United States
Department of
Agriculture

Forest Service

Pacific Northwest
Research Station

General Technical
Report
PNW-GTR-807

September 2010

Development of Lichen Response Indexes Using a Regional Gradient Modeling Approach for Large-Scale Monitoring of Forests

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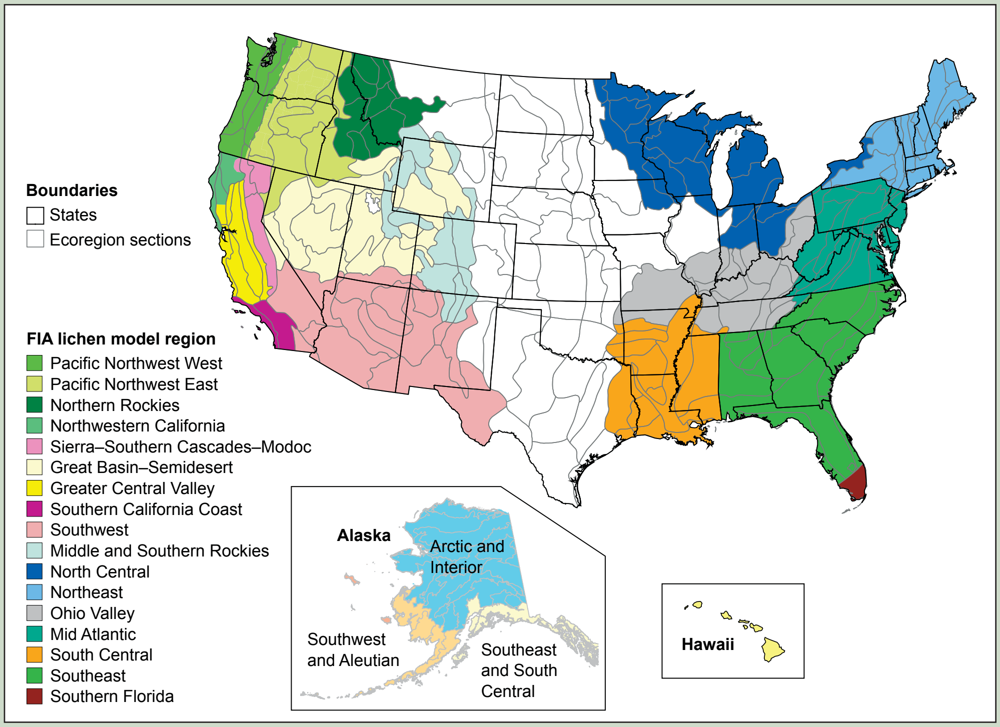

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This work was performed under cooperative agreements SRS 06-CA-11330145-079 and SRS 09-CA-11330145-101 with the Forest Inventory and Analysis Program for the senior author. The second author is a contractor under the first agreement.

Abstract

Will-Wolf, Susan; Neitlich, Peter. 2010. Development of lichen response indexes using a regional gradient modeling approach for large-scale monitoring of forests. Gen. Tech. Rep. PNW-GTR-807. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 65 p.

Development of a regional lichen gradient model from community data is a powerful tool to derive lichen indexes of response to environmental factors for large-scale and long-term monitoring of forest ecosystems. The Forest Inventory and Analysis (FIA) Program of the U.S. Department of Agriculture Forest Service includes lichens in its national inventory of forests of the United States, to help monitor the status of forested ecosystems. Development of a model for a specific region to calculate lichen response indexes that are correlated with air quality and major climate factors, and are also independent of each other, is a critical step in achieving program goals. These indexes are the primary lichen bioindicators used in FIA for assessing regional patterns and monitoring trends of lichen response to environment over time. This general approach is also applicable to other monitoring efforts. A first step in the modeling process is to identify an appropriate geographic region for a model. Unconstrained ordination alone, or combined with indicator species analysis followed by regression analysis, are two approaches borrowed from plant ecology that have been shown to generate successful regional lichen gradient models. Calculation of lichen response indexes for new plots not part of the original model is necessary to support long-term monitoring. We explain the rationale for recommended approaches, describe in detail the recommended steps in the model-development process, and explain how to document and evaluate results, all to support successful application of a model for monitoring. A template is included for documenting a model and archiving all products necessary to understand and apply it, as is required for each FIA model.

Keywords: Air pollution, air quality, biomonitor, climate, environmental response index, forest health, lichen, community, ordination.

Summary

Development of a regional lichen gradient model from community data is a powerful tool to derive lichen indexes of response to environmental factors for large-scale and long-term monitoring of forest ecosystems. The Forest Inventory and Analysis (FIA) Program of the U.S. Department of Agriculture Forest Service includes lichens in its national inventory of forests of the United States for large-scale monitoring of the status of forested ecosystems with tight budget constraints. The purpose of the FIA Program is to inventory forests of the Nation to facilitate responsible use, conservation, and maintenance of function for forested ecosystems. A critical step to achieve program goals for the lichen indicator is development of lichen response indexes for a region that are correlated with air quality and major climate factors, and are also independent of each other. These indexes are the primary lichen bioindicators used in FIA for assessing regional patterns and monitoring trends over time. This general approach is also applicable to other monitoring efforts.

A first step in the modeling process is to identify an appropriate geographic region for a model. A region must be large to support models that will remain useful for many years and response indexes that are sensitive primarily to large-scale environmental factors. Upper size is constrained by the need to limit the variation of the sampled lichen communities across a region to support a stable model. A region must be compact to allow linkage of change in lichen response indexes to lichen dispersal.

Unconstrained ordination alone, or combined with indicator species analysis followed by regression analysis, are two approaches borrowed from plant ecology that have been shown to generate successful regional lichen gradient models. Other analysis approaches that generate lichen response indexes are also acceptable if they satisfy the requirements for a successful gradient model. These requirements are explained in detail both to set benchmarks during model development and to support appropriate evaluation of a completed model. Calculation of lichen response indexes for new plots not part of the original model is necessary to support long-term monitoring. One should always first try to develop a single ordination model. Such a model has the possibility to generate all needed lichen response indexes from one analysis procedure. A hybrid model requiring several separate analyses has been successful for several regions where independent lichen air quality and climate response indexes could not be developed from a single ordination model.

We explain the rationale for the recommended approaches, describe in detail steps in the model development process for the two recommended approaches, and explain how to document and evaluate results, all to support successful application

of a model for monitoring. Many decisions must be made about appropriate data, data treatment, and data analysis at every step in the development of a model. These decisions differ depending on the characteristics of both the region to which the model will apply and the data to be used. Each decision has an impact on the quality of the final model, and no one set of decisions can be recommended in general. Evaluation of a model is required to establish the accuracy and precision of the lichen response indexes derived from the model; this precision in turn sets the limits on how large changes must be before they can be detected by monitoring with the indexes. A template is included for documenting a model and archiving all products necessary to understand and apply it, as is required for each FIA model and is critical for application of a model in any other situation as well.

We have provided in this document both a general overview of the usefulness of this approach for monitoring forest health with lichens, and detailed instructions for each step in developing and applying such a model in a monitoring program. The detailed explanations and justifications provided at each step also support application of the principles to achieve similar goals with new approaches or analytical techniques and in novel situations.

Contents

Introduction

The study of lichen communities in forest ecosystems allows researchers to address several key questions concerning natural resources: biodiversity, response to climate and air pollution, ability to provide ecosystem services, and sustainability of timber production (McCune 2000). Lichens are strong indicators of air pollution and are also indicators for forest response to other environmental factors such as climate (Bates and Farmer 1992, Nash 2008). Lichens have little economic value, so their responses are not confounded by deliberate human management. Monitoring the quality and sustainability of ecosystems with lichens has occurred worldwide for many different purposes, using many different methods, with many different constraints, and at many different spatial scales (Nimis et al. 2002).

The Forest Inventory and Analysis (FIA) Program of the U.S. Department of Agriculture Forest Service (USDA FS) monitors forests to facilitate responsible use, conservation, and maintenance of function for forested ecosystems. The FIA Program includes lichens in its surveys of forests on permanent plots across the Nation to inventory status (one-time assessment) and monitor trends (repeated assessment) in response of forests to environmental factors over time within quite strict budgetary constraints. It is the most extensive lichen monitoring program in the world, and is an excellent model for a large-scale program. As the only biological indicator in the FIA Program that is not a vascular plant, the lichen indicator is to some extent a potential surrogate for the many nonrepresented members of forest communities (for instance birds, insects, mycorrhizal fungi) that are also not vascular plants. Field data collection and analysis protocols for the FIA Program have been designed to address program purposes within program constraints (McCune 2000, Will-Wolf 2010).

Three major categories of assessment questions have been identified so far for lichens in the FIA Program: air quality, climate, and biodiversity. Questions about biodiversity can be addressed with relatively simple summaries of field data, but more complicated analyses are needed to evaluate response to environmental factors. Development of a multivariate lichen response model from community data is a powerful tool to indicate forest response to multiple environmental factors in such situations. Lichen response indexes derived from such a model are single numbers that indicate the response of lichens at a single site to particular defined environmental factors, as compared with response at other sites in the same region.

A critical step in the implementation of the lichen indicator in FIA is the development of such lichen response indexes from an "FIA lichen gradient model" for a geographically defined "FIA lichen model region." The two phrases in quotes are used throughout this document with very specific meanings (see glossary). The

Development of a lichen gradient model is a critical step in implementation.

goal of such a lichen gradient model is to develop lichen indexes that represent the response of the lichen community to the wide range of values for each important regional environmental factor (a response "gradient" for each factor) of interest to FIA for forest resource assessment (also see Jovan 2008 for an introduction to the model development process). Each lichen response gradient needs to be independent of all other lichen response gradients defined for that model. This powerful approach to developing biotic response indexes uses all lichen community data, so it is not as limited by idiosyncratic species distributions as are approaches that rely on response of a few species. These lichen response indexes are the primary lichen bioindicators used in FIA for assessing regional patterns and monitoring trends over time.

The primary target audience for this document is researchers interested in developing a lichen gradient model for the FIA Program. Researchers and data analysts, both inside and outside the FIA Program, who wish to improve their understanding of the rationale for FIA lichen response indexes should find this document helpful as well. Other researchers who want to assess patterns and monitor long-term trends for any biological community will also find this approach useful, especially in situations where monitoring of large and diverse areas must be accomplished within tight budget constraints. The rationale and methods for each step in developing a model for the FIA Program are described in detail to illustrate the importance of each decision along the way for ensuring the scientific validity and usefulness of the final product.

Authors assume at least basic understanding by the reader of general plant community ecology theory and practice, in particular the use of multivariate techniques for data analysis and analysis of plant community response to environmental gradients (see glossary). Reference to this document is **not** necessary to use lichen response indexes for the assessment of forest ecosystem patterns and trends. An appendix gives a template for model documentation that includes all necessary information for calculation of lichen response indexes from field data using a completed lichen gradient model. A glossary includes definitions of the most important words and phrases used in this document. Other USDA FS publications focus on assessment of the quality of FIA lichen data (Patterson et al., in press) and guidelines for standard analysis of FIA lichen data (Will-Wolf 2010).

Background and History of the Lichen Indicator

A lichen is a close association (symbiosis) of a fungus with photosynthesizing algae or cyanobacteria; this association is named for the fungus and functions as a discrete individual (an honorary "plant"). A lichen community is an assemblage of these "species" of lichens (Nash 2008). The sensitivity of lichens to air pollution, the response of lichens and lichen communities to climate, and the use of lichens as indicators are well-documented in scientific literature (McCune 2000, Muir and McCune 1988, Nimis et al. 2002, Richardson 1988). The protocols adopted for lichen sampling and data management in the FIA Program are designed and standardized to enhance ability to accurately assess patterns and monitor trends regionwide and at larger geographic scales. Data are less suitable to assess precisely the response of lichens to local and within-plot factors such as stand age, tree species composition, and recent disturbance history (Will-Wolf 2010). The precision of FIA lichen indicator data is constrained by requirements for protocols to be both affordable and consistently applied for monitoring thousands of plots across the entire Nation into the indefinite future (McCune 2000; Smith et al. 1993; Will-Wolf 1988; Will-Wolf et al. 2002b, 2004).

For the purposes of the FIA Program, the lichen sample population is restricted to macrolichens (leafy, tufted, or hanging lichens) found on living or standing dead woody substrates, including both trunks and branches of trees and shrubs. Only standing and recently fallen woody substrates are included, thereby standardizing the measurements to a class of substrates that can be found at all forested sites. Lichens are collected and assigned abundance scores by a trained (Will-Wolf 2007, Will-Wolf and Neitlich 2007) nonspecialist crew person in a time-constrained (up to 2 hours) search of an FIA plot following standard protocols (USDA FS 2004, 2010b), then are identified by a lichen specialist also following standard protocols (Will-Wolf 2009). These plot data collection protocols and low plot density together set limits on the precision achievable with lichen indicator data.

The lichen community indicator is implemented in the FIA Program in two phases (fig. 1).

1. In the calibration phase, a lichen gradient model is developed for lichen communities of a particular region and is calibrated to isolate and describe air quality, climate, and other gradients important for resource assessment. Lichen indexes of response to the described gradients are the products.
2. In the application phase, the model is used to calculate, for newly sampled plots, values for the lichen response indexes developed in the calibration phase. These indexes are the primary tools used to answer resource assessment questions concerning the spatial patterns and trends in the condition of our forest resources, as described above.

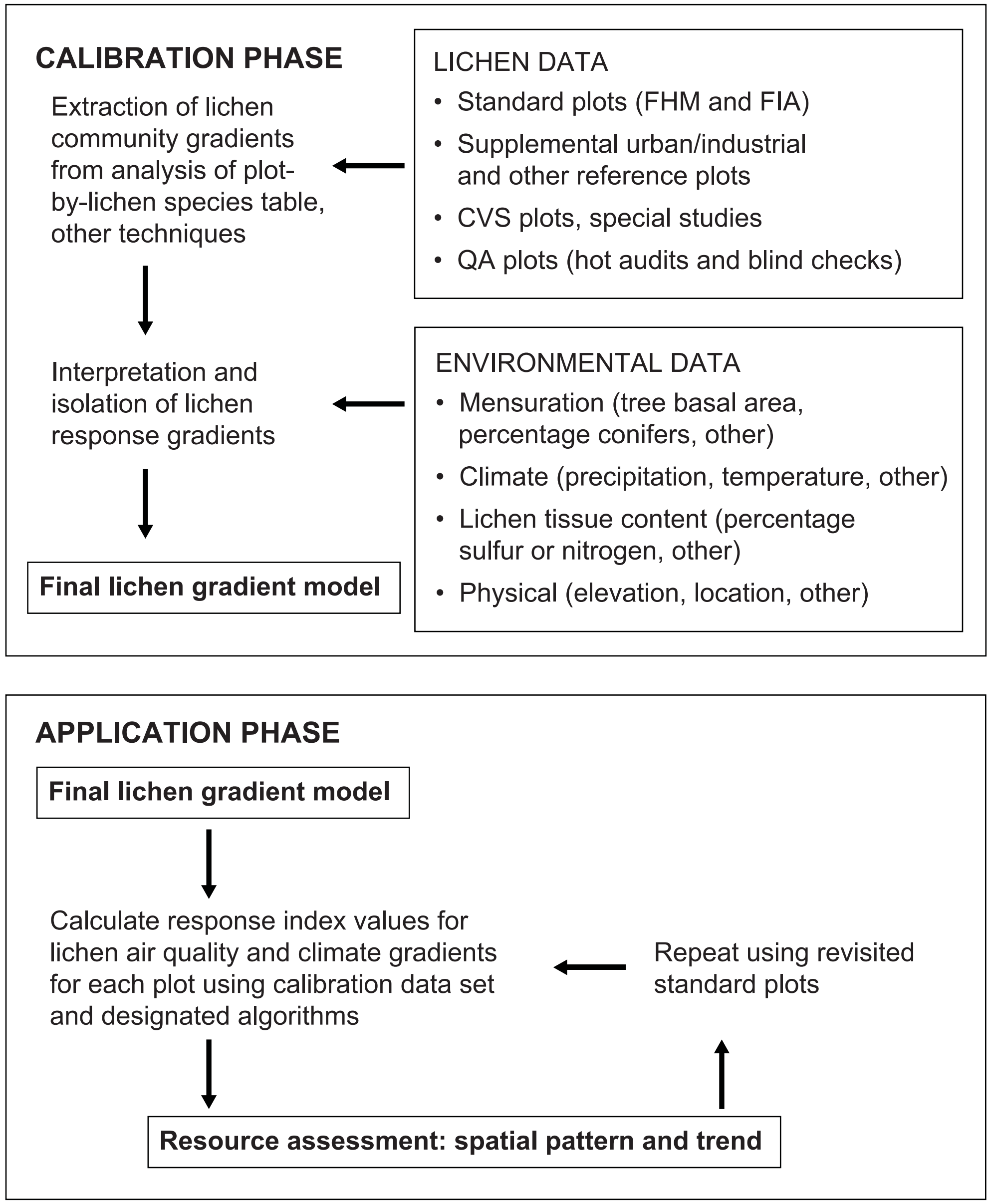

Figure 1—The two phases of implementation of the Forest Inventory and Analysis (FIA) lichen indicator–During the calibration phase, standard FIA plot data and other data are collected and a lichen gradient model is developed. During the application phase, lichen response indexes are calculated for new plots from the lichen gradient model based on lichen data collected for each plot. These plot indexes are used to analyze patterns across space and trends over time related to the defined lichen response gradients. Other abbreviations: CVS = U.S. Department of Agriculture Forest Service national forest current vegetation survey, FHM = Forest Health Monitoring Program, QA = quality assessment and quality assurance. Adapted from McCune et al. (1994).

