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A Lichen Biomonitoring Program to Protect Resources in the National Capital Region by Detecting Air Quality Effects

Natural Resource Report NPS/NCRN/NRTR—2011/450

ON THE COVER
Canoeists on the Potomac River viewed from the Chesapeake and Ohio Canal National Historical Park, one of the parks in the National Capital Region. Photograph by the author.

A Lichen Biomonitoring Program to Protect Resources in the National Capital Region by Detecting Air Quality Effects

Natural Resource Report NPS/NCRN/NRTR—2011/450

James D. Lawrey

George Mason University
Department of Environmental Science and Policy MSN 5F2
4400 University Drive
Fairfax, Virginia 22030-4444

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Abstract

Lichens are commonly used as biomonitors of air quality, and for this reason over 30 lichen biomonitoring projects have been done in areas managed by the National Park Service (NPS). This project established 102 permanent study plots at approved locations in nine park units of the National Capital Region (NCR) of the NPS, including CATO, CHOH, GWMP, HAFE, MANA, NAMA, NACE, ROCR, and PRWI. At each permanent plot, baseline floristic lichen surveys were done during 2004-2006 to assess community structure and diversity for comparison with ecologically similar areas. In addition, concentrations of elements (Hg, Cu, Pb, Zn, Ni, Cd, Cr, S) were measured for one target lichen species (*Flavoparmelia caperata*) collected at each plot. A selection of the plots were located at sites where samples have been collected in the past, some dating to the turn of the 20^{th} century. Over 700 voucher specimens were identified and curated for the project, including specimens of 45 bark-inhabiting macrolichen species. Pollution-sensitive species were found in most park units except those closest to the center of Washington, D.C., but they are apparently not common. Many of the dominant species are nitrophilous and/or pollution-tolerant species commonly observed throughout the eastern United States. Elemental analyses revealed no significant hot spots of pollution in the region. Concentrations of sulfur, Pb and Cu were significantly lower in lichens from PRWI than in those from other park units. Taken together, the floristic and element data suggest that nitrophilous, relatively pollution-tolerant lichen communities have developed over time in the NCR, probably the result of poor air quality in the past century and only slight improvement since. These results are consistent with those of several recent studies that analyzed lichen community patterns and/or element content in the mid-Atlantic region.

Acknowledgments

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Introduction

Lichens and Lichen Biomonitoring

Lichen sensitivity to air pollution has been recognized since the late 19th century and over 1500 papers have been published on the responses lichens make to changes in air quality (see reviews by Nash & Wirth 1988, Nash 1989, Richardson 1992, Hyvärinen et al. 1993, Stolte et al. 1993, Gries 1996, Conti & Cecchetti 2001, Garty 2000, 2001, Nash and Gries 2002, Nimis et al. 2002). These responses can be summarized as follows:

- Lichen floristic patterns change as pollution-sensitive species are replaced by pollution-tolerant species. For this reason, those species known to be especially sensitive or tolerant can be used as bioindicators of atmospheric quality.
- Sensitive species develop structural, physiological and behavioral changes in polluted habitats. These changes include reduced photosynthesis, bleaching and death of the photosynthetic partner (photobiont), and discoloration and reduced growth of the lichen fungus (mycobiont).
- Pollution-tolerant species are known to accumulate pollutant elements from the atmosphere, so that element concentrations measured in lichens can reflect ambient air quality conditions. Lichens that accumulate elements can therefore serve as "passive monitors" of air pollution.
- When transplanted to polluted sites, sensitive species exhibit physiological stress and increased mortality; tolerant species accumulate pollutant elements and can also exhibit measurable changes in physiology and growth rate.

Lichen Biomonitoring in the National Park Service (NPS)

Given their usefulness as biomonitors, the National Park Service (NPS) and the USDA Forest Service have each undertaken numerous lichen studies on federal lands during the last thirty years (Geiser & Reynolds 2002, Blett et al. 2003, Geiser et al. 2010). Over 30 lichen biomonitoring programs have been done in areas managed by the NPS. These generally involve (1) floristic surveys that document the lichen species present in parks and note particularly important indicator species, and (2) elemental analyses of common accumulator species to document background levels of certain pollutant elements.

