata***, *Ramalina farinacea, Ramalina menziesii, Ramalina subleptocarpha, <u>Sticta limbata</u>, Usnea arizonica, Usnea glabrata, Usnea substerilis*, ***Xanthoria fallax***
Zone 2 Temperature: 12.8 (2.3) Elevation: 815 (389)	*Collema furfuraceum, Collema nigrescens, Esslingeriana idahoensis, Evernia prunastri, Hypogymnia inactiva, Hypogymnia physodes, Parmelia sulcata, <u>Pseudocyphellaria anomala</u>, <u>Pseudocyphellaria anthraspis</u>, <u>Peltigera collina</u>*, ***Physconia enteroxantha***, ***Physcia aipolia***, *Platismatia herrei, Platismatia stenophylla, Usnea lapponica, Usnea subfloridana, Usnea wirthii*
Zone 3 Temperature: 9.6 (2.2) Elevation: 1476 (424)	*Bryoria capillaris, Bryoria fremontii, Cetraria chlorophylla, Cetraria merrillii, Cetraria platyphylla, Hypogymnia imshaugii, Letharia collina, Letharia vulpina, Melanelia elegantula, Melanelia exasperatula, Melanelia subelegantula, Melanelia subolivacea, Nodobryoria abbreviata, Nodobryoria oregana, Platismatia glauca, Usnea filipendula*
Zone 4: Cool, high-elevation forests Temperature: 7.6 (2.2) Elevation: 1943 (461)	*Ahtiana sphaerosporella, Parmeliopsis ambigua*

[a] Average temperature (°C) and plot elevation (m) are reported, followed by standard deviations in parentheses. Only species that are statistically significant indicators ($p < 0.05$), according to Indicator Species Analysis, are reported. Nitrophytes are in bold and stratified foliose cyanolichens are underlined.

Sidebar 13: *Feedback loops*

Warming predictions were compiled from three global climate models that differ in climate sensitivity (i.e., how sensitive temperature will be to greenhouse gas concentrations). An important determinant of climate sensitivity is the influence of environmental feedback loops wherein warming stimulates a biological or physical process that has positive feedback on temperature. One increasingly famous example with potentially global consequences is warming of the extensive Siberian permafrost. Thawing causes the release of greenhouse gases (methane and carbon dioxide) from the decomposing peat, which accelerates atmospheric warming, which then accelerates thawing, and so on. Based on the reconstruction of prehistoric climate trends from the study of ice cores, Torn and Harte (2006) argued that feedback loops will have considerable impact on future climate.

Jim Riley, OSU lichen group

Figure 53—*Ahtiana sphaerosporella* (*Ahtiana* lichen).

Figure 54—Both species of *Parmeliopsis* occurring in the Western United States: *P. hyperopta* (on left, bran lichen) and *P. ambigua* (on right, ambiguous bran lichen).

and their respective communities face a shrinking niche that may force their distributions polewards. Zones 1 through 3 may shift to higher elevations, although the more extreme climate scenarios (California Climate Change Center 2006a, 2006b) suggest it is plausible that zone 3 communities may also face a locally shrinking niche before 2100.

Nitrophytes will benefit from warming trends with increased abundance in temperate regions.

Nitrophytic indicator species identified by the ISA were asymmetrically distributed among climate zones, being primarily associated with the warm, low-elevation forests of zone 1 (table 17). Nitrophytes are most commonly used as nitrogen (N) indicators (see chapter 3 "Nitrophytes" section) although many species are known for their high tolerance to heat and light exposure. It has been proposed elsewhere (van Herk et al. 2002) that nitrophytes will benefit from warming trends with increased abundance in temperate regions. The apparent association of some nitrophytes with the warmest climate zone in northern and central California tentatively seems to support this notion. More investigation is needed, however, to rule out confounding by the high N deposition in the greater Central Valley (see chapter 4) where most zone 1 forests are located.