The first lichen gradient model was published in 1997 (McCune et al. 1997a, 1997b). Thus far, four more models have been completed and four are in progress. Only after such a model has been completed and implemented can a region move into the application phase (fig. 1).

Several lichen parameters can be calculated from FIA lichen data while the geographic area is still in the calibration phase (Will-Wolf 2010). The lichen species richness index is the total number of species recorded on an FIA plot. The total number of species in the data set for a specific geographic region represents regional diversity. The rate of species replacement, or turnover, across a specific geographic region can be calculated as regional diversity divided by average plot species richness index. All of these parameters are based on the count of lichen species at an FIA plot.

The lichen indicator was developed in 1990–1992 for the Environmental Monitoring and Assessment Program, was implemented in the USDA FS Forest Health Monitoring Program 1993–1999, and has been part of the FIA Program since 2000. Field and laboratory protocols for the lichen indicator have not changed; data from all years are fully compatible. The basic guidelines for analysis of lichen indicator data also remain unchanged since the beginning. Data from the first round of plot sampling are used to assess the initial condition and patterns of lichen communities in a region. Data from repeat samples of the same plots are used over time to monitor change in condition and in pattern of response to air quality, climate, and other environmental factors.

Assessment Questions

The general rationale behind key FIA lichen indicator assessment questions is addressed in more detail elsewhere (Geiser and Neitlich 2007; Jovan 2008; McCune 2000; McCune et al. 1997b; Will-Wolf 2010). In this document we discuss the major identified assessment questions (air quality, climate, and biodiversity) specifically as they relate to the development of lichen gradient models. Originally (McCune 2000; McCune et al. 1994, 1997b) the FIA lichen indicator's primary usefulness to the program was seen as estimating response to sulfur (S)- and nitrogen (N)-based air pollution. The purpose of a lichen gradient model was to develop indexes of response to air pollution statistically independent of response to climate. More recently, it has become apparent that lichen climate and biodiversity indexes are as important as lichen air quality indexes for assessing and monitoring forest health in the FIA Program (Jovan 2008, Will-Wolf et al. 2002a). We suggest guidelines for relating additional categories of potentially interesting assessment questions to completed lichen gradient models.

Lichen gradient models address assessment questions.

Air quality—

Does regional air quality affect our forests? Have the effects changed? If so, is air quality improving or deteriorating? In what areas is it changing?

Addressing these air quality assessment questions in the FIA Program with lichen data reflects lichen response primarily to S and N compounds in air pollution. A lichen air quality index requires the development of a regional lichen gradient model to quantify lichen response. Historically research has focused on lichen response to airborne acidic N and S compounds (often abbreviated in literature as NO_x^- and SO_x^-) and heavy metals from industry, traffic, and urban centers (Hawksworth and Rose 1976, Richardson 1998, Smith et al. 1993, van Dobben 1993). More recently, lichen communities have been shown to respond in different ways to ammonia (NH_4^+) and other usually alkaline N compounds that come primarily from agriculture and animal husbandry, and also from incomplete combustion of gasoline engines (Fenn et al. 2003a; Jovan and McCune 2005, 2006; Sillett and Neitlich 1996; van Dobben and ter Braak 1998). Related research (summarized in Jovan 2008) has identified two possible air pollution effects from alkaline N air pollution: increased pH that affects both lichens and substrate chemistry (only indirectly related to the chemical elements involved), and direct fertilizing effects of N compounds. Thus air pollution effects on lichens can have multiple sources with effects sometimes difficult to distinguish (Jovan 2008). This has made interpretation of lichen response to air pollution more complicated. The interpretation by McCune et al. (1997b) that their lichen air quality index for the Southeast Lichen Gradient Model represents response primarily to acidic urban/industrial pollution is supported by regional air quality data (NADP 2009) and more recent studies in a partially overlapping region (Will-Wolf et al. 2006). Geiser and Neitlich (2007) concluded that although all three potential types of pollution were present, acidifying pollutants and fertilizing N pollutants (Jovan 2009) were probably the most important factors affecting their lichen air quality index. Jovan and McCune (2005, 2006) concluded that in each of two regions, their lichen air pollution response index was most strongly linked to the combined effects of alkaline and fertilizing N compounds. For each FIA lichen gradient model, in the future, it will be important to consider all of these potential pollution sources and their effects on lichen response, and distinguish them to the extent possible as research progresses.

Climate—

Are changes in climate affecting our forests? If so, how do we characterize the effects? In what areas is it changing?

Changing climate is an ever-more-likely prospect whose impact on lichens and forests needs to be assessed (Bates and Farmer 1992, Ellis et al. 2007, Søchting 2004). The process for development of an FIA lichen gradient model was designed from the beginning to produce independent indexes for lichen response to climate and to air pollution (McCune et al. 1994, 1997b). Current climate response indexes for different lichen model regions differ in number and in the climate factors to which they are related; this is expected to be the case for future models as well. The McCune et al. (1997b) climate response index was correlated with temperature and elevation; the Geiser and Neitlich (2007) climate response index was correlated with temperature, moisture, and elevation. Jovan and McCune (2004) developed two independent indexes of lichen response to climate: one correlated with temperature and elevation, the other correlated with moisture. Will-Wolf et al. (in press) found that the FIA lichen species richness index was variously correlated with different climate factors in different regions of the coterminous United States, illustrating the variety of responses to climate exhibited by lichen communities of different areas.

Biodiversity—

Is the lichen component of biodiversity changing through time? What environmental drivers seem to be most strongly linked to patterns and changes in lichen biodiversity?

Lichens contribute a substantial proportion of the visible species of many forests and they participate in ecosystem processes such as nutrient cycling and species interactions in ecosystems (Nash 2008, Sharnoff and Rosentreter 2008). The FIA lichen species richness index tracks one aspect of lichen diversity patterns, is currently the only defined lichen biodiversity index, and does not require a lichen gradient model for its calculation. Species composition and abundance in lichen communities are not used directly to assess lichen diversity patterns; they are included in lichen air quality and climate indexes that require a lichen gradient model for their calculation. The model-derived lichen response indexes thus indirectly provide insights into potential causes for variation in lichen biodiversity and changes over time. Additional components of lichen biodiversity may emerge as products of the development of a lichen gradient model.

Other categories of assessment questions—
Other categories of assessment questions applicable to the lichen indicator are expected to arise in the future. For example one category of questions currently being investigated concerns the effect of nearby land cover on the FIA lichen species richness index across the conterminous United States. Preliminary findings suggest that for some large geographic areas (equal to or larger than FIA lichen model regions), nearby land use is correlated with lichen species richness index independent of air quality and climate factors, an interesting and unexpected finding (Will-Wolf, unpublished data). Such a finding, if confirmed, would suggest the need to consider landscape pattern factors (for example, the percentage of nearby land in forest) along with air quality and climate factors in the development of a lichen gradient model for some regions. Some correlation between a lichen air quality index and a tree health index for part of the Eastern Broadleaf Forest ecoregion has been found in one pilot evaluation (Will-Wolf and Jovan 2008). Possible linkage of a lichen land use response index with a tree health index would be of equal interest to FIA for forest health assessment. Linkage between a lichen response index and landscape pattern at large geographic scales is more likely to be found in the Eastern United States, where climate variation is relatively low and much of the landscape has been strongly modified by human activity.

For another example, Geiser and Neitlich (2007) identified one independent gradient in lichen species composition correlated with the relative abundance of N-fixing lichens in the community. This lichen response is probably related to pollution in some way, but it was uncorrelated with any of the authors' environmental or forest structure variables, so it remains undefined. A lichen biodiversity response index could be calculated for that model, but its usefulness for biomonitoring will be limited until it can be linked to one or more potential causal factors.

Most ecological studies are able to identify no more than three to four mutually independent environmental factors correlated with variation in community composition. This constraint applies to the lichen gradient modeling approach as well. Modeling approaches such as partial correlation or multiple regression can be used to explain the relative correlation of several additional environmental factors with a particular lichen response index at the scale of an entire lichen model region. Supplemental intensive studies designed to isolate the effects of these other environmental factors would be needed to assess the relative contribution of such additional variables to explaining lichen response indexes.

Lichen Community Gradient Models

The goal of each lichen gradient model is to provide indexes for lichen community response to air quality, to climate, and possibly to other environmental factors that vary at the scale of large regions. We use the term "model" in this document to mean a template for defining and calculating indexes of response to environmental factors of interest from the lichen species composition of a field plot. It is useful for each index developed from such a model to be as insensitive as possible to variation in local site factors such as stand structure and disturbance history, to avoid interfering with the desired goal of tracking large-scale patterns.

Rationale for Approach

The gradient model approach is particularly powerful for large-scale assessment of forest health with lichens and is required in the FIA Program for definitive assignment to plots of indexes representing responses by lichens to important regional environmental factors. The lichen species richness index (that does not require a model) usually relates to many factors that affect lichen communities, so interpreting how a change in this index relates to particular assessment questions is difficult without a gradient model (Will-Wolf 2010, Will-Wolf et al. 2006). For example, McCune et al. (1997b) found that the lichen species richness index for the Southeast Lichen Model Region was equally correlated with air quality and climate. Derived indexes representing response of lichen community **composition** that are correlated with individual environmental factors, on the other hand, are much more reliable indicators of the influences of those factors. One requirement for indexes of lichen response defined from a gradient model for the FIA Program is that they be independent of one another, so interpretation of response to one factor is not confounded by response to a different factor. Variations in these indexes across a region reflect the initial state of the resource with respect to assessment questions, and changes in these indexes over time reflect trends related to assessment questions.

The modeling approaches recommended here involve use of several common and well-tested analysis techniques applied to lichen species composition at a plot. Indexes based on most to all species at a plot (rather than a few preselected individual species) are preferred to ensure they can be calculated for a majority of FIA plots. Given the nature of FIA lichen data (Will-Wolf 2010) and variation across FIA lichen model regions, even common lichen species are usually found at no more than 50 to 70 percent of FIA plots in a lichen model region (Geiser and Neitlich 2007; Jovan and McCune 2005, 2006; McCune et al. 1997b; Will-Wolf et al. 2006).

Multivariate analysis is recommended to develop a lichen gradient model.

A multivariate lichen community analysis method should be the first model-building approach tried for two reasons: (1) it is possible to develop all necessary independent gradients and lichen response indexes from a single analysis, and (2) this modeling approach uses information for all the lichen species found at a plot. Unconstrained ordination is, for this purpose and for FIA Program needs, the most appropriate of several multivariate analysis approaches designed or adapted and currently in common use by ecologists to extract important information from large species-by-plot data tables (Legendre and Legendre 1998, McCune and Grace 2002 [both these references use the terms "ordination," "simple ordination," or "indirect gradient analysis" rather than "unconstrained ordination," contrasting them with "canonical" analysis or "constrained ordination"]; Økland 1996). In unconstrained ordination, the investigator identifies major gradients (ranges) of variation in macrolichen community composition, then compares these community gradients a posteriori with individual environmental factors. Unconstrained ordination is preferred for exploratory analysis and the development of a model. It avoids distortion of community gradients from a priori selection of environmental factors (required for constrained ordination), avoids bias from inclusion of correlated environmental factors, and allows for valid statistical evaluation of correlations between community gradients and environmental factors (McCune 1997b, Økland 1996). These characteristics are critical to unbiased development of lichen response indexes for factors of interest, to ensure indexes are scaled appropriately to response of lichens rather than to convenient measurement scales for environmental factors, and to reliably assign to new plots response index values for the developed gradients. Assigning lichen response indexes to plots not in the original model data set is a critical function to support monitoring, although use of an existing ordination model to do this is not a typical application for multivariate community analysis in plant ecology.

Nonmetric multidimensional scaling (NMS, or NMDS in some recent literature) ordination (Kruskal 1964) is an unconstrained ordination technique that has been preferred by FIA lichen gradient model developers historically because it generates minimal distortion of original patterns compared to other popular unconstrained ordination techniques (Minchin 1987). Other classes of multivariate analysis methods including classification, constrained ordination (including Canonical Correspondence Analysis and Redundancy Analysis), and direct gradient analysis (evaluating variation in species composition along preselected ranges of environmental factors), fail on one or more of the above criteria.

A hybrid modeling approach incorporating different analysis methods for response to different environmental factors may be needed when unconstrained ordination alone does not generate a satisfactory model. For some regions, an ordination model has not successfully extracted a lichen response index for air quality independent of a stronger climate response index. In this case, an alternate approach using indicator species and regression modeling has proved successful to define an independent air pollution response index. Objective, quantitative identification of sets of at least 6 to 10 indicator lichen species (indicators of poor air quality or of some other environmental factor, depending on what is needed) is the first step. The more indicator species that are identified the better, to enhance the liklihood that the final index reflects response to the factor much more than just chance variation in species distributions. Indicator Species Analysis (Dufrêne and Legendre 1997) has thus far been the most successful technique used to quantitatively identify indicators of polluted areas. This can be followed by construction of a regression model using the proportion of indicator species at a plot and the residuals from regression against the primary lichen response factor, to model response to the secondary factor independent from the primary factor.

Program Requirements

The two subsections below present the standards that must be met and the products that must be provided for a lichen gradient model useful in the FIA Program. A model developed using the approaches and techniques described later in this document can meet these standards and support provision of these products. New analysis approaches and techniques that meet these criteria would also be suitable for the FIA Program. The current FIA lichen indicator advisor has the responsibility to determine whether a new lichen gradient model meets all required criteria and is acceptable for use in the program. Many of these criteria would be appropriate for other monitoring programs as well.

