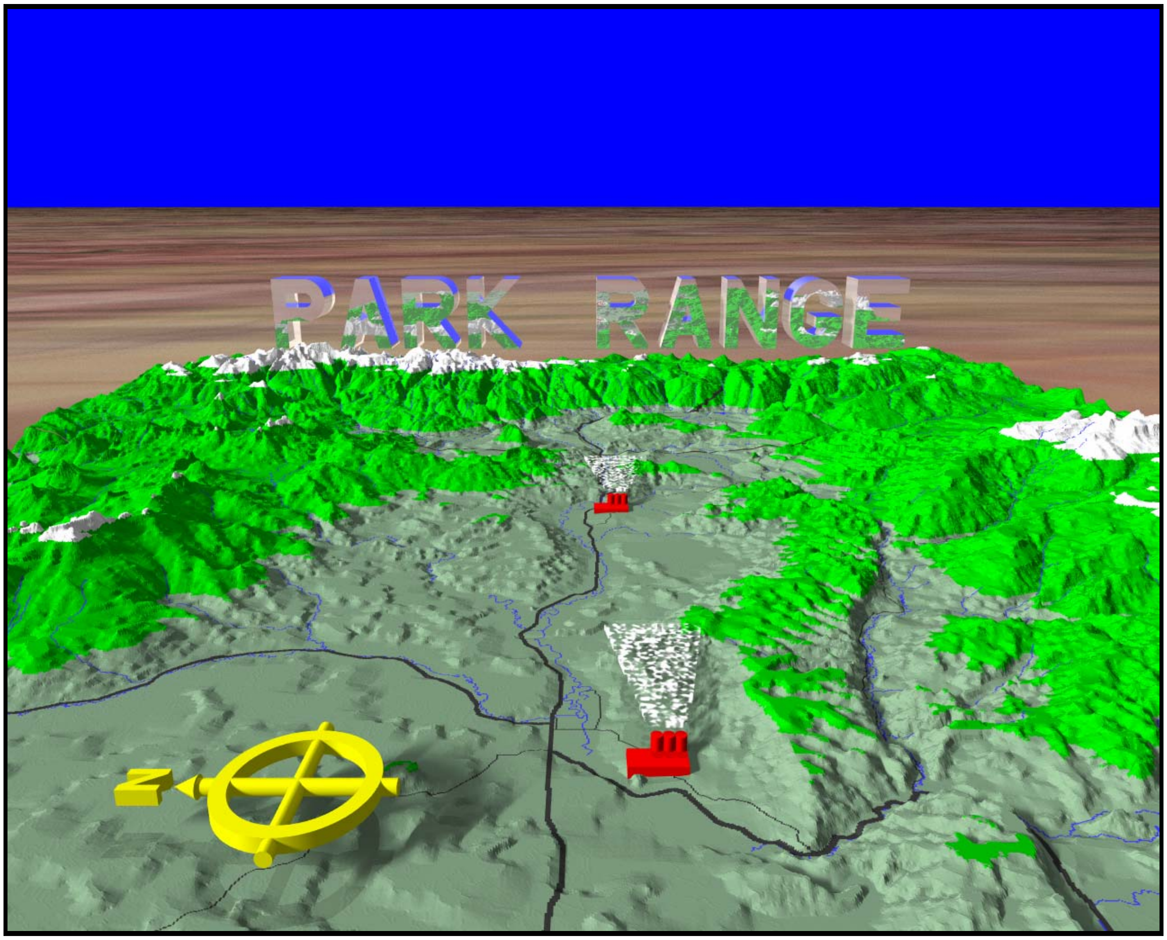
Impacts of Two Coal-Fired Power Plants on Lichen Communities in Northwestern Colorado



A report to the USDA Forest Service

By Eric B. Peterson[1] and Peter Neitlich[2]

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[1] Nevada Natural Heritage Program, 1550 East College Parkway Suite #145,Carson City, NV, 89706.

[2] White Mountain Research Station, 3000 East Line Street, Bishop, CA, 93514.

ABSTRACT

The USDA Forest Health Monitoring project (FHM) includes studies of lichen communities because lichens directly relate to several forest resource issues, including concerns over air pollution. Previous FHM lichen studies in Colorado culminated in a gradient model for the state which included environmental characters and air quality. That work also developed a method for calculating an air quality index at future sites from the proportion of pollution indicator lichens in the lichen communities. The previous work, as well as other studies, also suggest that air quality is low in the area of Colorado's Park Range and the Mount Zirkel Wilderness (Routt National Forest), attributable to two coal-fired power plants in the Yampa Valley, but lichen community data is sparse in the area. We added 35 plots to the area, mostly on the western and upper-eastern slopes of the Park Range. These plots should help us to understand environmental gradients and the influence of pollution in the area, and can be later resampled to determine changes in lichen communities with respect to changes in air quality. With a smaller study area, we found a greater number of environmental characteristics to which lichen community patterns corresponded, including elevation, the presence of hardwood trees, and forest structure. Though initial analyses hinted that we would also find strong pollution gradients in the area, once adjustments were made, any pollution gradients present were swamped by noise in the data from the complex topography and environment, and could not be statistically verified. There did remain the visual appearance of lower air quality as measured by the abundance of *Bryoria fuscescens* in the same area as other studies have found peaks in sulfur deposition. While no strong conclusions can be made about pollution gradients, we suggest pollution affects on lichen community composition are most likely concentrated in the area of Rabbit Ears and Buffalo Passes in the Park Range.

INTRODUCTION

Lichens and Air Pollution

The USDA Forest Health Monitoring project (FHM) includes studies of lichen communities because lichens directly relate to several forest resource issues. Lichen species are sensitive to a variety of habitat characteristics including light exposure, climate, and chemistry. Thus lichen communities are indicative of forest structural characters, environmental gradients, and severity of air pollution (Hale 1952; McCune 1993; Rikkinen 1995; Peterson & McCune 2001).

The sensitivity of lichens to air pollution is one of the primary topics in lichenology, as evidenced by more than 20 presentations addressing the subject at the symposium, “Progress and Problems in Lichenology at the Turn of the Millennium” (IAL 2000). Some lichen species are quite sensitive to pollution even at low levels and there are several documented cases of species being extirpated over large landscapes. *Lobaria scrobiculata* and *Usnea longissima* were frequent in moist forests of Scandinavia but are now restricted to a few areas of low pollution and are becoming extirpated from the Scandinavian landscape (Esseen et al. 1981; Hallingbäck 1989). The best documented cases of lichen losses associated with pollution are in Europe, however there is growing evidence of impacts on lichens in western North America as well. For example, the distribution and abundance of *Lobaria oregana* in western Oregon suggests that it is being influenced by air pollution from metropolitan areas of the Willamette Valley (Peterson & McCune 2001).

Some other lichens are quite tolerant of pollution. Several species including the remarkably sulfur tolerant species, *Lecanora conizaeoides* Nyl. ex Crombie (Belandria et al. 1989), appear to be new arrivals to the pacific northwest, invading the more industrialized areas (B. McCune personal communication; anonymous 1998). Even in regions where a pollution tolerant species naturally occurs, its abundance may increase with increasing pollution due to reduced competition from pollution-sensitive lichens.

The components of air pollution that are most damaging to lichens are sulfur compounds, followed by nitrogen compounds, then by numerous other forms of pollution including ozone and heavy metals (Gries 1996). Due to the wide variation in sensitivity among lichens to these pollutants, quantitative relationships can be established between the lichen communities and air quality (de Wit 1976; Richardson 1988; McCune et al. 1998).

Lichen Communities in Colorado

Colorado is a focal point for FHM sampling in the west. FHM lichen sampling began in Colorado in 1992 and continues to present. A gradient model by McCune et al. (1998) explored the major environmental gradients in the state that affect lichens. They further developed a method for assessing air quality according to lichen communities in newly sampled stands. The major natural gradient affecting lichens in the state was found to be elevation. While elevation probably does not directly influence lichen communities, it is very strongly correlated with temperatures and precipitation, which would directly influence lichen communities (Adams 1971; Coxson et al. 1984; Shirazi et al. 1996; Eldridge & Tozer 1997; Peterson & McCune 2001).

McCune et al. (1998) found distinct modifications to lichen communities in, or down wind of, major urban areas and other pollution sources. This allowed them to develop a list of species that are indicative of pollution. They used the proportion of pollution indicators in the lichen community to calculate an index of air quality with

Equation 1: $$\textit{Raw Air Score} = 100\left(1 - \frac{S_{poll}}{S}\right)$$

where S_{poll} is the sum of the abundance values among the pollution indicator species and S is the sum of the abundance values for all species at a site. While air scores calculated from equation 1 highlighted areas of significant pollution, the index also varied over elevation. McCune et al. adjusted the air scores to compensate for the correlation with elevation with

Equation 2: $$\textit{Adjusted Air Score} = \frac{RawAirScore - f(environment)}{SD}$$

where $f(environment)$ is the function developed by regressing the Raw Air Scores on environmental variables and SD is the standard deviation of the residuals from the regression. In their case, the Raw Air Scores seemed to be significantly influenced only by elevation, thus

Equation 3: $$f(environment) = a \bullet Elevation + b$$

where a is the slope of a regression equation and b is the intercept. Use of equation 3 with the McCune et al. values for a and b would be inappropriate for us, as that equation was developed for a much broader area, the entire state of Colorado. For our local study area, we needed to develop our own equation for $f(environment)$.

Air Pollution in the Park Range

Overall, the distribution of adjusted air scores across the state in McCune et al. (1998) seemed to match well with expected areas of intensified pollution. One area in Park Range of northwestern Colorado (Routt National Forest) showed low adjusted air scores despite a lack of large population centers. This mountain range is downwind of two coal-fired power plants in the Yampa Valley near the towns of Craig and Hayden. Prior to recent pollution controls in the Hayden plant, these power plants emitted a combined annual total of 20,000 metric tons of sulfur dioxide and 24,000 tons of nitrogen oxides (Jackson et al. 1996). The potential for impacts from these power plants on ecosystems in the Park Range, which includes the Mount Zirkel Wilderness, has received substantial attention. Impacts include low pH and high sulfates in the snowpack, and considerable changes to aquatic ecosystems (T. Blett, personal communication). Lichen tissue analysis from the Mount Zirkel Wilderness and nearby areas suggest that sulfur concentrations are greater there than anywhere else in western Colorado, and sulfur isotope analyses reveal the fingerprint of local power plant emissions (Jackson et al. 1996).

In 1993 the USDA Forest Service certified that the Mount Zirkel Wilderness airshed was impaired by power generation in the Yampa Valley. As a result, strict emission control technologies were mandated. The first of the plants to implement stricter pollution control is the Hayden plant, where controls went into effect in early 2000 (Denis Hadow, personal communication).

Despite the on going FHM lichen sampling in Colorado and the other attention received by the Park Range, lichen community sampling was still sparse in the area of the Park Range. To better understand the relationship of lichen communities to pollution deposition in the area we intensified FHM sampling with a focus on the western and upper eastern slopes of the Park Range. This intensified sampling allowed us to: (1) document the nature and degree of impacts to the lichen communities from 30 years of emissions and (2) establish a baseline with which to document the long term changes anticipated with air quality improvement from cleaner emissions.