Results of floristic studies can be accessed at the website "NPLichen, A Database of Lichens in the U.S. National Parks" at: http://www.nbii.gov/nplichen, a website developed and maintained by James Bennett of the U.S. Geological Survey and University of Wisconsin, Madison, WI, and Clifford M. Wetmore, of the University of Minnesota, St. Paul, MN. NPLichen lists over 29,000 records (over 2,500 species total) of documented occurrences of lichens in 149 park units of the U. S. National Park System.

Similarly, results of lichen element accumulation studies can be accessed at the website "NPElement, A Database of Lichen Elemental Concentrations in the U. S. National Parks" at http://www.nwhc.usgs.gov/our_research/np_element.jsp, a website developed by James Bennett to database all lichen element studies done in the National Park Service. NPElement lists element data (48 elements total) for 75 lichen species surveyed in 43 park units.

In the National Capital Region (NCR), a number of lichen biomonitoring efforts have been done during the past 30 years. The objective of the present study was to expand on these efforts by establishing permanent biomonitoring sites in nine national parks in the NCR. At each site, the abundance of all tree-inhabiting (corticolous) macrolichens was recorded and a sample of a single common species taken for elemental analysis. Baseline floristic and element levels were then used to detect and describe air pollution effects with the ultimate goal of protecting NCR resources in the future.

Lichen Biomonitoring in the National Capital Region

Lichens have been collected and studied in the Washington, D.C. region since the late 1800's, and numerous collections are available in the U.S. National Herbarium. Studies of lichens as environmental monitors in the region began in 1965 when Mason E. Hale, Jr., curator of lichens at the Smithsonian Institution, initiated long-term growth-rate studies of rock-inhabiting lichens on Plummers Island, Maryland in the Potomac River. Beginning in 1975, James Lawrey of George Mason University joined Hale in these studies and additional study sites were established at Great Falls, Maryland, Rock Creek Park in Washington, D.C. (Schwartzman et al. 1987, 1991), various other locations in the Washington area, and in Shenandoah National Park.

In addition to lichen growth rates, Hale and Lawrey did a number of comparative studies of lichen floristic composition and element accumulation in the Washington, D.C. area. These studies, and those of colleagues in the area: (1) established permanent study sites at various locations in the Washington, D.C. area; (2) provided long-term information about lichen growth rates and correlations with environmental variables (Hale 1970, Lawrey & Hale 1977, 1979); (3) began to document lichen floristic composition and element concentration at these permanent sites (Lawrey 1991, 1992); (4) provided information about element uptake patterns and mechanisms (Hale and Lawrey 1985, Schwartzman 1987, 1991); (5) provided comparative retrospective data for changes in lichen communities and element content during the past 100 years (Lawrey & Hale 1981, Lawrey 1993).

Sensitivity and tolerance

Certain lichen species are especially sensitive to air pollution, while others are especially tolerant. For example, many species are sensitive to even moderate levels of SO_2 pollution and rapidly disappear from polluted habitats. However, the "pollution lichen" *Lecanora conizaeoides* is very tolerant of SO_2 and other pollutants, and readily invades habitats vacated by sensitive species. Especially sensitive or tolerant species are referred to as "indicator species" because their presence or absences can be a relatively accurate predictor of the air quality. Fumigation experiments with whole lichens and isolated symbionts have established sensitivities for many lichens to SO_2, NOx, HF, ozone and metals. These studies have shown that even low concentrations of pollutants can be damaging to sensitive species. Lichen community composition can also indicate changes in air quality. In the United States, changes in lichen communities have been correlated with changes in air quality in southern California (Nash and Sigal 1998), Seattle (Johnson 1979), Indianapolis (McCune 1988), and the Ohio River Valley (Showman 1990, 1997).

A good survey of this literature can be found at the website “Air Quality and Lichens - A literature review emphasizing the Pacific Northwest, U.S.A.” at:

http://www.fs.fed.us/r6/aq/lichen/almanac.htm. Establishing the pollution sensitivity of lichens requires both field and laboratory study, and the most commonly used approaches are: (1) floristics and distribution mapping; (2) gradient analysis along known pollution or natural environmental gradients; (3) laboratory fumigation studies; (4) element accumulation; (5) transplants; (6) photography. Based on results of these studies, indices of lichen sensitivity have been developed to provide a measure of the air quality related values of information from lichen surveys. The most familiar published lichen sensitivity scales are those of Hawksworth and Rose (1970), de Wit (1976), Wirth (1991), and Insarova et al. (1992), all for European lichens. These scales are based on correlations between lichen distribution data and air quality monitoring data. In the Netherlands, where there is a country-wide, high-density air quality monitoring network, very accurate modeling of lichen responses to air quality has been done (van Dobben and ter Braak 1999).