Required performance standards—

To meet the goals for the FIA Program, a lichen gradient model must meet the following performance standards:

1. A model must define at least one lichen air quality response index and at least one lichen climate response index independent of each other and of other major environmental factors.
2. There must be an objective and unbiased method for estimating what proportion of variability in lichen community composition is explained by each lichen response index, and for estimating the strength and statistical reliability of the correlation of that index with the relevant environmental factor(s). Correlation of the relevant environmental factor(s) with that index must be strong enough to support the interpretation that the lichen index

represents lichen community response to that environmental factor. The set of indexes (minimum two, No. 1 above) developed from a single NMS lichen gradient model (or other acceptable single model) should account for at least 50 percent of the information in the full model lichen data set, as calculated using standard approaches. For a hybrid model, a reasonable standard is that each index from a hybrid model should account for at least 25 percent of total information in the data set used, as calculated using standard approaches.

3. The numerical values of the derived indexes should be scaled appropriately to the response of lichens (as opposed to convenient measurement scales for environmental factors). For instance, the same magnitude of differences between two index values at the high, middle, and low end of the numerical range of the index should represent approximately equivalent differences in lichen species composition. This simplifies analysis of trends over time. Such equivalent scaling of lichen responses happens automatically with unconstrained ordination; this must be evaluated for other model development techniques.
4. There must be an objective, repeatable, and reliable method to assign lichen response indexes to new plots, and to repeat samples of plots, from an existing model.
5. The variability of response indexes from repeated samples of the same plot in the same year must be calculated for each defined lichen response index to allow statistical evaluation of patterns and trends. This repeat sample variability for all lichen response indexes (applicable to FIA lichen data meeting standard quality criteria) must be small enough to support realistic trend analysis (see section "Evaluating a Lichen Gradient Model During Development," p. 37, for description of standards).
6. Calculation of all lichen indexes and estimates of variability must use data on lichen species composition at a plot. Only plot environmental factor(s) routinely archived by FIA (such as plot elevation or location) should be required for the calculation of a lichen response index, and then only when a lichen response index based solely on lichen species composition has proved unsatisfactory. No nonstandard field sampling by FIA crews should be required to calculate a lichen response index for FIA plots.

Models for FIA must meet these standards, provide these products, and cover regions that meet these criteria.

Required products—

Standardized documentation for the model is a required component of the final report to ensure that each lichen gradient model is usable in the FIA Program. We provide in an appendix a template for this standardized documentation. Copies of instructions and data files necessary for assignment of lichen indexes to sample plots are to be permanently archived and made available to government officials and the general public to calculate lichen response indexes from the model. Key required products include:

1. Clear description and rationale for the geographic region for which the model applies.
2. Clear description of procedures used to develop the model.
3. Clear description of all lichen response indexes developed from the model.
4. Clear description of accuracy, precision, and bias of all lichen indexes.
5. Detailed instructions for assigning lichen response indexes to new plots based on lichen sample data.
6. Original data sets, all other data sets, formulas, and information required for assignment of lichen response indexes are to be archived.

Requirements 3 and 5 are met with the formal documentation of a model using the template presented in the appendix. Requirements 1, 2, and 4 are usually met in the text of a lichen gradient model final report and peer-reviewed publication. Requirement 6 is met through archiving files with FIA regions and central information management offices, or another program that uses the model. Summaries of or information about requirements 2 and 6 are also included in the formal documentation of a model.

Lichen Model Regions

Because composition of lichen communities varies widely across the United States, separate gradient models are needed for different biogeographic regions. In this section, we describe proposed lichen model regions for the FIA Program and explain our rationale for the proposed boundaries. A reader interested in other applications for our modeling approach should review our explanation of boundary delineation (second subsection below). Selection of an appropriate geographic region for which the model will apply is a critical first step in developing the model that can affect the model's long-term success.

Proposed lichen model regions and funding priority—

We propose 17 potential FIA lichen model regions in the conterminous United States, with four additional regions for Alaska and Hawaii (fig. 2). Boundaries of regions where models are not currently being developed are tentative; they are expected to change somewhat as more information is accumulated. Table 1 presents our recommendations for funding priorities for these proposed lichen gradient models. These recommendations are based on current availability of FIA data

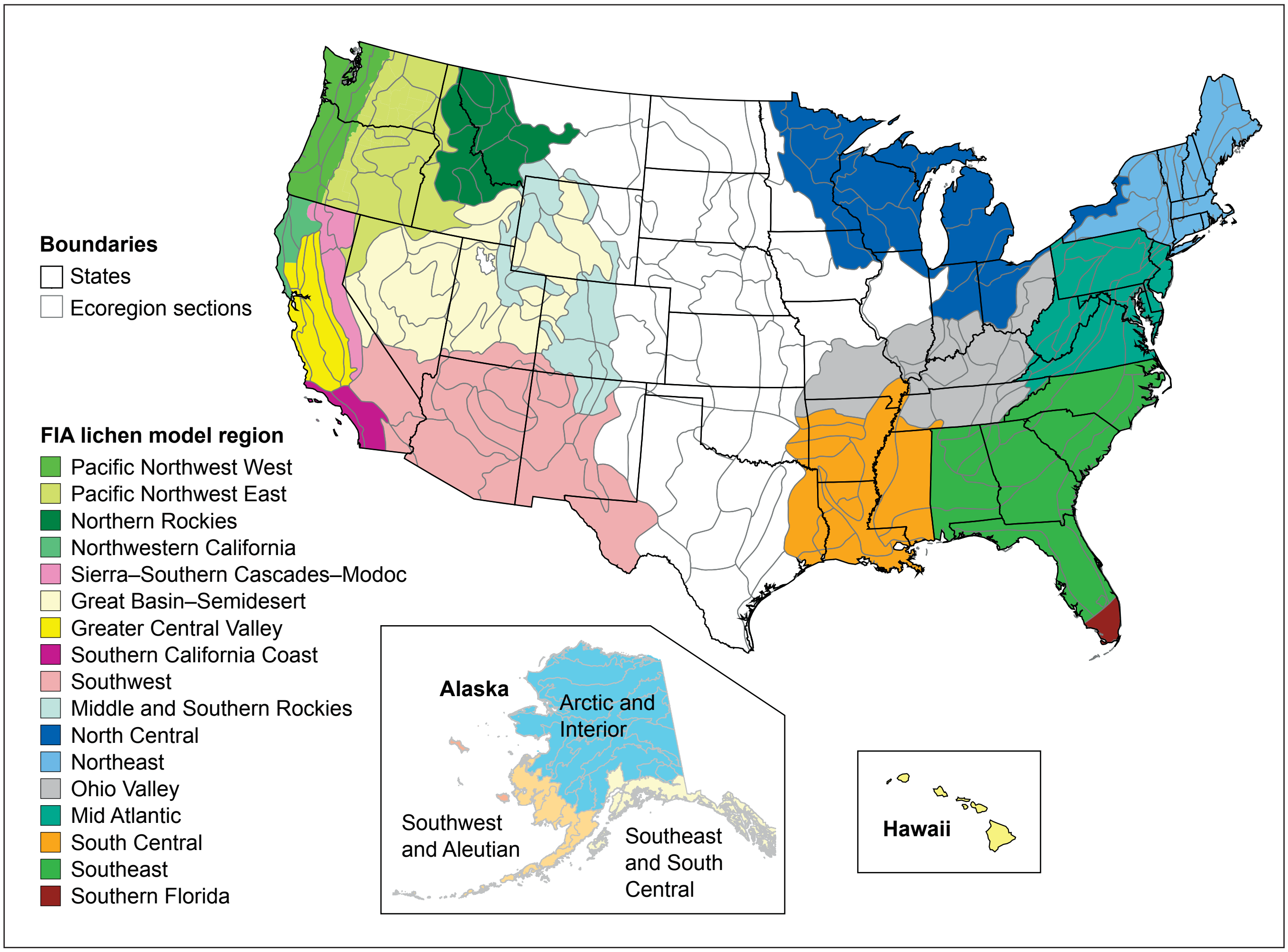

Figure 2—Boundaries of existing and proposed Forest Inventory and Analysis Program lichen model regions for the United States. Twenty-one regions (including Alaska and Hawaii) have been outlined as of 2010. Lichen model regions with completed models (see table 1) have had boundaries tested and found to be ecologically supported. Those with models in progress or not yet begun have proposed boundaries that may be revised as a lichen gradient model is completed. Many boundaries follow Bailey et al. (1994) and Cleland et al. (2005).

within the region, pollution severity (based on National Air Deposition Program ionic deposition maps, NADP 2009), and known regional forest health issues. Because lichen communities may well change over a 10-year period, data sets for development of a lichen gradient model should include data collected over no more than 5 to 8 years. Priorities reflect the need to develop models for some areas soon so older data do not become unusable. Indexes for forested plots not currently located in a lichen model region will be calculated from the model for the nearest adjacent lichen model region, then tested for their usefulness.

As of spring 2010, the Southeast Lichen Model Region (McCune et al. 1997b), Colorado (McCune et al. 1998), most of California (Jovan and McCune 2004, 2005, 2006), and Washington and Oregon west of the Cascade crest (Geiser and Neitlich

Table 1–Forest Inventory and Analysis Program (FIA) lichen model regions and progress toward completion of models

Lichen model region	Status	Funding priority	Regional issues	Publications
New England	In progress	Funded	High urban/industrial pollution in southern and coastal areas. Strong latitudinal gradient in regional pollution.	
Mid Atlantic	In progress	Funded	Urban/industrial pollution high in local areas; regional pollution affects coastal and northern sections.	
Southeast	Completed	Funded	Moderate localized pollution.	McCune et al. 1997a, 1997b
North Central	In future	Medium	Moderate/high pollution in some areas. 1994–1999 plot data available. Gradient model will require recent data.	
Ohio Valley	In future	Low	Pollution high. Plot data sparse as of 2009.	
South Central	In future	Low	Moderate pollution. No plot data as of 2009.	
Northern Rockies	In progress	Funded	Moderate localized pollution. Plot data available.	
Middle and Southern Rockies (Colorado)	(Colorado completed)	(Funded for Colorado) High	Moderate localized pollution. Test Colorado model for applicability to the broader region. If funded soon, an expanded model can include available older plot data.	Colorado: McCune et al. 1998
Southwest	In future	High	Moderate pollution. Plot data available.	
Pacific Northwest West	Completed	Funded	Urban/industrial pollution moderate/high in some areas; high lichen diversity in most areas.	Geiser and Neitlich 2007
Pacific Northwest East/Northern Great Basin	In progress	Funded	Moderate local pollution; high lichen diversity in most areas.	
Greater Central Valley (of California)	Completed	Funded	Agricultural and urban/industrial pollution severe.	Jovan and McCune 2004, 2005
California Sierras	Completed	Funded	Agricultural and urban/industrial pollution moderate/high in places.	Jovan and McCune 2004, 2006
Central Great Basin	In future	Medium	Moderate localized pollution. Plot data available; construct gradient model soon to link with older data.	
Alaska—Southeast and South Central	In progress	Funded	Coastal point sources of pollution; most of region high lichen diversity. Plot data available.	
Alaska—Southwest and Aleutian	In future	Low	Pollution extremely low. No plot data available as of 2009.	
Alaska—Interior and Arctic	In future	Low	Arctic haze, Eurasian pollution moderate. No plot data available as of 2009.	
Hawaii	In future	Low	Pollution moderate. No plot data available as of 2009.	

Notes: Twenty-one lichen model regions have been identified as of 2009. Three regions on figure 3–South Florida, Northwestern California, and Southern California Coast–are not listed in this table. Their small size probably precludes use of standard FIA lichen gradient model development techniques; indexes of lichen response to environmental drivers of interest may be developed in other ways. Also see table 2.

2007) have completed lichen gradient models in place and are in the application phase (fig. 1). Lichen gradient model development is in progress (table 1) in several other regions.

The number of proposed lichen model regions is a compromise between competing constraints on development of useful models. If a lichen model region is too large, representation of regional patterns with lichen response indexes becomes less reliable; repeat sample variability of indexes may be too high to support realistic trend analysis. Conversely, delineation of more and smaller model regions would inflate the cost of completing all models beyond the capacity of FIA Program funding and might not adequately represent large-scale patterns. The average lifetime of a lichen gradient model also affects cost to the program of the modeling effort. Climate change might reduce the effectiveness of trend detection from a more precise model for a smaller region faster than for a more general model for a larger region, and thus shorten the lifetime of a model for a too-small region. To balance all these factors, we have outlined the largest lichen model regions expected to support acceptable models.

Five currently delineated FIA lichen model regions might be studied for possible consolidation into other adjacent regions (table 2): three because they might be too small for model development using standard approaches, and two because gradient models for adjacent regions might well be successfully applied to calculate lichen response indexes for plots. The extent to which the existing model for the state of Colorado may apply to the broader Middle and Southern Rockies region (fig. 1, table 1) should be explored, as should the application of the recently funded model for the Northern Rockies region to some northern Colorado plots in areas ecologically similar to Wyoming and Montana mountains. Virginia plots, shown in figure 2 as part of the Mid Atlantic Lichen Model Region, are also treated as part of the Southeast Region. This assignment to two model regions will facilitate evaluation of the boundary between the two regions in the future. The feasibility of such region consolidations and boundary adjustments should be investigated after

Table 2—Separate lichen model regions (see fig. 2, table 1) worthy of study to group with other regions

Lichen model region	Alternate grouping
Southern Florida	Small; possibly combine with Southeast.
Ohio Valley	Possibly combine with adjacent regions, especially South Central.
Northwestern California	Small; possibly combine with Pacific Northwest West.
Southern California Coast	Small; possibly combine with Southwest.
Alaska—Southwest and Aleutian	Possibly combine with Alaska—Arctic and Interior.

models for adjacent areas have been established and more data are available. The FIA data archiving protocols have been designed to accommodate plots assigned lichen response indexes from multiple gradient models; this feature will facilitate future reevaluation of model region boundaries without massive reanalysis.

Model region boundary delineation—

We have based our designation of lichen model regions here on a combination of ecoregion boundaries (Bailey et al. 1994, Cleland et al. 2005, Omernik 1987, US EPA 2008), annual precipitation (Daly and Taylor 2000) for western regions, political boundaries, and estimated lichen species composition change across regions. Considering both usefulness and economical concerns for lichen gradient models (see above), we combined as many ecoregion provinces (or sections) as possible using these two moderately subjective but reasonable criteria:

1. **Lichen community variation cannot be too high within a lichen model region.** The collected wisdom of past and current gradient model developers is that if estimated change across a region in lichen species composition is too high, myriad problems arise in multivariate community analysis. For the FIA Program an estimate for such change is calculated as total lichen species number in the region divided by average number of species per plot (Will-Wolf 2010); if this value is more than about 10, problems arise (see McCune and Grace 2002). This species change estimate is related to the terms “beta diversity” and “species turnover rate” used in ecological literature. In practice, very high estimates of species change across regions are typically attained by combining adjacent areas that have very different floras. For instance, a combined data set for the Pacific Northwest West and East model regions has 284 lichen species at 846 plots, an average of 17.9 species per plot, and a species change estimate of 284/17.9 or 15.9 (Neitlich, unpublished data). A combined data set for the New England and Mid Atlantic model regions has 184 lichen species at 271 plots, an average of 11.5 species per plot, and a species change estimate of 184/11.5 or 16.0 (Will-Wolf, unpublished data). Both these species change estimates are much higher than desired, so the original lichen model regions should stay separate. Species change estimates are less than 10 for each of the four original model regions. Species change estimates were not examined on a quantitative basis countrywide because FIA lichen data are either very sparse or are absent for parts of several proposed model regions. We made judgment-based estimates for regions as needed.

2. **Lichen model regions must be geographically compact.** A requirement for geographically compact lichen model regions is included because geographic cohesion makes it reasonable to expect that lichens can disperse/migrate throughout the region. Thus a possible mechanism for change (lichen migration in response to changing climate or air pollution, for instance) can be linked with observation of changes in the related lichen response indexes over time. In the West, boundaries of compact regions were qualitatively aligned with precipitation range from a high-resolution annual precipitation data model (Daly and Taylor 2000). In the East, with more gradual change in climate across regions, boundaries were loosely related to the correspondence of ecoregion section boundaries with state boundaries.