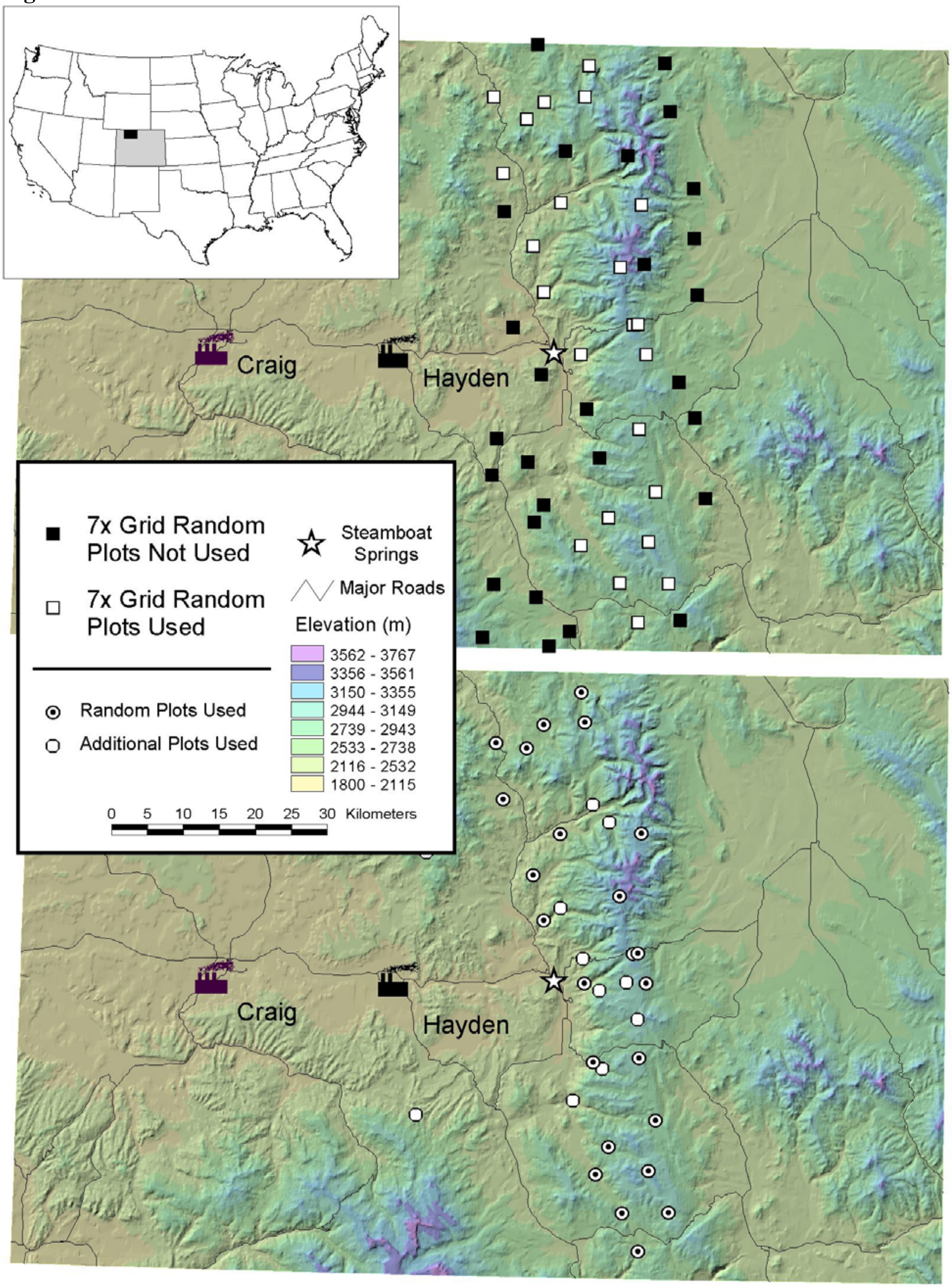
METHODS

Study sites

The Park Range of Northwestern Colorado is a component of the Rocky Mountains with the continental divide running along the northern part of the Park Range, then moving eastward of the southern part of the range. To the west of the Park Range is the Yampa Valley, which in its lower reaches is vegetatively similar to the Great Basin. Much of the Yampa Valley is sagebrush semi-desert with *Populus angustifolia* in riparian zones. On low hills and starting up into the mountains, *Quercus gambellii* occurs in dryer sites and frequently grows as a low shrub on southern slopes. Moister sites harbor *Populus tremuloides* and mixed conifers. The conifers include mainly *Abies* spp., *Picea engelmannii*, and *Pinus contorta* with occasional *Picea pungens* or *Pseudotsuga menziesii*. At high elevations (above 3000 m), only *Abies* spp. and *P. engelmannii* persist, sometimes in large contiguous stands, but frequently as small clumps interspersed with wet meadows.

Initially 51 plots locations were generated within a 0.5 degree longitude by 1 degree latitude block (Figure 1a). Each plot was randomly located within a 91 km^2 hexagonal grid cell, derived from the 7X intensification grid of the Forest Health Monitoring project. Of these, 28 were located on private lands or poorly accessible public lands (e.g. cliff faces or more than a few km off trail over steep terrain), leaving 23 random plots that were used in this study. In some cases, the position of the 'random' plots was slightly altered (< 1 km) to place the plot in forest, to reduce interference with the public, or to make it safely accessible. In all cases, the final plot placement was chosen prior to arrival at the point to avoid bias. Twelve additional plots were placed to help fill in geographical or environmental gaps; ten in the Park Range and one in each of the Elkhead and Flat Top mountain ranges (Figure 1b). For these additional plots, algorithms appropriate to the particular area for determining the final plot placement were chosen prior to leaving the vehicle (e.g. 200 m up the trail then 50 m to the right, perpendicular to the trail). Coordinates for all plots, along with some directions, are given in appendix A). Coordinates for all plots were found with, or recorded with, a Global Positioning System (GPS) with 15 m horizontal accuracy.

Figure 1. Plot locations in northwestern Colorado.



Sampling

Since the study focused on community composition, determining species presence was more important than quantifying the common species. Relative to numerous small plots, the use of a single large plot in each stand emphasized species capture over quantitative accuracy (McCune & Lesica 1992). The plot size and sampling followed the off-frame plot methods developed for the FHM program (Tallent-Halsell 1994; McCune et al. 1997; McCune 2000). Plots were circular with a radius of 34.7 m, yielding an area of 0.38 ha. Plot centers were permanently marked with an iron rod hammered into the ground and a white PVC pipe rising above the ground. The first author sampled all plots by ocular survey and recorded all macrolichen species found on: (1) woody vegetation (alive or dead) greater than 0.5 m above ground and accessible without climbing trees, and (2) recent litterfall, which provides a representation of the canopy epiphytes (McCune 1994). The survey time was limited to 2 hrs, with a minimum time of 0.5 hrs. Surveys stopped short of the maximum time only after (1) examining representatives of all microhabitats within the plot and (2) 10 minutes had elapsed without encountering a new species. The maximum time limit in this methodology is to prevent unequal sampling between areas that may or may not intrigue the sampler. Each species was assigned an abundance score as follows: 0 = absent; 1 = rare (1-3 thalli in plot), 2 = uncommon (4-10 thalli per plot), 3 = common (> 10 thalli per plot but less than half of appropriate substrates bearing the species, or if born by most of the appropriate substrate, then that substrate dominates in less than half of the plot), 4 = very abundant (more than half of appropriate substrates bearing the species). Individual thalli are difficult to distinguish in strongly colonial lichens such as species of *Cladonia* (DePriest 1993, 1994); we considered a continuous colony equal to an individual thallus. *Cladonia coniocraea* is difficult to distinguish from *C. ochrochlora* Flörke and may include some members of the latter species. *Usnea lapponica* and *U. substerilis* overlap in morphological characters so some poorly developed specimens could be misidentified. A number of specimens in the genera *Bryoria* and *Melanelia*, and the family Physciaceae were sent to experts for confirmation or final identification.

In addition to assessing the lichen community in each plot, we measured the prevailing slope and aspect with a compass and clinometer. These were transformed for analysis into a heat index with

Equation 4: Heat Index = $\left(\left(\frac{1-\cos(Aspect-45)}{2}\right)-0.5\right)\bullet\left(\frac{1-\cos(4\bullet Slope)}{2}\right)+0.5$

where *Slope* and *Aspect* are measured in degrees. Values range from zero (northeast facing 45° slope) to one (southwest facing 45° slope). Canopy cover was visually estimated from 5 subplots: at the plot center and at 4 equidistant points around the circumference. The subplots involved checking presence or absence of canopy directly above 5 points: the point for which the estimation was being made and 4 equidistant points at 5 meters from the central point (yielding canopy cover at 20% increments). Measurements from the 5 areas around the entire plot were then averaged for analysis of canopy density. Basal area for each tree genus was measured with an angle gauge at the same 5 subplots around the plot then averaged for the analysis; a standard deviation among the 5 subplots was calculated to analyze within-plot variation in tree density. We described topographic position into ranked categories (e.g. ridge, upper slope, mid slope, etc.). GPS elevation accuracy is frequently cited as 3 times that of its horizontal accuracy (= 45 m for the unit used), so USGS 30 m Digital Elevation Models were used to determine the elevations used for analysis (15 m accuracy; USGS s.d.). Average annual precipitation was determined from PRISM precipitation maps in vector format available from the internet (Daly et al. 1994; PRISM s.d.). Diameter at breast height (DBH) was measured for the largest conifer and the largest hardwood in the plot (consistently *Populus tremuloides* when any hardwoods were present). The same trees were cored with an 18 inch increment borer to determine maximum age of conifers and hardwoods. Cores were not taken from trees in plots at highly public places; for these, the age was estimated by regressing the age of cored trees with variables for DBH and tree species. All environmental and geographic measures are summarized in Table 1.

Data Analysis

As part of our goal of documenting the nature and degree of impacts to the lichen communities from pollution emissions, we searched for patterns in the lichen communities that might relate to pollution. This required one or more variables to represent the expected pollution patterns for correlating to lichen community patterns. Given the diverse topography, the pollution pattern may be complex. Thus two variables were chosen as pollution surrogates with no *a priori* way to determine which might better represent pollution: (1) distance from Steamboat

Springs and (2) distance from the Hayden (nearest) power plant. The first contrasts plots near the expected focal point of pollution coming up the valley, from more distant plots, forming a bimodal latitudinal gradient. The second includes the bimodal latitudinal gradient, but also incorporates an east-west gradient by contrasting plots in the foothills versus the higher mountains of the Park Range. Distances were calculated in ArcView 3.2 (ESRI 1999).

Table 1. Summary of environmental and geographic measures.

Abbreviation	Range	Notes
Elevation	2170 – 3306 m	Elevation of plot from USGS Digital Elevation Models
Heat Index	0.34 – 0.61	Calculated from slope and aspect with equation 4
Topo code	1 – 6	Consecutive values for topographic position, from riparian valley bottom to ridge top.
Conifer DBH	0 – 94 cm	DBH = diameter at breast height
Conifer BA	0 – 234 ft^2/acre	BA = basal area (cross-sectional area at breast height)
Conifer Age	0 – 507 yrs	Age of oldest conifer in plot
Conifer Richness	0 – 3	Number of conifer tree species in plot
Hardwood DBH	0 – 57 cm	DBH = diameter at breast height
Hardwood BA	0 – 122 ft^2/acre	BA = basal area (cross-sectional area at breast height)
Hardwood Age	0 – 197 yrs	Age of oldest hardwood in plot
Hardwood Richness	0 – 3	Number of hardwood tree species in plot
Hardwood P/A	0 – 1	Presence or absence of hardwood trees in plot
Total BA	18 – 234 ft^2/acre	BA = basal area (cross-sectional area at breast height)
SD BA	11 – 117	Standard deviation of 5 BA measurements at each plot
Maximum Age	50 – 507 yrs	Age of oldest conifer or hardwood in plot
Total Richness	1 – 4	Number of tree species in plot
Canopy Density	16 – 88 %	Estimated canopy density (see methods)
June Precipitation	1.25 – 2.25 in.	Estimated June precipitation from Daly et al. (1994)
July Precipitation	1.25 – 2.25 in.	Estimated July precipitation from Daly et al. (1994)
August Precipitation	1.25 – 2.25 in.	Estimated August precipitation from Daly et al. (1994)
Annual Precipitation	19 – 63 in.	Estimated Annual precipitation from Daly et al. (1994)
KM-Hayden	25 – 67 km	Distance to the Hayden power plant
KM-Steamboat	6 – 54 km	Distance to center of the town of Steamboat Springs
S	10 – 53	Sum of abundance scores for all spp. in plot
S_{poll}	0 – 16	Sum of abundance scores for pollution tolerant spp.
Raw Air Score	55.6 – 100	See equation 1
Adjusted Air Score	-1.84 – 2.19	See equation 3, *f*(environment) different from McCune et al. (1998); see results.
Bryoria fuscescens	0 – 4	Abundance of *B. fuscescens*
Bryoria Sum	0 – 11	Sum of abundance scores for *Bryoria* spp.
AdjBfus	-2.28 – 2.08	Adjusted *B. fuscescens* abundance scores

We summarized lichen diversity as species richness (alpha), community turnover (beta), landscape diversity (gamma), and the Shannon diversity index (Greig-Smith 1983). We calculated raw air scores using equation 1 and the list of pollution indicators from McCune et al. (1998). Our study found some species that were not found by the previous study. *Xanthoria fulva* is presumed to be a pollution indicator because it is a recent segregate of *X. fallax* and was included with that species in the original analysis by McCune et al. (1998). Otherwise we considered species unique to our study as not indicative of pollution. We then adjusted the air scores with the method from McCune et al. (equation 2). To determine $f(environment)$ we regressed our raw air scores on environmental variables that were identified as lichen community correlates by the ordination of our data set (below). Correlations between environmental and geographic variables (e.g. distance from the Hayden power plant), and our locally adjusted air scores were then calculated with Pearson's r^2. The air scores are solely based on the presence of <u>pollution tolerant</u> species, however our data set includes the genus *Bryoria*, which is <u>pollution sensitive</u> (Van Dobben 1993). Therefore we also examined the abundance of the most frequent member of that genus, and the sum of abundance scores across the genus, for correlations with environmental and geographic variables. The *Bryoria* variable with the strongest correlation was adjusted in the same manner as the air scores. Since predicted abundance values at some sites could be negative, we set a lower limit of zero for $f(environment)$. The adjusted *Bryoria* score was then examined for a maintained correlation with geographic variables.

