Chapter 3. Relationship of a Lichen Species Diversity Indicator to Environmental Factors Across the Coterminous United States

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Introduction

We have investigated relationships between one simple indicator of lichen species diversity and environmental variables in forests across the coterminous United States. We want to know whether this indicator can help quantify the influence that factors such as climate and air quality have on lichen biodiversity at large scales and whether it will be useful in monitoring changes in these factors. Since lichens are biologically distinct from the trees, shrubs, and herbaceous vegetation found on sample plots, a good indicator of effects on the lichen community complements other indicators and contributes to a more complete picture of potential effects of these causal factors on the entire forest ecosystem.

The Forest Inventory and Analysis (FIA) Program of the Forest Service, U.S. Department of Agriculture, collects lichen community data on its phase 3 (P3) plots (a subset of the full national phase 2 grid) because lichens are useful indicators of air quality impact, forest health, and forest ecosystem integrity across the United States [McCune 2000, Nimis and others 2002 (reviews), U.S. Department of Agriculture Forest Service 2007]. Collection of lichen data began in 1994 by the National Forest Health Monitoring (FHM) Program of the Forest Service, and has been continued by FIA since 2000. The standard lichen data collection protocols[1] have remained unchanged since 1994, permitting the FHM and FIA lichen data to be combined. Abundance for each macrolichen (a lichen that can be separated from its substrate) species on standing woody substrates in a 0.937-acre (0.379-ha) permanent plot is determined from samples collected by a trained and certified nonspecialist in a time-constrained (30-minute minimum to 2-hour maximum) survey (see footnote 1). A minimum certification standard (65 percent of species found by an expert) is achieved by each qualified field person. Restriction to macrolichens, use of trained nonspecialist field personnel, and time-constrained sampling make this indicator affordable. The time restriction also lessens (but does not remove) differences between field personnel and field lichen specialists (during training, audits, and quality assurance), and among field personnel with different abilities, in number of species collected on average. This increases the national comparability of data. Specimens are identified to species in the

[1] Forest Service, U.S. Department of Agriculture. 2005. Forest inventory and analysis national core field guide. Vol. 1: field data collection procedures for phase 3 plots. Version 3.0. Internal report. On file with: Forest Service, U.S. Department of Agriculture, Forest Inventory and Analysis, Rosslyn Plaza, 1620 North Kent Street, Arlington, VA 22209. [The current version is available online at http://fia.fs.fed.us/library/field-guides-methods-proc/ (Date accessed: January 2010)].

laboratory by lichen identification specialists.

Because FIA data are collected from permanent plots randomly located (one per sampling grid cell) within a regular nationwide sampling grid with no *a priori* stratification by other criteria, these data are unbiased in their representation of forest condition (Bechtold and Patterson 2005). The lichen indicator sampling protocol was designed to enable the program to monitor regional patterns in lichen diversity, community composition, and response to air quality and climate while minimizing, to the extent possible, the potentially confounding effects of local variation in tree species composition, forest type, and stand age (McCune and others 1997). With 12 years of data and most of the forested regions of the coterminous United States represented in the dataset to at least some extent, we can evaluate the success of this goal in part as we explore the potential of one lichen diversity indicator.

The FIA lichen database provides detailed information on lichen community composition. Because species distribution varies greatly across the country, lichen indicators based on lichen species composition in communities are more appropriate for smaller geographic regions. In contrast, the number of macrolichen species (lichen S) found on an FIA plot using the standard protocol is a lichen species diversity indicator consistent across the entire country. Lichen S is the simplest of several quantitative lichen indicators that can be derived from FIA lichen data. It is assumed that some less common macrolichen species are missed during sampling because of time constraints and use of nonspecialist field personnel (Will-Wolf and others 2002). If in spite of these limitations and other sources of variation, we find that lichen S is a good indicator of response to factors of interest, we have a useful tool to monitor forest ecosystems on a very broad scale.

For this study we focus on relationships between lichen S and environmental variables in forests across the coterminous United States to see how these relationships differ between Eastern States (our East region, figure 3.1) and Western States (our West region), and whether and how patterns vary among different ecoregions within the East and West (fig. 3.2). This helps us decide where lichen S can be most useful as an indicator for monitoring patterns and trends in forested ecosystems. This large-scale analysis provides a context and framework for generalizing from more intensive smaller scale analyses based on lichen community composition, of which there are already several published examples (e.g., Geiser and Neitlich 2007; Jovan 2009; Jovan and McCune 2005, 2006; McCune and others 1997; Will-Wolf and others 2006).

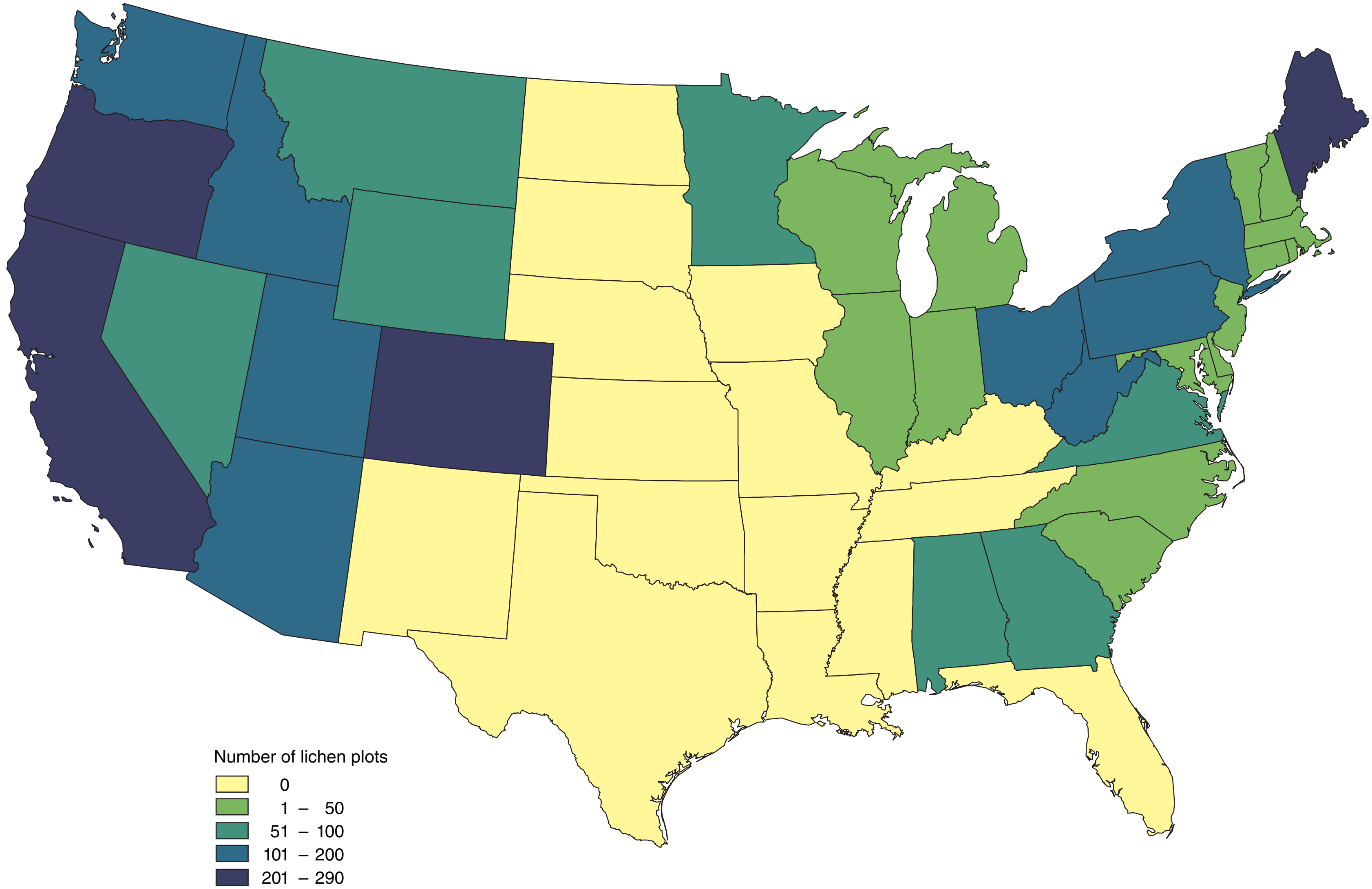


Figure 3.1—Summaries by State for numbers of plots (by category) included in this project. For this project, West region includes all States west of the Great Plains that have lichens data (colors other than yellow), and East region includes Minnesota plus all States east of the Mississippi river that have lichens data. Both size of State and number of years sampled affect number of plots available. (Data source: U.S. Department of Agriculture, Forest Service Forest Inventory and Analysis Program)

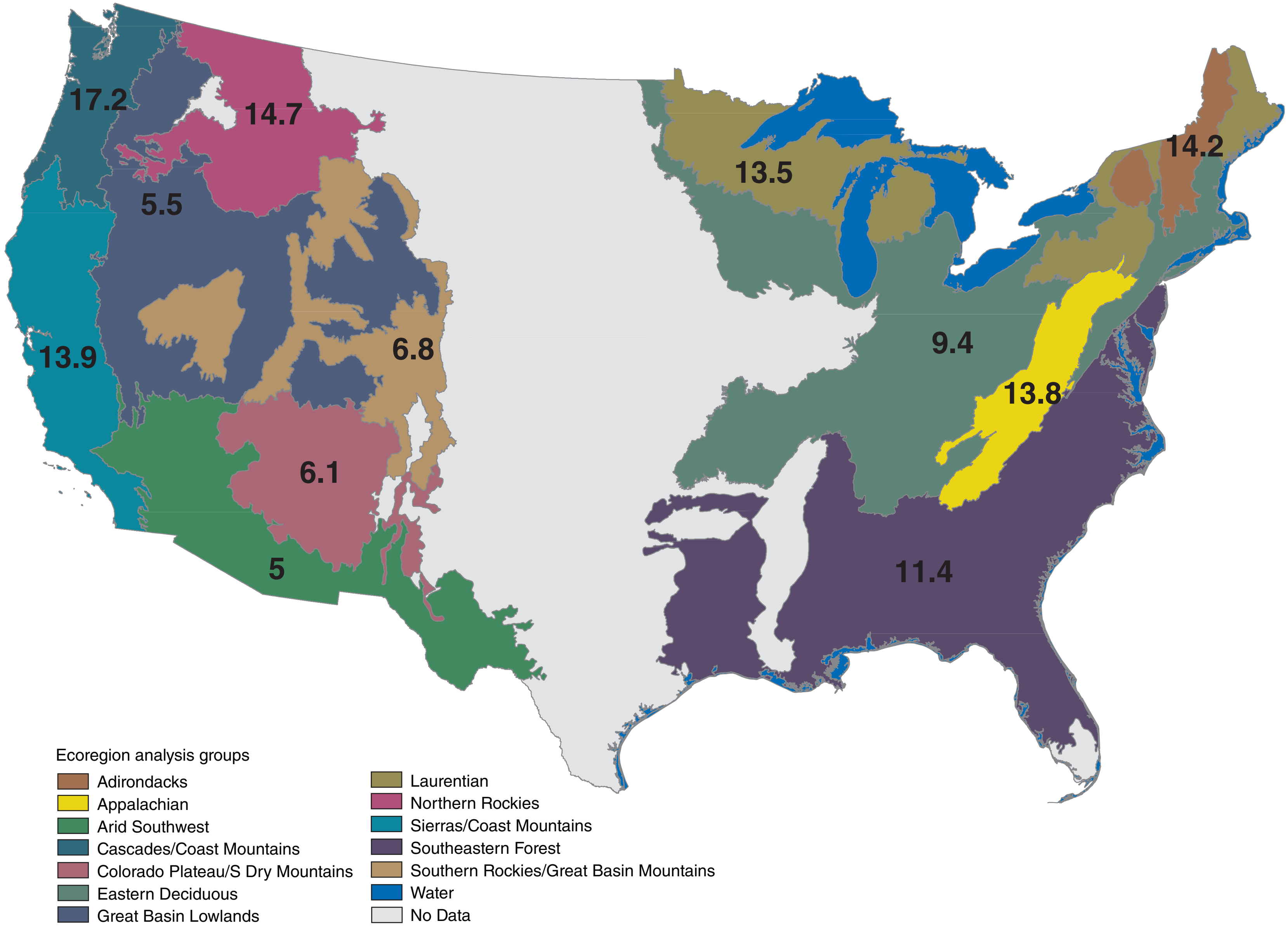


Figure 3.2—Ecoregion groups, based on Bailey's ecoregion provinces (Bailey 1989; Cleland and others 2005) used for analysis (areas in gray not included). For this project, West region includes all ecoregion groups west of the large gray area with no data, and East region includes all ecoregion groups east of this large gray area. Some ecoregion groups cover areas including States with no lichens data; compare with figure 3.1. Printed numbers are average for each ecoregion of Lichen S, the number of macrolichen species found per plot. Note the greater variation in average Lichen S between groups in the West. See appendix tables A3.1 and A3.3 for ecoregion provinces included in each group. (Data source: U.S. Department of Agriculture, Forest Service Forest Inventory and Analysis Program)

Methods

We used publicly available FIA lichen and tree data and approximate plot location[2] to develop explanatory variables and assign plots to analysis groups based on Bailey's ecoregion provinces (Bailey 1989, Cleland and others 2005). Lichen S, total live-tree basal area per acre (tree BA), and percentage of BA in softwoods (percent softwoods = conifers) were calculated for each plot. Tree BA and percent softwoods represent forest structure and composition independent of particular tree species composition and as such are appropriate to compare across the entire country and between all ecoregion groups. We chose these two tree variables because they are related to the amount and quality of lichen substrate on a plot. They were also readily available for most of the lichen plots in our data set (in contrast to other potentially usable forest structure variables). For the East (east of the Great Plains, figure 3.1), it has been demonstrated (e.g., McCune and others 1997) that very low tree BA on a plot is correlated with low lichen diversity. So, for the East data, we removed 61 plots with total live-tree BA < 21.9 square feet per acre (< 5 m^2/ha). In the West (west of the Great Plains), small trees and shrubs are known to harbor many lichens in some areas (e.g., Geiser and Neitlich 2007) and low tree BA is not correlated with low lichen diversity. So no tree BA limit was imposed for West plots. Some plots were resurveyed during the 12 years covered by our study; we included only the most recent data available for each plot. The number of plots per State (fig. 3.1) varied with both size of the State and number of years that sampling occurred. Lichen data were available for 3,276 plots, but tree data were not available for all of them. We analyzed a total of 1,399 plots in the West and 1,087 plots in the East. To maintain as large a sample as possible and to use the same data set for all analyses, we made no attempt to equalize the distribution of plots across any of the gradients represented by geographic, climate, or air quality variables.