The delineation process was therefore a guided, subjective, and iterative process based on the expert opinion of the authors and other gradient model developers, with the expectation that boundaries will be modified as gradient models are developed and tested. Figure 2 results from at least the third iteration of the delineation process following the two above criteria. Forested FIA plots are found in the white areas of figure 2, but plot density in those areas is estimated to be too low (probably fewer than one tenth of FIA forest health plots in the area are forested) to support the development of separate lichen gradient models. After these areas are sampled for lichens, indexes will be calculated for forested plots using the nearest adjacent lichen gradient model. If the resulting lichen response indexes are not adequate for pattern estimation and trend analysis there, alternate analytical approaches will be considered.

A quantitative, completely objective delineation process could have been attempted, based on current lichen data and environmental data, but was rejected at this time for several reasons:

1. There are currently several large geographic gaps in lichen data (no data for states in the Great Plains and South Central United States, Florida, Hawaii, and most of Alaska) and several areas of very sparse data (e.g., New Mexico, North Central States).

2. Defining thresholds of acceptable variation within and between regions based on lichen community variation, precipitation, annual temperature, and other environmental factors would still be ultimately subjective (like any attempt to divide a continuous variable into discrete groups).

3. In the Eastern United States, temperature appears to correlate more strongly with lichen community variation than does precipitation, whereas

in the West the reverse often happens (Geiser and Neitlich 2007; Jovan and McCune 2004; McCune et al. 1997b; Will-Wolf et al. 2006, in press). Such differences make a uniform national choice of climate-based factors for defining lichen model regions difficult.

4. The large amount of time and funding support that would be needed to quantitatively delineate lichen model region boundaries before developing the models was judged to be better spent completing individual lichen gradient models. Once models for several adjacent lichen model regions are completed, the subject of boundary delineation between these adjacent regions should be revisited.

Lichen Gradient Model Budgets

The FIA Program lichen gradient models are estimated to cost a minimum of $40,000 to $45,000 each (2002 dollars). Models completed with substantial involvement of FIA lichen indicator advisors and/or other FIA staff whose salary originates from other sources (i.e., other funding agreements or staff salary) might require less model-specific funding, whereas model development completely outsourced to contractors is likely to cost more than a "typical" estimate (table 3). A project to develop lichen response indexes from a lichen gradient model independent of an established data collection program would need to include much more funding for data collection and processing than estimated here (table 3).

Table 3—Sample budget for a basic Forest Inventory and Analysis Program lichen gradient model contracted to a university researcher

Item	Amount
	2002 dollars
Field work (30 lichen specialist crew-days)	9,000
Field work (30 GS-07 biotechnician crew-days)	5,700
Sample identification from 60 supplemental plots	3,600
Travel (6 people + expenses for 60 crew days)	9,240
Data analysis	8,960
Reporting	7,000
Subtotal direct costs:	43,500
Institutional indirect costs (0 to >50%)[a]	
Total (includes indirect costs):	At least 43,500

Notes: This sample budget assumes lichen data for many (100 or more) plots are available from an existing field inventory program to be used in the development of a model. If they are not, substantial additional costs for field data collection and sample processing must be planned.

[a]Depends on kind of institution, negotiated indirect cost rate

The Pacific Northwest West (completed) and Pacific Northwest East (in progress) models cost at least $60,000 per model, involving substantial supplemental funding and in-kind contribution through FIA field staff participation from the Pacific Northwest FIA region plus an equal partnership with National Forest System Region 6 via staff time and plot data. This is an unusual situation; other efforts have had or are expected to have funding and resources more similar to that shown in table 3. Two California lichen gradient models were completed via a contracted supervised graduate thesis at a cost of $75,000 for one complete model and field work for the second model, with about $16,000 additional funding from the Pacific Northwest FIA region to complete the second model (approximately $48,000 per completed model in 2003-2006). Funding gradient models gradually, no more than one or two per year, allows for greater oversight of model development and thus for higher quality models.

Lichen tissue element analysis is often included to facilitate better interpretation of air quality gradients; approximately $50 per plot (2002 dollars) must be added to typical cost estimates (table 3) to cover field, laboratory, and data management costs for this procedure. A report is planned to present the comparative value and costs of a variety of element analysis options for FIA lichen gradient models and other FIA research applications.

Development of a Lichen Gradient Model

In this section we describe the data needed for a lichen gradient model in the FIA Program, compare and recommend particular methods and tools for modeling, outline steps in developing the model, and propose methods to evaluate a model. All FIA lichen gradient models completed thus far have been developed using NMS ordination alone or in combination with Indicator Species Analysis (Dufrêne and Legendre 1997) followed by regression analysis.

Data Needs

An FIA lichen gradient model developer uses a combination of standard FIA lichen and other plot data, additional environmental data available from other public sources, and supplemental field data collected specifically for the model development project. Those planning independent projects can use these guidelines to organize their data collection efforts.

1. Data collected using standard FIA training and quality assessment protocols (Will-Wolf 2007), field protocols (USDA FS 2004, 2010a), and laboratory data management protocols (Will-Wolf 2009) for abundance of lichen species at

standard FIA plots distributed across an entire lichen model region for at least one year, preferably from multiple years. Data for at least 100 plots are needed for a single model region.

2. Data for abundance of lichen species at supplemental plots collected using standard FIA field and laboratory protocols in areas with known/measured poor air quality (urban/industrial areas and perhaps agricultural areas), spread across major climate and topographic gradients in the project region. A minimum of 20 plots is needed; double that number would be desirable.
3. Data from supplemental plots as needed from areas with documented very good air quality, spread across major climate and topographic gradients in the project region. Many standard FIA plots are in areas with relatively good air quality; a minimum of 20 plots total from known very good air quality areas must be present in the data set for model development. It is desirable to include in the model data set plots from "clean air" areas with field data collected by lichen specialists.
4. A minimum of 20 plots spread across all other major gradients of interest in the lichen model region. Some supplemental plots may be required to meet this objective. For instance, if regional gradients of young to old-growth forests or hardwoods (deciduous trees) to softwoods (conifer trees) are thought to be important, data from supplemental plots near endpoints of these gradients may need to be collected.

Data to support model development must meet several criteria.

The final data set of plots and lichen species (see 1 through 4 above) should be relatively free of geographic bias such as massive over- or underrepresentation of geographic areas or ecological macrohabitats. If plot density is sufficient, balancing the model data set across the demonstrated major environmental gradients is recommended. A hypothetical example of adequately balanced representation of 100 plots across three subdivisions of each of two major environmental gradients is illustrated in table 4.

Table 4—Hypothetical allocation of plots in an exercise to balance 100 plots across three categories each for two important environmental factors for a lichen gradient model data set

Elevation	Pollution	Number of plots
Low	Low	10
Med	Low	13
High	Low	10
Low	Med	10
Med	Med	12
High	Med	14
Low	High	12
Med	High	10
High	High	9

5. Forest mensuration data for all plots. At minimum, total plot live basal area and percentage of live basal area in hardwoods or softwoods are needed. Such data for standard FIA plots are available from program databases; equivalent data must be collected for all supplemental plots.

6. Climate and topographic data for all plots. This is best obtained with public databases and geographic information system coverages. Location and elevation are available for standard FIA plots from program databases.

7. Air quality estimates for all plots. This can be as simple as a binary value; plot has polluted air (1) or not (0). It is preferable to have quantitative estimates of SO_x, NO_x, and NH_4 for each plot. Quantitative emissions data for point sources near "poor air quality" supplemental plots and interpolated estimates of regional pollution can be obtained from public sources such as state databases, the National Air Deposition Program (NADP 2009), the National Acid Precipitation Assessment Program (NAPAP 1991), the Community Multiscale Air Quality System (CMAQ 2009), or other sources such as Fenn et al. (2003b). Available estimates should be carefully evaluated before being included in model data sets. For instance, McCune et al. (1997b) evaluated the available modeled estimates for air pollutants in the Southeast Lichen Model Region and rejected them in favor of a simple polluted/not polluted plot assignment.

8. If lichen tissue element content is also available, it is a tremendous asset to the set of data for environmental factors. This provides accurate and consistent data measured at plots to represent concentration of air pollutants (Geiser and Neitlich 2007, Jovan 2008, Nimis et al. 2002) for comparison with variation in lichen species composition and with modeled or estimated air quality data from off-plot monitoring networks. Data for S, N, and heavy metals are most useful. Tissue element data from all plots are desirable, though data from a subset of plots can be useful. Tissue element data are most reliable when all data are from the same lichen species. Finding one species at all plots is difficult for a large-scale project, so cross-species calibration is often necessary. There are a number of constraints limiting selection of lichen species for tissue element analysis; additional field sampling cost, time, and training need to be considered as well. Until an FIA Program document with recommendations is produced, researchers should consult the current FIA lichen indicator advisor and the most recent scientific literature when incorporating tissue analysis into a model development project.

Methods and Tools

In this section, we evaluate in detail two methods for building gradient models and briefly review available tools. Unconstrained ordination has been used successfully to develop at least part of all models completed to date. Identification of indicator lichen species coupled with regression modeling has been used to successfully define air quality gradients independent of climate for three of the models developed to date, where unconstrained ordination alone was not adequate. Researchers are encouraged to create and/or evaluate other methods and tools for possible use in developing lichen gradient models for the FIA Program. Any additional method or tool must be shown to meet the criteria stated in subsections "Required performance standards," p. 11, and "Required products," p. 12, and explained in detail in the next two subsections below before it is used to develop a final lichen gradient model. We include detailed discussion of how criteria are met for each step, to make transparent how each decision satisfies the purpose, rationale, and specific criteria for model development. "Scores" are the numerical values for a plot generated during analysis. These become lichen response "indexes" as their interpretation is defined by the analysis procedure.

Unconstrained ordination—

Currently the most widely used, most robust, and most effective unconstrained ordination technique for multivariate data reduction and identification of important gradients of species composition, when faced with heterogeneous community data sets, is NMS (or NMDS: Kruskal 1964, Legendre and Legendre 1998, McCune and Grace 2002, Minchin 1987). An NMS ordination uses a species-by-plot data set and is well-suited to species data that are non-normal or are on arbitrary or discontinuous scales (Mather 1976). The NMS can be used both as an ordination method and as a technique for assessing the dimensionality of a data set.

Other unconstrained ordination techniques and other multivariate model-building techniques may be acceptable if those techniques meet all requirements for the program and are shown in published literature to be robust and effective for FIA Program purposes. For instance, use of unconstrained ordination to develop a model for lichen response to important environmental gradients followed by constrained ordination (Jongman et al. 1995, Roberts 2008) to refine that model might be acceptable if all the requirements described in subsection "Required performance standards," p. 11, can be met.

A critical component of any ordination technique is the choice of a distance (or dissimilarity) measure; an algorithm that calculates a single number representing the difference between any pair of plots in the data set. The set of distances between all pairs of plots is the internal data set used by an unconstrained ordination algorithm to generate a multivariate model. The currently most robust and popular distance measure for use in NMS with a heterogeneous species-by-plot data set (one with many zeros for species in plots) is the Sørenson distance measure applied to species abundance data, also known as Bray-Curtis distance (Beals 1984, Faith et al. 1987). Other mathematically similar distance measures have been reported in the literature and would also be appropriate for such use. Critical characteristics for a robust distance measure in these circumstances are that (1) both rare and common species contribute substantially to the calculated distance (i.e., species abundance terms have no exponents in the distance algorithm), (2) the abundances of species common to both plots are standardized by the abundances of all species at either plot, and (3) joint absences from a pair of plots are not factored into the distance algorithm (Legendre and Legendre 1998, McCune and Grace 2002, Roberts 2008).

Ordination techniques that incorporate Reciprocal Averaging/Correspondence Analysis algorithms do not allow the user to select a distance method; the algorithms used imply a chi-squared distance measure (Jongman et al. 1995). This distance has been shown to be less robust and more subject to bias than the Sørenson-abundance/Bray-Curtis distance (Faith et al. 1987) for heterogeneous community data. So this entire class of ordination techniques (including also the popular canonical correspondence analysis and redundancy analysis) is less appropriate for lichen gradient modeling than are techniques that either allow the user to choose a more appropriate distance measure or incorporate a distance measure related to those recommended above.

Species abundance data may be relativized so that all plots have the same total abundance, or not, depending on the variation between plots in total species abundance. If variation in total lichen abundance at plots is moderate to high (coefficient of variation of total plot abundance is at least 40 to 50 percent), relativization removes the substantial noise from this source and enhances the signal from differences between plots based on variation in species composition (McCune and Grace 2002), which is desirable for developing a model useful for FIA Program purposes.

Several available proprietary or shareware (R packages, for instance) statistical or multivariate analysis software packages provide algorithms for NMS ordination and other ordination techniques. Many allow selection of the Sørenson-abundance/Bray-Curtis distance or a closely-related distance algorithm, and most allow data modification choices consistent with our recommendations. A tested software package used for published analyses and reviewed in recent published literature should be selected to reduce the chances that unrecognized software errors will affect the final lichen gradient model.

For the first lichen gradient model, developed for the Southeast Lichen Model Region, two lichen response indexes were developed using only NMS ordination, the Sørenson-abundance/Bray-Curtis distance, a data set of 203 plots, and species abundance data not relativized by plot (the coefficient of variation for plot abundance was much less than 50); that model accounted for 58 percent of original variation in distances between lichen plots (McCune et al. 1997b). The Pacific Northwest West model (Geiser and Neitlich 2007) was also successfully developed using NMS alone. A model for the California Sierras is described as a hybrid NMS model because two separate NMS ordinations using notably different data sets were required. The lichen air quality index applies to the California Sierras only (Jovan and McCune 2006), but the two lichen climate indexes apply to most of California (Jovan and McCune 2004). All of these models were developed using the PC-ORD[1] software package (McCune and Mefford 2006).

The PNW West model illustrates features of a successful lichen gradient model derived using ordination.

We describe the Pacific Northwest West lichen gradient model (Geiser and Neitlich 2007) in greater detail to illustrate both general and unique characteristics of one successful NMS lichen gradient model. From a data archive of more than 1,500 sampled plots, authors randomly selected 293 plots to balance the analysis data set for polluted versus clean air plots stratified across two climate/topographic gradients. The availability of so many plots with lichen data is likely to be unique to the Pacific Northwest region. Lichen species abundance data were not relativized by plot because variation among plots in lichen abundance was relatively small. The amount of such variation differs by region, and recommended practice is related to the amount of variation. Tissue element content from a single lichen species gave the best quantitative estimators for air pollution impact at a plot. Such data are not universally available for FIA lichen plots, nor is it likely that a single lichen species suitable for tissue element analysis would be found at each plot in most model regions. The final model illustrated in figure 3 explained about 83 percent of the original variation among plots in lichen species composition. Three axes (gradients) were extracted and two lichen response indexes were developed from the model. Axis 1 on the ordination joint plot (fig. 3), representing a lichen air quality response gradient, and axis 2, representing a lichen climate response gradient, each explained about 37 percent of original variation among plots. This is much better than the minimum expectation for a successful lichen gradient model as stated in "Required performance standards," No. 2, p. 11. The third and undefined lichen gradient from this model, represented by axis 3 in figure 3, might be considered

[1] The use of trade or firm names in this publication is for reader information and does imply endorsement by the U.S. Department of Agriculture of any product or service.