In the United States, sensitivity ratings are based on field data, literature surveys and fumigation experiments. Commonly cited sensitivity scales for U.S. lichens are summarized by Geiser et al. (2010), and include those of LeBanc and De Sloover (1970), Sigal and Nash (1983), Wetmore (1983), McCune and Geiser (1997) and Peterson et al. (1992). The lichen communities of the Pacific Northwest have been studied most thoroughly, and lichen sensitivities have been established for numerous species. A summary of this information can be found at the website: "The US Forest Service National Lichens and Air Quality Database and Clearinghouse" at: http://gis.nacse.org/lichenair/index.php?page=sensitivity. An illustrated listing of species and sensitivities is also available at the website: **"**Pacific Northwest Lichen Sensitivity Ratings by Species" available at: http://www.fs.fed.us/r6/aq/lichen/images.htm.

Categories of lichen biomonitors

Lichens can be assigned to various functional groups based on their ecosystem roles and responses to various pollutants. McCune et al. (2006) provide an overview and discussion of these groups for the Sierra Nevada National Parks, and we include those most useful for pollution monitoring in the NCR here. Certain lichens are also known to be especially pollution-sensitive or pollution-tolerant. Studies in the Pacific Northwest have helped to identify lichens that are especially sensitive or tolerant of pollution, and a provisional air quality rating system has been developed for numerous species (http://gis.nacse.org/lichenair/index.php?page=ratings#NS). The categories may overlap since, for example, nitrophiles or acidiphiles may also respond either positively or negatively to pollution:

1. Pollution-sensitive-- species that generally respond negatively to a wide range of pollutants. Examples of species commonly found in the NCR include *Ramalina* spp., *Tuckermannopsis* spp., and *Usnea* spp. (Figure 1).
2. Pollution-tolerant-- species that generally respond positively to a wide range of pollutants. In the NCR, examples include *Physcia millegrana* (one of the most pollution tolerant lichens in the U.S., McCune 2000), *Candelaria concolor*, *Parmelia sulcata*, and *Punctelia rudecta*.
3. Nitrophiles-- these species thrive in nutrient-enriched areas receiving N inputs from fertilizer application in agricultural areas or N emissions from power plants, automobile exhaust or industry (van Herk 1999). Among the most common in the NCR are

Candelaria concolor, *Flavoparmelia caperata*, *Flavopunctelia flaventior*, *Parmelia sulcata*, *Phaeophyscia orbicularis*, *Physcia aipolia*, *Physcia millegrana*, *Punctelia rudecta* and *P. subrudecta*.

4. Acidophiles-- these species thrive on acidic substrates, some natural (such as *Parmeliopsis* spp. on conifer bark), others (such as *Lecanora conizaeoides*) affected by acid deposition (van Dijk 1988, van Herk 1990).
5. Nitrogen-fixers-- these species contain cyanobacteria that fix atmospheric N. They are most commonly collected from shady, moss-covered rocks, soil and tree bases. Most are sensitive to all forms of pollution, especially SOx and NOx deposition, but also ozone. Herbarium records indicate that cyanolichens were once common the Washington, D.C. area. Some species (*Coccocarpia palmicola*, *Collema furfuraceum*, *Leptogium cyanescens*, *Peltigera* spp.) can still be found occasionally in the NCR.
6. Lichen parasites-- Some fungi, known as lichenicolous fungi, are known to grow exclusively on lichens. These were included in lichen surveys since they may respond positively or negatively to changes in atmospheric quality.

Objectives

Given the success of these previous studies and the need to expand coverage of these biomonitoring efforts, a new project was undertaken in 2002 to accomplish the following tasks:

1. establish additional permanent study sites in nine national parks in the NCR.
2. collect floristic and elemental data systematically within each permanent study site so that a baseline of lichen biomonitoring information is available.
3. assign species to indicator categories based on existing information about pollution sensitivity.
4. compare data from new sites with previously collected data wherever possible.
5. determine schedule of resampling.