Climate data [(1971–2000) 30-year average annual rainfall, average maximum July temperature, and average minimum January temperature] were generated on a 4-km^2 grid using the climate source model (Daly and Taylor 2000). Air quality data [(1998–2004) average annual wet deposition of SO_4^{--}, NO_3^-, and NH_4^+] were estimated from an interpolated 5-km^2 grid of National Atmospheric Deposition Program data (Coulston and others 2004).

[2] Forest Service, U.S. Department of Agriculture, 2010. Forest Inventory and Analysis Database, version 3. U.S. Department of Agriculture, Forest Service, Washington Office. Internal Report. http://fia.fs.fed.us/tools-data/. [Date accessed: January 2010].

Elevation data were acquired from the National Elevation Dataset (U.S. Geological Survey 1999) on a 1-km^2 grid. Using ArcGIS 8.3©, plot locations were intersected with the climate grids, air quality grids, and the elevation grid to generate a set of plot variables for statistical analysis. Maps were also generated to illustrate ecoregion groups and geographic variation in air quality variables.

We analyzed data separately for the East and West regions (fig. 3.1) because ecological systems are known to be very different in the Eastern and Western coterminous United States (compare column 2 of tables 3.1 and 3.2). Within the East or West, we then further subdivided the data for analysis into Bailey's ecoregion groups (fig. 3.2) to aid us in interpreting the large-scale patterns. In the East, we found grouping by ecoregion division useful and convenient (fig. 3.2, appendix tables A3.1 through A3.5). In the West, Bailey's ecoregion divisions are less geographically compact and more interspersed than in the East, so we used an alternative grouping of ecoregion provinces into analysis units that are relatively cohesive geographically (fig. 3.2, appendix tables A3.6 through A3.12). We chose this approach because lichen dispersal rate is expected to be higher within compact geographic areas and changes in lichen indicators over time (tracking this is desired for such indicators) relate to dispersal of species to plots as well as to losses of species from plots. There were few forested plots located in Great Plains ecoregions, so these ecoregions were not included in the smaller scale analyses of either eastern or western ecoregion groups.

Variables for East and West regions are summarized in tables 3.1 and 3.2; for East groups see appendix tables A3.1 through A3.5 and for West groups see appendix tables A3.6 through A3.12. Explanatory variables often represent geographic gradients of values across a region rather than random variation around a central tendency, so their values are reported as ranges. Mean and standard deviation are included as a convenience for qualitative comparison between groups. Estimated NH_4^+

Table 3.1—Ranges and correlations among lichen S and geographic, climate, air quality, and forest structure variables in the East region

Variable	Range (average ± sd)	Spearman correlations (rho) (N = 1087[a], years = 1994–2005)										
		Lichen S	Lat.	Long.	Elev.	Precip.	Max. July temp.	Min. Jan. temp.	NO_3^-	SO_4^{--}	NH_4^+	Tree BA
Lichen S	0 – 33 (12.1 ± 6.3)											
Latitude (decimal degrees, S to N)	30.64 – 49.18	0.149										
Longitude (decimal degrees, W to E)	–96.95 – –67.11	—	0.425									
Elevation (m)	0 – 1660 (310 ± 219)	—	—	—								
Precipitation (mm)	483 – 1919 (1099 ± 192)	—	**–0.550**	—	—							
Max. July temp. (°C)	21.9 – 33.9 (28.2 ± 2.5)	**–0.196**	**–0.825**	**–0.516**	**–0.556**	—						
Min. Jan. temp. (°C)	–24.3 – 5.0 (–9.7 ± 6.0)	—	**–0.966**	—	—	**0.514**	**0.866**					
NO_3^- (kg/ha/year)	5.70 – 22.51 (12.28 ± 3.02)	**–0.454**	—	—	—	—	—	—				
SO_4^{--} (kg/ha/year)	4.32 – 28.98 (15.88 ± 4.87)	—	—	—	—	—	—	—	**0.883**			
NH_4^+ (kg/ha/year)	0.70 – 4.32 (2.53 ± 0.70)	—	—	**–0.565**	—	—	—	—	**0.575**	**0.486**		
Tree BA (square foot per acre)	22.1 – 579.5 (94.7 ± 50.5)	—	0.116	—	—	—	—	—	—	—	—	
Percent BA softwoods	0 – 100 (26.2 ± 33.6)	0.184	—	—	—	—	—	—	—	–0.440	—	—
Best overall full regression model		**r^2 = 0.305, $p < 0.0005$: Lichen S = 23.480 –0.814 NO_3^- + 0.007 elev. –1.706 NH_4^+ (–0.008 Min. Jan.)** S larger with cleaner air, higher elevation (cooler winters)										

— = cells with dashes indicate weaker correlations; max. = maximum; min. = minimum; sd = standard deviation; lat. = latitude; long. = longitude; elev. = elevation; precip. = precipitation; temp. = temperature; NO_3^- = nitrate; SO_4^{--} = sulfate; NH_4^+ = ammonium; BA = basal area; S = south; N = north; W = west; E = east; m = meter; mm = millimeter; °C = degree Celsius; kg = kilogram; ha = hectare.

Positive correlations are in black; negative are in red. Single correlations with rho > 0.447 (in bold, all with $p < 0.0005$) account for at least 20 percent of variation; correlations with Lichen S stronger than this cutoff suggest potential for an indicator. The strongest correlation for each class of variables is included for comparison (if $p < 0.01$) even if below the cutoff. Correlations between environmental variables with rho ≥ 0.775 (at least 60 percent of variation accounted for) indicate those two variables should not be entered in the same regression model. The best overall regression model (at bottom), with contributing variables listed in descending order of significance, is only slightly better than the best minimal model; minor variables ($p \leq 0.05$ but usually $p \geq 0.005$) are listed in parentheses.

[a] Removed E plots with total live-tree BA < 21.8966 square feet per acre (< 5 m^2/ha).

Table 3.2—Ranges and correlations among Lichen S and geographic, climate, pollution, and forest structure variables in the West region

		Spearman correlations (*rho*)				(N = 1,399 plots, years = 1994–2005)						
Variable	Range (average ± sd)	Lichen S	Lat.	Long.	Elev.	Precip.	Max. July temp.	Min. Jan. temp.	NO_3^-	SO_4^{--}	NH_4^+	Tree BA
Lichen S	0 – 45 (10.8 ± 7.8)											
Latitude (decimal degrees, S to N)	31.42 – 48.96	**0.487**										
Longitude (decimal degrees, W to E)	−124.41 – −103.1	**−0.485**	—									
Elevation (m)	0 – 3740 (1687 ± 778)	**−0.528**	—	**0.714**								
Precipitation (mm)	171 – 4731 (853 ± 624)	**0.490**	**0.499**	**−0.560**	—							
Max. July temp. (°C)	15.7 – 38.3 (26.5 ± 4.2)	—	**−0.488**	—	—	**−0.522**						
Min. Jan. temp. (°C)	−22.6 – 4.7 (-7.4 ± 5.2)	—	—	**−0.751**	**−0.773**	—	—					
NO_3^- (kg/ha/year)	0.38 – 5.90 (2.81 ± 1.01)	—	—	**0.552**	—	—	—	—				
SO_4^{--} (kg/ha/year)	0.18 – 7.53 (1.98 ± 1.06)	—	—	—	—	—	—	—	**0.727**			
NH_4^+ (kg/ha/year)	0.00 – 2.14 (0.61 ± 0.36)	−0.329	**−0.497**	—	—	—	—	—	**0.571**	—		
Tree BA (square foot per acre)	1.5 – 650.2 (105.4 ± 83.6)	0.255	—	—	—	0.379	—	—	—	—	—	
Percent BA softwoods	0 – 100 (84.2 ± 31.1)	—	—	—	—	—	—	−0.294	—	—	—	—
Best overall full regression model		**r^2 = 0.404, p < 0.0005: Lichen S = 12.563 −0.005 elev. + 0.296 lat. + 0.013 BA −0.023 Max. July (−1.706 NH_4^+)** S larger lower elevation, more north, with more/larger trees, cooler summers (cleaner air)										
Best minimal linear regression model		r^2 = 0.377, p < 0.0005: Lichen S = −30.044 −0.003 elev. + 0.515 lat. −0.216 long S larger lower elevation, more north, more west										

— = cells with dashes indicate weaker correlations; max. = maximum; min. = minimum; sd = standard deviation; lat. = latitude; long. = longitude; elev. = elevation; precip. = precipitation; temp. = temperature; NO_3^- = nitrate; SO_4^{--} = sulfate; NH_4^+ = ammonium; BA = basal area; S = south; N = north; W = west; E = east; m = meter; mm = millimeter; °C = degree Celsius; kg = kilogram; ha = hectare.

Positive correlations are in black; negative are in red. Single correlations with rho > 0.447 (in bold, all with p < 0.0005) account for at least 20 percent of variation; correlations with Lichen S stronger than this cutoff suggest potential for an indicator. The strongest correlation for each class of variables is included for comparison (if p < 0.01) even if below the cutoff. Correlations between environmental variables with rho ≥ 0.775 (at least 60 percent of variation accounted for) indicate those two variables should not be entered in the same regression model. The best overall full regression model (bottom of table), with contributing variables listed in descending order of significance, is notably better than the best minimal model (also included for comparison). Minor variables (p ≤ 0.05 but usually p ≥ 0.005) in the best overall regression model are listed in parentheses.

(fig. 3.3A) was interpreted to represent pollution from agricultural sources. Estimated NO_3^- and SO_4^{--} (NO_3^- in figure 3.3B) were interpreted to represent acidic pollution primarily from urban/industrial sources.

We investigated relationships between lichen S and environmental variables first using scatterplots and simple correlations (Sokal and Rohlf 1995). All statistical analyses were carried out in SPSS for Windows (Release 13.0.1© SPSS, Inc. 1989–2004). We report the nonparametric Spearman rank correlation coefficient *rho* in all cases since we did not test whether data met assumptions for parametric tests. With our large sample sizes, many minor correlations are statistically significant; we focus our discussion on the more important correlations that appear to account for 20 percent or more of variation in a relationship (significant at $p < 0.0005$ for any analysis with >100 plots). This subset of the statistically significant results presumably represents the more biologically important relationships that are relevant to assessing the usefulness of lichen S as an indicator.

We used multiple regression as a tool to identify the multiple factors that are together the best predictors for lichen S. Our models are intended only to suggest combinations of the most important explanatory variables, rather than as reliable predictive models. All independent variables were measured or estimated with notable estimation error (not fixed as assumed for regression models). This is common for ecological studies and should always be remembered when interpreting the resulting regression models. Those of our environmental variables that are strongly correlated with one another (see tables 3.1 and 3.2; appendix tables A3.1 through A3.12) were never used in the same regression model. Development of regression models employed a variety of approaches; all final-reported models used forced simultaneous entry of selected significant ($p \leq 0.05$) variables to eliminate any bias from order of entry or elimination. For each regression model we report adjusted r^2, p-value, and the full model (unstandardized B coefficients) with variables listed in descending order of significance in the model (based on t-values).

We constructed two kinds of models. Minimal regression models focused on a single variable category and only the most important variables (usually $p \leq 0.0005$) were entered. Full regression models, in contrast, equally considered variables from all categories and included minor significant variables ($0.05 \geq p \geq 0.005$). Alternate regression models with similar strength (adjusted r^2) were the norm. The best regression model of each kind had the highest adjusted r^2 of alternate forced entry models. The best full model (always had the highest r^2) was designated the best overall model.

(A)

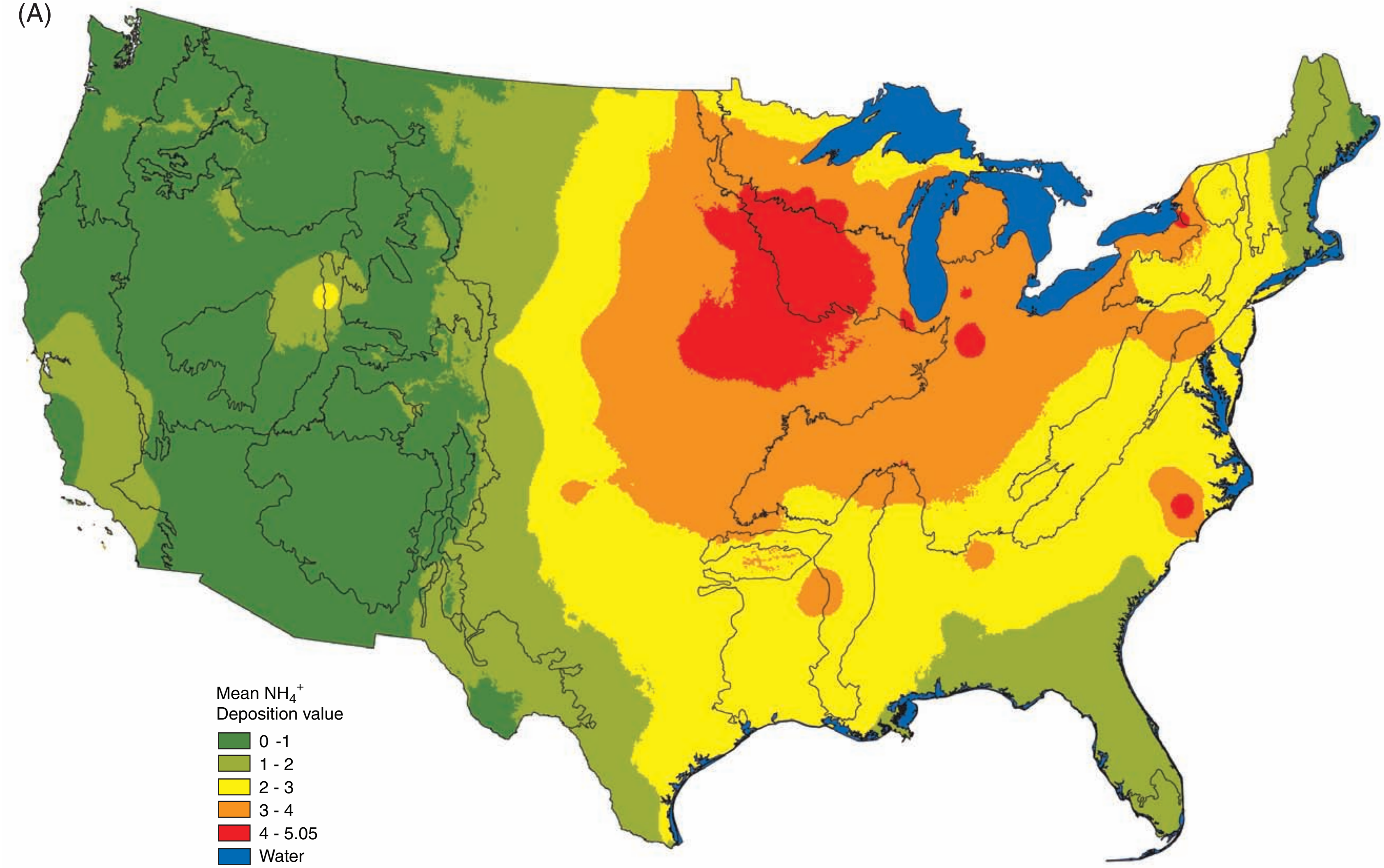


Figure 3.3—Air pollutant wet deposition (kg/ha/yr) modeled from National Atmospheric Deposition Program data. Black lines mark boundaries of ecoregion groups (see fig. 3.2). (A) NH_4^+ represents effects of agriculture; (B) NO_3^- represents urban/industrial effects. Note amounts for both are much higher in the East. (Data source: 1998-2004 average annual deposition from an interpolated 5-km^2 grid of National Atmospheric Deposition Program data [Coulston and others 2004]). *(continued on next page)*