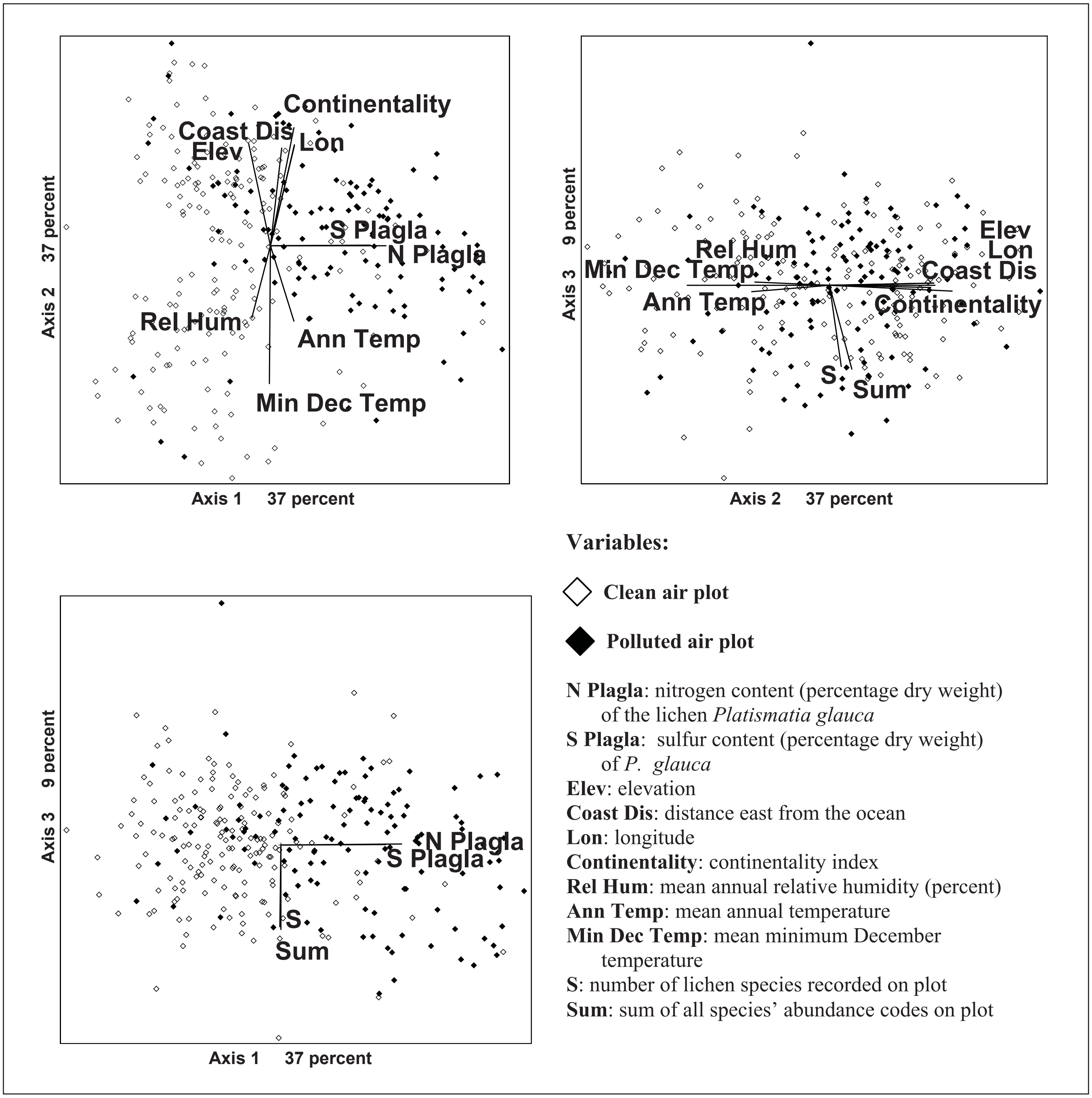

Figure 3—Nonmetric multidimensional scaling (NMS) ordination diagrams for the Pacific Northwest West lichen gradient model (PNWW). These three two-dimensional (two axes) graphs illustrate plot distribution on the three NMS axes (lichen response gradients) developed for the PNWW model and their interpretation. Axis 1 represents an air pollution response gradient, axis 2 represents a climate response gradient, and axis 3 represents an undefined lichen community response gradient. Each axis label includes the percentage of total information about differences between plots that is represented on that axis. Lines superimposed on each graph represent the correlation of the named factor with the two axes. In such an ordination joint plot (see glossary) from an NMS model, the information portrayed by these lines is external to the ordination analysis (secondary information). Length of line from the central point indicates strength of correlation, and direction of line indicates both the sign of the correlation and the degree to which the factor is correlated with both axes. A line strictly parallel with one axis has no significant correlation with the other axis. An axis is assigned meaning based on its correlation with these factors. Coding of plot symbols and interpretation of names for lines are given in the legend. Values assigned from the model for an FIA plot represent position along axes 1 and 2, and become the lichen air quality index and the lichen climate index, respectively, for that plot. Modified from Geiser and Neitlich (2007).

unimportant because it explains only 9 percent of original variation. It is however the only gradient from that model that is correlated with both number of lichen species at a plot and total lichen abundance. If a causal factor could be defined for this gradient, the lichen species richness index could become a more useful bioindicator for this region. For all other completed lichen gradient models, the lichen species richness index has been strongly correlated with at least one of the defined lichen response indexes, so this situation for the Pacific Northwest West lichen gradient model is unusual.

Calculate plot indexes from an unconstrained ordination model—
There is currently only one tool widely available to calculate lichen response indexes for new plots or repeat samples of plots from an existing ordination model. This tool, submodule NMS Scores under module Ordination in software package PC-ORD (McCune and Mefford 2006), is an iterative procedure to assign to a set of plots numerical values for each ordination axis (lichen response gradient) of an existing model, using an algorithm based on the mathematics of NMS. This tool uses lichen abundance by species for each new plot and requires the choice of a distance measure. The recommendation is to use the same distance measure used to develop the model. A data set of the lichen abundance by species in the model for each plot in the model (the model data set) and a data set of numerical values (scores) of each model plot for each model axis are also required. The software also calculates estimates of fit of each new plot to the original model, allows the user to specify criteria for poor fit, and provides flags for three kinds of poor fit. The score for each plot on each model axis (gradient) then becomes its lichen response index for that gradient (formally related to a named environmental factor). This tool was developed specifically to calculate scores for new plots along axes (defined environmental response gradients) of an existing NMS model. It could possibly be used to calculate scores for new plots along axes (gradients) from any kind of unconstrained ordination model, and possibly even along axes (gradients) from a constrained ordination model, but this should be tested thoroughly before being implemented for a new lichen gradient model. Other software to accomplish this purpose can be recommended by gradient model developers, as long as it has been thoroughly tested. A possible future option is development of FIA Program–specific software (by program staff or through contracting) to assign lichen response indexes to new plots using any kind of ordination model that meets program specifications.

Regression model using indicator species—
Regression modeling after selection of indicator species has been a successful tool used in a hybrid lichen gradient model when a single ordination model does not

generate independent lichen community response gradients that can be linked to climate and air pollution. So far, the problem has been to derive a second gradient representing lichen response to air quality that is independent of a strong primary lichen climate response gradient. The following procedure has proved successful. First a set of lichen species that indicate poor air quality has been developed using Indicator Species Analysis (Dufrêne and Legendre 1997) to identify species that are significantly associated with plots having poor air quality. Other means to identify significant indicator species for one extreme of a particular gradient can also be used for this approach, subject to meeting requirements and guidelines in subsection "Program Requirements," p. 11. To be useful across an entire lichen model region, probably at least 6 to 10 lichen indicator species must be identified. Next a raw lichen air quality (or other factor) response score for each plot is calculated. A further step, if necessary, is to calculate an independent adjusted lichen air quality index based on a regression or other statistical model that includes both the raw lichen air quality score and the confounding primary climate-related factor. A linear regression model to express the adjusted lichen air quality index for a plot as the residual after regressing the raw air quality score on the primary and confounding climate factor would be a simple example for this further analysis step. Such a simple example is illustrated in detail in section "NMS ordination plus indicator species plus regression," p. 33. All major statistical software packages (including shareware R packages) provide appropriate tools for developing various kinds of regression models.

For the construction of a lichen gradient model for the state of Colorado (McCune et al. 1998), an NMS two-dimensional ordination of 126 lichen plots clearly showed that climate as represented by elevation was strongly correlated with the most important variation in lichen composition, generating a lichen climate index. Lichen composition was also strongly correlated with an air quality factor, but this factor was correlated as well with the lichen climate/elevation gradient. This meant an independent lichen air quality index could not be developed using NMS alone. A list of indicator species was extracted using module "Indicator Species Analysis" in PC-ORD (McCune and Mefford 2006), then a lichen air quality response index independent of climate was calculated from a simple linear regression model using a proprietary statistical software package. For this hybrid model, the lichen climate index explained 37 percent of original variation among all plots in the model, and the regression model for the lichen air quality index explained 35 percent of variation (had an adjusted r^2 of 0.35) among a subset of the plots. This is better than the minimum expectation for a successful hybrid lichen gradient model as stated in "Required performance standards," No. 2, p. 11.

The need for hybrid models may occur in several West lichen model regions where air pollution is worse at lower elevations. For the California Sierras hybrid model (Jovan and McCune 2006), an independent lichen air quality index was developed from an indicator species/regression model approach, and two independent climate indexes were developed from an NMS model for most of California (Jovan and McCune 2004). Similar problems may also occur in parts of the East where air pollution is strongly correlated with latitude or longitude.

Steps in Building a Lichen Gradient Model

Details matter for developing a model.

One should always first attempt to develop a lichen gradient model using NMS ordination or another acceptable multivariate analysis procedure, then proceed to a hybrid model only if the multivariate analysis model is not completely successful (see discussion in subsection "Rationale for Approach," p. 9. The steps below are described for NMS, indicator species analysis, and regression modeling, techniques that have been successful for completed FIA lichen gradient models. A lichen gradient model developed using other techniques should have modifications of these steps documented as part of the final report.

Multivariate NMS ordination model—

1. Compile a lichen species-by-plot model data set including both standard and supplemental plot data that represent the range of very good to very poor air quality conditions across the full range of other important environmental conditions (elevation, temperature, precipitation, etc.) in a region (see subsection "Data Needs" above, p. 20). For FIA data, modify the lichen species names in the final data set to match usage in the earliest inventory year included in the data set, following instructions in the official FIA reference lichen species comments table. This standardizes taxonomic usage across all years the data were collected, and is necessary only if taxonomic usage changed during those years. The latest version of the official FIA table must be obtained from the internal program database; contact the FIA lichen indicator advisor or an FIA information management office. The version available on the Web (USDA FS 2010a) is not as current, but may be adequate depending on the inventory years for the lichen data being used. Second, further modify the lichen species names as needed for analysis, for instance by combining several related and ecologically similar uncommon species into a single species group. Perform this second kind of modification of lichen species categories as little as possible, to facilitate calculation of indexes for new plots from the completed model as easily as possible. Any modifications to use of lichen species categories applied to the model

data set must also be applied to all new plots to be assigned lichen response indexes from the model in future. Examine the original lichen data set for outlier plots, plots having very few species, and species found at very few plots; remove plots or species as desired to reduce noise and generate a more stable solution. This is standard practice in development of ordination models (Legendre and Legendre 1998, McCune and Grace 2002).

2. Compile a second matrix of environmental and other variables associated with each plot in the model data set. Variable classes represented in the second matrix should include climate, pollution, tissue element content if available, forest structure measurements, and lichen community summary values such as lichen species count and summed lichen abundance for each plot. Consider including as separate variables logarithmic or other transformations of original environmental data; response of biotic communities to such factors is often not linear with respect to the scale in which scientists measure an environmental factor (Legendre and Legendre 1998, McCune and Grace 2002). Identifying such instances is important to accurate interpretation of lichen response.

3. Perform an NMS ordination using many independent runs (up to 50 is common) at each of several dimension settings. Choose an appropriate distance measure such as the Sørenson-abundance/Bray-Curtis distance measure (see subsection "Unconstrained ordination," p. 23). Determine the dimensionality of the data set by comparing solutions at different dimensions, and choosing the dimensionality that on average deviates from random most strongly. Test this by comparing with multiple runs of randomized data. Next, perform multiple NMS runs (often up to 100) with the chosen number of dimensions to ensure that the chosen final solution is stable and represents a configuration with the lowest possible deviation from the matrix of original pairwise distances between plots (usually called lowest stress) as reported by the software. All of these tasks can be performed in several available multivariate analysis program packages (including shareware R packages).

4. Rotate the chosen solution to maximize the correlation of ordination axes with the second-matrix environmental factors of greatest interest to address assessment questions (a "climate" axis and an "air quality" axis, for instance). These axes then represent lichen response to those environmental factors in the model, and plot scores on each axis become the indexes of lichen response to those factors. The ordination axis most

strongly correlated with air quality should be rotated so that plots reflecting poorer air quality (more pollution) have higher values on the axis. This convention facilitates interpretation of lichen air quality indexes from this model as estimating potential risk of injury from air pollution. It is useful for presentation but not necessary for analysis to rotate the solution so that axis 1 expresses the most variation among plots attributed to any axis. The final solution must meet all the requirements stated below in subsection "Evaluating a Lichen Gradient Model During Development," p. 37, including both strength and independence of correlations with environmental factors of interest. Many, but not all, available multivariate analysis program packages (including shareware R packages) allow such rotations. If the ability to perform such a rigid rotation of a two-, three-, or four-dimensional point cluster is not available in the multivariate analysis package used, a graphics software package can be used to perform the rotation. Model developers must then statistically evaluate the proportion of original variation among plots on each final rotated axis in a separate operation.

5. Archive the final model data set and the set of coordinates of all plots on the final set of rotated axes chosen from step 4. Together these two data sets compose the final ordination gradient model. Complete the template for documentation of a gradient model, including all information and instructions needed to assign to new plots or to resampled plots response indexes for each defined gradient from the model.

6. Investigate correlations of second-matrix variables and species abundance values with the axes in the final gradient model (step 5) to support full interpretation of the final gradient model and variation in lichen community composition in the region. Calculate correlations of abundance of each individual lichen species with final axes to interpret a species' response along climate and air quality gradients. Report the proportion of original variation among plots on each final model axis. Lists of lichen species characteristic of different climate subregions and of species characteristic of low and high air quality are also useful products. Archive an ordination joint plot showing second matrix variables plotted over the basic ordination diagram as lines representing strength of correlation of second matrix variables with ordination axes (see glossary).

7. Calculate lichen response indexes for new FIA plots as well as for plots included in the model data set using the original plot data (not the final

model data set) as modified following instructions for species categories. Such calculations require the archived model data set and the archived set of lichen model axis scores. Follow all instructions in the model documentation for preparation of the data set of new plots and selection of options for assigning scores to plots. Calculations can be done using submodule NMS Scores in PC-ORD (McCune and Mefford 2006), which derives indexes for a set of plots by using the lichen gradient model and finding the position of best fit for each of these plots on each model axis without shifting the positions (scores) of the archived set of model plots. Additional software may be available in the future for this purpose. In PC-ORD/NMS Scores, if more than one lichen response index is to be derived from an NMS model, choose option "simultaneous axes" to optimize overall fit of plots to all ordination axes in the model (McCune and Grace 2002). If only one response index is to be derived from the NMS model, choose option "one axis at a time." NOTE: the archived scores for model plots are based on a data set modified for model development. Calculation of lichen response indexes for these same plots should be based on the original plot data rather than data modified for the model, so these indexes are equivalent to indexes calculated for new plots and repeat samples of plots (full plot data not included in the archived model).