Table 18—Indicator species of moisture zones in northern and central California[a]

Zone 1: Wet forests Wet days: 99 (21) Precip: 153.2 (55.2)	*Alectoria sarmentosa, Alectoria vancouverensis, Bryoria capillaris, Bryoria trichodes, Cladonia fimbriata, Cladonia furcata, Cladonia ochrochlora, Cladonia subsquamosa, Cladonia transcendens, Cladonia verruculosa, Esslingeriana idahoensis, Hypogymnia enteromorpha, Hypogymnia inactiva, Hypogymnia occidentalis, Hypogymnia physodes, <u>Lobaria pulmonaria</u>, Parmeliopsis hyperopta, Parmotrema arnoldii, Platismatia glauca, Platismatia herrei, Platismatia stenophylla, <u>Pseudocyphellaria anthraspis</u>, Ramalina dilacerata, Sphaerophorus globosus, Usnea filipendula, Usnea scabrata, Usnea wirthii*
Zone 2 Wet days: 89 (18) Precip: 126.7 (57.8)	*Alectoria imshaugii, Bryoria fremontii, Bryoria pseudofuscescens, Cetraria chlorophylla, Cetraria merrillii, Cetraria orbata, Cetraria platyphylla, Dendriscocaulon sp., Hypogymnia imshaugii, Leptogium cellulosum, Letharia vulpina, <u>Nephroma helveticum</u>, <u>Nephroma resupinatum</u>, Nodobryoria abbreviata, Nodobryoria oregana, Parmelia hygrophila, Parmelia sulcata, <u>Pseudocyphellaria anomala</u>, <u>Peltigera collina</u>, Parmeliopsis ambigua, Usnea glabrescens, Usnea substerilis*
Zone 3 Wet days: 70 (19) Precip: 87.6 (36.5)	*Leptogium pseudofurfuraceum, Letharia columbiana, Physconia isidiigera*
Zone 4: Dry forests Wet days: 62 (18) Precip: 79.7 (39.3)	***Candelaria concolor, Flavopunctelia flaventior,*** *Melanelia glabra,* ***Phaeophyscia orbicularis, Physcia adscendens,*** *Physcia biziana, Parmelia quercina,* ***Punctelia perriticulata***, ***Xanthoria fallax***, ***Xanthoria fulva, Xanthoria oregana***

[a] Average numbers of wet days per year and precipitation (cm) are reported, followed by standard deviations in parentheses. Only species that are statistically significant indicators ($p < 0.05$), according to Indicator Species Analysis, are reported. Nitrophytes are bolded and stratified foliose cyanolichens are underlined.

Proposed Moisture Effects

Indicator species, mean number of wet days, and mean precipitation per climate zone from the second gradient detected by NMS are displayed in table 18. Ranges overlapped for both moisture variables, although means steadily declined between zones. Wet days decreased by 10, 19, and 8 days between consecutive zones while precipitation decreased by 27, 39, and 8 cm, respectively. Three of the four moisture zones had 11 or more indicator species. Unlike temperature, there is no clear outlook for precipitation trends in California. According to the three main climate models summarized by the California Climate Change Center (2006a, 2006b), precipitation patterns may remain stable, increase, or decrease. Even if precipitation itself does not change, however, temperature changes will affect relative humidity and thus increase the amount of moisture available to lichens.

Species associated with the wettest zone (zone 1) and the driest zone (zone 4) are most likely to endure range contractions in the study region depending on which way (if any) precipitation patterns swing. The high moisture requirements of cyanolichens are met primarily in the wet zones 1 and 2 (see chapter 6 "Large Stratified Cyanolichens" section), and based on the specialized ecology of this group, it is suspected that species will be relatively inflexible to both moisture and temperature regime changes. Nitrophytic indicator species are again asymmetrically distributed among climate zones, being associated with dry forests of zone 4. Many nitrophytes and most especially *Xanthoria* species (fig. 26c) are considered highly xerophytic (Loppi and Pirintsos 2000, Loppi et al. 1998, Pirintsos et al. 1998). But as mentioned in the previous section, part of the observed pattern could result from the high N impact in the greater Central Valley where zone 4 plots are most common.