(B)

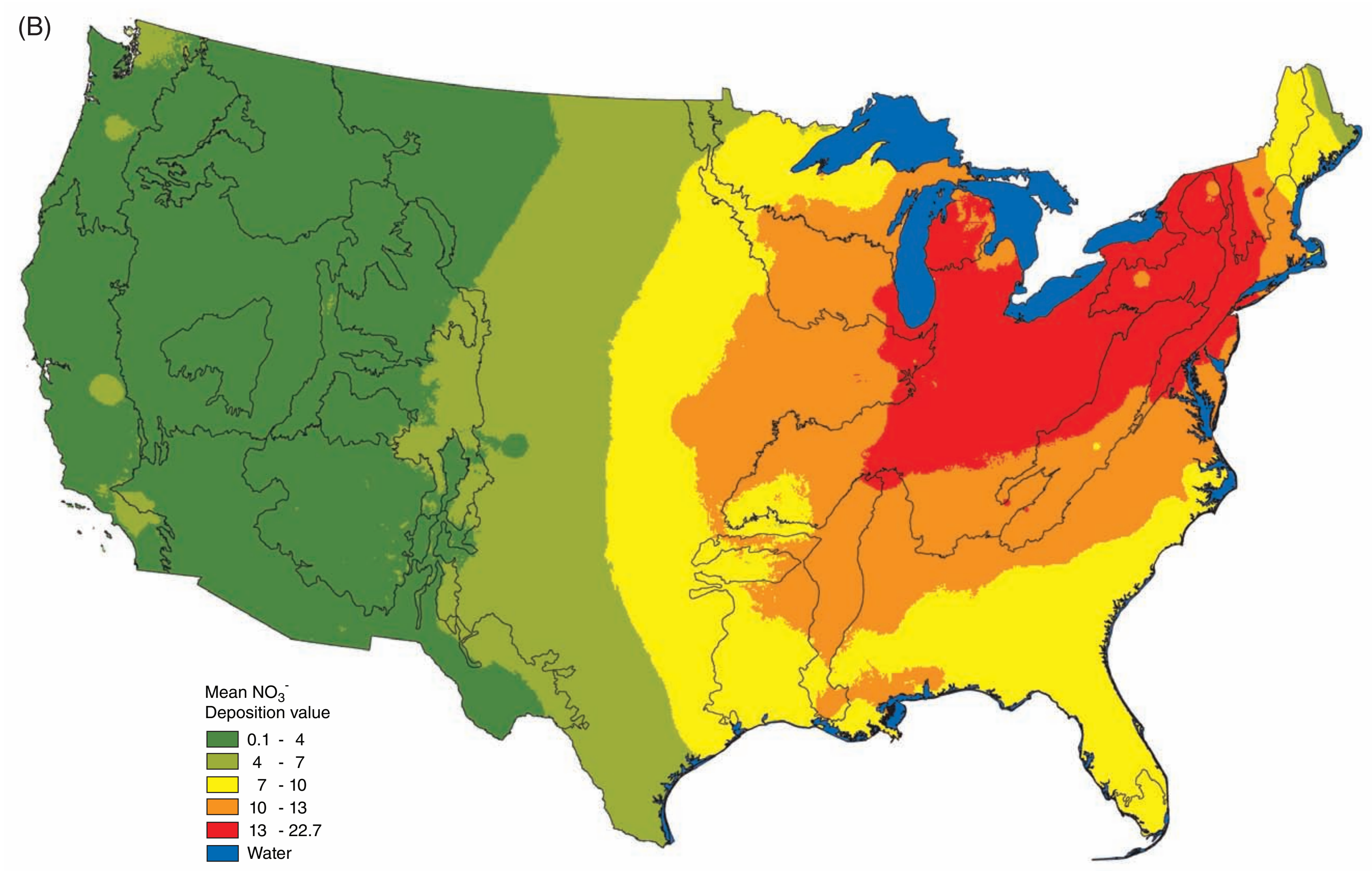


Figure 3.3 (continued)—Air pollutant wet deposition (kg/ha/yr) modeled from National Atmospheric Deposition Program data. Black lines mark boundaries of ecoregion groups (see fig. 3.2). (A) NH_4^+ represents effects of agriculture; (B) NO_3^- represents urban/industrial effects. Note amounts for both are much higher in the East. (Data source: 1998-2004 average annual deposition from an interpolated 5-km^2 grid of National Atmospheric Deposition Program data [Coulston and others 2004])

Results and Discussion

Quantitative relationships of lichen S with environmental variables for East and West regions are presented in tables 3.1 and 3.2; results for East and West groups are presented in appendix tables A3.1 through A3.12. The most important results are summarized in table 3.3. Both simple correlations and multiple regressions reflect linear relationships, while scatterplots allow us to visualize both linear and nonlinear relationships (figs. 3.4 through 3.6). Our conservative approach of reporting only the more robust relationships focuses attention on where and how lichen S may be most useful as an indicator of environmental conditions. Estimated NO_3^- and SO_4^{--} are strongly correlated with each other (Spearman $rho^2 \geq 0.50$) in both regions and all but two West ecoregion groups. Since single correlations of lichen S with NO_3^- were most often stronger than with SO_4^{--} (slightly weaker for two west ecoregion groups), we used only NO_3^- (fig. 3.3B) to represent acidic pollution.

General lichen diversity patterns—While average lichen S is higher in the East (table 3.1), overall variability and maximum lichen S are both higher in the West (table 3.2). There is of course more variation in elevation and climate in the West than in comparable geographic areas in the East. Air quality variables are more important in the East than in the West; this is probably related to the much higher levels of individual pollutants in the East (fig. 3.3, tables 3.1 and 3.2). For these large geographic scales our air pollution variables are probably correlated with other human impacts to the landscape, e.g., forest fragmentation. Therefore, we interpret relationships between lichen S and our pollution variables as potentially representing a combination of effects of air quality and other undefined human impacts on lichen S. In most cases our two forest vegetation variables, tree BA and percent softwoods, were not strong explanatory variables for our lichen diversity indicator; they show few important correlations as single variables and are only minor contributors to regression models in most cases. These findings suggest that lichen S is indeed relatively insensitive to important aspects of local variation in forest structure and is, in most areas, more responsive to large-scale variables such as climate and air quality.

Scatterplots supplement linear correlations and multiple regression results. The selected scatterplots we include (figs. 3.4 through 3.6) show that the relationships of lichen S with environmental variables often limit relationships. That is, the explanatory variable appears mostly to impose an upper limit on lichen S but no lower limit.

Table 3.3—Important patterns relating environmental variables to Lichen S and each other for East and West regions and ecoregion groups, summarized from tables 3.1 and 3.2, appendix tables A3.1-A3.5 with quantitative results for East groups, and appendix tables A3.6-A3.12 for West groups

EAST REGION:	Lichen S is higher with cleaner air, but is not linked to other variables. Summer and winter temperatures are strongly positively correlated, Regression model is weak.					
Ecoregion	Laurentian Forest	Adirondacks	Appalachian	Eastern Deciduous	Southeastern	
Average Lichen S	13.5	14.2	13.8	9.4	11.4	
Patterns	Lichen S is higher north, with cleaner air. Region has cooler temperatures, cleaner air. Regression model is strong.	Lichen S is higher north and east, with cleaner air. Region has cooler temperatures, cleaner air, all pollutants correlated. Regression model is strong.	Lichen S is higher south and west, at higher elevations, with cleaner air. Region has cool temperatures, poorer air quality, all pollutants correlated. Regression model is intermediate.	No strong patterns with Lichen S. Region has warm temperatures, poorer air quality. Regression model is weak.	No strong patterns with Lichen S. Region has warmer temperatures, cleaner air, all pollutants correlated. Regression model is very weak.	

WEST REGION:	Lichen S is higher to the north, to the west, at lower elevations, wetter, and with cleaner air. Summer and winter temperatures are weakly correlated. Regression model is intermediate.						
Ecoregion	Cascades/Coast Mountains	Sierras/Coast Mountains	Northern Rockies	Southern Rockies/ Great Basin Mountains	Great Basin Lowlands	Colorado Plateau/ Southern Dry Mountains	Arid Southwest
Average Lichen S	17.2	13.9	14.7	6.8	5.5	6.1	5.0
Patterns	No strong patterns with Lichen S. Summer & winter temperatures are weakly correlated. Regression model is very weak.	Lichen S is higher west, at lower elevations. Summer & winter temperatures are moderately correlated, N pollutants correlated. Regression model is weak.	Lichen S is higher north, west, at lower elevations, with poorer air quality. Summer & winter temperatures are weakly correlated. Regression model is intermediate.	Lichen S is higher east. Summer & winter temperatures are moderately correlated. Regression model is weak.	Lichen S is higher north. Summer & winter temperatures are weakly correlated, pollutants correlated. Regression model is intermediate.	Lichen S is higher at higher elevations, wetter, with cleaner air. Summer & winter temperatures are moderately correlated, Regression model is intermediate.	Lichen S is higher at higher elevations, wetter, cooler summer temps, with more trees. Summer & winter temperatures are weakly correlated, Regression model is strong.

Instead of a central tendency well represented by an average response of lichen S at a particular level of the variable, the distribution of lichen S is solid because many additional factors may also limit lichen S. This pattern is common in studies of organism-environment relationships in natural communities because organisms are affected simultaneously by more than the single displayed factor (Thomson and others 1996). Such a limited relationship can be observed in a scatterplot but is much more difficult to express statistically and is often not well represented by a linear correlation or regression model.

We found that in most cases the relation of lichen S to the environment differed among ecoregion groups within region and between groups and the region as a whole. This suggests that it may be necessary to have different response models for different ecoregion groups, even though this may cause difficulties estimating response for plots located near boundaries between ecoregion groups.

East Lichen Diversity Patterns—*East Region—* In the East, the strongest linear relationship is between lichen S and NO_3^-, accounting for about 20 percent of variation in lichen S (table 3.1). Maximum lichen S drops as NO_3^- rises (fig. 3.5A), and a lower proportion of plots with very low lichen S occurs where NO_3^- is below 10 kg/ha/year. The few plots with NO_3^- above 18 kg/ha/year limit our ability to make strong assertions about areas with pollution this high. A comparison of the scatterplots of lichen S vs. latitude (fig. 3.4A) with the plots of NO_3^- vs. latitude (fig. 3.5B) shows that maximum lichen S dips at the same latitudes as NO_3^- peaks (~40 to 43° N.; coincident with eastern urban/industrial corridors). Because these latter two relatively strong relationships are not linear, neither lichen S nor NO_3^- is strongly correlated with latitude (table 3.1). The stronger response of lichen S to NO_3^- than to NH_4^+ suggests that acidic pollution and urban industrial effects have so far contributed more than agricultural effects to reduced lichen S in the East.

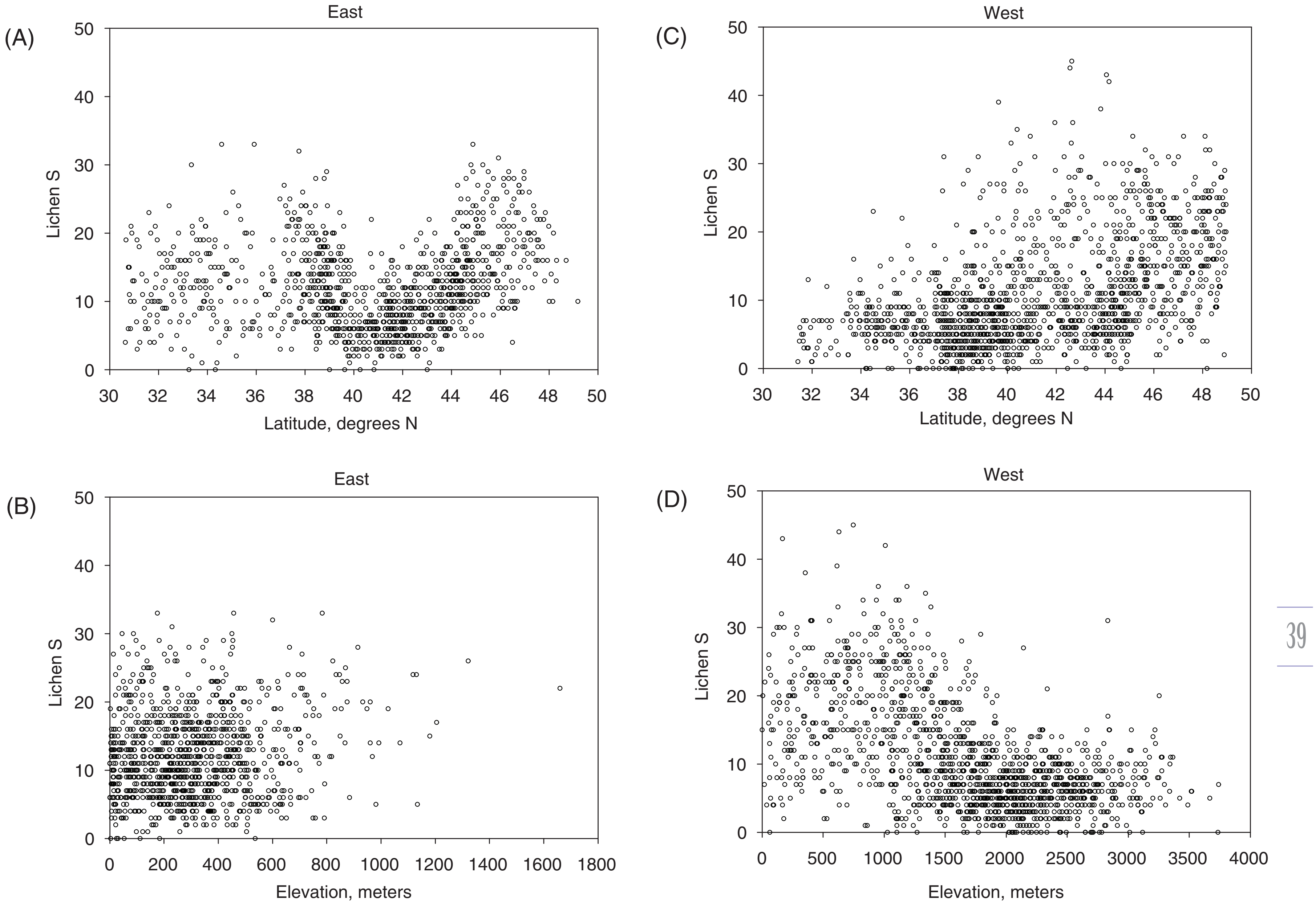


Figure 3.4—Scatterplots for geographic variables. (A) East – Maximum Lichen S dips at 40-43˚ N latitude; (B) East – Lichen S shows little relation to elevation. (C) West – Maximum Lichen S increases as latitude increases (more N); (D) West – Maximum Lichen S decreases as elevation increases. (Data sources: U.S. Department of Agriculture, Forest Service Forest Inventory and Analysis Program and the U.S. Geologic Survey)