8. Estimate how well the model applies to each plot. Submodule NMS Scores in PC-ORD reports two kinds of user-specified poor fit of a plot to a model: too far beyond an extrapolation limit for either end of the model gradient, and exceeding a final stress criterion (calculated using the same algorithms as for stress in NMS ordination (McCune and Grace 2002). Recommendations for FIA lichen gradient models are to set the extrapolation limit criteria to 10 percent of original model axis (gradient) length beyond either end of the original gradient. Any plot whose score is beyond this range (+ or –) is flagged for poor fit. For stress-based fit calculated in NMS Scores, it is recommended that the final stress criterion be selected to be two standard deviations above the average plot stress parameter as calculated for a population of at least 100 standard FIA plots from the same model region. Recommended extrapolation limits and the selected final stress criterion are then archived and included with model documentation, and are entered into NMS Scores before calculation of scores for new plots. Any plot whose calculated fit is outside the entered criteria is flagged for poor fit. For plots fitted to an NMS lichen gradient

model using other software, or for plots fitted to a lichen gradient model developed using a different multivariate analysis approach, the extrapolation limit criteria above can easily be applied. A new software-specific criterion for defining stress-related poor fit to the model would need to be established and documented as part of model development.

Hybrid model: NMS ordination plus indicator species plus regression—

1. Perform steps 1 through 3 as for an NMS ordination lichen gradient model above. If the best NMS solution fails to generate a model with a lichen air quality gradient that is independent of the major lichen climate gradient(s), then consider building a hybrid model. The steps below are written for deriving an independent lichen air quality index in this situation using "pollution" indicator species and a simple linear regression model, the simplest combination of methods published so far. Either choice might be different for an actual lichen model region. Specific examples are given from the Colorado model (McCune et al. 1998) and the California Sierras model (Jovan and McCune 2006). If instead there is a need to derive an independent lichen response index of some other kind, follow the steps below as modified for the relevant environmental factors.

2. Examine the lichen climate response gradient (primary gradient) with which the air quality factor (or other secondary environmental factor) is most closely confounded. Create a "subset" lichen species-by-plot data set by removing all nonpolluted plots that have values for the climate factor most strongly correlated with the primary gradient that are outside the range of values for that same factor in the set of "polluted air" plots (or the range of another secondary environmental factor).

3. Develop a list of lichen indicator species using the subset of lichen data and an appropriate software package (see subsection "Regression model using indicator species," p. 27) as well as other approaches to identify lichen species that have strong indicator value for identifying plots in that region that have poor air quality. Each species included must have a quantitative estimate of its strength as an indicator in that region. NOTE: just as a different NMS lichen gradient model must be developed for each different bioclimatic region, a different set of "pollution" (or another environmental factor) indicator lichen species must be derived for each different bioclimatic region.

4. Develop a formula to calculate a raw lichen air quality score for each plot based on the entire lichen species composition at a plot. In this example, it is accomplished by calculating the relative abundance of pollution indicator lichen species at the plot:

$$\text{Raw lichen air quality score} = 100 \times (\text{SUM}_{\text{poll}}/\text{SUM}_{\text{all}})$$

where SUM_{poll} is the sum of the abundance scores of all lichen species that indicate polluted conditions and SUM_{all} is the sum of the abundance scores of all lichen species recorded for the plot. This raw lichen air quality score has a maximum of 100 when all lichen species are pollution-tolerant indicators. The minimum possible value is zero when none of the lichen species present are pollution indicators. Note this raw score is calculated so that plots with more polluted air have high scores, to facilitate interpretation of the final lichen response index as estimating potential risk of injury from air pollution. This is the recommended strategy. A similar approach was used to calculate raw lichen air quality scores for the California Sierras model (Jovan and McCune 2006), whereas for the Colorado model (McCune et al. 1998) the original raw lichen air quality score was highest for clean air plots.

5. Include the raw lichen air quality score (calculated for all plots in the original data set) as a variable in the environmental data set. Correlate with the best NMS model (step 1 in this section) to see if air quality as represented by the raw score is now decoupled from the confounding climate variable. If it is, this becomes the final lichen air quality index. If it is not, which is to be expected and as was the case with both the Colorado and California Sierras lichen gradient models, proceed to the next step.

6. Raw lichen air quality scores can be adjusted to reduce the influence of the confounding climate variable by using a regression approach. In the next step for the example introduced in step 4, it is done by calculating residuals from linear regression of raw lichen air quality scores on the confounding climate-related factor:

$$\text{Adjusted lichen air quality index} = [(\text{Raw air quality score} - (a \times \text{Climate factor} + b)]/\text{SD}$$

where a is the slope of the regression equation, b is the intercept, and SD is the standard deviation of the residuals from a regression model with raw air quality score as the dependent variable and the climate factor as the independent variable. The adjusted index expresses the lichen response to air quality of a plot as the number of standard deviations away from expectation for a given value of the climate factor. If more than one independent variable is entered into a regression model, forced simultaneous entry rather than any form of stepwise entry should be used for the final regression model to confirm there has been no bias from order of entry. For the Colorado model, a linear regression model based on plot elevation was adequate, but for the California Sierras model, a more complicated regression model (also based on plot elevation) was required. NOTE: the choice of climate-related factor to include in a regression model is constrained for use in the FIA Program by the need to have values for that factor for all sample plots to which the model will be applied (see "Required performance standards" No. 6, p. 12). In practice, this means that latitude, longitude, elevation, and combinations of these factors are the primary choices, as location and elevation are the only climate-related factors routinely available for FIA plots.

7. Include this adjusted lichen air quality index (calculated for all plots in the original data set from either all lichen species or only those in the model data set, as directed in model documentation) as a variable in the environmental data set, and compare with the best NMS model (step 3 above) to see if adjusted lichen air quality index is now decoupled from the confounding climate index. It is expected to be, as was the case with the Colorado and California Sierras Lichen Gradient Models. This then becomes the final lichen air quality response index. The final hybrid model must meet all the requirements stated below in subsection "Evaluating a Lichen Gradient Model During Development," p. 37, including both strength and independence of correlations with environmental factors of interest.

8. Archive the final NMS model data set, the final NMS model axis scores, the list of air quality indicator lichen species for the region, the list of all plots and lichen species included in the subset lichen air quality gradient data set, and the formula to calculate the adjusted lichen air quality index for new plots and repeat samples of plots including all needed numbers such as standard deviation of regression residuals, all of which together compose the hybrid lichen gradient model for that region.

9. Assign lichen response indexes for the climate factor(s) to all plots included in the original lichen data set plus any additional standard plots based on full original plot lichen data. Use recommended software and all necessary

final model data sets and products listed in instructions for applying the model. Follow all instructions in the documentation for preparation of the data set of plots to be assigned lichen indexes and selection of options in the software to be used (see step 7 in subsection "Multivariate NMS ordination model," p. 31). If using routine "NMS Scores" in software package PC-ORD (McCune and Mefford 2006), choose option "simultaneous axes" to calculate two or more lichen response indexes from an NMS model, or choose option "one axis at a time " to calculate a single lichen response index for each plot (McCune and Grace 2002).

10. Assign lichen air quality indexes (or other indicator species/regression-based lichen response indexes) to all plots included in the original lichen data set plus any additional standard plots based on full original plot lichen data by calculating relative abundance of "pollution" indicator lichen species at a plot (steps 3 and 4), then calculating adjusted lichen air quality index (step 6) for each plot. Follow all instructions in the documentation for preparation of the data set of plots to be assigned lichen response indexes and selection of options for assigning indexes to plots.

11. Estimate how well both parts of a hybrid model apply to each new plot. Criteria for assessing how accurately the ordination part of a hybrid model generates a lichen response index for each plot are explained in step 8 of section "Multivariate NMS ordination model," p. 32. Extrapolation limit criteria can be established in the same way for an indicator species/regression model. There is no standard approach for calculating a stress criterion for applying an indicator species/regression model to new plots. One possible estimate is the proportion of lichen species at a plot that are not found in the regression model data set. We have no established guidelines for interpreting fit to a regression model using this criterion to define stress-related poor fit. Analysis of statistics for fit of plots to such models should be a priority in the near future to aid in developing such guidelines.

12. As an alternative to using pollution indicator lichen species in step 3, the above sequence may be attempted by identifying clean air indicator lichen species. Such an approach may be helpful in a lichen model region that has generally relatively clean air or for special studies (e.g., evaluation monitoring) where few or no pollution indicator lichen species may be found over broad parts of the area of interest. This approach is likely to generate useful lichen gradient response indexes primarily for areas with relatively low ecological variation, as clean air lichen indicator species must be found in most

habitats in the region to be reliable indicators. The use of pollution or clean air indicator lichen species will probably result in less ability to discriminate on the end of the lichen air quality response gradient not represented by indicator lichen species.

Evaluating a Lichen Gradient Model During Development

An effective NMS lichen gradient model (including all gradients defined) should explain at least 50 to 60 percent of the variation among distances between pairs of plots in the model data set. This criterion should be applied to the NMS ordination component of a hybrid gradient model as well. Such a statistic is almost always reported by ordination software; its exact calculation differs by ordination technique and by software. Report the basis for this calculation in the software used to develop the model. If the model does not achieve this goal, then two remedies should be explored. Both remedies require iterative alterations and model testing.

a. The data set can be enlarged, by adding more years of standard plots, by collecting more supplemental plot data, or both.
b. The boundaries of the model region can be adjusted.

An effective lichen gradient model should have correlation r^2 values of 0.3 to 0.4 or higher between defining variables (climate or air quality factors) and major axes of the ordination. The factors used to define and align the ordination axes that will generate lichen response indexes must be relatively uncorrelated with one another (correlations not significant or correlations closer to zero than ± 0.5). If this is so, the major factors will appear close to orthogonal on an ordination joint plot. Failure to achieve at least 75 to 80° (maximum 90°) separation (geometric degrees) or ≥85 percent (maximum 100 percent) orthogonality for both ordination axes and the major environmental factors correlated with them should trigger use of a hybrid model development approach. For a hybrid model, the lichen response index derived from indicator species selection and regression modeling must achieve the above level of separation from all ordination axes used to define lichen response indexes. If this cannot be achieved with the steps outlined above, a new procedure for a hybrid model must be developed.

With an effective lichen gradient model, we have found that if a field crew person obtains 65 percent or more of the count of species found on that plot by a lichen specialist, then the lichen response indexes from field crew data for that plot will mostly fall within 10 to 12 percent of the indexes from expert data, as compared with model gradient length (see glossary). With within-plot variation at 10 to 12 percent or less, it is reasonable to expect that deviations in lichen response index over time of 15 percent or more of model gradient length suggest real change has occurred (Will-Wolf 2010). The ability of lichen data meeting the field measurement quality objective (MQO) to generate lichen response indexes that meet laboratory MQOs (table 5) needs to be demonstrated for each new lichen gradient model. Failure to achieve this relationship indicates the model is not adequate and an improved model must be developed.

Field crew certification exams by specialists conducted during training and data quality checks during the field season (Will-Wolf 2007) provide the data needed to test whether achievement of MQOs for field data generate lichen response indexes that meet laboratory MQOs. If such data (repeat samples of the same plot) from training or data quality assessment are not available for a region, a reference plot exercise should be conducted concurrent with lichen gradient model development, to provide appropriate data for this test.

Evaluating, Comparing, and Calibrating Completed Lichen Gradient Models

Evaluating a Completed Lichen Gradient Model

We hope a model will be useful for 50 years.

A lichen gradient model should be expected to have a finite lifespan, beyond which it is no longer valid. Reorganization of biotic communities over time in response to climate change or other large-scale alterations of environmental context is a distinct possibility in today's world. The lifespan of a lichen gradient model is yet to be tested; we hope that models will remain valid for more than 50 years, or about five current sampling cycles. The validity of the lichen gradient model can be tested after each sampling cycle is completed.

Every completed lichen gradient model includes instructions for assessing how well plots fit with the model. When a new plot is assigned lichen indexes from an NMS gradient model using module NMS Scores in PC-ORD (see step 8 in subsection "Multivariate NMS ordination model," p. 32), plots are flagged for two different types of poor fit: too far outside the range of the original model gradient at either end (fit flags 2 and 3), plus unspecified poor fit (fit flag 1). For plots fitted to an NMS lichen gradient model using other software, or for plots fitted to a lichen gradient model developed using a different multivariate analysis approach, similar flags for poor fit are also reported. For a model component developed using an indicator species/regression model approach, methods for estimating how well a plot can be fitted to the model are less well established (see step 11 in subsection "Hybrid model: NMS ordination plus indicator species plus regression," p. 36.

If for a particular lichen model region the proportion of plots with poor fit increases substantially over time, this may suggest that the lichen gradient model is losing its validity. A suggested guideline is that if the percentage of all lichen plots

Table 5—Measurement quality objectives (MQO) for Forest Inventory and Analysis Program lichen data, and their method of assessment

Field and laboratory data	MQO	Method of assessment
Minimum plot standard (field MQO)	65 percent	Percentage of a lichen specialist's count of species that a crew person finds on the same plot (laboratory data). This is the minimum score for crew to pass training certification, field training recertification, and for minimum acceptable quality of field crew species (laboratory) data as compared with specialists' species (laboratory) data.
Completeness	90 percent	Percentage of forested plots searched for lichen data (field data).
Accuracy of archived laboratory data	95 percent	Percentage of plots with archived lichen laboratory data that have been 100 percent proofread and represent exactly the plot lichen species count and abundance from the lichen identification specialist's report.
Quality of archived laboratory data	90 percent	Percentage of crew samples from plots achieving the minimum plot standard for data quality: 65 percent of a lichen specialist's species count (laboratory data) based on a blind resurvey of the same plot.
Lichen response indexes	**MQO**	**Method of assessment**
Bias	10–12 percent	Signed deviation from "true" indexes (from lichen specialist laboratory data). In practice, plot laboratory data achieving the minimum standards (above) should yield indexes that meet this MQO.
Accuracy	10–12 percent	Absolute deviation (sign ignored) from "true" indexes (from lichen specialist laboratory data). In practice, plot laboratory data achieving the minimum standards (above) should yield indexes that meet this MQO.
Precision	10–12 percent	Deviation between indexes from measurement of the same plot in the same year by both field crew and lichen specialists. Data that meet the MQOs for bias and accuracy should meet this MQO. For pattern and trend analysis, deviations of indexes between subregions and/or years are considered evidence of differences or change only if they exceed this precision standard.
Quality of archived lichen response indexes	95 percent	Percentage of archived plot values for one particular lichen response index that achieve the target MQO for accuracy, bias, or precision.

Notes: For a successful lichen gradient model, it is demonstrated during development that if the lichen species field and laboratory MQOs are met, MQOs for lichen response indexes are met. All four target MQOs for lichen response indexes require that a lichen gradient model be in place for their calculation.

for a year with flags for poor fit increases by 10 percent from one sampling cycle to the next or reaches 20 percent, the lichen gradient model should be reevaluated. The type of flags will help diagnose the nature of the poor fit and suggest remedies.

In several instances, plots from an area not included in a particular lichen model region may need to be assigned lichen response indexes by using the nearby existing lichen gradient model. For instance, northern Florida plots will in the future be assigned lichen response indexes from the Southeast Lichen Gradient Model, which included no Florida plots. A suggested guideline is that if the proportion of plots in the new area with any flag for poor fit is 10 percent or more when at least 50 plots are tested, that lichen gradient model does not adequately represent the new area. Remedies will differ depending on the location. If an area is located between or near two lichen model regions with completed models, geographically defined groups of plots should be assigned to the lichen model region whose model provides the best average fit to the entire group of plots.

Comparing and Calibrating Lichen Gradient Models

Calibrating between lichen response indexes developed for different regions would allow one to monitor trends in lichen response across multiple lichen model regions in a single analysis. The first requirement for such calibration is the development of lichen gradient models for adjacent lichen model regions. Measured air quality data for a range of plots in each region can be used to compare with ranges of lichen air quality indexes between regions. Data on lichen tissue element content can also be of help in comparing lichen air quality indexes between regions. Lichen climate indexes between regions can also be linked this way, and the relation of individual climate factors to lichen community composition can be compared between regions.