Table 19—Temperature and moisture scores for northern and central California by air quality model area (1998–2001, 2003): greater Central Valley (GCV), greater Sierra Nevada (GSN) and Northwest Coast (NWC)[a]

Parameter	Total	GCV	GSN	NWC
Number of plots surveyed	264	76	121	67
Number of plots by temperature zone:				
Warmest (-2.59 to -1.04)	67	44	6	17
Warm (-1.04 to 0.01)	65	25	15	25
Cool (0.01 to 0.87)	66	5	43	18
Coolest (0.87 to 2.14)	66	2	57	7
Temperature score extremes	-2.59 to 2.14	-2.59 to 2.10	-2.07 to 2.14	-2.46 to 1.27
Average temperature score	-0.02	-0.96	0.73	-0.32
Standard deviation of temperature scores	1.13	0.79	0.88	0.92
Number of plots by moisture zone:				
Wettest (-2.28 to -0.71)	66	5	16	45
Wet (-0.71 to 0.13)	66	11	39	16
Dry (0.13 to 0.89)	68	25	40	3
Driest (0.89 to 2.22)	64	35	26	3
Moisture score extremes	-2.28 to 2.22	-1.17 to 2.22	-2.20 to 2.13	-2.28 to 1.57
Average moisture score	0.08	0.77	0.21	-0.92
Standard deviation of moisture scores	1.04	0.83	0.82	0.83

[a] The ranges of temperature and moisture zones are based on natural breaks in the data as described in chapter 7. Plots were excluded from analysis if they lacked species, had no species in common with the calibration plots, or were duplicate surveys used for quality assurance purposes.