To understand the relevance of ecological gradients to the macrolichen communities we sampled, we conducted multivariate analyses with PC-ORD 4.06 (McCune & Mefford 1999). We analyzed interrelationships between taxa and relationships of taxa to stand structure, composition, and environmental features by ordinating plots in species space with NMS (non-metric multidimensional scaling; Kruskal 1964; Mather 1976) and overlaying environmental variables. NMS uses an iterative search for an ordination with low stress, as measured by the relationship between ranked distances in the original multidimensional space and the ranked distances in the reduced dimensions of the ordination. To determine the number of dimensions for the final ordination, NMS was first run in autopilot mode with 90 runs for each of 6 dimensionalities with random initial configurations and the minimum stress obtained was plotted for each dimensionality. The number of dimensions used for the final ordination was determined by the 'break' in the curve. To ensure that the ordination avoids a local stress minimum, the final analysis was run 1000 times with random initial configurations; the run resulting in the lowest final stress was used for the analyses. NMS was used in the global form with a stability criterion of 0.00001, and ending after 500 iterations or 50 continuous iterations within the stability criterion. Following the suggestion of testing multiple ordinations (Økland 1996) we also ran Bray-Curtis ordination (Beals 1984, McCune and Beals 1993) to check that our final NMS solution accounted for more of the initial variation in the dataset than the Bray-Curtis ordination and that both ordinations revealed similar patterns. Correlations between the NMS ordination and the environmental variables were calculated with both Pearson's r^2. Percent of variation in the original data that was included in the ordination was calculated with Pearson's r^2 correlating the distances between plots in the ordination with the distances in the original data.

We also used NMS in a predictive mode to fit our plots to the ordination of McCune et al. (1998). In doing so, we had to adjust our data set to match theirs, using several species groups. Thus *Bryoria* species other than *B. fuscescens* were grouped as "*Bryoria*", *Usnea substerilis* was grouped into *U. lapponica*, and *Xanthoria fulva* was grouped into *X. fallax*. In grouping the species, the maximum abundance value among the species in the group was used. *Usnea cavernosa* was not placed in the *Usnea* group because it is a very distinctive species and would likely have been kept separate if it had been found in the previous study. Species unique to our data set and not fitting into one of their species groups were kept as independent species. We compared the pattern of our plots fitted to that ordination to the distance from the Hayden power plant by rotating the ordination until the McCune et al. adjusted air score vector was weighted entirely onto the first axis, then removing the McCune et al plots and correlating the distance variable with the first axis for just our plots.

To assess bias in the selection of the non-randomly located plots, we used MRPP (Multi-Response Permutation Procedure; Biondini et al. 1985). MRPP tests for differences in communities between groups. In addition to providing a *p*-value, MRPP also provides a measure within-group variation relative to the total data set variation. When within-group variation is less than expected from total variation, *R* greater than zero (possible values from -1 to +1); when within group variation is greater than expected from total variation, *R* less than zero. Generally a groups with different communities will have *R* substantially greater than zero.

To reduce noise from rare species, those occurring in less than five percent of the plots (two or fewer) were deleted from the data set prior to multivariate analyses; for NMS in predictive mode, this was applied only to species unique to our data set. The quantitative version of Sørensen distance was used for MRPP, NMS, and Bray-Curtis ordination. Ordination of biotic community data benefits from NMS over other ordination techniques by having no assumption of multivariate normality, being robust to a large proportion of zero values, and having been demonstrated to yield the most accurate representation of underlying data structure with several test data sets (Minchin 1987; Clarke 1993). MRPP is also non-parametric and robust to typical community datasets. Data from this study are stored on the accompanying compact disk. A guide to the files is provided in Appendix B.

RESULTS

General Descriptors

Plots were distributed across a broad elevational range from 2170 m, at the base of the Park Range, to 3306 m, within 1 km of the continental divide. Estimated annual precipitation at these sites ranges from 48 cm to 160 cm. Maximum tree age ranged from 50 to 507 years. Five plots included small streams or lake edges with riparian vegetation. Twenty two plots lacked hardwood trees while only one entirely lacked conifer trees.

A total of 42 species of lichen were found among the 35 plots (Table 2). Species richness (alpha diversity) within plots ranged from 4 to 17 species ($\bar{x}$ = 10.76; *SD* = 3.65). Deleting species that occurred in less than 5 percent of the plots (2 or fewer plots) for the multivariate analyses left a data set of 25 species. Plots that were randomly chosen did not differ significantly

Table 2. Species found in study, along with abbreviations for those plotted on the ordination (Abbr.), the number of plots in which the species occurred (Occur.), and the Pearson correlation (*r*) of the species' abundance and distance from the Hayden power plant (Hayden). Species in bold are pollution indicators (McCune et al. 1998).

Species	Abbr.	Occur.	Hayden
Bryoria fremontii (Tuck.) Brodo & D. Hawksw.	Bryo frem	8	0.29
Bryoria fuscescens (Gyelnik) Brodo & D. Hawksw.	Bryo fusc	28	0.61
Bryoria lanestris (Ach.) Brodo & D. Hawksw.	Bryo lane	6	0.23
Candelaria concolor **(Dickson) Stein**	Cand conc	31	-0.06
Cladonia chlorophaea (Flörke ex Sommerf.) Sprengel	-	1	0.12
Cladonia coniocraea (Flörke) Sprengel *group*	Clad coni	3	0.05
Cladonia fimbriata (L.) Fr.	-	2	0.10
Evernia divaricata (L.) Ach.	Ever diva	5	-0.01
Hypogymnia austerodes (Nyl.) Ras.	-	2	0.02
Melanelia elegantula **(Zahlbr.) Essl.**	Mela eleg	25	-0.11

Table 2 (continued)

Melanelia exasperatula (Nyl.) Essl.	Mela exas	34	-0.08
Melanelia subelegantula (Essl.) Essl.	Mela sube	4	-0.26
Melanelia subolivacea (Nyl.) Essl.	Mela subo	16	-0.67
Parmeliopsis ambigua (Wulfen) Nyl.	Pops ambi	8	0.25
Parmeliopsis hyperopta (Ach.) Arnold	-	1	0.12
Phaeophyscia cernohorskyi (Nadv.) Essl.	Phph cern	5	-0.24
Phaeophyscia ciliata (Hoffm.) Moberg	Phph cili	5	-0.33
Phaeophyscia decolor (Kashiw.) Essl.	-	1	-0.18
***Phaeophyscia nigricans* (Flörke) Moberg**	Phph nigr	6	-0.17
***Phaeophyscia orbicularis* (Neck.) Moberg**	Phph orbi	5	-0.33
Physcia adscendens (Fr.) H. Olivier	Phys adsc	27	-0.30
***Physcia aipolia* (Ehrh. ex Humb.) Fürur**	**-**	2	-0.26
***Physcia biziana* (Massal.) Zahlbr.**	**-**	1	-0.18
Physcia dimidiata (Arnold) Nyl.	-	2	-0.26
Physcia dubia (Hoffm.) Lett.	-	2	-0.24
Physcia stellaris (L.) Nyl.	Phys stel	12	-0.57
Physcia tenella (Scop.) DC.	Phys tene	25	-0.35
Physcia tribacia (Ach.) Nyl.	-	1	-0.18
***Physciella chloantha* (Ach.) Essl.**	Phll chlo	3	-0.16
Physconia enteroxantha (Nyl.) Poelt	-	2	-0.23
Ramalina obtusata (Arnold) Bitter	-	1	-0.11
Ramalina sinensis Jatta	-	2	0.03
Rhizoplaca chrysoleuca (Sm.) Zopf	-	2	0.11
Usnea cavernosa Tuck.	Usne cave	5	0.23
Usnea hirta (L.) F. H. Wigg.	-	1	0.34
Usnea lapponica Vainio	Usne lapp	19	0.52
Usnea substerilis Mot.	Usne subs	34	0.00
Vulpicida pinastri (Scop.) J. -E. Mattsson & M. J. Lai	-	2	0.13
***Xanthoria fallax* (Hepp) Arnold**	Xant fall	13	-0.60
***Xanthoria fulva* (Hoffm.) Poelt & Pet.**	Xant fulv	16	-0.52
Xanthoria montana Lindblom	Xant mont	23	-0.49
Xanthoria polycarpa (Hoffm.) Rieber	-	1	0.06

in community composition from the additional, more arbitrarily chosen plots (MRPP; p = 0.107, R = 0.015), suggesting that bias was avoided in the selection of the additional plots. Measures of lichen diversity are given in Table 3 and correlation values between environmental, geographic, and several lichen community variables are provided in Table 4.

Table 3. Diversity measures.

Alpha (α)	11.2
Beta ($\beta = \gamma / \alpha$)	3.75
Gamma (γ)	42
Shannon Diversity Index (H)	2.295

Gradients in Lichen Communities

NMS of the 35 plots resulted in a two dimensional ordination (Figures 2, 3, & 4) that accounted for 73.4 % of the variation in the original data set (51.7 % on axis 1 and 21.7 % on axis 2). For comparison, BC ordination accounted for 45.8 % (39.7 % on axis 1 and 6.2 % on axis 2). Although the BC ordination was largely 1 dimensional, it did show correlations similar to those of the NMS ordination. The ordinations revealed that the dominant lichen community gradient corresponded to a transition between plots with a large hardwood component and plots that were in pure or nearly pure conifer forests. Elevation was correlated with this gradient, as there was a general pattern of hardwood trees dominating lower elevations and completely disappearing at high elevations. Estimated July precipitation was also correlated, possibly due to the increase in thunderstorm precipitation at higher elevations. The second axis of the ordination was less easy to explain as no environmental gradients correlated with it. Species that plotted high on the second axis (particularly *Bryoria fremontii*, *B. lanestris*, *Evernia divaricata*, and *Usnea cavernosa*) were pollution sensitive or characteristic of late successional, structurally heterogeneous conifer stands. Rotating the ordination to maximize the weight of these species on axis 2 reveals a substantial correlation between the post-rotation axis and the distance from Hayden ($r = 0.56$, $r^2 = 0.32$). Since many sites from the Rabbit Ears Pass and Buffalo Pass areas plotted high on this rotated axis (Figure 5), it did not correlate with distance from Steamboat Springs.

Figure 2. NMS stress reduction from increasing dimensionality. Stress values are plotted from the NMS analysis in autopilot mode, including 90 runs and 400 iterations for each of 6 dimensionalities.

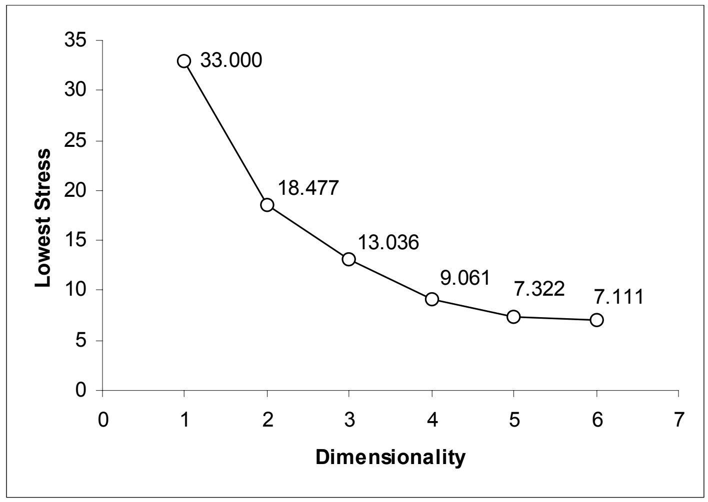


Table 4. Pearson correlations between all variables examined, including environmental, geographic, and several lichen community factors. Numbers below the diagonal are *r* values, while above the diagonal they are r^2 values (values $\geq$ 0.20 in red). See Table 1 for abbreviations.