Calibration of lichen response indexes between regions will also allow quantitative comparison of differential response of individual lichen species between regions, and will contribute much-needed improvement in the understanding of geographical variation in the effectiveness of environmental indicators. Evaluation and modification of lichen model region boundaries can also probably be conducted most efficiently by comparing and calibrating lichen gradient models for adjacent regions.

Summary Discussion

Development of a lichen gradient model for calculation of lichen response indexes to assess patterns and monitor trends in response to environmental factors has been an effective and powerful tool for the FIA Program to implement large-scale and long-term monitoring within tight budget constraints. This approach should be considered for other large monitoring programs. Developing the model is an exacting process. Choice of an appropriate lichen model region and modeling approach are critical first steps, but they do not guarantee success. Appropriate choices must be made at each of the many steps in the development of a model. Failure to do this at any step along the way can seriously impair the usefulness and scientific validity of the entire model. It is reasonable to expect that inappropriate choices at early stages in model development may have multiplicative rather than just additive impacts on the accuracy and precision of the monitoring that can be done with the final lichen response indexes.

With this in mind, we have examined the rationale and techniques for each step in the modeling process in great detail. We have provided a reporting template that supports application of a completed model to monitoring for many years. We anticipate this attention to detail will make the model development process more transparent for future FIA Program lichen gradient models. We also hope this approach will clarify the model development process and the usefulness of our recommended approaches and techniques for researchers designing their own biomonitoring projects and programs.

Acknowledgments

Funding was provided under cooperative agreements between Southern Research Station Forest Inventory and Analysis (FIA) and the University of Wisconsin-Madison. Author Will-Wolf has been FIA Program lichen indicator co-advisor 1995–2001, advisor 2002–2007, co-advisor 2008–2009, and is developing two FIA lichen gradient models. Author Neitlich has been FIA lichen indicator co-advisor 1995–1998, advisor 1999–2001, has developed one completed FIA lichen gradient model, and is developing another model.

This report is substantially modified from Neitlich et al. (2001), but takes much of its organization and content from that document. All other lichen gradient model developers, especially FIA lichen indicator developer Bruce McCune (Oregon State University [OSU]) and current FIA lichen indicator advisor Sarah Jovan (OSU and Pacific Northwest FIA), have contributed to the content of this document. Sarah Jovan, Paul Patterson (Interior West FIA), and Paul Rogers (Utah State University) provided insightful reviews of drafts of this report. The final product is the responsibility of the authors.

English Equivalents

1 hectare (ha) = 2.47 acres (ac)

1 kilometer (km) = 0.621 mile (mi)

1 meter (m) = 3.28 feet (ft)

1 square meter per hectare (m^2/ha) = 4.37 square feet per acre (ft^2/ac)

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Appendix: Template for a Report Section Formally Documenting a Lichen Gradient Model and Its Implementation

This required part of a final Forest Inventory and Analysis (FIA) Program lichen gradient model report should be written for ecologists and analysts both inside and outside the FIA Program who will calculate lichen response indexes for new plots from data collected within an FIA lichen model region. All required instructions and pointers to needed data files and software must be included; details whose purpose is to support understanding of the model development process should not be included here.

[LICHEN MODEL REGION] LICHEN GRADIENT MODEL DOCUMENTATION AND SPECIFICATIONS FOR CALCULATING LICHEN RESPONSE INDEXES FOR NEW PLOTS

1. BASIC MODEL DOCUMENTATION

Fill in the specific information for each topic listed in bold. Useful information and general instructions are written for each. Labels or values that change with each gradient are indicated between brackets.

Creation Date:

Updated Date:

Description of Changes:

Lichen Model Region Name:

Geographic Extent/Region Boundaries (verbal description): Include a map at the end of the document.

Geographic Extent/Region Boundaries (operational definition): If available, describe in detail how plots are assigned to this region.

FIA Administrative Regions included:

States included:

Number and brief description of all lichen response indexes 1- [X] defined for the region: List by order of importance, if order is defined. Index numbering is cumulative across all response indexes developed for a single lichen model region, whether from a single ordination model or from a hybrid model. Name lichen response index by major interpretation, i.e., pollution or air quality response index, climate/moisture or climate/temperature response index, etc. Name should clearly distinguish it from all other defined lichen response indexes in that region, i.e. lichen climate/elevation response index vs. lichen climate/latitude response index, etc.—list an undefined lichen community response gradient if necessary, for instance an undefined ordination axis required for model development. Indicate interpretation of index values, i.e., larger lichen response indexes indicate plots with more polluted air, or plots in cooler conditions, etc. Briefly describe the type, and number if needed, of model procedure(s) from which the lichen response index was developed, i.e., NMS ordination (lichen response index 1, 2, etc.); indicator species identification plus regression (lichen response index 1, 2, etc.); etc.

[named lichen response index 1]; [model type]; [interpretation of index values]

[named lichen response index X]; [model type]: [interpretation of index values]

Lichen gradient model developers: List names, institutions, phone numbers, and emails.

2. DETAILED MODEL DOCUMENTATION AND SPECIFICATIONS FOR DETERMINING LICHEN RESPONSE INDEXES FOR NEW PLOTS
Include a separate subsection for each type of model used to develop lichen response indexes listed in Part 1.

List the number and type of models described in this section. Label as subsection 2A, 2B, 2C, etc.

2A. 1. DESCRIPTION OF MODEL [X]. Explanations for a nonmetric multidimensional scaling (NMS) ordination type of model for lichen response indexes 1, 2, etc. Describe another kind of ordination model similarly.

References for full description of model: Include internal and/or public Forest Service final report from model developers and location stored as well as publication of the model in a peer-reviewed journal.

Software and version used to develop the model:

Amount of original information in the final model, as compared with information in the model data set: This is often reported as a percentage.

Method used by the software to calculate this amount of information in the final model: Most methods calculate proportion of variance of distances between pairs of plots that is represented on the final ordination axes. The calculation method is specific to the ordination technique and the software.

Brief description of lichen response indexes and length of gradients developed from this model: Copy lines from first section and add text—some of this is redundant, but redundancy is useful and important here. For gradient length, report the range of model scores for plots (length of axis for an NMS or other ordination model) based on the final reduced model data set. Do **not** report here the range of the lichen response indexes for plots in the model data set that were calculated using complete plot data. This second range based on lichen response indexes is likely to be different from the first range, as the model gradient is usually developed from a data set with some uncommon species excluded, and lichen response indexes for the same plot are calculated with all uncommon species included.

Number of plots included in the model:

Criteria for choice and/or exclusion of plots: Briefly document all criteria: e.g., plots chosen to balance clean and dirty plots for 12 classes of environment; plots with tree basal area less than a minimum excluded and reason; plots with fewer than x species excluded; plots missing environmental data excluded; plots determined to be outliers as defined by developers or by software were excluded; etc.

Number of species included in the model:

Taxonomic usage year for model lichens data: No matter when lichen data were actually collected, the "taxonomic usage year" for the model is the year (= variable INVYR in FIA database tables) for which the REF_LICHEN_SPECIES and REF_LICHEN_SPP_COMMENTS tables best match the taxonomic choices made for the model data set.

Criteria for modification and/or exclusion of taxa: species at < x plots excluded, for others excluded state reason. List by at least acronym from the REF_LICHEN_SPECIES table all taxa combined into groups for analysis, clearly indicate which acronym remains in the data set, how abundances for combined taxa are determined. All species names, numerical codes, and species acronyms MUST match a record in the FIA REF_LICHEN_SPECIES table.

Rules for determining abundances for combined taxa at one plot:

Abundances: individual taxa	Abundance: final combined taxon
1 + 1	2
1 + 1 + 1 + 1 + 1	2
More than five 1s	3
1 + 2	2
2 + 2	2
1 + 1 + 2	2
1 + 1 + 1 + 2	3
1 + 2 + 2	3
3 + any others	3
4 + any others	4

Example list of combined taxa from internal FIA documentation (Jovan et al. 2008) for the Pacific Northwest West model (Geiser and Neitlich 2007):

For the following list, the "merged into" acronym is the one retained in the final model data set [Statements have been ordered here alphabetically by the "merged into" acronym.]:

Bryfri merged into Bry

Vulcan merged into Cetcan

Clafur, Clanor, Clapyx, Claumb merged into Cladonia. [This action combined four uncommon species that would probably have each been removed from the model data set, into a genus group large enough to be retained in the model data set.]"

Clacon merged into Claoch

CLASUBSQ merged into Clasqu (the former acronym is found in a Region 6 [National Forest] lichen species master list but not in the FIA REF_LICHEN_SPECIES table; the final archived model data set has only acronyms in the FIA list)

Clabel merged into Clatra

Usndip (FIA), USNSST, and USNPAC merged into Usn (the two acronyms USNSST and USNPAC are found in a Region 6 [National Forest] lichen species masterlist but not in the FIA REF_LICHEN_SPECIES table; the final archived model data set has only acronyms in the FIA list)

Usncha merged into Usnfil

Xanulo merged into Xanfal

List of taxa included in the ordination model: Model developers can name a separate archived file rather than include a list here. The list should include species code, species acronym, genus, and species name. In a separate archived file or a list if included in the documentation file (or both), all species names, numerical codes, and species acronyms must match a record in the appropriate FIA REF_LICHEN_SPECIES table

Abundances relativized to row totals for the model? [YES, NO]

Distance measure used: For instance, Sørenson-abundance/Bray-Curtis distance.

Gradient model lichen data set and format: Note—because computer software and file formats change frequently and archived files need to be usable for many (up to 50) years, choice of file format for archiving necessary data sets is very important. Only very general file formats should be used, and it may be advisable to submit each file in two formats, for instance the format specified by the recommended software to be used, and also as an ASCII text file or a file in xml format. It may be deemed necessary to submit hard copy versions of each file for emergency backup of electronic files. Apply a consistent and informative naming convention to all electronic files for a particular lichen gradient model, to facilitate identifying the needed files long after they have been archived.

File name and type: For example, [Lichen model region name] lichen model region model data set [filetype extension] is a plot-by-species table in [specified]format, with FIA P3_PLOT numbers and/or other codes [specify the code(s)] designating plots and species acronyms as in field SPP_ACRONYM of FIA database table REF_LICHEN_SPECIES.

The format specified should be acceptable for software used to assign lichen response indexes to new plots, for instance module NMS Scores of PC-ORD [give version number] (McCune and Mefford 2006) or other software. If necessary, include a crosswalk table of public plot codes in the model data set to private FIA plot codes for internal FIA Program use. Give a brief rationale for the format submitted, and the software needed to use this file to assign lichen response indexes to new plots.

Where archived: Give the appropriate FIA office to contact. When the model data set is archived as a file linked to a database or on the Web, give appropriate location information. NOTE: all such files for currently completed models identify plots with FIA P3(FHM)HEXID number, which is considered private information. This file MUST be available to any FIA regional analyst calculating plot lichen indexes for archiving. Any outside user must first negotiate a confidentiality agreement with FIA, or a version of this file with public plot identifiers can be posted on the Web.

NMS model axis (gradient) scores:

File name and type: For example, [Lichen model region name-model-axis-scores] [filetype extension], in [specified file format]. A file named xxx.gph in ASCII text format is the format currently required to assign lichen response indexes to new plots using module NMS Scores of PC-ORD v5.2 (McCune and Mefford 2006). Give rationale for the format submitted, and the software needed to use this file for assigning lichen response indexes to new plots. The codes used to identify plots in this file must match exactly the codes used to identify plots in the model data set.

Where archived: Give the appropriate FIA office to contact. When the axes data set is archived as a file linked to a database or on the Web, give appropriate location information. NOTE: all such files for currently completed models identify plots with P3(FHM)HEXID number, which is considered private information. This file MUST be available to any FIA regional analyst calculating plot lichen response indexes for archiving. Any outside user must first negotiate a confidentiality agreement with FIA, or a version of this file with public plot identifiers must be posted on the Web.

Model environmental data set: NOTE—this file should be archived for documentation of the lichen gradient model, but it should not be necessary for assignment of lichen response indexes to new plots with an ordination model.

File name and type: For example, [Lichen model region name] lichen gradient model environmental data set [file type extension] is a plot x environmental factor table in [specify] format, with FIADB P3_PLOT numbers or other codes designating plots. One choice is the format acceptable for plotting environmental factor vectors on the final model graph using module GRAPH of PC-ORD [specify software version] (McCune and Mefford 2006). The codes used to identify plots in this file must match exactly the codes used to identify plots in the model data set. Give rationale for the format submitted, and the software needed to use this file to re-create the model diagram. See model references for description and origin of environmental factors.

Where archived: Give the appropriate FIA office to contact. When the environmental variables data set is archived as a file linked to a database or on the Web, give appropriate location information. NOTE: currently all such files identify plots with P3(FHM)HEXID number, which is considered private information. This file may be useful to regional analysts and outside users analyzing and interpreting plot indexes. Any outside user must first negotiate a confidentiality memorandum of understanding with FIA, or a version of this file with public plot identifiers can be posted on the Web.

2A. 2. SPECIFICATIONS FOR CALCULATING LICHEN RESPONSE INDEXES FOR NEW PLOTS FROM MODEL [X]. Explanations are for specifications for calculating lichen response indexes from an NMS ordination model.

Software used to calculate lichen response indexes: At publication of this report, lichen response indexes are calculated for new plots using an NMS model by fitting plots to model axes with module NMS Scores in PC-ORD software v. 4.30 or later (McCune and Mefford 2006). A cautionary note about running NMS Scores–our experience is this routine can be very time consuming. It is convenient to allow the routine to run overnight. Test the run time for fitting 10 plots, then based on the time for this run, include only the number of plots at one time that are likely to be completed overnight. Alternately, run this routine on a computer that can be set aside and allowed to run for as long as necessary. For PC-ORD, each plot must have a unique identifier in a single field of maximum eight spaces. The private FIA variable P3(FHM)HEXID meets this criterion. Give directions and settings for any other software used in detail similar to that included below.

Preparation of data: All taxa should be combined exactly as for the model data set. First consult the relevant REF_LICHEN_SPP_COMMENTS table and follow all instructions for reconciling taxonomic changes between the taxonomic usage year for the model data set and the inventory year(s) for the plots to be fitted to the model. Next, follow any instructions given in model documentation above for further modification or combining taxa for the model. Assign lichen response indexes to new plots from the lichen gradient model using this modified data set.

Calculate lichen response indexes using all taxa, or calculate indexes using only taxa included in the model [follow recommendation for the model]. Each model should have one of these recommendations stated.

The default recommendation should be to use all taxa at each plot. If the recommendation is to use only taxa included in the model, documentation should include a brief justification.

Species abundances relativized by plot totals for the model?: [YES, NO] For assigning response indexes to new plots, follow the procedure adopted for the model.

Selecting setup options for fitting plots to model [X] using module NMS Scores in PC-ORD:

- Select [the distance measure used for the model analysis] distance measure.
- Select Simultaneous method for fitting. This choice is most often the appropriate choice for assigning lichen indexes to a new FIA plot for program purposes, to better maintain the status of indexes being independent of one another. In some cases, model developers may recommend and justify the choice to fit axes one at a time.
- Select user-defined unspecified fit (stress) criterion, then enter this fit criterion. The unspecified fit (stress) criterion for fitting to this model is determined by model developers. A reasonable criterion might be two standard deviations higher than average unspecified fit (stress) calculated from assigning lichen response indexes for the model to more than 100 plots in a single NMS Scores run.
- Set NMS Scores extrapolation limit to ± 10 percent.
- Be sure to DESELECT the NMS Scores option “List Intermediate Results.”

Saving the output from an NMS Scores run: For saving output from some other software, give instructions in equivalent detail.