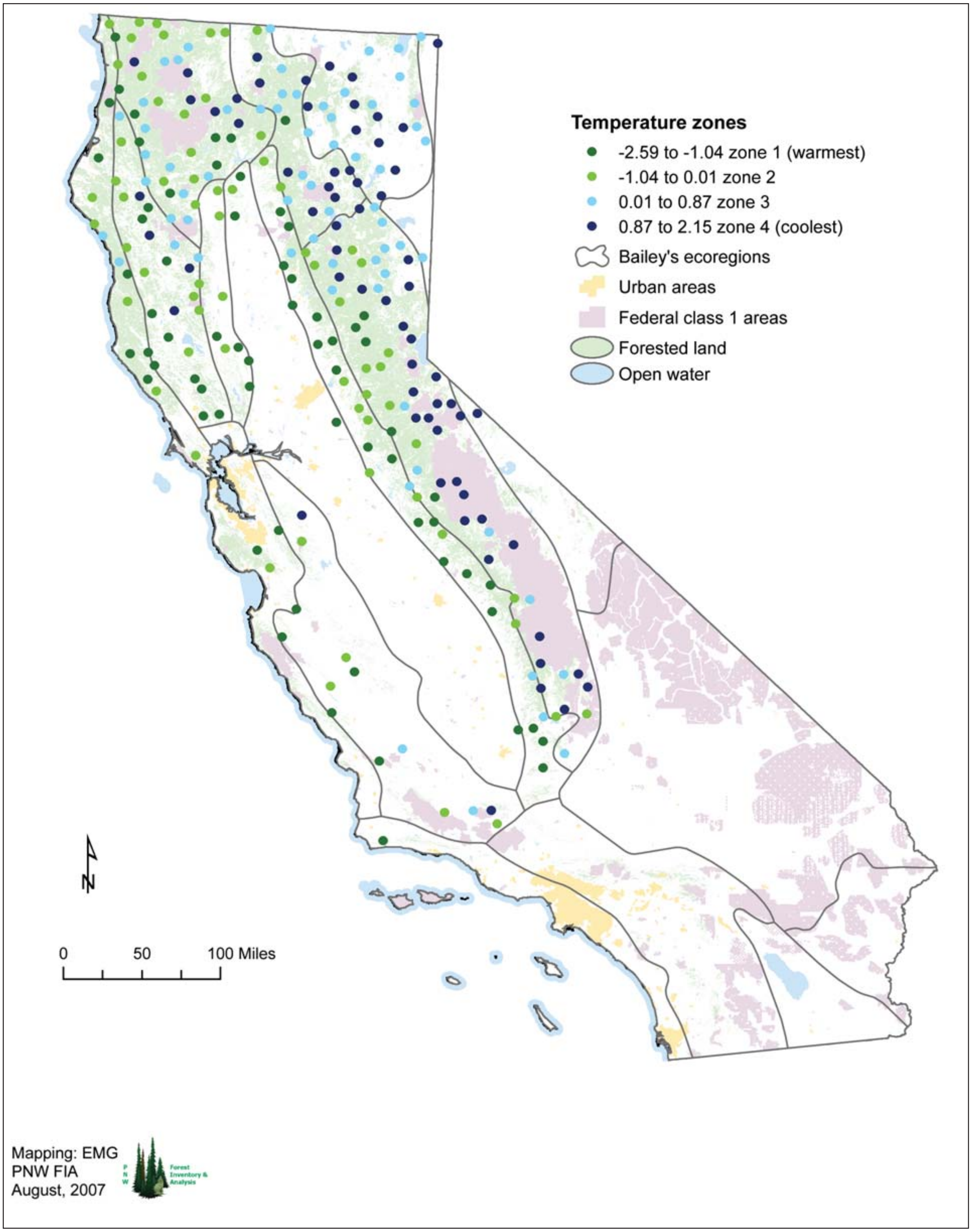

Figure 55—Temperature scores for northern and central California categorized by temperature zone. See figure 14 for ecoregion codes.

Summary of Climate Patterns in Northern and Central California

The northern and central California climate model was applied to a full cycle of FIA Lichen Community Indicator data (n = 264; 1998 to 2001, and 2003) to describe landscape-scale macroclimatic patterns. About 80 percent of these plots were summarized by Jovan and McCune (2004) although the former study had a different objective and analytical approach. Large-scale climate patterns are displayed in table 19. Compare these patterns with those for the smaller model areas defined by Jovan and McCune (2004) for air quality studies (fig. 53). The distribution of climate scores reflects how forests in the greater Central Valley tend to be hot and dry compared to the warm and wet conditions of the marine-influenced Northwest Coast. Forests in the greater Sierra Nevada are relatively cool overall, whereas moisture levels are more variable.

Spatial Temperature Patterns

The spatial heterogeneity of lichen-derived temperature zones in northern and central California roughly echoes the underlying topography. The warm forests of zone 1 are predominantly distributed among the low-elevation landforms of the nitrophyte-rich greater Central Valley model area but extend, to a lesser extent, into low elevations in the Northwest Coast (figs. 52 and 55). Plots in the latter region include a higher diversity of temperature regimes with forests classified from all four zones. Cooler zone 3 and 4 forests are distributed widely outside the greater Central Valley, primarily in the mid to high elevations of the various mountain ranges. A more-or-less continuous aggregation of these cooler forests lies within the greater Sierra Nevada model area, beginning in the eastern, high-elevation Klamath Range, and incorporating sites on the Modoc Plateau, southern Cascades Range, Tahoe Basin, and Sierra Nevada Range.

Spatial Moisture Patterns

The wettest (zone 1) forests are mostly concentrated in the Northwest Coast, whereas forests of the greater Central Valley are almost entirely classified among the dry zones 3 and 4 (fig. 56). Moisture differs latitudinally in the greater Sierra Nevada, with forests getting drier to the south. The northern half of this region has forests with a wider variety of moisture regimes, including sizeable pockets of wet zone 2 forests and more isolated instances of wetter zone 1 forest.