Scatterplots indicate that for the East, elevation and climate variables are not strong single predictors of lichen S even as limiting factors (figs. 3.4B, 3.6A, 3.6B, and 3.6C); this is confirmed by weak simple correlations (table 3.1). One reason for the lack of climate pattern may be the interrelations of climate variables in the East. Summer and winter temperatures are tightly correlated across the East region (table 3.1) and in all but one East group (appendix tables A3.1 through A3.5) representing a single gradient of warm to cool. For the East region as a whole, precipitation decreases to the north as does temperature (table 3.1). This pattern suggests that higher precipitation may alleviate the drying effect of higher temperatures in the East and may lead to a narrower range of moisture conditions for plants (potential evapotranspiration) than appears from temperature or precipitation alone. The suite of East climate variables thus appears to effectively collapse for our data set to a single major (and

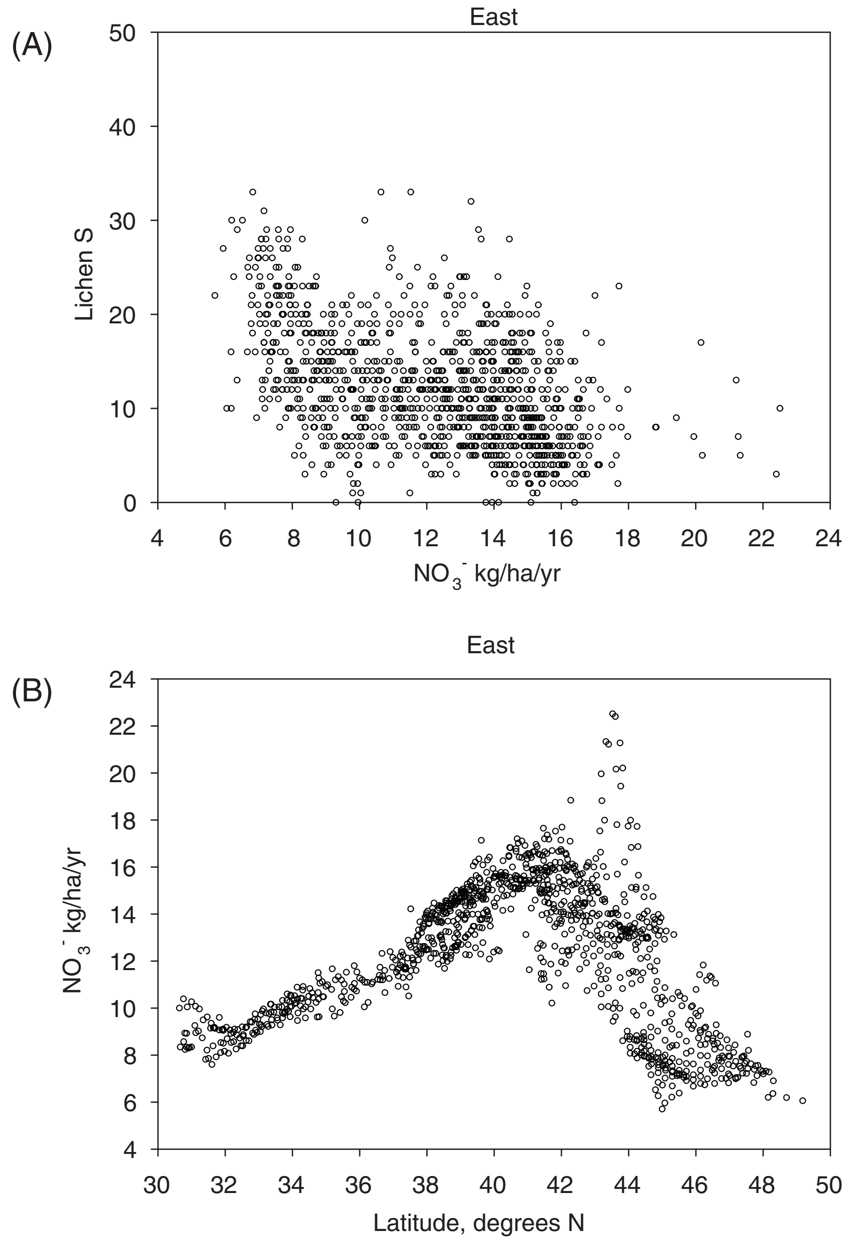
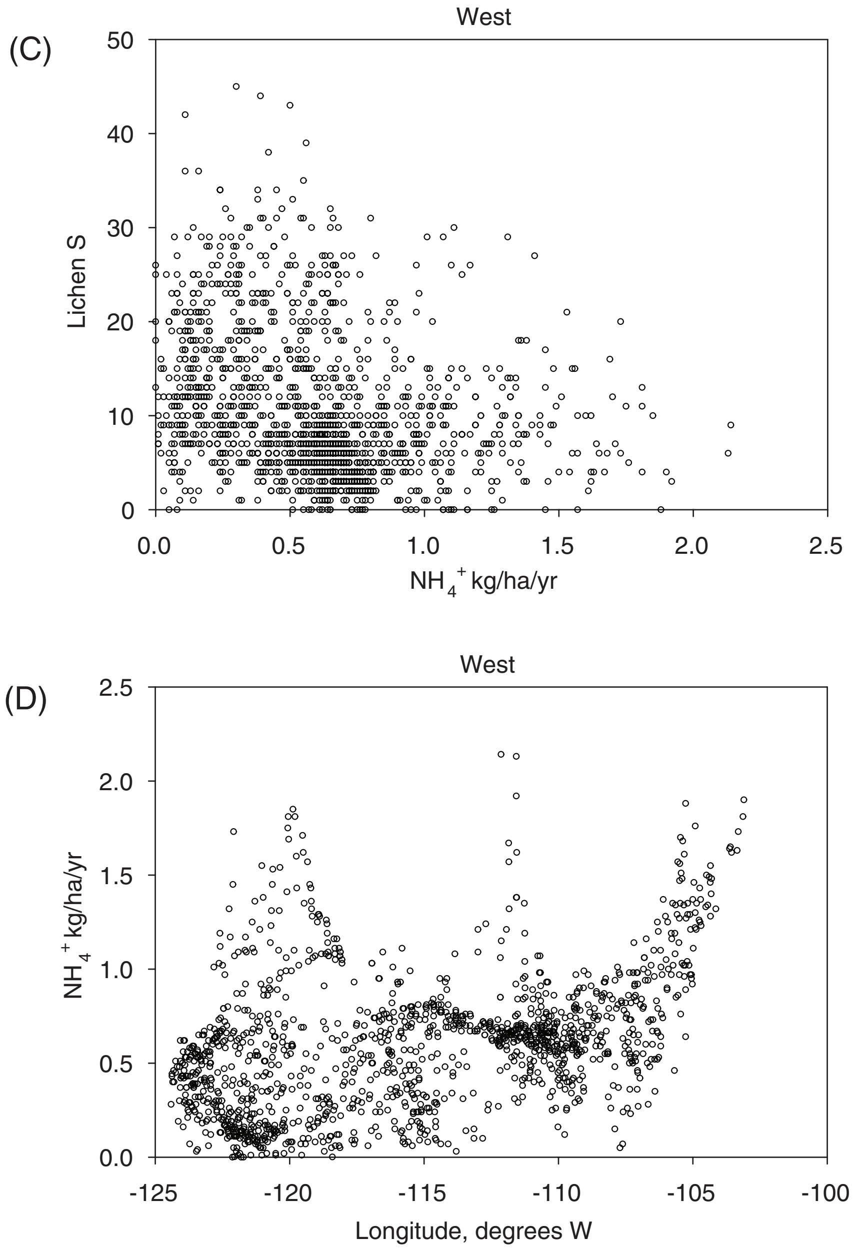


Figure 3.5—Scatterplots for pollution variables. (A) East – Maximum Lichen S decreases as NO_3^- increases; (B) East – NO_3^- mostly peaks at 40-43° N latitude (A and B together explain the pattern in figure 3.4A). (Data sources: 1998-2004 average annual deposition from an interpolated 5-km^2 grid of National Atmospheric Deposition Program data [Coulston and others 2004], and from U.S. Department of Agriculture, Forest Service Forest Inventory and Analysis Program) (continued on next page)



relatively shallow) gradient of warm to cool climates with moderate variation in moisture. Also, all three climate variables have narrower ranges than in the West region.

For the East region, only multiple regression models including NO_3^- were reasonably informative. The minimal regression models are fairly weak. The overall best full regression model including four variables (table 3.1) explains a little more than 30 percent of variation in lichen S, and is not much better than the best minimal model ($r^2 = 0.300$, model not shown). Lichen S is "predicted" to be larger where pollution is lower, at higher elevations, and where winters are cooler.

East Ecoregion Groups—Average lichen S is higher in the mountainous Adirondacks and Appalachian ecoregion groups and in the northern Laurentian Forest group than it is in the other two groups (fig. 3.2, table 3.3; differences among groups were not evaluated

Figure 3.5 (continued)—Scatterplots for pollution variables. (C) West – Maximum Lichen S decreases as NH_4^+ increases; (D) West – Maximum NH_4^+ has a geographic pattern; it dips at longitudes corresponding to Coast, Sierra/Cascade, and Rocky Mountain ranges and peaks in lowlands. (Data sources: 1998-2004 average annual deposition from an interpolated 5-km^2 grid of National Atmospheric Deposition Program data [Coulston and others 2004], and from U.S. Department of Agriculture, Forest Service Forest Inventory and Analysis Program) statistically). Within these three groups higher lichen S occurs at higher elevations and/or farther north, strengthening an interpretation that in the East, lichen S is higher when temperatures are cooler. The rank order of average lichen S for ecoregion groups does not match the order of average air quality for the five ecoregion groups, while it does match the order of average temperatures for them, lending further support to a temperature explanation. However, in all three cooler ecoregion groups, warmer conditions (lower elevations or more southern location) are also correlated with higher NO_3^-, because that is where urban areas and industry are concentrated. With our data, it thus remains difficult to tease apart impacts of temperature and air quality on lichen S within and even between ecoregion groups (table 3.3). Two intensive studies (McCune and others 1997, Will-Wolf and others 2006) demonstrate for Southeastern and Mid-Atlantic States (including most of the Appalachian ecoregion group) that lichen S is larger at higher elevations and/or cooler areas independent of air quality effect.

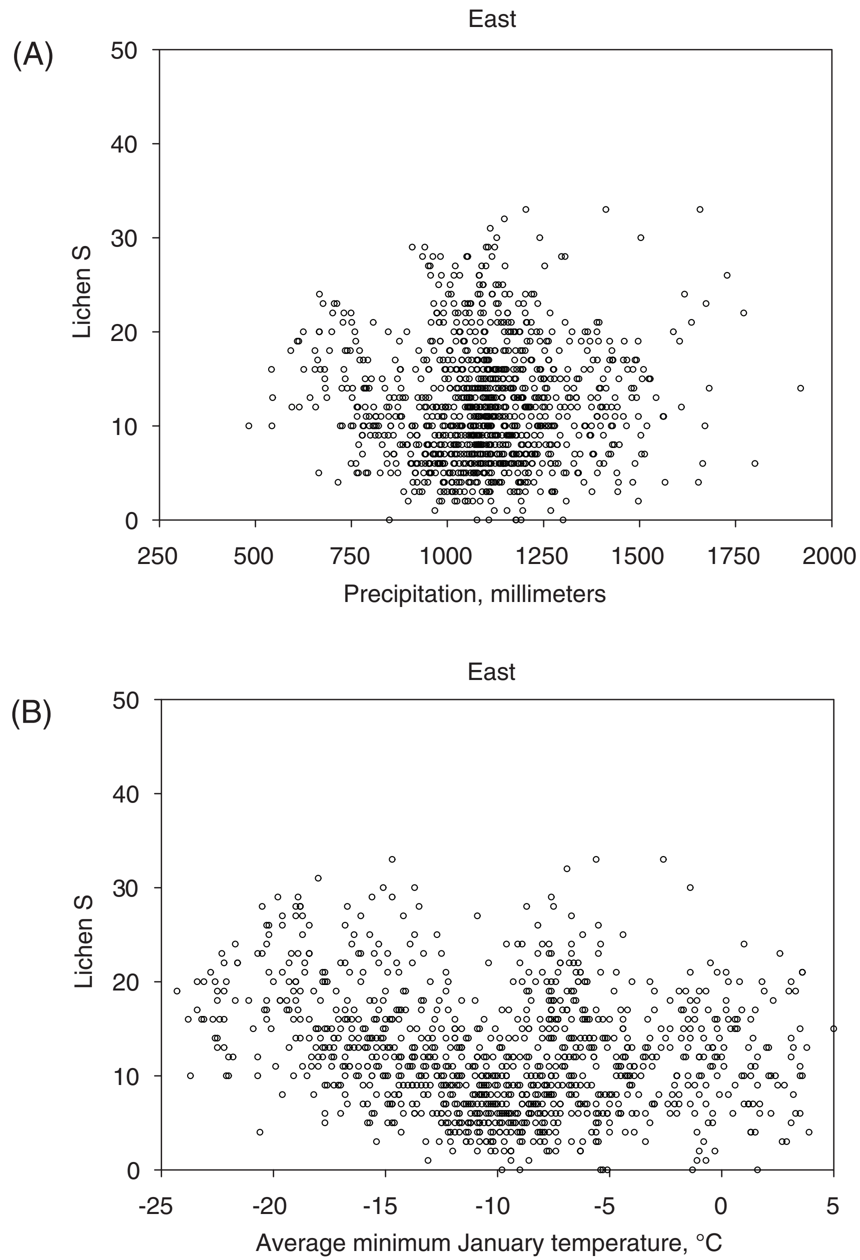


Figure 3.6—Scatterplots for climate variables. (A) East—Lichen S vs. precipitation; (B) East – Lichen S vs. average minimum January temperature. (Data sources: 30-year climate averages from Daly and Taylor 2000, and from U.S. Department of Agriculture, Forest Service Forest Inventory and Analysis Program) (continued on next page)