	Elevation	Heat Index	Topo code	Conifer DBH	Conifer BA	Conifer AGE	Conifer Rich.	Hardwood DBH	Hardwood BA	Hardwood AGE	Hardwood Rich	Hardwood P/A	Total BA	SD BA	Maximum Age	Total Richness	Canopy Density	June Precip.	July Precip.	August Precip.	Annual Precip.	KM-Hayden	KM-Steamboat	**S**	*S*poll	Raw Air Score	Adjusted Air Score	***Bryoria fuscescens***	*Bryoria* Sum	AdjBfus
Elevation	-	0.00	**0.40**	**0.33**	0.11	**0.57**	0.01	**0.35**	0.17	**0.35**	**0.39**	**0.45**	0.11	0.13	**0.47**	**0.28**	0.09	**0.56**	**0.32**	**0.39**	**0.67**	0.14	0.00	**0.46**	**0.38**	0.06	0.00	0.02	0.02	0.00
Heat Index	-0.06	-	0.02	0.00	0.00	0.02	0.00	0.00	0.01	0.00	0.01	0.02	0.01	0.00	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.01	0.08	0.02	0.00	0.04
Topo code	0.63	-0.15	-	0.03	0.00	0.21	0.11	0.11	0.01	0.10	0.04	0.05	0.01	0.00	0.18	0.14	0.00	**0.26**	0.14	**0.54**	**0.24**	0.02	0.11	0.17	0.05	0.00	0.00	0.01	0.01	0.01
Conifer DBH	0.57	0.01	0.18	-	0.02	**0.35**	0.02	0.11	0.02	0.11	0.12	0.21	0.01	0.06	**0.29**	0.01	0.08	**0.26**	0.04	0.05	**0.33**	0.02	0.00	0.03	0.05	0.00	0.00	0.00	0.03	0.00
Conifer BA	0.33	0.02	0.05	0.14	-	0.03	0.15	0.02	**0.21**	0.02	0.11	0.04	0.01	0.01	0.01	0.00	0.22	0.00	0.02	0.03	0.06	0.04	0.01	0.03	0.13	0.19	0.04	0.08	0.05	0.01
Conifer AGE	0.76	-0.15	0.45	0.59	0.18	-	0.00	0.17	0.07	0.15	0.17	**0.24**	0.05	0.08	**0.95**	0.12	0.04	**0.50**	**0.29**	**0.25**	0.50	0.12	0.01	**0.20**	**0.20**	0.01	0.00	0.02	0.06	0.02
Conifer Rich.	-0.09	0.07	-0.32	0.15	0.39	-0.05	-	0.02	0.01	0.01	0.05	0.01	0.00	0.01	0.01	**0.42**	0.15	0.03	0.00	0.13	0.02	0.00	0.12	0.01	0.03	0.12	0.01	0.01	0.01	0.00
Hardwood DBH	-0.59	-0.04	-0.33	-0.34	-0.15	-0.41	0.12	-	0.17	**0.98**	**0.52**	**0.80**	0.16	0.00	0.07	**0.28**	0.10	0.11	0.14	0.11	**0.25**	**0.35**	0.01	**0.46**	**0.45**	0.18	0.00	0.15	0.09	0.00
Hardwood BA	-0.41	-0.08	-0.11	-0.12	-0.46	-0.27	-0.12	0.41	-	0.19	**0.51**	**0.27**	**0.87**	0.00	0.06	**0.25**	0.06	0.09	0.08	0.08	0.13	0.05	0.02	**0.28**	0.39	0.16	0.02	0.02	0.03	0.00
Hardwood AGE	-0.59	-0.06	-0.31	-0.33	-0.15	-0.39	0.10	0.99	0.44	-	**0.52**	**0.82**	0.18	0.00	0.07	**0.27**	0.12	0.10	0.12	0.11	**0.26**	**0.29**	0.01	**0.52**	**0.49**	0.18	0.00	0.10	0.05	0.00
Hardwood Rich.	-0.63	-0.07	-0.20	-0.34	-0.33	-0.41	-0.23	0.72	0.71	0.72	-	**0.75**	**0.44**	0.00	0.12	**0.29**	0.10	0.16	**0.23**	0.06	0.17	**0.27**	0.11	**0.42**	**0.59**	0.28	0.01	0.13	0.09	0.01
Hardwood P/A	-0.67	-0.13	-0.22	-0.46	-0.21	-0.49	-0.08	0.90	0.52	0.90	0.86	-	**0.24**	0.00	0.16	**0.29**	0.14	0.19	**0.21**	0.08	**0.27**	**0.31**	0.05	**0.53**	**0.64**	**0.29**	0.01	0.08	0.07	0.00
Total BA	-0.33	-0.08	-0.11	-0.08	-0.11	-0.23	0.03	0.40	0.93	0.42	0.66	0.49	-	0.01	0.05	**0.35**	**0.22**	0.10	0.08	0.06	0.09	0.03	0.01	**0.27**	**0.31**	0.07	0.01	0.00	0.01	0.00
SD BA	0.36	0.07	0.05	0.25	0.08	0.29	0.08	0.07	0.06	0.04	0.06	-0.03	0.10	-	0.08	0.00	0.06	0.14	0.02	0.00	0.14	0.02	0.00	0.02	0.00	0.05	0.03	0.08	0.09	0.00
Maximum Age	0.69	-0.18	0.43	0.54	0.12	0.98	-0.07	-0.27	-0.25	-0.26	-0.35	-0.40	-0.23	0.29	-	0.12	0.06	**0.51**	**0.28**	**0.24**	**0.41**	0.06	0.00	0.15	0.14	0.00	0.00	0.00	0.03	0.02
Total Richness	-0.53	0.01	-0.38	-0.12	0.07	-0.34	0.65	0.53	0.50	0.52	0.54	0.54	0.59	0.04	-0.35	-	**0.37**	**0.21**	0.13	**0.25**	0.15	0.05	0.00	**0.34**	0.19	0.01	0.00	0.01	0.00	0.00
Canopy Density	-0.30	-0.02	-0.03	-0.29	0.47	-0.21	0.39	0.31	0.25	0.34	0.32	0.37	0.47	-0.24	-0.24	0.61	-	0.16	0.02	0.03	0.12	0.00	0.01	0.12	0.07	0.00	0.00	0.04	0.01	0.00
June Precip.	0.75	-0.04	0.51	0.51	0.05	0.71	-0.16	-0.33	-0.30	-0.32	-0.40	-0.44	-0.32	0.38	0.71	-0.46	-0.41	-	0.15	**0.31**	**0.62**	0.01	0.03	**0.20**	0.13	0.00	0.01	0.04	0.00	0.02
July Precip	0.56	-0.02	0.37	0.19	0.13	0.54	0.02	-0.37	-0.29	-0.35	-0.48	-0.46	-0.27	0.12	0.53	-0.36	-0.16	0.38	-	**0.31**	0.05	**0.43**	**0.27**	**0.26**	**0.31**	0.14	0.05	0.07	0.04	0.02
August Precip.	0.63	-0.06	0.73	0.23	0.17	0.50	-0.36	-0.32	-0.28	-0.33	-0.25	-0.29	-0.24	0.03	0.49	-0.50	-0.16	0.55	0.56	-	**0.23**	0.04	0.05	**0.26**	0.12	0.00	0.01	0.00	0.00	0.00
Annual Precip.	0.82	0.06	0.49	0.57	0.23	0.71	-0.14	-0.50	-0.36	-0.51	-0.41	-0.52	-0.30	0.37	0.64	-0.39	-0.35	0.79	0.21	0.48	-	0.01	0.12	**0.29**	**0.20**	0.01	0.00	0.00	0.01	0.00
KM-Hayden	0.38	0.06	0.12	0.15	0.20	0.34	0.06	-0.59	-0.22	-0.53	-0.52	-0.56	-0.17	-0.13	0.24	-0.22	0.04	0.09	0.66	0.21	0.12	-	**0.48**	0.14	**0.26**	**0.22**	0.01	**0.38**	**0.24**	0.02
KM-Steamboat	-0.02	-0.03	-0.33	-0.06	0.12	0.08	0.34	-0.11	-0.14	-0.09	-0.32	-0.23	-0.11	0.02	0.05	0.01	0.11	-0.17	0.52	-0.22	-0.34	0.69	-	0.00	0.07	0.14	0.00	0.21	0.10	0.04
S	-0.68	-0.12	-0.42	-0.18	-0.18	-0.45	0.11	0.68	0.53	0.72	0.65	0.73	0.52	-0.13	-0.39	0.58	0.35	-0.45	-0.51	-0.51	-0.54	-0.37	-0.07	-	**0.59**	0.07	0.01	0.00	0.01	0.02
*S*poll	-0.62	0.00	-0.22	-0.22	-0.36	-0.45	-0.17	0.67	0.63	0.70	0.77	0.80	0.55	0.03	-0.38	0.44	0.26	-0.35	-0.55	-0.35	-0.45	-0.51	-0.27	0.77	-	**0.63**	0.14	0.10	0.11	0.00
Raw Air Score	0.25	-0.12	-0.06	0.06	0.44	0.12	0.34	-0.42	-0.40	-0.43	-0.53	-0.54	-0.27	-0.23	0.05	-0.11	0.03	0.03	0.37	0.06	0.09	0.47	0.38	-0.27	-0.79	-	**0.48**	0.21	**0.27**	0.02
Adjusted Air Sc.	0.02	-0.29	-0.02	-0.07	0.19	0.02	0.10	-0.03	-0.14	-0.04	-0.12	-0.09	-0.07	-0.16	0.05	-0.02	-0.05	0.10	0.22	0.09	-0.01	0.07	0.06	0.09	-0.37	0.69	-	0.01	0.08	0.05
B. fuscescens	0.13	-0.13	0.11	0.04	0.28	0.15	0.11	-0.39	-0.14	-0.32	-0.36	-0.29	-0.04	-0.28	0.05	-0.08	0.19	-0.19	0.26	0.00	-0.03	0.61	0.46	-0.03	-0.31	0.46	0.10	-	**0.74**	**0.44**
Bryoria Sum	0.14	-0.04	0.08	0.19	0.22	0.24	0.10	-0.29	-0.19	-0.23	-0.30	-0.26	-0.12	-0.30	0.16	-0.07	0.10	-0.05	0.20	0.00	0.10	0.49	0.32	0.08	-0.33	0.52	0.28	0.86	-	**0.37**
AdjBfus	0.00	-0.20	0.12	-0.01	0.11	0.13	0.04	-0.02	-0.04	-0.01	-0.08	0.03	0.00	-0.05	0.13	-0.02	0.02	-0.13	0.13	0.06	-0.02	0.16	0.20	0.13	-0.02	0.14	0.23	0.67	0.61	-

Figure 3. Final NMS ordination with variables jointly plotted. Circles represent the ordered position of the plots on two axes. Labeled lines represent environmental and other variables; the length of the line corresponds to the strength of the correlation with a minimum of $r = 0.200$. HW = hardwood. For other abbreviations, see Table 1.

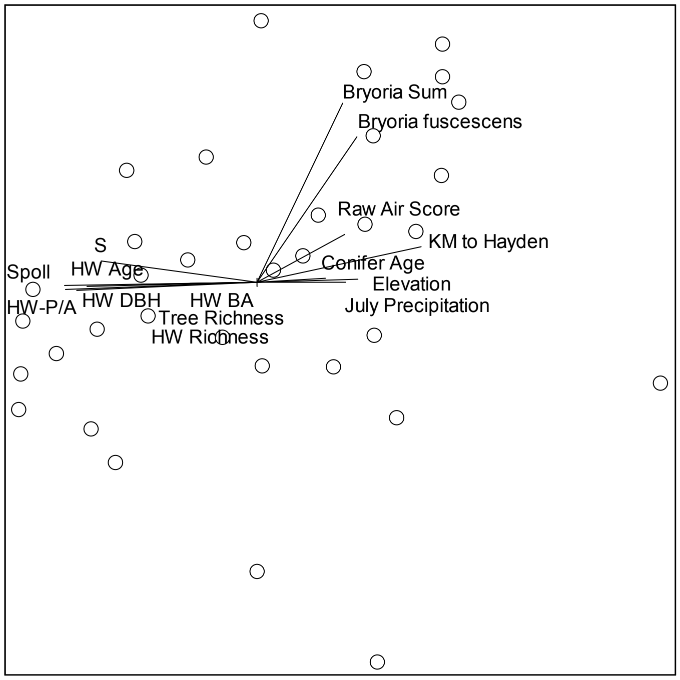


Figure 4. Final NMS ordination with species plotted. Open circles represent the ordered position of the plots on two axes. Dots represent the weighting of species included in the ordination analysis. For species abbreviations, see Table 2.