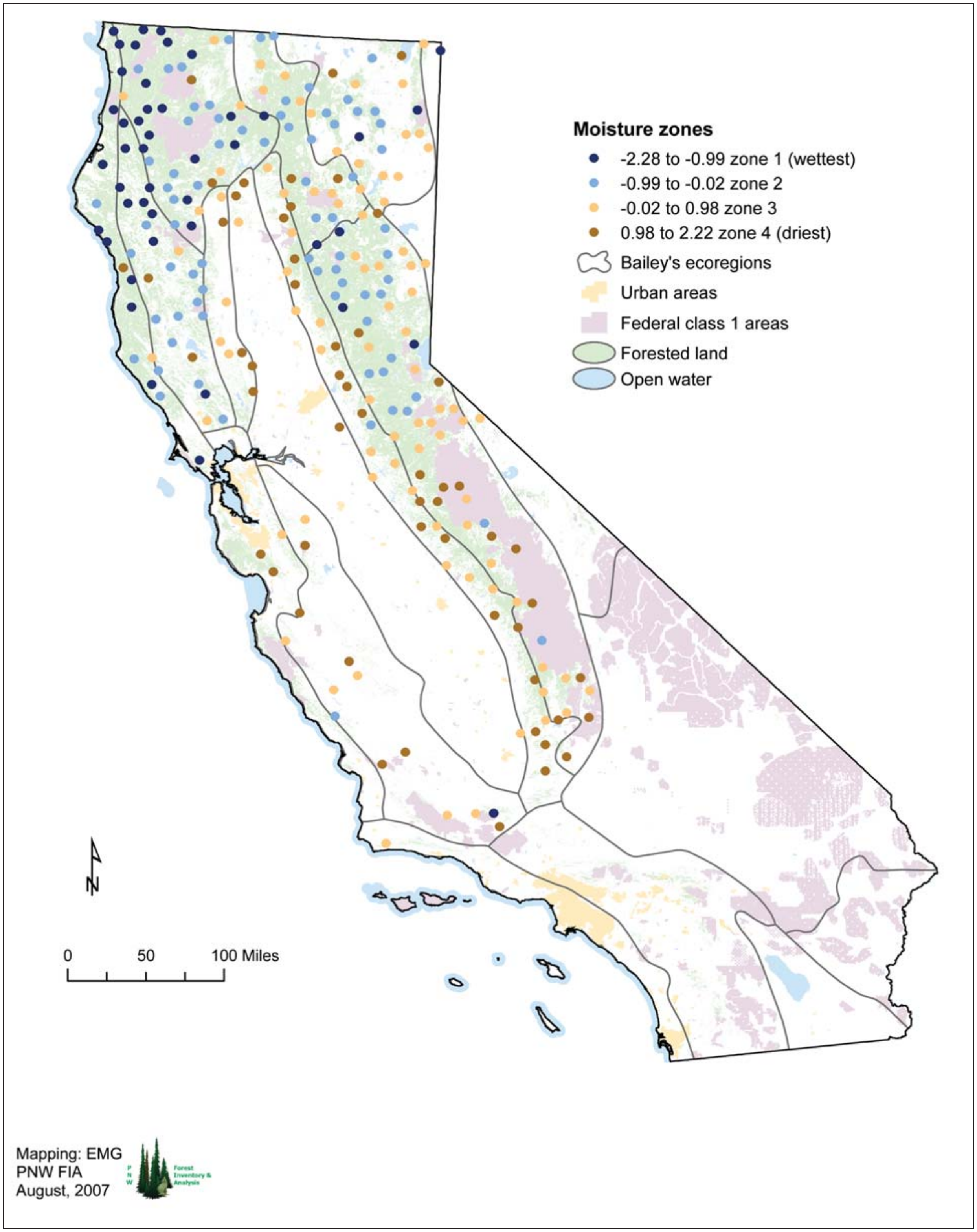

Figure 56—Moisture scores for northern and central California categorized by moisture zone. See figure 14 for ecoregion codes.