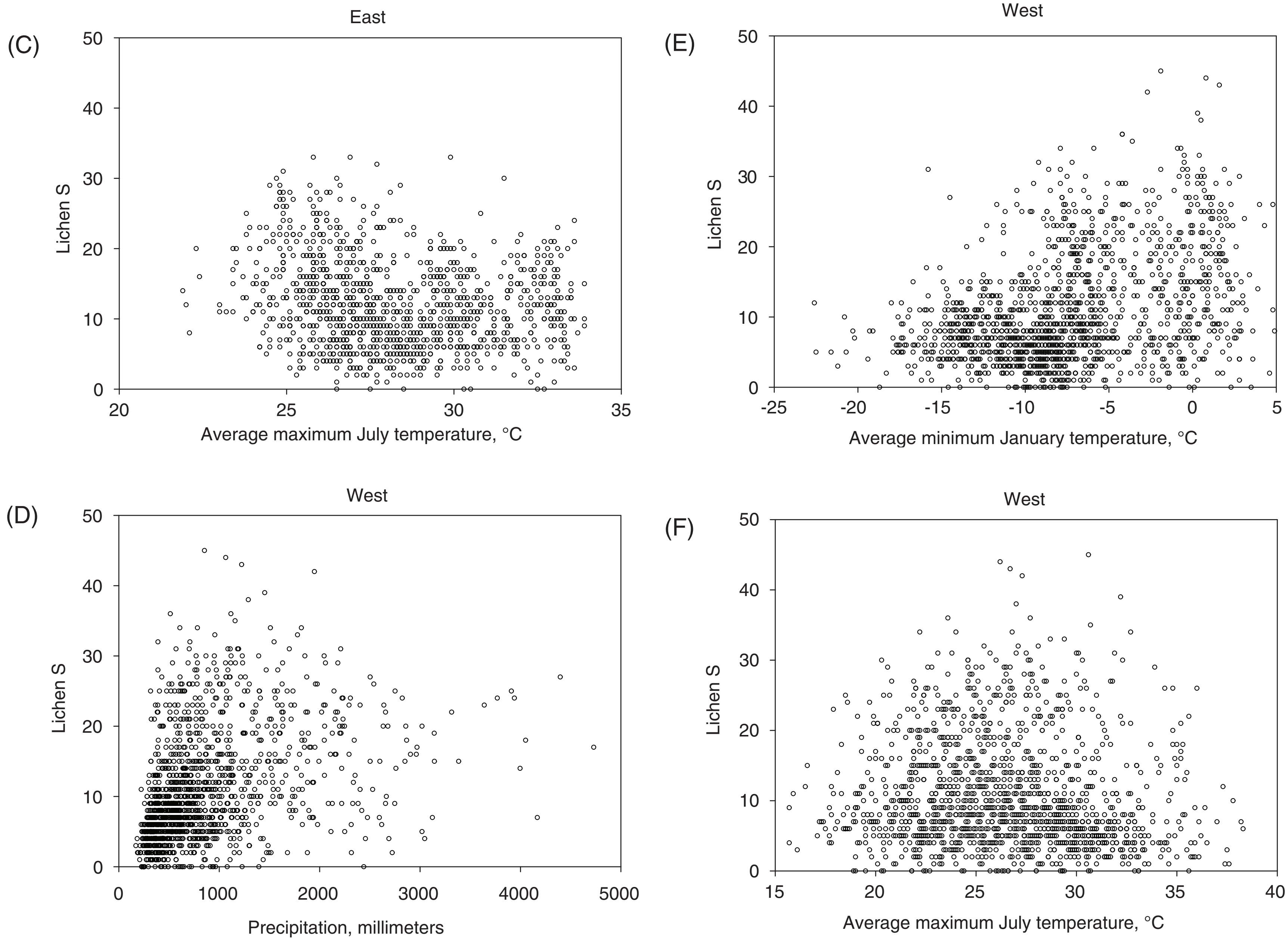


Figure 3.6 (continued)—Scatterplots for climate variables. (C) East—Lichen S vs. average maximum July temperature. Note that in the East (A, B, C) Lichen S shows little relation to any of the climate variables. (D) West—Maximum Lichen S is limited at very low average precipitation. (E) West—Maximum Lichen S increases with average minimum January temperature; (F) West—Maximum Lichen S is lower where average maximum July temperature is either lower or higher. (Data sources: 30-year climate averages from Daly and Taylor 2000, and from U.S. Department of Agriculture, Forest Service Forest Inventory and Analysis Program)

If lichen diversity is indeed naturally lower where it is warmer in several parts of the East, the higher levels of pollutants (associated with lower lichen S) in many of those same warmer areas may have further reduced lichen diversity there. The combined effect of air quality and temperature would thus effectively increase the range of higher to lower lichen biodiversity across the East region.

Air quality is lower to the south within the Laurentian Forest, Adirondacks, and Eastern Deciduous ecoregion groups (appendix tables A3.1, A3.2, and A3.4) and is lower to the north within the Appalachian and southeastern ecoregion groups (appendix tables A3.3 and A3.5). All five of these patterns within ecoregions reflect increased midlatitude pollution (in either the Ohio Valley urban/industrial corridor or the midlatitude east coast urban/industrial region) that produces the pattern on the scatterplot of NO_3^- vs. latitude in figure 3.5B.

The Eastern Deciduous and Southeastern ecoregion groups show weak relationships of all environmental variables with lichen S, and the best regression models explain small proportions of the variation in lichen S (table 3.3). Both are quite large geographic areas (fig. 3.2) that have low within-group variation in climate and pollution as compared with other East ecoregion groups. A reasonable interpretation is that relationships of lichens to environment are more subtle, probably reflected as variation in species composition rather than in lichen S for these two ecoregion groups.

West Lichen Diversity Patterns—*West Region*—In contrast to the East, scatterplots in the West region showed strong responses of lichen S to the environment, and this was confirmed by correlations (table 3.2). Maximum lichen S increases linearly with latitude (fig. 3.4C) and decreases linearly with elevation (fig. 3.4D), both supported by strong correlations (table 3.2). Lichen S is also significantly higher to the West. Very low precipitation coincides with low lichen S (fig. 3.6D), while maximum lichen S increases steeply as precipitation increases for sites near the drier end of the precipitation gradient, reflected in a moderate positive correlation (table 3.2). At precipitation levels above 800 to 1000 mm/year, maximum lichen S no longer increases with precipitation, suggesting precipitation limits lichen S only below 1000 mm/year. Winter temperatures may also affect lichen S in the West; the upper limit of lichen S increases as January temperatures increase (fig. 3.6E). It appears that maximum July temperature might limit lichen S at both ends; the upper limit of lichen S is highest at midrange, declining with departure to both lower and higher average maximum temperatures (fig. 3.6F). Such essentially nonlinear temperature patterns are not reflected in strong correlations (table 3.2).

Even though in the West region maximum NH_4^+ levels are low (table 3.1), NH_4^+ deposition still appears to limit maximum lichen S (fig. 3.5C). This is the strongest relationship between lichen S and air quality for the West region and is confirmed by a moderate negative correlation (table 3.2). The scatterplot of NH_4^+ vs. longitude (fig. 3.5D) suggests strong geographic variation in levels of NH_4^+, explaining perhaps why the negative correlation of lichen S with NH_4^+ is not stronger (table 3.2). The longitudes of peaks for NH_4^+ levels in this scatterplot correspond roughly to lowlands where most agriculture occurs, while the longitudes of troughs correspond to north-south mountain ranges.

Minimal regression models are generally stronger for the West than for the East. The overall best full regression model including five variables is notably better than the best minimal model (both shown in table 3.2), explaining about 40 percent of variation in lichen S. Two variables without important single correlations contribute significantly to the best model: total plot BA and average maximum July temperature.

Climate variables have wide ranges for the West region and strong differences between West ecoregion groups, resulting in strong and varied correlations between climate and geography (table 3.2, appendix tables A3.6 through A3.12). Summer and winter temperatures are not strongly correlated with one another in the West region nor in several of the West groups. Precipitation is either negatively correlated with temperature (West region and some groups) or is independent of temperature in some ecoregion groups. For the former groups, lower precipitation where temperatures are warmer exaggerates the drying effect of higher temperatures, giving a wider range of moisture conditions (potential evapotranspiration) for plants than indicated from either precipitation or temperature alone across the same area. Thus, there is no single climate gradient for the

West and for West regions. All three climate variables must be considered independently, and they relate differently to each other and to geographic variables in the various ecoregion groups. Geographic variables representing integrated climate conditions often have stronger patterns with lichen S than do the direct climate variables (tables 3.2 and 3.3) in our data sets.

In the West region and several ecoregion groups, lichen S is higher in lower elevation areas where air quality also is often lower. Thus, the impact of air quality in these West areas would be to reduce lichen S in higher diversity areas and decrease the overall range of lichen S (as opposed to increasing its range in some East ecoregion groups).

West Ecoregion Groups—For four of the West ecoregion groups, the best full regression model supports further use of lichen S (strong or intermediate in table 3.3), predicting almost 40 percent or more of variation in lichen S (appendix tables A3.8 and A3.10 through A3.12). Precipitation is the strongest contributor to regression models for the Arid Southwest and Colorado Plateau/Southern Dry Mountains groups that have the driest climates and the lowest maximum lichen S. For the Northern Rockies and Great Basin Lowlands ecoregion groups, geographic variables contribute more than do climate variables to best regression models (see discussion above under West Region). The wide variation between ecoregion groups in correlations between environmental variables is probably the reason relations of lichen S to explanatory variables are so varied between regions (table 3.3). It seems clear that better predictive models for different regions will need to be developed independently.

For three West ecoregion groups the best regression model explains relatively little variation in lichen S. Regression models for the Sierras/Coast Mountains and the Southern Rockies/Great Basin Mountains ecoregion groups explain 20 to 30 percent of variation in lichen S; each region also has a strong geographic variable (table 3.3, appendix tables A3.9 and A3.12). Jovan and McCune (2005, 2006) and Jovan (2008) found strong relationships of lichen species composition and some response of lichen S with similar explanatory variables for the Sierras/Coast Mountains ecoregion in more intensive studies covering smaller areas. The Cascades/Coast Mountains ecoregion group, with the highest average lichen S in our entire study (fig. 3.2, table 3.3), shows extremely weak correlations of our environmental variables with lichen S. Tree BA, the strongest, is weakly correlated with lichen S, and the best full regression model, including tree BA and NH_4+ pollution, predicts only 11 percent of the variation in lichen S (appendix table A3.6). Intensive studies of lichen communities in this ecoregion group using FIA data (Geiser and Neitlich 2007, Jovan 2008, Will-Wolf and others 2006) confirm that here lichen S does not vary with environmental variables; one must examine species composition to explore response to environment.

East-West Comparisons—If pollution and other human activities increase, they will likely occur more at lower elevations in both the East and West regions, but they may well have quite different broad impacts on lichen diversity in the two regions. The occurrence of higher lichen S at higher elevations in mountainous East ecoregion groups means that the more species-rich areas will be less affected by increased human activities. In contrast, higher lichen S at lower elevations in most mountainous West ecoregion groups means that the more species-rich and vulnerable areas will also be more affected by increased human activities, perhaps resulting in much greater reduction in regional biodiversity for lichens in the West than in the East.

Some notable differences in climate between West and East may have important implications for developing indicators of response to climate. In the East, where summer and winter temperatures are positively correlated in most areas and links between climate and geography are similar between areas, if lichen S can be shown to be correlated with some new climate variable such as evapotranspiration, it can be expected to be useful across scales and between ecoregion groups. Calibration of lichen S response between areas will be straightforward.

For the West, in contrast, the lack of a single pattern of correlations between climate variables and the varied links between climate and geography variables pose distinct challenges for developing lichen S as a climate indicator. Geographic variables that presumably integrate the effects of climate are currently the strongest predictors of lichen S in the West region and most ecoregion groups. However, the very different combinations of how climate variables are linked to geographic variables in the West region versus ecoregion groups (between scales) and between ecoregion groups suggest that as climate changes, the relation between climate and geography may also change in unexpected ways. For example, in one ecoregion the predictive power of elevation for lichen S might currently relate most to variation in winter temperatures, while in an adjacent ecoregion the predictive power of elevation might relate most to summer temperatures that are weakly correlated with winter temperatures. In the first region, after some period of climate change, its own original relationships might be replaced by those for the adjacent region. Use of elevation as the predictor for lichen S indicating climate response in the first ecoregion would need to be developed with such possibilities in mind, so as to avoid misinterpretations when using lichen S for trend analysis.

Further Studies—Followup studies for particular regions and ecoregion groups should address a number of issues to improve the use of lichen S as an indicator. Suggestions for each region are summarized in table 3.4. For any region, additional climate variables such as potential evapotranspiration should be explored to see if stronger climate signals emerge. Variables that represent other human impacts, such as intensity of agricultural and reduction in percent forest near plots, can be developed and tested. Variables that represent other aspects of forest structure, such as number of tree species, average tree size, or proportion of early versus late-successional tree species, can be developed from FIA tree data and tested to further explore relationships with local plot conditions. More complicated models including covariates, nonlinear terms, and interaction terms can also be explored for ecoregion groups. For more in-depth analyses of ecoregion groups, data sets should perhaps have more equal representation of plots across the geographic area under study. For the most promising regions, cross-indicator analyses should also be considered. After final models for adjacent ecoregion groups have been completed, between-group studies should explore how to best interpret response at plots near boundaries.

For three of five East ecoregion groups, lichen S has potential to be a useful indicator for response to both pollution and climate if variables representing these factors and also independent of each other can be developed. Developing such variables requires more intensive studies tailored to the particular region. Explanatory climate variables seem to behave similarly enough between East ecoregion groups that approaches to improving predictive models for one East ecoregion group may be applicable to at least some other groups.