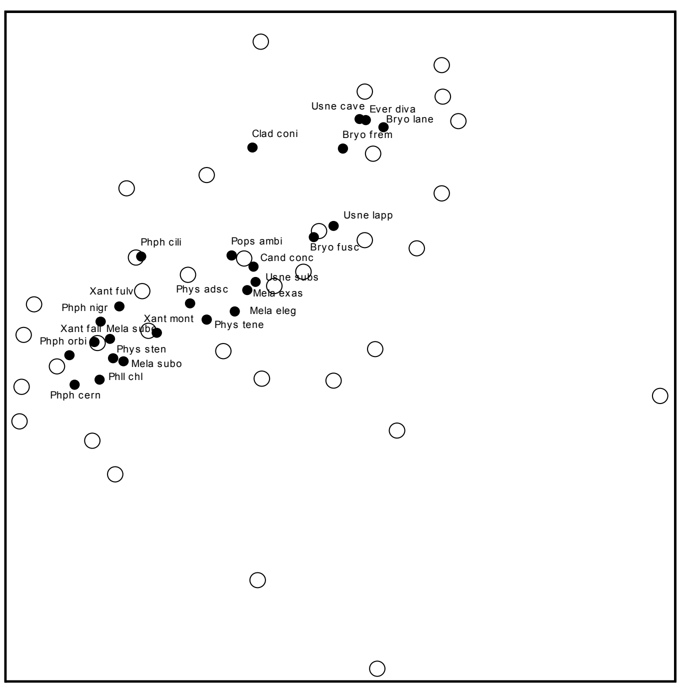
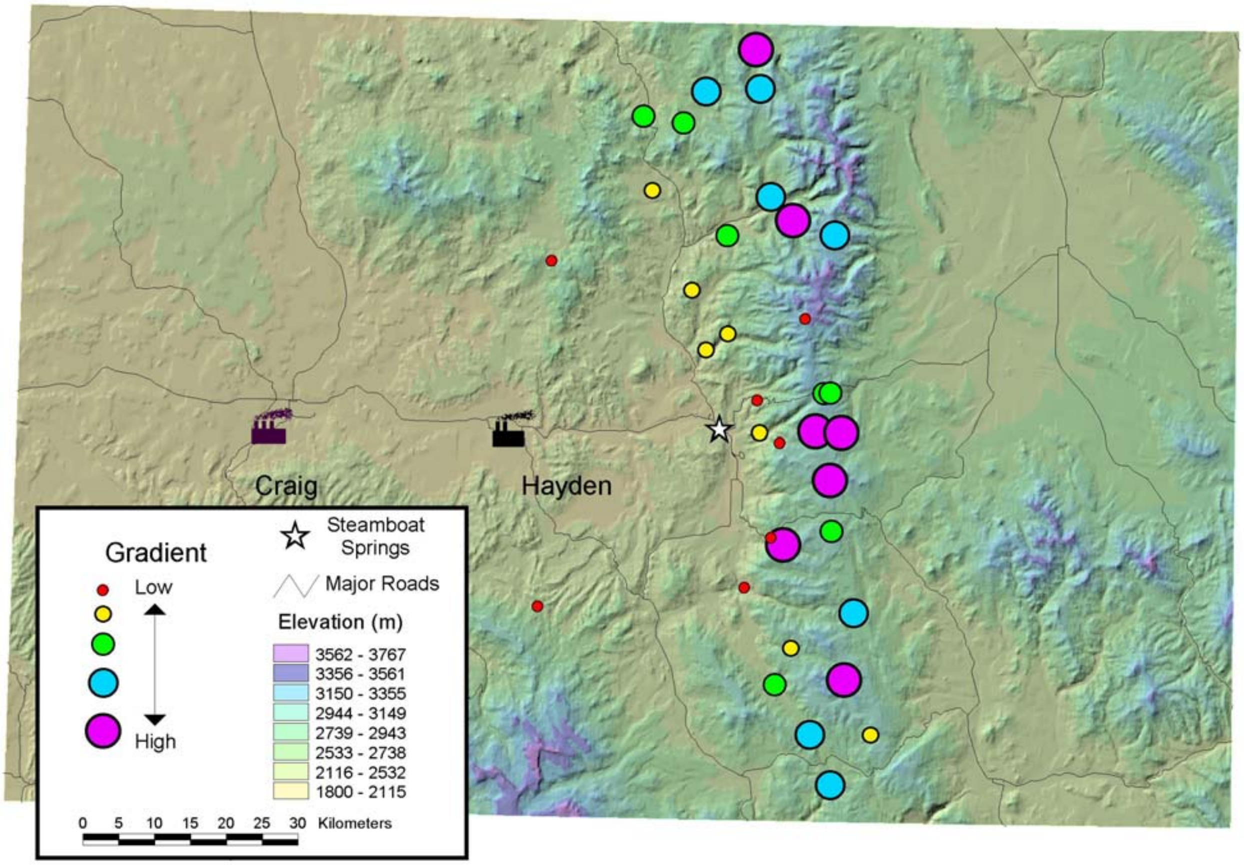
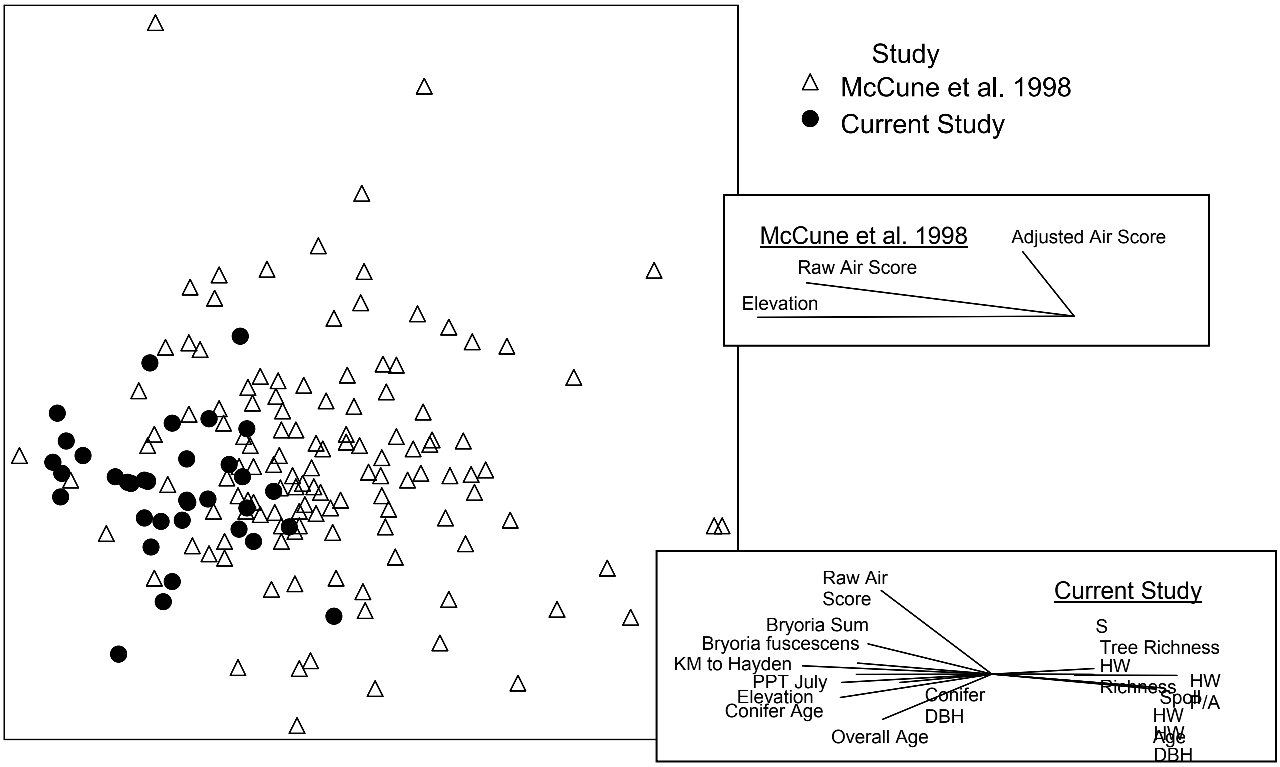


Figure 5. Map of scores form ordination axis 2 rotated to maximize the weight of species that are pollution sensitive and characteristic of late successional, structurally heterogeneous conifer stands.



Use of NMS in predictive mode fitted our plots to a rather small portion of the ordination from McCune et al. (1998; Figure 6). According to the gradients revealed in their ordination, our plots were relatively high in elevation and intermediate to slightly high in air quality. Gradients within our plots on the combined ordination were distorted substantially from the ordination of our plots alone. However, the main trend from hardwood dominated sites at low elevation to pure conifer sites at high elevation was still prevalent. Although the correlation vector for distance from Hayden among our plots was at a different angle from the Adjusted Air Score vector in the McCune et al. plots, scores for our plots on their adjusted air score gradient did correlate with distance from the Hayden power plant ($r = 0.61$, $r^2 = 0.37$).

Figure 6. Current plots scored to NMS ordination of McCune et al. (1998) with variable vectors (insets). The variable vectors represent the strength of variable correlation (length) and the direction (radiating from the centroid of the particular study's plots). HW = hardwood. For other abbreviations, see Table 1.



Air Quality Scores and *Bryoria* Abundance

Raw air scores for our sites ranged from 55.6 to 100 ($\bar{x}$ = 74.7, *SD* = 10.9). Only one site completely lacked species that indicate pollution according to McCune et al. (1998), thus receiving the score of 100. These raw air scores correlated with distance from the Hayden power plant ($r = 0.47$, $r^2 = 0.22$); however, they also correlated strongly with a variety of other environmental variables (Table 4). When the raw air scores were regressed on the environmental variables suggested by our ordination, a much more complex equation was developed than the one used by McCune et al. Our equation became quadratic with respect to elevation and also included the presence of hardwoods (Table 5). The resulting locally adjusted air scores, which corresponded to standard deviations away from the expected value for the site, ranged from –1.84 to 2.19 ($\bar{x}$ = 0.008, *SD* = 0.965). When we tried including the distance from the Hayden power plant in the regression equation it was rejected from the regression equation at $p = 0.714$.

Table 5. Regressions for adjustment of raw air scores and *Bryoria fuscescens* abundance with variables suggested by the NMS ordination joint plot.

Raw Air Score as a function of environment:

Variable	Coefficient	Std Error	Significance
Constant	-374.63	101.77	0.000878
Elevation	0.331	0.07218	0.0000695
Elevation^2	-0.00005973	0.00001277	0.0000542
Hwood(PA)	-9.822	3.345	0.00620

Source	SS	MS	F	F-sig	df
Regression	2102.726	700.9087	13.77923	0.000006949	3
Residual	1576.878	50.86703			31
LOF Error	1576.420	52.54733	114.7660	0.073750	30
Pure Error	0.457865	0.457865			1
Total	3679.604	100			34

R2	0.571
R2 adj	0.530
SE	7.132
Collinearity	0.00184
CV	9.484

Bryoria fuscescens abundance as a function of environment:

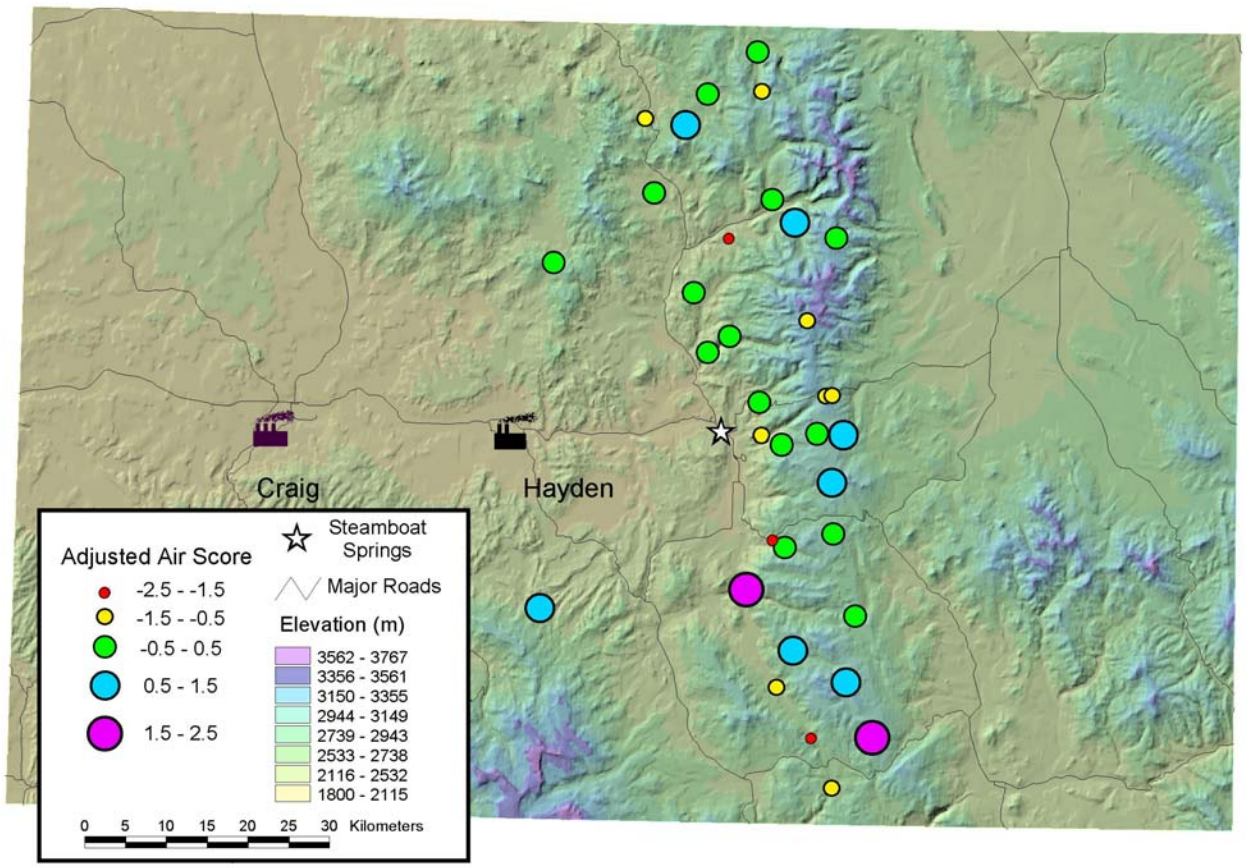
Variable	Coefficient	Std Error	Significance
Constant	-47.52	13.78	0.00169
Elevation	0.03679	0.00987	0.000802
Elevation^2	-0.000006682	0.000001759	0.000662
Hwood DBH	-0.284	0.06878	0.000271
Hwood Age	0.07010	0.01911	0.000944