Conclusions

The current composition of lichen communities in northern and central California is strongly patterned on macroclimatic gradients in forest temperature and moisture. Based on the framework built with NMS and ISA, it is apparent how temperature and moisture changes might affect community composition and the arrangement of forest climate zones across the landscape. Being an indicator species for a particular climate zone implicitly suggests a greater sensitivity to climate change than that of species with wide distributions spanning multiple zones. Additional study is needed to assess potential impacts to rare species, however, which are neglected by the ISA. Odds are that rare species are inherently at greater risk of climate-driven extinction than abundant species simply for having low numbers. Ultimately the ecological outcome of climate change by 2100 will be determined by the complex interplay of many environmental factors, including but not limited to the rate and amount of change in temperature and moisture. Sensitive species will need to reach a habitat that is not only climatically suitable, but one that also meets all the species' nutrient requirements, provides adequate substrate, and has tolerable air quality. Factors affecting the likelihood of successful colonization, like dispersal ability, ecological amplitude, adaptability, and habitat fragmentation are bound to be important predictors of change at the species level. Although not accounted for in these baseline data, the influence of these factors are expected to surface as the FIA Program begins assessment of climate trends with the Lichen Community Indicator data.

Lichen communities in northern and central California are strongly patterned on macroclimatic gradients in forest temperature and moisture.

Chapter 8: Overall Conclusions

The Lichen Community Indicator of the Forest Inventory and Analysis (FIA) Program, U.S. Department of Agriculture, is an important scientific resource. These data document the distributions of epiphytic lichens in western forests with unprecedented detail and scope. This report explores only a few examples of the many applications these data have for environmental monitoring, namely, the use of lichen community parameters for indicating biodiversity, air quality, and forest climate. These baseline assessments will help natural resource managers identify forests at high risk of degradation as well as areas of high conservation importance. Moreover, the gradient models themselves are tools that can benefit anyone who surveys lichens using the FIA protocol and desires to evaluate forest health within the model's geographic boundaries. If coverage by the systematic grid of FIA plots is insufficient for a particular monitoring objective, new plots can be surveyed and scored using the local model.

These baseline assessments will help natural resource managers identify forests at high risk of degradation as well as areas of high conservation importance.

As we continue refining biomonitoring tools, FIA and collaborators will be able to obtain ever more accurate and specific information on local conditions affecting lichens and the surrounding forest. Considerable progress has been made applying and identifying nitrogen (N) indicator species in the Pacific Western States. As stated in part III, however, designations are preliminary and meant to serve as a basis for more rigorous inquiry. Statistical indicators of climate were identified for the western Pacific Northwest and a large chunk of California in part IV, although, again, indicator designations are meant to serve as a starting point for further investigation.

Upcoming projects include use of the FIA Lichen Community Indicator data for developing critical loads for lichens and N, completion of a gradient model for the eastern Pacific Northwest, completion of a gradient model for the Northwest Coast in California, and planning for development of a gradient model for southern California in and near the Los Angeles Basin. Work will begin shortly on the next phase of the FIA Lichen Indicator, trend analysis. Besides allowing managers and scientists to evaluate changes to forest health in the short term, continual monitoring of epiphytic lichen communities will ultimately allow an invaluable long-term ecological perspective on forest health in the region.

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English Equivalents

When you know:	**Multiply by:**	**To get:**
Centimeters (cm)	0.394	Inches
Meters (m)	3.28	Feet
Kilometers (km)	0.621	Miles
Kilograms (kg)	2.205	Pounds
Hectares (ha)	2.47	Acres
Square kilometers (km^2)	0.386	Square miles
Degrees celsius (°C)	1.8˄°C + 32	Degrees Farenheit

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