Conclusion

Lichen S, the number of lichen species found at an FIA plot, shows a number of strong relationships to environmental variables across the coterminous United States. Our findings confirm that forest structure has relatively little impact on lichen S at such large geographic scales. For some ecoregion groups within the East and West, lichen S is correlated with few of our variables, and the best regression model is weak. Lichen S alone currently shows no potential as a useful indicator there, probably because important relationships in those regions must be linked to relative abundance of different lichen species.

Table 3.4—Summary of the potential usefulness of Lichen S as an environmental indicator for East and West regions and ecoregion groups, and suggested avenues for future research. Potential usefulness is extrapolated from results summarized in table 3.3

EAST REGION:	Lichen S is potentially useful as an indicator of response to air quality but not to other environmental factors as represented by current variables.						
Next steps for research	Derive a potential evapotranspiration variable; investigate its relationship with Lichen S. Evaluate relationships between air pollution variables and other variables representing human impacts such as forest fragmentation, agriculture, and urbanization to improve interpretation of Lichen S response. Explore other local forest structure variables.						
East Ecoregions:	Laurentian Forest	Adirondacks	Appalachian	Eastern Deciduous	Southeastern		
Usefulness of Lichen S	Moderate – response to air quality & temperature	Moderate – response to air quality & temperature	Moderate – response to air quality & temperature	Low	Low		
Next steps for research	Evaluate response to air quality vs climate	Evaluate response to air quality vs climate	Evaluate response to air quality vs climate	Explore evapotranspiration variable, other human impact variables	Explore evapotranspiration variable, other human impact variables		
WEST REGION:	Lichen S is potentially useful as an indicator of climate and of response to air quality after accounting for climate.						
Next steps for research	Investigate combining Lichen S with other region-wide biological indicators of response to climate for a cross-indicator analysis. Derive a potential evapotranspiration variable; investigate its relationship with Lichen S. Explore other local forest structure variables.						
West Ecoregions:	Cascades/Coast Mountains	Sierras/Coast Mountains	Northern Rockies	Southern Rockies/Great Basin Mountains	Great Basin Lowlands	Colorado Plateau/ Southern Dry Mountains	Arid Southwest
Usefulness of Lichen S	Low	Low	Moderate – response to winter temperatures	Low	Moderate – response to air quality & latitude	Moderate – response to longitude	High – response to precipitation & summer temperatures
Next steps for research	Not needed; other research available	Not needed; other research available	Investigate cross-indicator analyses	Explore evapotranspiration variable	See region next steps. Evaluate response to air quality vs climate	See region next steps. Evaluate response to air quality vs climate.	See region next steps

The fact that pollution and not environment has the strongest correlation with lichen S in the East region suggests that air pollution representing human impact has already had a measurable negative impact on lichen biodiversity across the East. For the East as a whole, it appears lichen S may be a useful indicator for response to pollution and other human impacts but not for response to changes in climate. For three of five East ecoregion groups, lichen S may be a useful indicator for response to both pollution and climate, but separating the two factors is difficult.

The lack of strong correlations between lichen S and pollution variables in the West region suggest that human activities are not yet having a major impact on lichen biodiversity across the region as a whole, though some relationships between lichen S and pollution suggest vulnerability. If pollution and other human impacts increase in the West, increases will likely occur more at lower elevations where lichen S is usually higher. Thus, they may impact the most diverse lichen communities and have a stronger than expected impact on regional biodiversity. For the West as a whole and for four of seven West ecoregion groups, lichen S has potential as a useful indicator for response to climate and possibly for response to pollution as well.

Some notable differences in climate between the West and East have important implications for developing indicators of response to climate. In the East, with a more uniform climate, an improved climate variable can be anticipated to be broadly useful to link with lichen S. For the West, in contrast, the lack of a single pattern of correlations between climate variables and the varied links between climate and geography variables pose distinct challenges for developing lichen S as a climate indicator. Different models for each ecoregion will likely be needed, and calibrating between regions may be difficult.

Strong response patterns have emerged even though lichen S is affected by many sources of variation in addition to those of interest to us. It appears that despite these limitations and probably because the FIA lichen sample protocol is designed to average across much local variation, this relatively imprecise lichen diversity indicator does indeed have potential for tracking response to pollution and/or environment. The variation we found shows each area to be studied needs its own separate model for how lichen S responds to environmental factors. Our analyses provide useful baselines for comparison with resurveys and trend analysis for the future and highlight logical next steps for developing better models.

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Table A3.1—Laurentian Forest ecoregion group in the East region

		Spearman correlations (*rho*)			(Bailey's province codes = 211, 212; N = 278[a]; years = 1994–2004)							
Variable	Range (average ± sd)	Lichen S	Lat.	Long.	Elev.	Precip.	Max. July temp.	Min. Jan. temp.	NO_3^-	SO_4^{--}	NH_4^+	Tree BA
Lichen S	2 – 33 (average 13.5 ± 6.8 sd)											
Latitude (decimal degrees, S to N)	41.14 – 49.18	**0.597**										
Longitude (decimal degrees, W to E)	−95.31 – −67.11	—	—									
Elevation (m)	6 – 818 (336 ± 178)	—	—	**−0.562**								
Precipitation (mm)	542 – 1609 (967 ± 179)	—	**−0.507**	**0.765**	—							
Max. July temp. (°C)	22.0 – 29.4 (26.4 ± 1.00)	—	—	—	—	—						
Min. Jan. temp. (°C)	−8.9 – −24.3 (−14.8 ± 3.83)	**−0.546**	**−0.903**	—	—	—	—					
NO_3^- (kg/ha/year)	5.70 – 22.40 (11.67 ± 3.99)	**−0.687**	**−0.771**	—	**0.477**	—	—	**0.656**				
SO_4^{--} (kg/ha/year)	4.32 – 25.31 (13.22 ± 5.71)	**−0.633**	**−0.940**	—	—	**0.502**	—	**0.845**	**0.869**			
NH_4^+ (kg/ha/year)	0.70 – 4.23 (2.52 ± 0.90)	—	—	**−0.790**	—	**−0.512**	—	—	**0.477**	—		
Tree BA (square foot per acre)	22.1 – 330.8 (96.3 ± 48.5)	—	—	—	—	—	—	—	—	—	—	
Percent BA softwoods	0 – 100 percent (30.9 ± 35.4)	—	—	—	—	—	—	—	**−0.481**	—	—	—
Best overall full regression model		**r^2 = 0.527, p < 0.0005: Lichen S = 32.913 −0.717 NO_3^- + 1.359 lat. (+ 0.146 long. + 0.006 precip.)** Lichen S larger with less acidic air pollution, more north (more east, wetter).										

— = cells with dashes indicate correlations weaker than the cutoff; max. = maximum; min. = minimum; sd = standard deviation; lat. = latitude; long. = longitude; elev. = elevation; precip. = precipitation; temp. = temperature; NO_3^- = nitrate; SO_4^{--} = sulfate; NH_4^+ = ammonium; BA = basal area; S = south; N = north; W = west; E = east; m = meter; mm = millimeter; °C = degree Celsius; kg = kilogram; ha = hectare.
Range and intercorrelations of Lichen S plus geography, climate, pollution, and forest structure variables; the best regression model is given at bottom. Positive correlations are in black; negative are in red. Single correlations with *rho* > 0.447 (in bold, all with p < 0.0005) account for at least 20 percent of variation; correlations with Lichen S stronger than this cutoff suggest potential for an indicator. Correlations between environmental variables with *rho* ≥ 0.775 (at least 60 percent of variation accounted for) indicate those two variables should not be entered into the same regression model. The best overall regression model is included with contributing variables listed in descending order of significance; minor variables (p ≤ 0.05 but usually p ≥ 0.005) are listed in parentheses.
[a] Removed E plots with total live-tree BA < 21.8966 square feet per acre (< 5 m^2/ha).

Table A3.2—Adirondacks ecoregion group in the East region

Variable	Range (average ± sd)	Spearman correlations (*rho*) (Bailey's province code = M211; N = 152[a]; years = 1994–2004)										
		Lichen S	Lat.	Long.	Elev.	Precip.	Max. July temp.	Min. Jan. temp.	NO_3^-	SO_4^{--}	NH_4^+	Tree BA
Lichen S	3 – 31 (average 14.2 ± 5.8 sd)											
Latitude (decimal degrees, S to N)	42.07 – 47.40	**0.534**										
Longitude (decimal degrees, W to E)	–75.30 – –68.69	**0.574**	**0.712**									
Elevation (m)	155 – 960 (429 ± 152)	—	—	**–0.601**								
Precipitation (mm)	812 – 1681 (1118 ± 147)	—	—	—	**0.504**							
Max. July temp. (°C)	21.9 – 28.0 (25.3 ± 1.28)	—	**–0.616**	—	—	—						
Min. Jan. temp. (°C)	–10.9 – –20.4 (–16.1 ± 2.13)	**–0.486**	**–0.877**	—	—	—	**0.720**					
NO_3^- (kg/ha/year)	7.16 – 17.79 (11.58 ± 2.66)	**–0.544**	**–0.795**	**–0.951**	—	—	—	**0.668**				
SO_4^{--} (kg/ha/year)	7.81 – 18.82 (12.64 ± 3.04)	**–0.534**	**–0.884**	**–0.870**	—	—	**0.564**	**0.784**	**0.940**			
NH_4^+ (kg/ha/year)	1.12 – 3.22 (1.93 ± 0.48)	**–0.497**	**–0.625**	**–0.940**	—	—	—	**0.561**	**0.925**	**0.871**		
Tree BA (square foot per acre)	24.1 – 283.0 (104.0 ± 52.1)	—	—	—	—	—	—	—	—	—	—	
Percent BA softwoods	0 – 100 percent (39.1 ± 33.5)	—	—	—	—	—	—	—	—	—	—	—
Best overall full regression model		**r^2 = 0.429, p < 0.0005: Lichen S = 38.491 + 1.261 long. (+ 1.587 lat.)** Lichen S larger more east, (more north).										

— = cells with dashes indicate correlations weaker than the cutoff; max. = maximum; min. = minimum; sd = standard deviation; lat. = latitude; long. = longitude; elev. = elevation; precip. = precipitation; temp. = temperature; NO_3^- = nitrate; SO_4^{--} = sulfate; NH_4^+ = ammonium; BA = basal area; S = south; N = north; W = west; E = east; m = meter; mm = millimeter; °C = degree Celsius; kg = kilogram; ha = hectare.

Range and intercorrelations of Lichen S plus geography, climate, pollution, and forest structure variables; the best regression model is given at bottom. Positive correlations are in black; negative are in red. Single correlations with *rho* > 0.447 (in bold, all with p < 0.0005) account for at least 20 percent of variation; correlations with Lichen S stronger than this cutoff suggest potential for an indicator. Correlations between environmental variables with *rho* ≥ 0.775 (at least 60 percent of variation accounted for) indicate those two variables should not be entered into the same regression model. The best overall regression model is included with contributing variables listed in descending order of significance; minor variables (p ≤ 0.05 but usually p ≥ 0.005) are listed in parentheses.

[a] Removed E plots with total live-tree BA < 21.8966 square feet per acre (< 5 m^2/ha).

Table A3.3—Appalachian ecoregion group in East region

Variable	Range (average ± sd)	Spearman correlations (*rho*) (Bailey's province code = M221; N = 140[a]; years = 1994–2005)										
		Lichen S	Lat.	Long.	Elev.	Precip.	Max. July temp.	Min. Jan. temp.	NO_3^-	SO_4^{--}	NH_4^+	Tree BA
Lichen S	1 – 33 (average 13.8 ± 7.7 sd)											
Latitude (decimal degrees, S to N)	34.77 – 41.24	–0.506										
Longitude (decimal degrees, W to E)	–84.14 – –75.75	–0.480	0.907									
Elevation (m)	152 – 1660 (598 ± 263)	0.457	–0.539	–0.542								
Precipitation (mm)	894 – 1919 (1154 ± 188)	—	—	–0.499	0.513							
Max. July temp. (°C)	24.1 – 30.4 (27.9 ± 1.47)	—	—	—	–0.647	—						
Min. Jan. temp. (°C)	–3.4 – –10.5 (–7.5 ± 1.50)	—	–0.758	–0.657	—	—	0.555					
NO_3^- (kg/ha/year)	10.48 – 17.20 (13.80 ± 1.67)	–0.498	0.933	0.749	–0.531	—	—	–0.681				
SO_4^{--} (kg/ha/year)	16.03 – 24.33 (20.08 ± 1.90)	—	0.837	0.614	—	—	—	–0.656	0.926			
NH_4^+ (kg/ha/year)	2.09 – 3.42 (2.67 ± 0.26)	–0.518	0.845	0.750	–0.675	—	—	–0.460	0.851	0.768		
Tree BA (square foot per acre)	23.0 – 500.7 (103.2 ± 58.9)	—	—	—	—	—	—	—	—	—	—	
Percent BA softwoods	0 – 95.48 percent (7.8 ± 18.1)	—	—	—	—	—	—	—	—	—	—	—
Best overall full regression model	**r^2 = 0.373, p < 0.0005: Lichen S = 207.782 –5.226 lat. (– 0.293 Min. Jan. – 0.012 precip.)** Lichen S larger more south, (cooler winters, drier).											

— = cells with dashes indicate correlations weaker than the cutoff; max. = maximum; min. = minimum; sd = standard deviation; lat. = latitude; long. = longitude; elev. = elevation; precip. = precipitation; temp. = temperature; NO_3^- = nitrate; SO_4^{--} = sulfate; NH_4^+ = ammonium; BA = basal area; S = south; N = north; W = west; E = east; m = meter; mm = millimeter; °C = degree Celsius; kg = kilogram; ha = hectare.
Range and intercorrelations of Lichen S plus geography, climate, pollution, and forest structure variables; the best regression model is given at bottom. Positive correlations are in black; negative are in red. Single correlations with *rho* > 0.447 (in bold, all with p < 0.0005) account for at least 20 percent of variation; correlations with Lichen S stronger than this cutoff suggest potential for an indicator. Correlations between environmental variables with *rho* ≥ 0.775 (at least 60 percent of variation accounted for) indicate those two variables should not be entered into the same regression model. The best overall regression model is included with contributing variables listed in descending order of significance; minor variables (p ≤ 0.05 but usually p ≥ 0.005) are listed in parentheses.

[a] Removed E plots with total live-tree BA < 21.8966 square feet per acre (< 5 m^2/ha).