Source	SS	MS	F	F-sig	df
Regression	40.63071	58	10.27585	0.00002312	4
Residual	29.65501	42	0.988500		30
Total	70.28571	100			34

R2	0.578
R2 adj	0.522
SE	0.994
Collinearity	0.00004312
CV	46.40

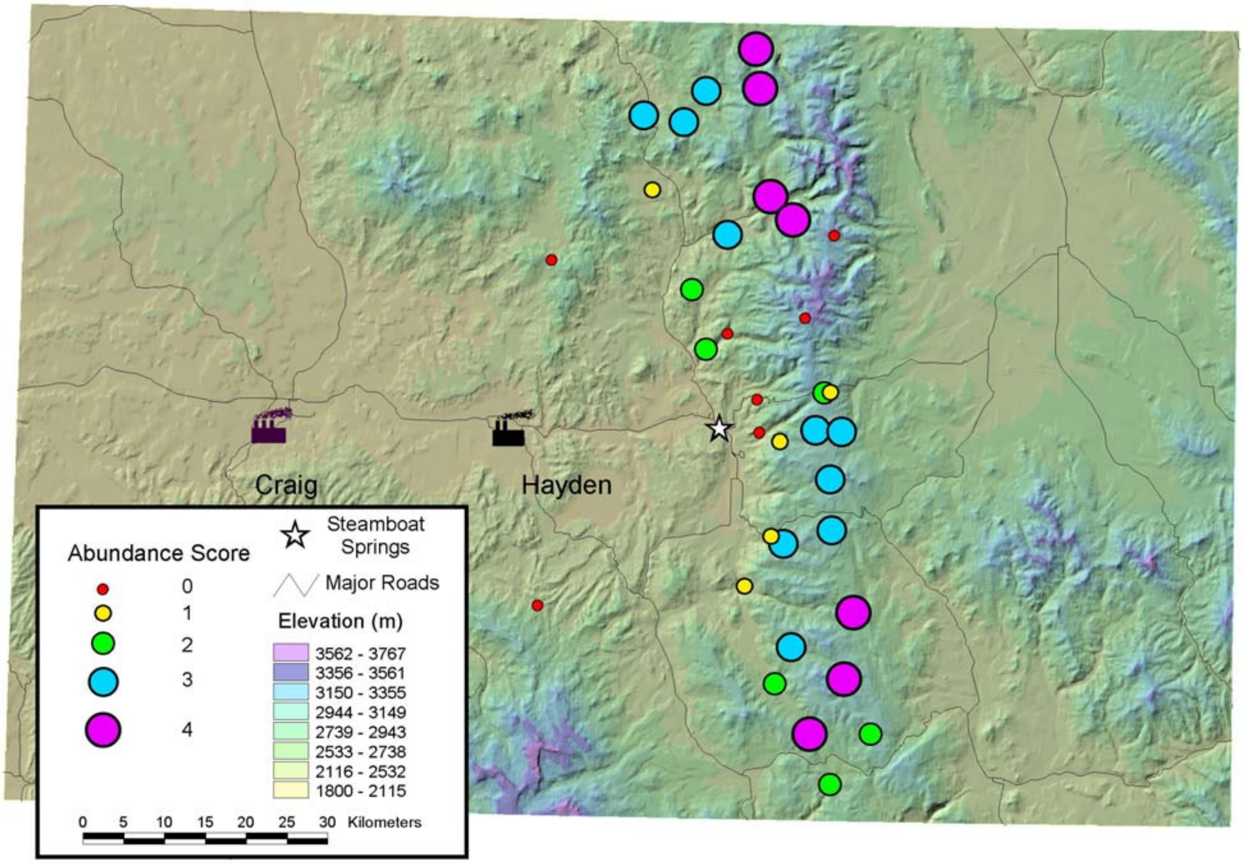
The adjusted air score did not correlate with the distance from the Hayden power plant either (r = -0.17, r^2 = 0.03; Figure 7)

Figure 7. Map of locally adjusted air scores in plots.



Three species of the pollution-sensitive genus *Bryoria* were sampled in our study. Of these, *B. fuscescens* was the most frequent. The sum of abundance scores for the genus correlated well with distance from the Hayden power plant (r = 0.49, r^2 = 0.24), while the abundance of *B. fuscescens* alone correlated even more strongly (r = 0.61, r^2 = 0.38; Figure 8). Adjustment of the abundance of *B. fuscescens* via a regression equation similar to the adjustment for the air score resulted in values from –2.28 to 2.08 ($\bar{x}$ = -0.005, SD = 1.004). With this adjustment, the correlation with distance from the Hayden power plant was lost (r = 0.16, r^2 = 0.02). There appears to be a dip among the highest values of adjusted *B. fuscescens* abundance between Rabbit Ears Pass and Buffalo Pass (Figure 9). However, the noise of various sites throughout the mountain range prevents acceptably strong correlations between adjusted *B. fuscescens* values and the distance from Hayden, from Steamboat Springs, or from the area of the

Figure 8. Map of *Bryoria fuscescens* abundance (raw) in plots.

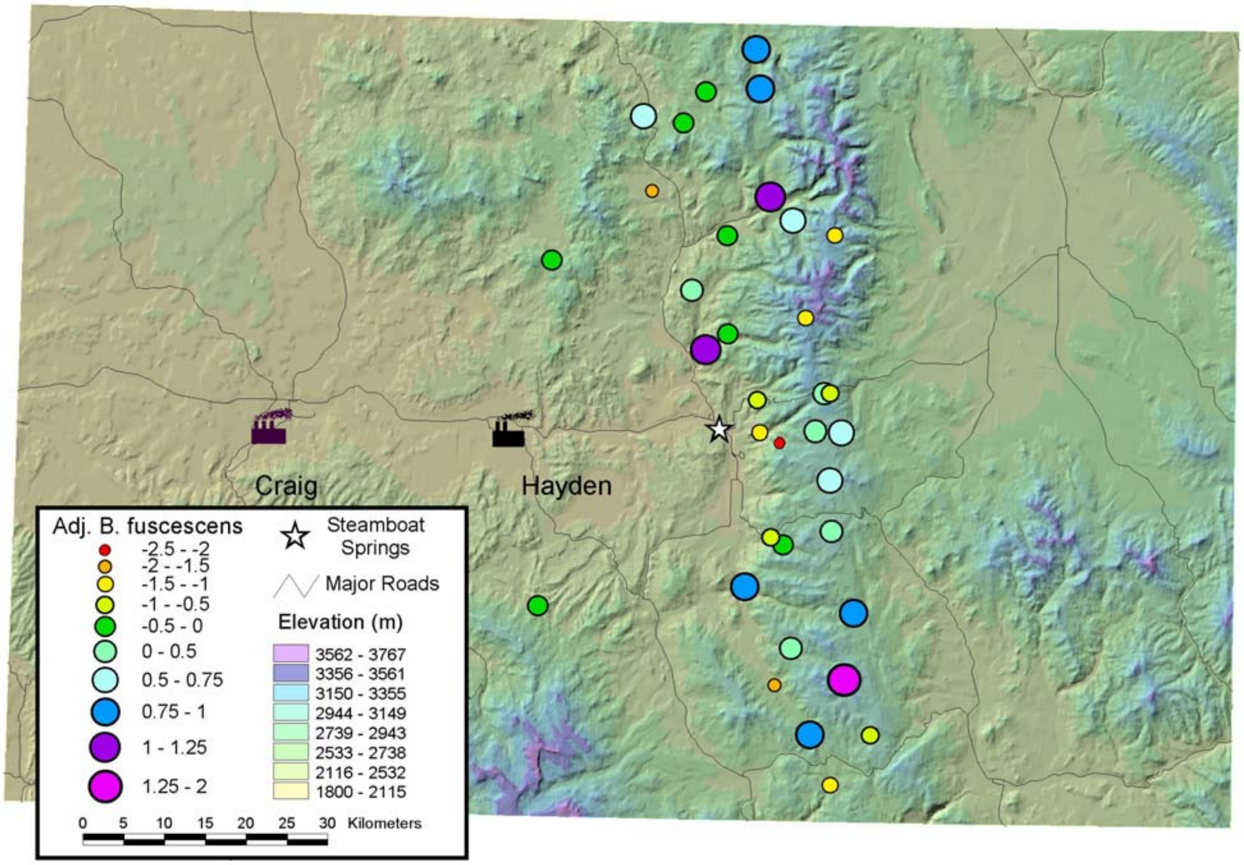


passes. The noise remains problematic even when the data set is restricted to coniferous sites within the range of elevations that appear best for *B. fuscescens* (2500 – 3200 m).

Discussion

The microhabitats in which lichens grow can vary greatly within a geographic region depending on forest structure, age, and tree species (Tibell 1992; McCune 1993; Peterson & McCune 2001). Differences in elevation and precipitation add further variation (Hyvärinen et al. 1992; Holien 1996; Peterson & McCune 2001). So in regions where forests encompass a broad range of densities, grow over diverse topography, and range from pure hardwood stands to pure conifer stands, detecting clear patterns in lichen communities on top of these other factors can be very challenging and must involve consideration of these environmental complexities.

Figure 9. Map of adjusted *Bryoria fuscescens* abundance in plots. Symbols encoded to increase resolution of high adjusted values.



The Park Range Complexities

Two variables were identified as possible surrogates for the expected pollution patterns: distance from Steamboat Springs and distance from the Hayden power plant. The latter variable consistently showed stronger correlations with lichen data and environmental variables. Therefore our discussion of possible pollution patterns and complicating environmental variables will focus mostly, but not entirely, on the distance from the Hayden power plant.

Hardwoods, particularly *Populus tremuloides*, dominate the edges of the Yampa Valley and the lower foothills of the Park Range. A mosaic of mixed hardwood and conifer stands dominates middle elevations. High elevations are dominated by a combination of conifer stands and open meadows. Since the power plants are located in the bottom of the Yampa Valley, as one moves away from the power plants, one goes first through hardwood forests, then transitions into conifer forests. Thus there is a natural correlation between forest type and distance from the power plants.

The species that McCune et al. (1998) identified as pollution indicators are native to the region and have natural habitats aside from any pollution gradients. Most of these species naturally occur on hardwoods (McCune & Goward 1995). Thus, even without pollution, these species would likely have been concentrated in the foothills of the Park Range, and be negatively correlated with distance from the Hayden power plant. Similarly, the genus *Bryoria* primarily inhabits conifers (though we did occasionally find it on hardwoods). Thus *Bryoria* would likely have a positive correlation with distance from Hayden, irrelevant to pollution. Finding patterns in the lichen communities that remain after accounting for these natural gradients is the greatest challenge of this study.

Accounting for Natural Gradients

Both our air scores and the abundance of *B. fuscescens* changed with elevation in the form of a quadratic equation. This accounts for a general increase in both air scores and *B. fuscescens* over elevation, but with a drop in scores or abundance at the highest elevations. In these highest elevations epiphytic diversity drops probably due to the harsh subalpine habitat where trees are scoured by wind blown snow. Air scores at these elevations dropped because despite the low diversity, *Candelaria concolor*, a pollution indicator, was nearly always present. The abundance of *B. fuscescens* probably dropped simply due to the unfavorable environment.

Raw air scores were demonstrated to be greatly influenced by the simple presence or absence of hardwoods. All plots with hardwoods contained *Populus tremuloides*. Although this species rarely harbors lichens on the smooth white bark, the frequent old branch scars provide and extremely diverse microhabitat. A single scar may easily harbor numerous individuals of five or more species. Thus a single trunk of *P. tremuloides* can add many of these hardwood (and pollution) associated species at densities that reach and abundance score of 3 (common).

The abundance of *Bryoria fuscescens* was also influenced by forest composition. *B. fuscescens* increased with hardwood age, but decreased with hardwood trunk diameters. It is somewhat surprising that this conifer associated species related to two hardwood characteristics, and it should be noted that it continued to do so even when <u>all</u> our conifer measures were considered in the regression. *Bryoria* species often do best in old, humid forests. The presence of hardwoods implied by the use of hardwood variables in the equation is probably indicating humid stands. The increase in *Bryoria* with increasing hardwood age matches with an increase in the genus as a forest ages. And the decrease with hardwood diameter probably relates to conifers being fairly dense in the stand, slowing hardwood growth.