Management Questions

The management questions addressed by this study are:

1. What is the present distribution of species richness in lichen communities sampled in the largest parks of NCR?
2. How do community distribution, species richness and relative species abundance compare with what should be found in ecologically similar areas along the Potomac River?
3. What evidence is there for changes in air quality over time?
4. What evidence is there for present-day pollution hot spots? What are the implications when pollution thresholds are exceeded?

Methods

Site Selection and Establishment of Sampling Plots

Beginning in 2003, permanent sampling plots were established in nine park units:
Catoctin Mountain Park, MD (CATO)
Chesapeake and Ohio Canal National Historical Park, MD, WV, and DC (CHOH)
George Washington Memorial Parkway, VA (GWMP)
National Mall and Memorial Parks, DC (NAMA)
National Capital Parks-East, DC and MD (NACE)
Prince William Forest Park, VA (PRWI)
Rock Creek Park, DC (ROCR)
Harpers Ferry National Historical Park, MD, VA, WV (HAFE)
Manassas National Battlefield Park, VA (MANA)

These park units were selected based on their size and wide geographic distribution in the NCR. During the first year of the project (2003), permits were obtained to collect lichens in seven park units (CATO, CHOH, GWMP, NACC, NACE, ROCR, PRWI) of the National Capital Region. Two additional units (MANA, HAFE) were added to the project in 2005. Each park was visited prior to the establishment of plots to meet with and discuss project objectives with appropriate staff persons, usually the Natural Resources Manager.

During the first three years (2003-5) of the project, permanent study plots were established at approved locations in seven park units (CATO, CHOH, GWMP, NAMA, NACE, ROCR, PRWI) of the National Capital Region. In two parks (PRWI and CATO), sites were located within 1 km^2 grids; at the other parks, sites were located to provide maximum coverage; and in NAMA a site was located near the IMPROVE aerosol sampler on Haines Point on the Potomac River in southeastern Washington, DC. During the field season 2006, five additional permanent sites were established in HAFE, and four in MANA. The total number of permanent plots is 102.

Floristic Surveys and Estimates of Abundance

At each permanent site, lichen floristic information was collected to establish a baseline of the floristic composition of lichen communities in each of the parks. The sampling protocol is similar to that of McCune et al. (1997), which was used in the Forest Health Monitoring program (complete details of methods in Tallent-Halsell, 1994); the only difference is that a plot of 20 x 20 m was used instead of a circular plot with a 36.6 m radius. This smaller plot size was necessary to accommodate most of the CHOH sites. Within each plot, a GPS reading is recorded in the center, and all woody plants (living and dead boles) are surveyed for macrolichens. Lichens on fallen branches and downed trees are also included, but lichens growing on tree bases (0.5 m above ground and lower) are excluded since these generally represent a distinctive terricolous (ground-dwelling) community composition. At least two hours is spent in each plot and during this time all lichen species observed in the plot are noted or collected (at least one voucher specimen is obtained if possible, and if permitted). In addition to presence/absence, an estimate of abundance is made using a 4-step scale: 1 = < 3 individuals in plot; 2 = 4-10 individuals in plot; 3 = > 10 individuals in plot; 4 = more than half boles and branches in the plot have the subject species present.

Elemental Analysis

To obtain element accumulation information, a single target species (*Flavoparmelia caperata*, Fig. 1) was collected in sufficient quantities to analyze for pollutant elements. This species was chosen because it has been used in previous studies of lichen element accumulation in NPS parks and USDA Forest Service sites in the Mid-Atlantic region (Lawrey 1985, Lawrey and Hale 1979, 1981, 1988, 1993, Kinsman 1990). The Agricultural Analytical Services Laboratory at Pennsylvania State University did all laboratory analyses. Elements chosen for analysis included metals (Cd, Cu, Pb, Ni, Cr, Zn, using EPA method 3051) total sulfur (EPA 3051 digest) and Hg (EPA method 7471). Many of these elements have been studied in previous lichen surveys in the NCR. At Plummers Island (CHOH), for example, retrospective elemental uptake of Pb has been measured using lichen samples collected at various times dating to 1907 (Lawrey and Hale, 1979, 1981; Lawrey, 1993). One of the goals of the present study was to expand the lichen element baseline information throughout the NCR and in consultation with CUE elements were chosen for study with this goal in mind.