Save run specifications. Save run specifications as text in a file that can be archived as metadata for the assigned plot lichen response indexes. Consult the FIA Program information management unit before submitting files for archiving, to decide appropriate file format. Add calculation date, software name, and version to this file. AXIS SUMMARY STATISTICS in NMS Scores output refer only to that particular set of plots and are not of general interest, so they should not be archived.

Save plot lichen response indexes and flags for poor fit. The assigned axis scores become the plot lichen response indexes. Information in the output table BEST-FIT SCORES ON EACH AXIS from all runs of NMS Scores for the population of plots in one inventory year should be saved in a separate file to be archived, and when data structures are in place, to be uploaded to the FIA database. Consult the FIA Program information management unit before submitting files for archiving, to decide appropriate file format. For simultaneous fit, only one column for Fit and Flag is output for all the axes on which scores are assigned. For archiving in the FIA database, duplicate the Fit and Flag columns to accompany values for each defined lichen response index (= axis), and add a column for inventory year.

It is convenient to maintain in this file both a single-field plot identifier the analyst might choose to use and the STATECD, COUNTYCD, NIMS_PLOT and FIADB_PLOT (FIA database field names) identifier fields in a master file, to facilitate relinking the results of analysis with the standard FIA plot identifiers for upload to the FIA database and crosswalking with other data. Neither NIMS_PLOT nor FIADB_PLOT is by itself a unique plot identifier, so state and county codes must always be linked with one of these plot codes.

Field names and form of file to archive: These field names should be included in each record for each plot. FIA P3(FHM)HEXID (or other unique plot identifier(s) if used), STATECD, COUNTYCD, NIMS_PLOT, FIADB_PLOT, Inventory year, Lichen gradient model region code, Response_index_1, Response_index_1_fit, Response_index_1_flag, Response_index_2_index, Response_index_2_fit, Response_index_2_flag, etc.

The default value for the Response index X flag field is "0." All plots having a value higher than the user-specified maximum acceptable stress-related fit criterion are assigned a flag value of "1" for general poor fit, entered in the "flag" field. If the lichen response index for a plot is more than 10 percent higher than the maximum for a plot in the model, as compared with full model gradient (= axis) length (see glossary), a flag value of "2" is entered; if it is more than 10 percent lower than the minimum for a plot in the model as compared with full gradient length, a flag value of "3" is entered in the "flag" field for that plot. If a plot qualifies for two fit flags, the higher flag value is entered.

Each plot has one row or record. The file to be submitted should be in a format agreed upon after consultation with FIA Program information managers. After an official FIA database structure has been developed for such files, this file will need to conform to the designated upload format.

Estimating fit and assigning poor-fit flags with alternate software: Identify plots with lichen response index values beyond the acceptable range for each gradient using criteria analogous to those detailed above. Estimate stress-related or unspecified fit of plots to the model; identify those plots whose fit value is beyond the criterion. Assign the same three flag values as above to indicate the different kinds of poor fit.

2B. 1. DESCRIPTION OF MODEL [Y] Explanations for indicator species/ regression model type, for lichen response indexes 2, 3, etc.

Model description: Indicate briefly the exact kind of model developed, for instance indicator species identification based on abundance of species, followed by linear regression.

References for full description of model: Include reference to the internal Forest Service final report from model developers (and location of archived copy) as well as publication of the model in a peer-reviewed journal.

Software and version(s) used to develop the model: Include name, date, version number for all software, such as "the Indicator Species Analysis module in PC-ORD v5.2 (McCune and Mefford 2006)" and the name and version of a statistics package used to develop a regression model, etc.

Brief description of lichen response indexes and length of gradients developed from this model: Give number and brief description of lichen response indexes developed from this model. Copy lines from the first section—this is redundant, but redundancy is useful here. For each response index, give the range of model lichen scores (gradient length) calculated from the final reduced model data set, not the range of lichen response indexes calculated for plots included in the model using full plot data.

Number of plots included:

Criteria for choice and/or exclusion of plots: Write "Same as for model X," "Subset of plots in model X within a certain elevation range," etc. or include full documentation of criteria.

Number of species included:

Taxonomic usage year for model lichens data: The "taxonomic usage year" is the year for which notes in an FIA REF_LICHEN_SPP_COMMENTS table match the taxonomic choices made for the model data set, no matter when data were actually collected.

Criteria for modification and/or exclusion of taxa: Write "Same as for model X," "Subset of species in model X" with additional criteria [specify], etc., or give full documentation of criteria. It is very desirable for these criteria to be the same for all response indexes developed for a hybrid model, to reduce confusion and to simplify the task of modifying data before calculation of all lichen response indexes for plots. All species names, numerical codes, and species acronyms MUST match a record in the FIA REF_LICHEN_SPECIES table.

List of [pollution] indicator species: Note: it is not necessary that all of these species are included in the model data set. The list should include species code, species acronym, genus, and species name for each species.

Source for list of [pollution] indicator taxa: For instance, list software name and version used to determine indicator species, list published literature sources, or both. Note which indicator taxa were shown to be significant indicators quantitatively.

List of all taxa, including indicator species, included in the model data set: List in documentation or provide the name of an archived file that lists the taxa. The list and/or file should include species code, species acronym, genus, and species name. All species names, numerical codes, and species acronyms must match a record in the NIMS_REF_LICHEN_SPECIES table.

Abundances relativized to row totals for the model? [YES, NO]

Model equation: Includes all parameters needed to define the model, such as regression coefficients, standard deviations, etc. and precise definition including units for all terms in a model equation, or other needed inputs.

List plot environmental data, if any, and units required as inputs to this model: Include elevation in meters, latitude in decimal degrees, etc. Give FIA database field name and the table where this information resides, if appropriate. Geographic information such as elevation, latitude, or longitude related to exact plot locations should be used.

2B.2. SPECIFICATIONS FOR DETERMINING LICHEN RESPONSE INDEXES FOR NEW PLOTS WITH MODEL Y. Explanations of specifications for determining lichen response indexes from indicator species/regression model type.

Software used to calculate lichen response indexes: Indicate any specific software needed. For a common kind of analysis such as linear regression that is available in many software packages, indicate particular form of the model, choices, specification of error terms, etc. that should be used when calculating response indexes for new plots from the model.

Preparation of data: All taxa should be combined exactly as for the model. Consult the most recent FIA REF_LICHEN_SPP_COMMENTS table; follow all instructions for reconciling taxonomic changes between the taxonomic usage year for the model data set and the inventory year(s) for the new plots to be assigned lichen response indexes from the model.

Calculate lichen response indexes using all taxa, or calculate using only taxa included in the model [follow recommendation for the model]. Each model should have the recommendation stated. The default recommendation should be to use all taxa, modified according to instructions. If the recommendation is to use only taxa included in the model, documentation should include a brief justification.

Abundances relativized by plot totals for the model? [YES, NO] For assigning lichen indexes to new plots, follow the procedure adopted for the model.

Required environmental data. Obtain for each plot all environmental data, if any, required as inputs to this model (elevation, latitude, etc.). All values should be in the units used for the model. Obtain data for the model from the FIA database field name and table where this information resides, if appropriate. Information related to exact plot locations should be used.

Calculating lichen response indexes for new plots with the model: Insert a detailed step-by-step protocol for calculating lichen response indexes for new plots with the model. Emphasize units for values wherever needed. If appropriate, append a spreadsheet file with formulas embedded.

Estimating the degree of fit of a plot to the model: This explanation is a suggested method for estimating the degree of fit to an indicator species/regression type model. Other methods chosen should be documented in similar detail.

The relative abundance of species at a plot that are NOT included in the regression model data set (AbNOT) is an estimate of the degree of fit of that plot to the model. This value can be calculated as:

$$\text{AbNOT} = 100 \times \frac{\sum \text{abundance scores for all species at the plot NOT in the model data set}}{\sum \text{abundance scores for all species at the plot}}$$

Assigning a flag for poor fit: The default value for this field is "0." If for this model, a maximum acceptable value of AbNOT for adequate fit to the model has been recorded, then all plots having a value higher than this maximum acceptable value should be assigned a value of "1" for general poor fit recorded in the "flag" field. If the lichen response index for a plot is more than 10 percent higher than the maximum for a plot in the model as compared with the full range of lichen gradient scores for plots in the original model (gradient length), enter a flag value of "2" for too high; if it is more than 10 percent lower than the minimum for a plot in the model as compared with gradient length in the original model, enter a flag value of "3" for too low. If a plot qualifies for two fit flags, enter the higher flag value.

If no threshold value of AbNOT for adequate fit (or no other general fit criterion) has been determined, assign flags for poor fit based only on criteria related to gradient length.

Saving the lichen response indexes: For archiving and uploading into the FIA database, add lichen response index, fit value, and fit flag to an existing file that includes other response indexes for the same plots in the same region. Recall that lichen response indexes for a single region are numbered consecutively even if they are derived with different techniques. For instance, lichen response indexes 1 and 2 might have come from an ordination model as described in section A of documentation, and lichen response index 3 has come from a regression model as described in section B of documentation. All three response indexes with their fit values and fit flags would be archived in the same file.

Field names and form of file to archive: Use the field names and format as described in section "Saving the output," p. 56, for an ordination gradient model X.

Glossary

application phase—The second phase in implementation of the lichen indicator in the Forest Inventory and Analysis (FIA) Program. In this phase, lichen data are collected from standard FIA plots and are assigned indexes for response to environmental factors defined from an existing regional "FIA lichen gradient model." Many analyses based on these indexes are possible in this phase.

calibration phase—The first phase of implementation of the lichen indicator in the FIA Program. In this phase, lichen data are collected from standard FIA plots and limited analyses are conducted. Supplemental data are collected and an "FIA lichen gradient model"for a particular "FIA lichen model region" is developed. This phase lasts for a region until a gradient model is completed and implemented.

FHM—The Forest Health Monitoring Program in the U.S Forest Service. Current focus is nationwide reports and special projects.

FIA—The Forest Inventory and Analysis Program in the U.S. Forest Service. Responsible for nationwide collection of data describing the Nation's forests, from plots located on a permanent grid.

FIA lichen gradient model—A quantitative model developed for a particular "FIA lichen model region." Such a model relates lichen community composition in the region to major environmental factors of interest, such as climate and air quality. Abbreviated after first use under a topic as "lichen gradient model" or just "model" in appropriate context and when usage is unambiguous.

FIA lichen indicator—Collectively refers to lichen species and communities as used in the standard national FIA Program as biomonitors of forest health, including all the different indexes developed from the lichen data collected, and more loosely to all aspects of lichens in the program. Often abbreviated in text as "lichen indicator."

FIA lichen indicator advisor—An FIA employee or contractor whose responsibility it is to advise and collaborate with the FIA Program on all aspects of the FIA lichen indicator from data collection through analysis and reporting to long-term planning. This person has a Ph.D. or equivalent professional training in both lichenology and community ecology. A major responsibility is to oversee maintenance of high standards related to lichenology expertise in all aspects of the program. Often abbreviated in text as "indicator advisor" or "lichen IA."

FIA lichen model region—A geographic area defined for the FIA Program for which a quantitative "FIA lichen gradient model" will link lichen community composition to major environmental factors of interest including climate and air quality. After such a gradient model has been developed, FIA plots within this region have response indexes calculated from lichen data for all environmental factors defined from the model for this region. Abbreviated after first use under a topic as "lichen model region" or just "region" in appropriate context and when usage is unambiguous.

gradient—The term as used in plant ecology and for this document is defined as a range of values ordered from small to large (or vice versa) for either an environmental factor or a derived number representing some biotic factor of interest. For instance, an ordination axis score is a derived number that for a lichen gradient model represents an aspect of lichen species composition at one plot. The entire ordered range of scores for one ordination axis thus represents a species composition gradient. And the full ordered range of average summer high temperatures for a set of plots represents a gradient for summer temperature.

gradient length—The largest minus the smallest score on a published lichen model gradient. Specifically, gradient length is the full range of scores on one ordination axis or full range of values from a regression or other model, for plots in the original model based on the archived modified model data set. Gradient length is not the range of lichen response indexes for the same set of plots as calculated based on full plot data. Gradient length is reported in documentation for the lichen gradient model and does not change over time. Differences between resampled plots for lichen response indexes are converted to percentage of the published model gradient length for comparison with data quality objectives.

inventory—Defined for the FIA Program as a one-time assessment across a geographic region of the patterns of forest vegetation and its components based on field sampling of permanent plots.

inventory year—Defined for the FIA Program as the calendar year in which the majority of plots in that group were sampled: FIA database variable INVYR. A group of plots is identified each calendar year for sampling following standard program protocol, with most sampled during the spring through fall seasons of that year.

lichen air quality index—A unitless numerical index that represents the position of an FIA plot at one particular time on an air quality gradient defined from a quantitative "FIA lichen gradient model" for a particular "FIA lichen model region." This index is one of a class of derived "lichen response indexes." The index is calculated based on lichen species composition from one sample of a plot. The air quality gradient as defined is statistically independent of all other lichen response gradients defined for that particular lichen gradient model. The air quality gradient may be related to measured or modeled quantities of particular pollutants, but the index is not defined in terms of those measured units.

lichen climate index—A unitless numerical index that represents the position of an FIA plot at one particular time on a climate gradient defined from a quantitative "FIA lichen gradient model" for a particular "FIA lichen model region." This index is one of a class of derived "lichen response indexes." The index is calculated based on lichen species composition from one sample of a plot. The lichen climate gradient as defined is statistically independent of all other lichen response gradients defined for that particular lichen gradient model. The lichen climate gradient may be related to measured or modeled values of particular climate components such as average summer temperature or average annual rainfall, but the index is not defined in terms of those measured units.

lichen index—A unitless numerical value based on FIA lichen data that represents some defined relative performance or response of lichens at an FIA plot. Both primary indexes and response indexes derived from a lichen gradient model are included under this phrase.

lichen response index—A unitless numerical value that represents the status of an FIA plot at one particular time with respect to one of the gradients defined for lichen response to an environmental factor from a quantitative lichen gradient model. The derived index is an indicator of lichen community response to the environmental factor. A response index is calculated based on lichen species composition from one sample of a plot. Each lichen response gradient defined for a model is statistically independent of all other lichen response gradients defined for that particular model.

lichen species richness index—The count of macrolichen species recorded from an FIA plot surveyed following standard protocols. This primary index is available for any FIA plot surveyed for lichens; it is an indicator of relative (not absolute, see Will-Wolf 2010) diversity of the lichen community at that plot at that time. Often abbreviated after first use under a topic as "richness index" when usage is unambiguous.

measurement year—The year in which a plot was actually visited in the field for sampling: FIA database variable MEASYR. Most plots in an "inventory year" are visited for lichen sampling in the spring through fall seasons of the inventory year, but visits in the winter of the following year for lichen sampling are possible. In the latter case, measurement year and inventory year would differ.

monitoring—Defined for the FIA Program as repeated assessment over multiple years and across a geographic region of the patterns and trends of forest vegetation and its components from repeated field sampling of the same population of permanent plots.

multivariate analysis—A kind of data analysis, here of ecological communities, that identifies in a single analysis the most important patterns of many species at many plots, and often also the related patterns of many environmental variables measured at many plots.

ordination—A particular kind of multivariate data analysis whose goal for ecological studies is to graphically portray the most important patterns among many sampling units (often plots) and many species (or other attributes of the sampling units), and the relations of those patterns to many environmental variables (either primary or secondary to ordination analysis), in very few (usually two to four) dimensions, or independent axes.

ordination joint plot—By convention, a graph that displays field plots with proximity representing similarity (or "distance") based on the lichen species data, with superimposed lines that represent the direction and strength of correlation between environmental factors and the displayed axes of the graph (Legendre and Legendre 1998, McCune and Grace 2002). Depending on the ordination technique used, the superimposed lines may represent information external or internal to the ordination analysis itself.

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