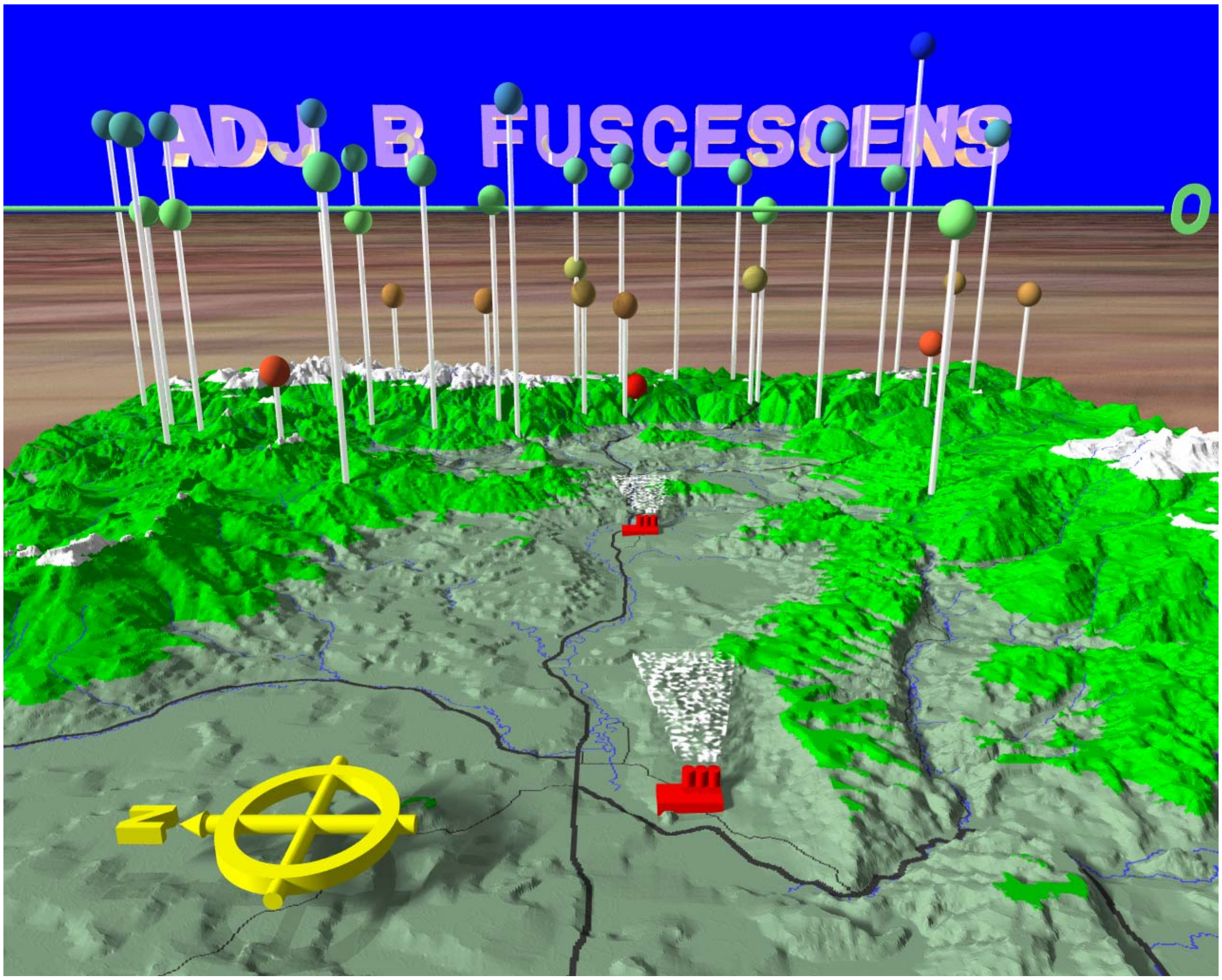
Lichen Community Patterns and the Question of Pollution

We found a number of patterns in the lichen communities that could relate to a pollution gradient. Our ordination showed similar correlation vectors for the distance from the Hayden power plant, raw air scores, and species that are pollution sensitive and characteristic of old heterogeneous conifer forests (Figures 3 & 5). Further, scores from fitting our plots to the adjusted air score gradient in the McCune et al. (1998) ordination directly correlated with distance from the Hayden power plant. Our locally adjusted air score, however, did not correlate with community patterns in our ordination or with our pollution surrogate variables. The abundance of *Bryoria fuscescens* directly correlated with distance from the Hayden power plant. Adjustment of *B. fuscescens* to account for natural environmental variation eliminated the statistical correlation, though the visual appearance of a correlation remains (Figure 10). From this, there are at least 4 possible conclusions that can be drawn with respect to pollution influencing lichen communities in the Park Range:

(1) *Pollution is not currently affecting lichen community composition*. Statistically, this would be the cleanest conclusion to draw from this study because all potential correlations in our lichen communities dissolve when environmental characters are accounted for. However, the increase of sulfur compounds in lichen tissues in the area of Rabbit Ears and Buffalo Passes suggests that lichens are being affected (Jackson et al. 1996). It would seem naïve to think that lichen community composition would not be influenced. And there is at least the visual appearance of a pollution pattern remaining in the adjusted *Bryoria fuscescens* abundance (Figure 10).

(2) *Pollution affects lichen community composition but the pattern of its influence is more complex than can be modeled by either of our surrogate variables*. This would not be an unreasonable conclusion because the topography of the area most likely leads to pooling, eddying, and funneling of air and pollution as they flow up the valley and over the mountains. However, high complexity is not possible to model in the present study and

Figure 10. Three-dimensional rendition of study region and adjusted *Bryoria fuscescens* abundance. Heights of ball-toped bars and colors of balls relate to the adjusted *B. fuscescens* abundance. The horizontal green shows the zero level. Colors are red where the abundance values are much less than expected from elevation and forest structure, green where the values are similar, and blue where the values are much higher than expected.



sulfur compounds in lichen tissue samples suggest that pollution is in fact focused on the area around Rabbit Ears and Buffalo Passes (Jackson et al. 1996).

(3) *Pollution affects lichen community composition mainly at low elevation, but is statistically confounded by valley-to-mountain environmental gradients*. This conclusion would be reasonable and congruent with our initial correlations in the ordination, the scores from our plots fitted to the McCune et al. (1998) ordination, and the raw *Bryoria fuscescens* abundance. Lack of correlation after adjustments could be explained by the complex environment causing too much noise in the data, resulting in statistical failure. However,

there is no reason to believe that the natural valley-to-mountain gradients are incomplete in their accounting for these lichen community patterns, while there is reason to expect the pattern in Figure 6 to represent greater age and heterogeneity of forests further into the mountains.

(4) *Pollution affects lichen community composition mainly in the vicinity of Rabbit Ears Pass and Buffalo Pass but is hidden in the noise created by a variety of environmental gradients*. This conclusion would accept the need to adjust response variables to environmental characteristics and, like the previous, would rely on statistical failure due to noise in the data from a complex environment. However, of the 4 possible conclusions, this one is the most compatible with the observation by Jackson et al. (1996) of a peak in sulfur concentrations in the vicinity of Rabbit Ears and Buffalo Passes, which tapers off to the north and south. It is also compatible with the visually apparent (though statistically insignificant) lack of high adjusted abundance scores for *B. fuscescens* in the same area (Figure 10). With this conclusion the potential pollution gradient would be modeled by the distance from Steamboat Springs, or even better, by the distance from the mountain passes.

Prioritizing statistical significance at the cost of biological significance would imply that the first would be the most appropriate conclusion. However, biological significance can be important though it is often ignored due to statistical failure through type II error (not detecting a true pattern). All of the latter 3 possible conclusions rely on this statistical failure with various explanations of the cause. The last of the possible conclusions is most compatible with remaining data, including both the appearance of Figure 10 and the results of Jackson et al. (1996).

One of our goals with this study was to document the nature and degree of impacts to the lichens communities from pollution emissions. While we have not documented the degree of the impacts with certainty, we have documented much of the nature. There is little doubt that the nature of pollution affects on lichen community composition in the Park Range is complex and correlated with natural gradients. We have also established that the natural gradients in the area involve elevation, forest composition (hardwood vs. conifer), and for at least a few species, forest structure and microenvironment. With this information, any future research on lichen communities in the area that involve additional plots might be focused both within an elevational band and within a forest type. To study pollution tolerant species, we would recommend sampling only pure *Populus tremuloides* stands, while to study pollution sensitive species, we would recommend limiting sampling to stands composed of a combination of *Abies* and *Picea*, or (to maximize diversity) *Abies*, *Picea*, and *P. tremuloides*. Limiting sampled stands to old forests would also help. Choosing sites *a priori* for such a study design would be difficult, but will become easier as vegetation maps improve. We would recommend consultation with the Colorado Natural Heritage Program for the best available vegetation maps.

Our other goal was to establish a baseline data set so that the same plots could be resampled at some time in the future. Such resampling would allow determination of changes in lichen communities in response to reductions in air pollution or other environmental changes. Interestingly, resampling might also help elucidate which of our possible conclusions is most accurate. For example, if the fourth possible conclusion is correct then increases in adjusted *Bryoria fuscescens* would be expected in the vicinity of the passes, but not in the sites toward the northern and southern ends of the mountain range (after accounting for site specific changes such as increased forest age).

More generally, we have demonstrated that variable topography and environment complicates the interpretation of pollution gradients in lichen community data. Some complications could be avoided by *a priori* knowledge of the environmental gradients that affect lichen community composition and the ability to control for those gradients in the sampling design. Gradients that are not controlled in the sampling design must be accounted for in the analyses before conclusions can be drawn about pollution gradients. A simplistic analysis would have incorrectly drawn strong conclusions about a pollution gradient, modeled as distance from the Hayden power plant. Our complex analysis revealed that strong conclusions could not be drawn about pollution gradients and implied that the more appropriate model for a pollution gradient (if there is one) would be the distance from Steamboat Springs or the area of the passes.

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Literature Cited

Adams, M.S. 1971. Temperature response of carbon dioxide exchange of *Cladonia rangiferina* from the Wisconsin pine barrens, and comparison with an alpine population. American Midland Naturalist 86: 224-227.

Anonymous 1998. Invasion of Pollution-tolerant Lichens in the Pacific Northwest. A product of the Lichens & Bryophytes class (BOT 465/565), 1998 and Other Contributors. Oregon State University, Department of Botany and Plant Pathology. http://www.bcc.orst.edu/~bot465/invasion.htm

Beals, E. W. 1984. Bray-Curtis ordination: an effective strategy for analysis of multivariate ecological data. Advances in Ecological Research 14: 1-55.

Belandria, G., Asta, J., and Nurit, F. 1989: Effects of sulphur dioxide and fluoride on ascospore germination of several lichens. Lichenologist 21: 79-86.

Biondini, M. E., C. D. Bonham, and E. F. Redente. 1985. Secondary successional patterns in a sagebrush (Artemisia tridentata) community as they relate to soil disturbance and soil biological activity. Vegetatio 60: 25-36.

Clarke, K. R. 1993. Non-parametric multivariate analyses of changes in community structure. Australian Journal of Ecology 18: 117-143.

Coxson, D., Webber, M. R., and Kershaw, K. A. 1984. The thermal operating environment of corticolous and pendulous tree lichens. Bryologist 87: 197-202.

Daly, C., Neilson, R. P., and Phillips, D. L. 1994. A statistical-topographic model for mapping climatological precipitation over mountainous terrain. Journal of Applied Meteorology 33: 140-158.

DePriest, P. T. 1993. Variation in the *Cladonia chlorophaea* complex I: morphological and chemical variation in Southern Appalachian populations. Bryologist 96: 555-563.

DePriest, P. T. 1994. Variation in the *Cladonia chlorophaea* complex II: ribosomal DNA variation in a Southern Appalachian population. Bryologist 97: 117-126.

De Wit, T. 1976. Epiphytic lichens and air pollution in the Netherlands. Bibliotheca Lichenologica 5: 1-226.

Eldridge, D. J. and Tozer, M. E. 1997. Environmental factors relating to the distribution of terricolous bryophytes and lichens in semi-arid eastern Australia. Bryologist 100: 28-39.

ESRI 1999. ArcView GIS 3.2. Environmental Systems Research Institute, Inc. Redlands, California, U.S.A.

Esseen, P.-A., Ericson, L., Lindstrom, H., and Zackrisson, O. 1981. Occurrence and ecology of *Usnea longissima* in central Sweden. Lichenologist 13: 177-190.

Greig-Smith, P. 1983. Quantitative Plant Ecology. Third edition. Oxford: Blackwell Scientific Publications. 359 p.

Gries, C. 1996. Lichens as indicators of pollution. Pp. 240-254. In: Nash, T. H. Lichen Biology. Cambridge University Press, Cambridge, U.K.

Hale, M. E. Jr. 1952. Vertical distribution of cryptogams in a virgin forest in Wisconsin. Ecology 33: 398-406.

Hallingbäck, T. 1989. Occurrence and ecology of the lichen *Lobaria scrobiculata* in southern Sweden. Lichenologist 21: 331-341.

Holien, H. 1996. Influence of site and stand factors on the distribution of crustose lichens of the Caliciales in a suboceanic spruce forest area in central Norway. Lichenologist 28: 315-330.

Hyvärinen, M., Halonen, P. and Kauppi, M. 1992. Influence of stand age and structure on the epiphytic lichen vegetation in the middle-boreal forests of Finland. Lichenologist 24: 165-180.

IAL 2000. The Fourth IAL Symposium, Progress and Problems in Lichenology at the Turn of the Millennium. Universitat de Barcelona, Barcelona. [Abstracts from the International Association for Lichenology's fourth symposium, held in Barcelona, Spain, 2-8 September 2000.]