Table A3.4—Eastern Deciduous ecoregion group in the East region

Variable	Range (average ± sd)	Spearman correlations (*rho*)			(Bailey's province codes = 221, 222, 223; N = 266[a]; years = 1994–2005)							
		Lichen S	Lat.	Long.	Elev.	Precip.	Max. July temp.	Min. Jan. temp.	NO_3^-	SO_4^{--}	NH_4^+	Tree BA
Lichen S	0 – 21 (average 9.4 ± 4.5 sd)											
Latitude (decimal degrees, S to N)	34.79 – 48.30	—										
Longitude (decimal degrees, W to E)	−96.05 – −70.42	—	**0.450**									
Elevation (m)	7 – 584 (250 ± 111)	—	—	—								
Precipitation (mm)	545 – 1378 (1064 ± 136)	—	—	**0.533**	—							
Max. July temp. (°C)	26.0 – 32.4 (28.6 ± 1.20)	—	**−0.821**	**−0.516**	—	—						
Min. Jan. temp. (°C)	−1.9 – −22.5 −9.3 ± 2.92	—	**−0.881**	**−0.657**	—	—	**0.728**					
NO_3^- (kg/ha/year)	6.36 – 22.51 (14.1 ± 2.18)	−0.253	**−0.601**	—	**0.450**	—	—	—				
SO_4^{--} (kg/ha/year)	4.88 – 28.98 (18.97 ± 4.17)	—	—	—	**0.550**	—	—	**0.494**	**0.844**			
NH_4^+ (kg/ha/year)	1.42 – 4.32 (2.87 ± 0.65)	−0.268	—	**−0.749**	—	**−0.607**	—	—	—	—		
Tree BA (square foot per acre)	22.2 – 579.5 (87.1 ± 50.7)	—	—	—	—	—	—	—	—	—	—	
Percent BA softwoods	0 – 100 percent (11.5 ± 22.7)	—	—	—	—	—	—	—	—	—	—	—
Best overall full regression model		**r^2 = 0.257, p < 0.0005: lichen S = 32.644 −6.949 NH_4^+ − 0.702 long. (+ 0.432 NO_3^-)** Lichen S larger with less ammonia pollution, more west, (more acidic air pollution).										

— = cells with dashes indicate correlations weaker than the cutoff; max. = maximum; min. = minimum; sd = standard deviation; lat. = latitude; long. = longitude; elev. = elevation; precip. = precipitation; temp. = temperature; NO_3^- = nitrate; SO_4^{--} = sulfate; NH_4^+ = ammonium; BA = basal area; S = south; N = north; W = west; E = east; m = meter; mm = millimeter; °C = degree Celsius; kg = kilogram; ha = hectare. Range and intercorrelations of Lichen S plus geography, climate, pollution, and forest structure variables; the best regression model is given at bottom. Positive correlations are in black; negative are in red. Single correlations with *rho* > 0.447 (in bold, all with p < 0.0005) account for at least 20 percent of variation; Correlations weaker than the cutoff are included for Lichen S (p < 0.0009) because they were the two highest correlations found. Correlations between environmental variables with *rho* ≥ 0.775 (at least 60 percent of variation accounted for) indicate those two variables should not be entered into the same regression model. The best overall regression model is included with contributing variables listed in descending order of significance; minor variables (p ≤ 0.05 but usually p ≥ 0.005) are listed in parentheses.

[a] Removed E plots with total live-tree BA <21.8966 square feet per acre (< 5 m^2/ha).

Table A3.5—Southeastern ecoregion group in the East region

Variable	Range (average ± sd)	Spearman correlations (*rho*) (Bailey's province codes = 231, 232; N = 239[a]; years = 1994–99)										
		Lichen S	Lat.	Long.	Elev.	Precip.	Max. July temp.	Min. Jan. temp.	NO_3^-	SO_4^{--}	NH_4^+	Tree BA
Lichen S	0 – 33 (average 11.4 ± 5.5 sd)											
Latitude (decimal degrees, S to N)	30.64 – 40.26	—										
Longitude (decimal degrees, W to E)	-88.34 – -74.03	–0.246	**0.834**									
Elevation (m)	0 – 476 (112 ± 104)	0.274	—	**–0.570**								
Precipitation (mm)	1038 – 1670 (1259 ± 152)	—	**–0.738**	**–0.857**	—							
Max. July temp. (°C)	28.5 – 33.9 (31.9 ± 1.14)	—	**–0.894**	**–0.687**	—	**0.543**						
Min. Jan. temp. (°C)	5.0 – -6.3 (-1.5 ± 2.73)	—	**–0.950**	**–0.691**	—	**0.649**	**0.910**					
NO_3^- (kg/ha/year)	7.60 – 15.03 (10.55 ± 1.62)	—	**0.927**	**0.678**	—	**–0.605**	**–0.888**	**–0.939**				
SO_4^{--} (kg/ha/year)	9.63 – 20.00 (15.29 ± 2.33)	—	**0.909**	**0.648**	—	**–0.595**	**–0.896**	**–0.935**	**0.978**			
NH_4^+ (kg/ha/year)	1.35 – 3.60 (2.40 ± 0.41)	—	**0.745**	**0.475**	—	—	**–0.702**	**–0.730**	**0.717**	**0.732**		
Tree BA (square foot per acre)	22.6 – 309.2 (91.4 ± 45.6)	—	—	—	—	—	—	—	—	—	—	
Percent BA softwoods	0 – 100 percent (40.8 ± 37.36)	—	—	—	—	—	—	—	—	—	—	—
Best overall full regression model		**r^2 = 0.134, $p < 0.0005$: Lichen S = 15.571 (+ 0.018 elev. – 2.593 NH_4^+)** Lichen S larger (higher, with less ammonia air pollution).										

— = cells with dashes indicate correlations weaker than the cutoff; max. = maximum; min. = minimum; sd = standard deviation; lat. = latitude; long. = longitude; elev. = elevation; precip. = precipitation; temp. = temperature; NO_3^- = nitrate; SO_4^{--} = sulfate; NH_4^+ = ammonium; BA = basal area; S = south; N = north; W = west; E = east; m = meter; mm = millimeter; °C = degree Celsius; kg = kilogram; ha = hectare. Range and intercorrelations of Lichen S plus geography, climate, pollution, and forest structure variables; the best regression model is given at bottom. Positive correlations are in black; negative are in red. Single correlations with *rho* > 0.447 (in bold, all with $p < 0.0005$) account for at least 20 percent of variation; Correlations weaker than the cutoff are included for Lichen S ($p < 0.0009$) because they were the two highest correlations found. Correlations between environmental variables with *rho* ≥ 0.775 (at least 60 percent of variation accounted for) indicate those two variables should not be entered into the same regression model. The best overall regression model is included with contributing variables listed in descending order of significance; minor variables ($p \leq 0.05$ but usually $p \geq 0.005$) are listed in parentheses.
[a] Removed E plots with total live-tree BA <21.8966 square feet per acre (< 5 m^2/ha).

Table A3.6—Cascades/Coast Mountains ecoregion group in West region

Variable	Range (average ± sd)	Spearman correlations (*rho*) (Bailey's province codes = 242, M242; N = 213; years = 1998–2001)										
		Lichen S	Lat.	Long.	Elev.	Precip.	Max. July temp.	Min. Jan. temp.	NO_3^-	SO_4^{--}	NH_4^+	Tree BA
Lichen S	0 – 43 (average 17.2 ± 8.3 sd)											
Latitude (decimal degrees, S to N)	42.12 – 48.96	—										
Longitude (decimal degrees, W to E)	−124.41 – −119.87	—	—									
Elevation (m)	0 – 2110 (853 ± 581)	—	—	**0.754**								
Precipitation (mm)	294 – 4731 (1733 ± 831)	—	—	**−0.506**	—							
Max. July temp. (°C)	16.5 – 28.6 (23.5 ± 2.52)	—	**−0.538**	—	—	—						
Min. Jan. temp. (°C)	−12.3 – 4.8 (−2.54 ± 3.57)	—	—	**−0.892**	**−0.849**	**0.482**	—					
NO_3^- (kg/ha/year)	0.74 – 5.27 (2.79 ± 1.05)	—	**0.832**	—	—	—	—	—				
SO_4^{--} (kg/ha/year)	0.32 – 7.53 (3.54 ± 1.53)	—	**0.678**	**−0.702**	—	**0.558**	—	**0.501**	**0.706**			
NH_4^+ (kg/ha/year)	0.00 – 1.32 (0.33 ± 0.25)	0.191	—	**−0.514**	**−0.751**	—	—	**0.609**	—	**0.531**		
Tree BA (square foot per acre)	1.8 – 650.2 (164.3 ± 112.8)	0.313	—	—	—	—	—	—	—	—	—	
Percent BA softwoods	0 – 100 percent (88.8 ± 24.3)	—	—	**0.498**	**0.581**	—	—	**−0.567**	—	—	—	—
Best overall full regression model		**r^2 = 0.113, p < 0.0005: Lichen S = 11.945 + 0.023 tree BA (+ −4.461 NH_4^+)** Lichen S larger with more/bigger trees, (with more ammonia air pollution).										

— = cells with dashes indicate correlations weaker than the cutoff; max. = maximum; min. = minimum; sd = standard deviation; lat. = latitude; long. = longitude; elev. = elevation; precip. = precipitation; temp. = temperature; NO_3^- = nitrate; SO_4^{--} = sulfate; NH_4^+ = ammonium; BA = basal area; S = south; N = north; W = west; E = east; m = meter; mm = millimeter; °C = degree Celsius; kg = kilogram; ha = hectare. Range and intercorrelations of Lichen S plus geography, climate, pollution, and forest structure variables; the best regression model is given at bottom. Positive correlations are in black; negative are in red. Single correlations with *rho* > 0.447 (in bold, all with p < 0.0005) account for at least 20 percent of variation; correlations weaker than the cutoff are included for Lichen S (p < 0.006) because they were the two highest correlations found. Correlations between environmental variables with *rho* ≥ 0.775 (at least 60 percent of variation accounted for) indicate those two variables should not be entered into the same regression model. The best overall regression model is included with contributing variables listed in descending order of significance; minor variables (p ≤ 0.05 but usually p ≥ 0.005) are listed in parentheses.

Table A3.7—Sierras/Coast Mountains ecoregion group in the West region

Variable	Range (average ± sd)	Spearman correlations (*rho*) (Bailey's province codes = 261, M261, 262, M262, 263; N = 254; years = 1998–2003)										
		Lichen S	Lat.	Long.	Elev.	Precip.	Max. July temp.	Min. Jan. temp.	NO_3^-	SO_4^{--}	NH_4^+	Tree BA
Lichen S	0 – 45 (average 13.9 ± 8.5 sd)											
Latitude (decimal degrees, S to N)	33.71 – 43.68	—										
Longitude (decimal degrees, W to E)	−124.10 – −116.66	**−0.469**	**−0.659**									
Elevation (m)	37 – 3118 (1240 ± 698)	**−0.474**	—	**0.550**								
Precipitation (mm)	224 – 4052 (1048 ± 587)	—	—	**−0.554**	—							
Max. July temp. (°C)	18.9 – 37.3 (28.9 ± 3.86)	—	—	—	**−0.646**	—						
Min. Jan. temp. (°C)	−12.3 – 4.9 (−2.24 ± 3.78)	—	—	—	**−0.821**	—	**0.559**					
NO_3^- (kg/ha/year)	0.69 – 5.08 (2.21 ± 0.96)	—	**−0.880**	**0.612**	—	—	—	—				
SO_4^{--} (kg/ha/year)	0.18 – 3.33 (1.34 ± 0.57)	—	—	—	**−0.516**	—	—	**0.675**	**0.604**			
NH_4^+ (kg/ha/year)	0.11 – 1.85 (0.70 ± 0.42)	—	**−0.889**	**0.597**	—	—	—	—	**0.948**	**0.540**		
Tree BA (square foot per acre)	1.9 – 568.4 (122.3 ± 94.2)	—	—	—	—	—	—	—	—	—	—	
Percent BA softwoods	0 – 100 percent (68.2 ± 38.9)	—	—	—	**0.694**	—	**−0.544**	**−0.713**	—	**−0.504**	**0.694**	—
Best overall full regression model		**r^2 = 0.293, p < 0.0005: lichen S = 24.938 – 0.067 elev. –5.445 NH_4^+** Lichen S larger lower, with less ammonia air pollution.										

— = cells with dashes indicate correlations weaker than the cutoff; max. = maximum; min. = minimum; sd = standard deviation; lat. = latitude; long. = longitude; elev. = elevation; precip. = precipitation; temp. = temperature; NO_3^- = nitrate; SO_4^{--} = sulfate; NH_4^+ = ammonium; BA = basal area; S = south; N = north; W = west; E = east; m = meter; mm = millimeter; °C = degree Celsius; kg = kilogram; ha = hectare.
Range and intercorrelations of Lichen S plus geography, climate, pollution, and forest structure variables; the best regression model is given at bottom. Positive correlations are in black; negative are in red. Single correlations with *rho* > 0.447 (in bold, all with p < 0.0005) account for at least 20 percent of variation; correlations with Lichen S stronger than this cutoff suggest potential for an indicator. Correlations between environmental variables with *rho* ≥ 0.775 (at least 60 percent of variation accounted for) indicate those two variables should not be entered into the same regression model. The best overall regression model is included with contributing variables listed in descending order of significance; minor variables (p ≤ 0.05 but usually p ≥ 0.005) are listed in parentheses.

Table A3.8—Northern Rockies ecoregion group in West region

Variable	Range (average ± sd)	Spearman correlations (*rho*)	(Bailey's province codes = M332, M333; N = 235; years = 1996–2005)									
		Lichen S	Lat.	Long.	Elev.	Precip.	Max. July temp.	Min. Jan. temp.	NO_3^-	SO_4^{--}	NH_4^+	Tree BA
Lichen S	2 – 34 (average 14.7 ± 7.4 sd)											
Latitude (decimal degrees, S to N)	43.42 – 48.96	**0.531**										
Longitude (decimal degrees, W to E)	−120.84 – −109.48	**−0.533**	—									
Elevation (m)	497 – 2953 (1525 ± 527)	**−0.657**	**−0.652**	**0.545**								
Precipitation (mm)	316 – 2153 (850 ± 311)	—	—	—	—							
Max. July temp. (°C)	17.8 – 30.5 (24.7 ± 2.47)	—	—	—	**−0.649**	**−0.515**						
Min. Jan. temp. (°C)	−15.4 – −2.8 (−9.3 ± 2.68)	**0.450**	—	**−0.620**	**−0.636**	—	—					
NO_3^- (kg/ha/year)	0.38 – 3.49 (2.08 ± 0.62)	**0.487**	**0.773**	—	**−0.738**	—	—	—				
SO_4^{--} (kg/ha/year)	0.21 – 3.25 (1.32 ± 0.69)	**0.568**	**0.687**	**−0.499**	**−0.846**	—	**0.568**	**0.508**	**0.904**			
NH_4^+ (kg/ha/year)	0.00 – 1.09 (0.37 ± 0.23)	—	—	—	—	—	**0.464**	—	**0.601**	**0.503**		
Tree BA (square foot per acre)	4.0 – 340.2 (98.4 ± 64.3)	—	—	—	—	—	—	—	—	—	—	
Percent BA softwoods	0 – 100 percent (97.2 ± 12.5)	—	—	—	—	—	—	—	—	—	—	—
Best overall full regression model		**r^2 = 0.463, p < 0.0005: lichen S = –167.956 –1.124 long. –0.004 elev. + 1.274 lat.** Lichen S larger more west, lower, more north.										