Jackson, L. L., Geiser, L., Blett, T., Gries, C., and Haddow, D. 1996. Biogeochemistry of lichens and mosses in and near Mt. Zirkel Wilderness, Routt National Forest, Colorado: influences of coal-fired power plant emissions. U.S. Department of the Interior, Open-file Report 96-295. Denver.

Kruskal, J. B. 1964. Nonmetric multidimensional scaling: a numerical method. Psychometrika 29: 115-129.

Kurina, L. M. and Vitousek, P. M. 1999. Controls over the accumulation and decline of a nitrogen-fixing lichen, *Stereocaulon vulcani*, on young Hawaiian lava flows. Journal of Ecology 87: 784-799.

Mather, P. M. 1976. Computational methods of multivariate analysis in physical geography. J. Wiley and Sons, London.

McCune, B. 1993. Gradients in epiphyte biomass in three *Psudotsuga-Tsuga* forests of different ages in western Oregon and Washington. Bryologist 96: 405-411.

McCune, B. 1994. Using epiphyte litter to estimate epiphyte biomass. Bryologist 97: 396-401.

McCune, B. 2000. Lichen communities as indicators of forest health. Bryologist 103: 353-356.

McCune, B. and Beals, E. W. 1993. History of the development of Bray-Curtis ordination. Pages 67-79. In J. S. Fralish et al., editors, Fifty Years of Wisconsin Plant Ecology. Wisconsin Academy of Sciences, Arts and Letters, Madison.

McCune, B., Dey, J. P., Peck, J. E., Cassell, D., Heiman, K., Will-Wolf, S. and Neitlich, P. N. 1997. Repeatability of community data: species richness versus gradient scores in large-scale lichen studies. Bryologist 100: 40-46.

McCune, B. and Goward, T. 1995. Macrolichens of the northern Rocky Mountains. Mad River Press, Eureka, California.

McCune, B. and Lesica, P. 1992. The trade-off between species capture and quantitative accuracy in ecological inventory of lichens and bryophytes in forests in Montana. *Bryologist* 95: 296-304.

McCune, B. and Mefford, M. J. 1999. Multivariate analysis of ecological data version 4.08. MjM Software, Gleneden Beach, OR. USA.

McCune, B., Rogers, P., Ruchty, A., and Ryan, B. 1998. Lichen Communities for Forest Health Monitoring in Colorado, USA. A Report to the USDA Forest Service.

Minchin, P. R. 1987. An evaluation of the relative robustness of techniques for ecological ordination. Vegetatio 69: 89-107.

Økland, R. H. 1996. Are ordination and constrained ordination alternative or complementary strategies in general ecological studies? Journal of Vegetation Science 7: 289-292.

Peterson, E. B. and McCune B. 2001. Diversity and succession of epiphytic macrolichen communities in low-elevation managed conifer forests in western Oregon. Journal of Vegetation Science, in press.

PRISM s.d. Climate mapping with PRISM. http://www.ocs.orst.edu/prism/prism_new.html

Richardson, D. H. S. 1988. Understanding the pollution sensitivity of lichens. Botanical Journal of the Linnaean Society 96: 31-43.

Rikkinen, J. 1995. What's behind the pretty colours? A study on the photobiology of lichens. Bryobrothera 4: 1-239.

Shirazi, A. M., Muir, P. S., and McCune, B. 1996. Environmental factors influencing the distribution of the lichens *Lobaria oregana* and *L. pulmonaria*. Bryologist 99: 12-18.

Tallent-Halsell, N. G. (ed.). 1994. Forest Health Monitoring 1994 Field Methods Guide. U.S. Environmental Protection Agency, Washington, D. C.

Tibell, L. 1992. Crustose lichens as indicators of forest continuity in boreal coniferous forests. Nordic Journal of Botany 12: 427-450.

USGS s.d. USGS Digital Elevation Model Data. http://edc.usgs.gov/glis/hyper/guide/usgs_dem.

Van Doben, H. F. 1983. Vegetation as a monitor for deposition of nitrogen and acidity [Vegetatie als monitor voor depositie van stikstof en zuur]. Rijksuniversiteit te Utrecht, Utrecht.

APPENDIX A.

Plot locations. NC = data not collected. PVT = original placement was on private land. PUB = exact placement was altered to avoid interfering with a public area. TREE = exact placement was altered to place plot in forested location. SAFETY = exact placement of plot was altered for safety reasons. ALG = pre-determined algorithm for selecting plot placement. In some cases the initially provided coordinates were located with the GPS, then after several minutes additional satellites were detected, altering the coordinate readout slightly; in such cases, the altered coordinates are what are recorded here. UTM positions (zone 13) were determined from the GPS at plot center.

Plot Name	Latitude	Longitude	UTM N	UTM E	Comments
701 AlternateTrail	40.88067	106.98217	4527444	333004	PVT, moved southward to first certain public land on west side of road. ALG = up trail until GPS odometer read 0.2 km (0.15 rounded up?), then placed on north side of trail
706 SteamboatLake	40.78783	106.96433	4517078	334263	PVT, ALG= just inside a northward projection of forest (to fit both in forested area and on state land)
709 LittleRedPark	40.87350	106.91567	4526474	338576	
711 CandyMtn	40.66350	106.89567	4503141	339767	
714 BigRedPark	40.91300	106.87933	4530809	341734	TREE, moved directly north until within forest (ended up on road 500F), then westward to avoid someone's camp
717 MadCreek	40.58900	106.87100	4494806	341664	TREE, moved slightly to be within nearest forested area
720 FlyClouds	40.73267	106.83917	4510709	344700	PVT, ALG = moved to nearest certain public land (local ownership mosaic), then from good parking on spur road walked random distance into forest following magnetic north.
723 WestFork	40.91767	106.79050	4531368	349179	GPS began to vary by more than 0.5 km (due to narrow canyon?) so plot was moved to a landmark location: the southern intersection of the West Fork Trail and the trail from Manzanares lake. Plot center is at middle of trail intersection.
724 SteamboatWest	40.48633	106.78000	NC	NC	PVT, TREE. Plot moved slightly southeast to be on public land and to be in forest
725 BlackMtn	40.96717	106.79900	4536658	349332	SAFETY (thunder/wind storm in disintegrating forest). Original point was ca. 1 km off trail. ALG = 0.2 km directly toward the plot.
726 Morrison	40.17133	106.74717	4448297	348391	
729 SilverCreek	40.21733	106.72150	4453313	353514	
730 Ebert Lake	40.63133	106.70783	4499235	355563	TREE, due to lack of forest, plot was centered on nearest clump of trees.
732 LynxPass	40.10867	106.68867	NC	NC	SAFETY (thunder/wind storm in disintegrating forest on steep slope). ALG = 100 paces beyond where decision was made to alter plot position.
733 PairedWest	40.53733	106.67533	4488751	358120	
734 PairedEast	40.53817	106.66517	4488832	359010	

735	Windy Meadows	40.73583	106.66250	4510763	359622	
736	Erythronium	40.36533	106.65900	4469612	359142	
738	Crusty	40.04600	106.65333	4434170	358959	
739	Cows	40.48867	106.64600	4483295	360508	
740	Divide	40.17883	106.63350	4448892	360927	
741	SarviceCreek	40.26250	106.62067	4458149	362190	
744	GoreCreek	40.11050	106.58883	4441224	364591	
A01	WyomingTrail	40.78233	106.76917	4516097	350712	ALG = placed maximum distance drivable up road FR433 with lower end of plot at edge of forest road opening
A02	Spring Ck	40.52750	106.78417	4487840	348871	ALG = down trail from Spring Creek Campground until crossed riparian zone then placed on east side of trail.
A03	Swamp Park	40.60983	106.83483	4497066	344781	ALG = up Swamp Park trail until (1) trail crosses creek, (2) trail bends westward within forest, then chose random compass direction and random number of paces (≤ 100) and still falling within the forest.
A04	Stagecoach	40.29283	106.79917	4461818	347069	ALG = 100 paces up trail beyond gate at edge of private land, followed by random compass direction and random number of paces (≤ 100) and falling within forest.
A05	Harrison Ck	40.34683	106.73733	4467701	352453	ALG = Needed humid site in area of Rabbit ears pass so found trail down to creek and placed the S edge of the plot along the side of the creek.
A06	Dumont Lake	40.42900	106.66267	4476698	358972	ALG = edge of plot at edge of forest at end of road, center located in random compass direction.
A07	Fish Creek	40.47517	106.74633	4481961	351968	ALG = hiked up trail until 4PM (= 1hour, 20 minutes if I recall correctly) then aimed at nearest trees and walked a random number of paces (≤ 100)
A09	Ugly Resevoir	40.48967	106.68867	4483499	356914	ALG = Drove southward on road until blocked by gate, then set plot just inside forest on the east side of the road.
A10	Flattop Edge	40.26383	107.13667	4459230	318309	ALG = Followed road southeastward until first pullout on road within National Forest, then placed plot just inside nearest forest (across creek)
A11	Elkhead	40.69733	107.12750	4507332	320249	ALG = Followed road northeastward until first spur road within National Forest, then placed plot just inside nearest forest
A12	Blowdown	40.75367	106.73183	4512868	353808	ALG = Went to end of trial head and placed plot just inside forest on randomly chosen side of trailhead parking.
A27	RoadWork	40.35667	106.75767	4468825	350743	Location chosen directly between 727 and 728 because neither of them were in practical locations (several km of off-trail hiking across very steep slopes)

APPENDIX B.

Guide to the Compact Disk. This CD should be readable by most Personal Computers from 2000 or newer. All files with the extensions .wk1 and .gph are organized for use with PC-Ord (McCune & Mefford 1999) version 4, while all GIS files are for use with ArcView 3.2 (ESRI 1999).

Root Directory:

Report.doc	The final report to the Forest Service in Microsoft Word 2000 format.
VarNames.txt	A text file with brief explanations of the variable names used in various GIS and data files.

Data Directory

Spp-all.wk1	Abundance data for all species found in this study, in a spread sheet format.
Spp-2.wk1	Abundance data for species with 3 or more occurrences. This was the data set used for the multivariate analyses.
Envir.wk1	Environmental and accessory data for use in analyses. See VarNames.txt in the root directory for an explanation of variable names.
NMS01r.gph	Scores for plotting the sites in the NMS ordination.
NMS01g.gph	Scores for plotting the species in the NMS ordination.
NMS01.txt	Output from running NMS in PC-Ord.
Hybrid.wk1	Species abundance data for running NMS Scores in PC-Ord. This includes data from McCune et al. (1998).
Hybrid-env.wk1	Contains only one variable to distinguish our sites from the McCune et al. sites; for use with Hybrid.wk1 in PC-Ord.
Hybrid.gph	Scores for plotting the NMS Scores ordination with our sites and those from McCune et al.
NMSSco01.txt	Output from running NMS Scores.

GIS Directory

GIS-figures.apr	Project file for ArcView used to create the figures in this report.
Plots.xxx	Shape file data for plot locations. Includes much of the environmental data and some species data.
7xlocations.xxx	Shape file for the 51 randomly located potential plots.
ESRI-cnty.xxx	Shape file from ESRI showing county boundaries for Colorado.*

ESRI-rds-clip.xxx	Shape file from ESRI showing main roads in the area of this study.*
ESRI-states.xxx	Shape file from ESRI showing state boundaries for the United States.*
mccune_me.xxx	Shape file data for sites used both by McCune et al. and by the present study. Includes some species and air score data.
Point sources.xxx	Shape file for the power plants and roughly the center of Steamboat Springs
Ppt-ann.xxx	Shape file for estimated Annual Precipitation (Daly et al. 1994; PRISM s.d.) for Colorado.
Ppt-jun.xxx	Shape file for rstimated June Precipitation (Daly et al. 1994; PRISM s.d.) for Colorado.
Ppt-jul.xxx	Shape file for estimated July Precipitation (Daly et al. 1994; PRISM s.d.) for Colorado.
Ppt-aug.xxx	Shape file for estimated August Precipitation (Daly et al. 1994; PRISM s.d.) for Colorado.
Waterbodies.xxx	Shape file for large lakes in the study area, mostly sketched in by Eric Peterson (for small scale maps only).
8x_meter-utm	(directory) Grid data from 1 degree digital elevation models (DEMs) of the study area, reprojected into UTM zone 13 coordinates, resulting in roughly 90 X 90 m cells. Use requires files stored in the INFO directory as well.
Hillshade8xm	(directory) Grid data for hillshading to use in topographic displays generated from the 1 degree DEMs. Use requires files stored in the INFO directory as well.
30meter-utm	(directory) Grid data mosaic from 1:24000 DEM's for the study area, includes some holes. This is the data used to determine the elevations of our plots.
Info	(directory) Contains files necessary for use with grid data (above).

Misc Directory

ER	(directory) Contains setup files for the shareware Essential Regression which was used as an add-in to Microsoft Excel 2000 for regression analyses.

* = Legal use of these files requires a license for ArcView 3.2.