— = cells with dashes indicate correlations weaker than the cutoff; max. = maximum; min. = minimum; sd = standard deviation; lat. = latitude; long. = longitude; elev. = elevation; precip. = precipitation; temp. = temperature; NO_3^- = nitrate; SO_4^{--} = sulfate; NH_4^+ = ammonium; BA = basal area; S = south; N = north; W = west; E = east; m = meter; mm = millimeter; °C = degree Celsius; kg = kilogram; ha = hectare. Range and intercorrelations of Lichen S plus geography, climate, pollution, and forest structure variables; the best regression model is given at bottom. Positive correlations are in black; negative are in red. Single correlations with *rho* > 0.447 (in bold, all with p < 0.0005) account for at least 20 percent of variation; correlations with Lichen S stronger than this cutoff suggest potential for an indicator. Correlations between environmental variables with *rho* ≥ 0.775 (at least 60 percent of variation accounted for) indicate those two variables should not be entered into the same regression model. The best overall regression model is included with contributing variables listed in descending order of significance; minor variables (p ≤ 0.05 but usually p ≥ 0.005) are listed in parentheses.

Table A3.9—Southern Rockies/Great Basin Mountains ecoregion group in the West region

Variable	Range (average ± sd)	Spearman correlations (*rho*) (Bailey's province codes = M331, M341; N = 324; years = 1994–2005)										
		Lichen S	Lat.	Long.	Elev.	Precip.	Max. July temp.	Min. Jan. temp.	NO_3^-	SO_4^{--}	NH_4^+	Tree BA
Lichen S	0 – 31 (average 6.8 ± 3.7 sd)											
Latitude (decimal degrees, S to N)	37.01 – 45.42	—										
Longitude (decimal degrees, W to E)	–116.86 – –104.44	**0.473**	—									
Elevation (m)	1585 – 3740 (2552 ± 426)	—	—	—								
Precipitation (mm)	230 – 1495 (616 ± 239)	—	—	—	**0.478**							
Max. July temp. (°C)	15.7 – 33.2 (24.1 ± 3.58)	—	—	—	**–0.800**	**–0.681**						
Min. Jan. temp. (°C)	–15.4 – –2.8 (–9.29 ± 2.68)	—	—	—	**–0.546**	**–0.488**	**0.611**					
NO_3^- (kg/ha/year)	1.87 – 5.90 (3.56 ± 0.90)	—	**–0.467**	**0.746**	**0.473**	—	—	—				
SO_4^{--} (kg/ha/year)	1.14 – 3.04 (2.00 ± 0.47)	0.414	—	**0.805**	**0.448**	—	—	—	**0.949**			
NH_4^+ (kg/ha/year)	0.05 – 2.14 (0.77 ± 0.32)	—	—	—	—	—	—	—	—	—		
Tree BA (square foot per acre)	1.5 – 361.5 (94.0 ± 63.4)	—	—	—	—	—	—	—	—	—	—	
Percent BA softwoods	0 – 100 percent (84.8 ± 31.1)	—	—	—	—	—	—	—	—	—	—	—
Best overall full regression model		**r^2 = 0.223, p < 0.0005: lichen S = 52.959 + 0.443 long. (+ 0.614 NO_3^-)** Lichen S larger more east (with more acidic air pollution).										

— = cells with dashes indicate correlations weaker than the cutoff; max. = maximum; min. = minimum; sd = standard deviation; lat. = latitude; long. = longitude; elev. = elevation; precip. = precipitation; temp. = temperature; NO_3^- = nitrate; SO_4^{--} = sulfate; NH_4^+ = ammonium; BA = basal area; S = south; N = north; W = west; E = east; m = meter; mm = millimeter; °C = degree Celsius; kg = kilogram; ha = hectare. Range and intercorrelations of Lichen S plus geography, climate, pollution, and forest structure variables; the best regression model is given at bottom. Positive correlations are in black; negative are in red. Single correlations with *rho* > 0.447 (in bold, all with p < 0.0005) account for at least 20 percent of variation; one correlation weaker than the cutoff is included for lichen S (p < 0.0009) because it is the second highest correlation found. Correlations between environmental variables with *rho* ≥ 0.775 (at least 60 percent of variation accounted for) indicate those two variables should not be entered into the same regression model. The best overall regression model is included with contributing variables listed in descending order of significance; minor variables (p ≤ 0.05 but usually p ≥ 0.005) are listed in parentheses.

Table A3.10—Great Basin Lowlands ecoregion group in the West region

		Spearman correlations (*rho*)	(Bailey's province codes = 341, 342; N = 143; years = 1994–2005)									
Variable	Range (average ± sd)	Lichen S	Lat.	Long.	Elev.	Precip.	Max. July temp.	Min. Jan. temp.	NO_3^-	SO_4^{--}	NH_4^+	Tree BA
Lichen S	0 – 27 (average 5.5 ± 4.5 sd)											
Latitude (decimal degrees, S to N)	36.96 – 48.16	**0.541**										
Longitude (decimal degrees, W to E)	−121.40 – −106.32	—	—									
Elevation (m)	528 – 2823 (1867 ± 462)	−0.405	**−0.628**	**0.462**								
Precipitation (mm)	171 – 961 (391 ± 139)	—	—	—	—							
Max. July temp. (°C)	19.6 – 34.3 (28.5 ± 2.54)	—	—	—	—	**−0.576**						
Min. Jan. temp. (°C)	−16.2 – −3.5 (−8.88 ± 2.48)	—	—	**−0.733**	—	—	—					
NO_3^- (kg/ha/year)	1.04 – 4.16 (1.57 ± 0.55)	—	**−0.499**	**0.723**	**0.519**	—	—	**−0.453**				
SO_4^{--} (kg/ha/year)	0.21 – 3.31 (1.57 ± 0.55)	—	—	**0.541**	—	—	—	—	**0.757**			
NH_4^+ (kg/ha/year)	0.02 – 1.32 (0.64 ± 0.28)	—	—	**0.524**	—	—	—	—	**0.597**	—		
Tree BA (square foot per acre)	1.8 – 308.6 (70.6 ± 58.7)	—	—	—	—	—	—	—	—	—	—	
Percent BA softwoods	0 – 100 percent (88.5 ± 28.3)	—	—	—	—	—	—	—	—	—	—	—
Best overall full regression model		**r^2 = 0.468, p < 0.0005: Lichen S = −38.103 + 1.049 lat. −5.484 NH_4^+ + 1.783 NO_3^-** Lichen S larger more north, with less ammonia air pollution, with more acidic air pollution.										

— = cells with dashes indicate correlations weaker than the cutoff; max. = maximum; min. = minimum; sd = standard deviation; lat. = latitude; long. = longitude; elev. = elevation; precip. = precipitation; temp. = temperature; NO_3^- = nitrate; SO_4^{--} = sulfate; NH_4^+ = ammonium; BA = basal area; S = south; N = north; W = west; E = east; m = meter; mm = millimeter; °C = degree Celsius; kg = kilogram; ha = hectare. Range and intercorrelations of Lichen S plus geography, climate, pollution, and forest structure variables; the best regression model is given at bottom. Positive correlations are in black; negative are in red. Single correlations with *rho* > 0.447 (in bold, all with p < 0.0005) account for at least 20 percent of variation; one correlation weaker than the cutoff is included for Lichen S (p < 0.0009) because it is the second highest correlation found. Correlations between environmental variables with *rho* ≥ 0.775 (at least 60 percent of variation accounted for) indicate those two variables should not be entered into the same regression model. The best overall regression model is included with contributing variables listed in descending order of significance; minor variables (p ≤ 0.05 but usually p ≥ 0.005) are listed in parentheses.

Table A3.11—Colorado Plateau/Southern Dry Mountains ecoregion group in the West region

		Spearman correlations (*rho*)				(Bailey's province codes = 313, M313; N = 151; years = 1994–2005)						
Variable	Range (average ± sd)	Lichen S	Lat.	Long.	Elev.	Precip.	Max. July temp.	Min. Jan. temp.	NO_3^-	SO_4^{--}	NH_4^+	Tree BA
Lichen S	0 – 14 (average 6.1 ± 2.7 sd)											
Latitude (decimal degrees, S to N)	33.08 – 37.99	—										
Longitude (decimal degrees, W to E)	–113.81 – –106.95	—	—									
Elevation (m)	1088 – 2800 (1954 ± 356)	**0.460**	—	—								
Precipitation (mm)	183 – 826 (451 ± 152)	**0.545**	**–0.532**	—	—							
Max. July temp. (°C)	23.5 – 38.3 (30.3 ± 3.04)	**–0.495**	—	—	**–0.927**	**0.578**						
Min. Jan. temp. (°C)	–14.3 – 1.5 (–7.54 ± 2.93)	—	—	**–0.540**	**–0.750**	—	**0.650**					
NO_3^- (kg/ha/year)	2.41 – 4.40 (3.22 ± 0.36)	**0.513**	—	**0.492**	**0.861**	—	**–0.808**	**–0.712**				
SO_4^{--} (kg/ha/year)	1.39 – 2.87 (2.03 ± 0.29)	**0.489**	—	**0.697**	**0.629**	—	**–0.569**	**–0.564**	**0.849**			
NH_4^+ (kg/ha/year)	0.29 – 0.86 (0.63 ± 0.10)	—	—	—	—	—	—	—	—	—		
Tree BA (square foot per acre)	2.3 – 255.9 (83.0 ± 56.0)	—	—	—	—	—	—	—	—	—	—	
Percent BA softwoods	0 – 100 percent (88.4 ± 25.4)	—	—	—	—	**–0.543**	—	—	—	—	—	—
Best overall full regression model		**r^2 = 0.356, p < 0.0005: lichen S = 42.393 + 0.007 precip. + 0.403 long. + 1.678 NO_3^-** Lichen S larger wetter, more east, with more acidic air pollution.										

— = cells with dashes indicate correlations weaker than the cutoff; max. = maximum; min. = minimum; sd = standard deviation; lat. = latitude; long. = longitude; elev. = elevation; precip. = precipitation; temp. = temperature; NO_3^- = nitrate; SO_4^{--} = sulfate; NH_4^+ = ammonium; BA = basal area; S = south; N = north; W = west; E = east; m = meter; mm = millimeter; °C = degree Celsius; kg = kilogram; ha = hectare. Range and intercorrelations of Lichen S plus geography, climate, pollution, and forest structure variables; the best regression model is given at bottom. Positive correlations are in black; negative are in red. Single correlations with *rho* > 0.447 (in bold, all with p < 0.0005) account for at least 20 percent of variation; correlations with Lichen S stronger than this cutoff suggest potential for an indicator. Correlations between environmental variables with *rho* ≥ 0.775 (at least 60 percent of variation accounted for) indicate those two variables should not be entered into the same regression model. The best overall regression model is included with contributing variables listed in descending order of significance; minor variables (p ≤ 0.05 but usually p ≥ 0.005) are listed in parentheses.

Table A3.12—Arid Southwest ecoregion group in the West region

		Spearman correlations (*rho*)	(Bailey's province codes = 321, 322; N = 39; years = 1999–2005)									
Variable	Range (average ± sd)	Lichen S	Lat.	Long.	Elev.	Precip.	Max. July temp.	Min. Jan. temp.	NO_3^-	SO_4^{--}	NH_4^+	Tree BA
Lichen S	0 – 13 (average 5.0 ± 2.7 sd)											
Latitude (decimal degrees, S to N)	31.42 – 36.70	—										
Longitude (decimal degrees, W to E)	–115.67 – –109.22	—	**–0.571**									
Elevation (m)	844 – 2448 (1544 ± 398)	**0.607**	—	—								
Precipitation (mm)	257 – 669 (445 ± 116)	**0.555**	**–0.467**	—	**0.499**							
Max. July temp. (°C)	27.1 – 37.6 (32.6 ± 2.40)	**–0.591**	—	—	**–0.891**	**–0.630**						
Min. Jan. temp. (°C)	–7.1 – 2.8 (–1.95 ± 2.46)	—	**–0.758**	—	—	—	—					
NO_3^- (kg/ha/year)	2.07 – 3.94 (3.04 ± 0.42)	—	—	—	**0.631**	**0.618**	**–0.643**	—				
SO_4^{--} (kg/ha/year)	1.41 – 2.75 (2.07 ± 0.38)	—	**–0.876**	**0.781**	—	**0.527**	—	—	**0.643**			
NH_4^+ (kg/ha/year)	0.42 – 0.90 (0.69 ± 0.09)	—	—	—	—	—	—	—	**0.449**	—		
Tree BA (square foot per acre)	4.7 – 160.0 (54.1 ± 40.4)	**0.555**	—	—	**0.609**	**0.519**	**–0.603**	—	—	—	—	
Percent BA softwoods	0 – 100 percent (42.8 ± 44.3)	—	**0.720**	**–0.533**	—	—	—	**–0.464**	—	**–0.627**	—	—
Best overall full regression model		**r^2 = 0.593, p < 0.0005: lichen S = 25.626 + 0.020 precip. + 1.364 lat. (+ 0.415 long.)** Lichen S larger wetter, more north, (more east).										

— = cells with dashes indicate correlations weaker than the cutoff; max. = maximum; min. = minimum; sd = standard deviation; lat. = latitude; long. = longitude; elev. = elevation; precip. = precipitation; temp. = temperature; NO_3^- = nitrate; SO_4^{--} = sulfate; NH_4^+ = ammonium; BA = basal area; S = south; N = north; W = west; E = east; m = meter; mm = millimeter; °C = degree Celsius; kg = kilogram; ha = hectare. Range and intercorrelations of Lichen S plus geography, climate, pollution, and forest structure variables; the best regression model is given at bottom. Positive correlations are in black; negative are in red. However correlations reported here with *rho* > 0.447 (in bold) have p < 0.005 because there are so few plots in this group; correlations with Lichen S stronger than this cutoff suggest potential for an indicator. Correlations between environmental variables with *rho* ≥ 0.775 (at least 60 percent of variation accounted for) indicate those two variables should not be entered into the same regression model. The best overall regression model is included with contributing variables listed in descending order of significance; minor variables (p ≤ 0.05 but usually p ≥ 0.005) are listed in parentheses.