A project website was developed and maintained by the author on the GMU server (URL: http://mason.gmu.edu/~jlawrey/CUE/). This was intended to describe past and present lichen biomonitoring efforts in the NCR, to briefly outline the objectives of the project, and to provide summary results and conclusions understandable to the public. The website outlines the project objectives, methods, and results, and all pertinent literature is cited. It features webpages for each participating park unit, and summarizes the floristic and elemental data for each permanent study site. A separate page summarizes the project results, and there is a listing of pertinent web links concerning lichens and lichen biomonitoring.

Figure 1 . Images of macrolichens. Left: the corticolous macrolichen *Flavoparmelia caperata*, which was sampled from every site for elemental analysis. Right: *Usnea ceratina*, an acidophilous pollution-sensitive fruticose lichen. Images used with permission from Paul Diederich, http://www.lichen.com/

Results

Floristic Composition of Lichen Communities in Study Plots

Over 700 voucher specimens were identified and curated for the project. This includes specimens of 45 corticolous lichen species, for which measures of abundance were recorded at each study plot (a summary is available in Table 1, abundance data is in Appendix I). Curated specimens were sent to the Center for Urban Ecology. Some species were found in nearly all plots (*Flavoparmelia caperata* was sampled for elemental analysis at every plot), and others were found in only certain plots or certain geographic areas.

The 45 macrolichens and three lichen-associated parasites observed in the plots are listed in Table 2. These species commonly make up epiphytic macrolichen communities representative of the Mid-Atlantic region at the present time. Species found in the survey and known to be particularly sensitive or tolerant of pollution are also noted in Table 2.

Many of the dominant species are nitrophilous and/or pollution-tolerant (*Punctelia rudecta*, *Flavoparmelia caperata*, *Myelochroa aurulenta*, *Physcia* spp. and *Phaeophyscia* spp., *Pyxine sorediata*), and these have likely dominated lichen communities in the eastern United States for much of the past century. The same species were also observed commonly by McCune et al. (1997) in the Southeastern United States in permanent plots established for the Forest Health Monitoring Program.

In cases where lichen surveys were done in the past and comparisons can be made, present-day communities are far less diverse and contain fewer sensitive species than communities that existed at the same sites in the past century. For example, on Plummers Island, Maryland, where the lichenologist Bruce Fink and various members of the Washington Biologists' Field Club (website http://www.pwrc.usgs.gov/resshow/perry/bios/WBFCHome.htm) collected lichens early in the 20th century, the list of species includes many not found now in the mid-Atlantic region. Many of these species are also recognized as pollution-sensitive (Table 3). Floristic data collected since that time, including this project, indicate the lichen communities at Plummers Island are now far less diverse and include no pollution-sensitive species (Table 3). Historical lichen collections done at ROCR and the Great Falls area (GWMP) also indicate that sensitive species were present in the past, but these areas were probably not sampled as intensively as the communities at Plummers Island. Data for Plummers Island specimens can be accessed at the Smithsonian Department of Botany website at: http://botany.si.edu/dcflora/DCPlummers/index.htm and specimen information for collections made at other NCR sites can be accessed at the Flora of Washington DC-Baltimore Area website at: http://botany.si.edu/dcflora/.

Some lichen species were found to have restricted distributions, but this is not always the result of the effects of air quality. For example, certain lichens found only in CATO are typical northern (*Allocetraria oaksiana*) and mountain (*Flavopunctelia soredica*) species. Communities in the parks closest to the center of Washington, D.C. (NAMA, NACE) had the fewest species with the lowest abundance scores. These communities were made up mostly of pollution-tolerant, nitrophilous species (Physcia millegrana, Punctelia rudecta, Flavoparmelia caperata, Phaeophyscia rubropulchra).

Pollution sensitive species were found throughout the study area, but always had low abundance scores (Tables 1 and 2). Plots from PRWI and MANA typically contained the most sensitive species.

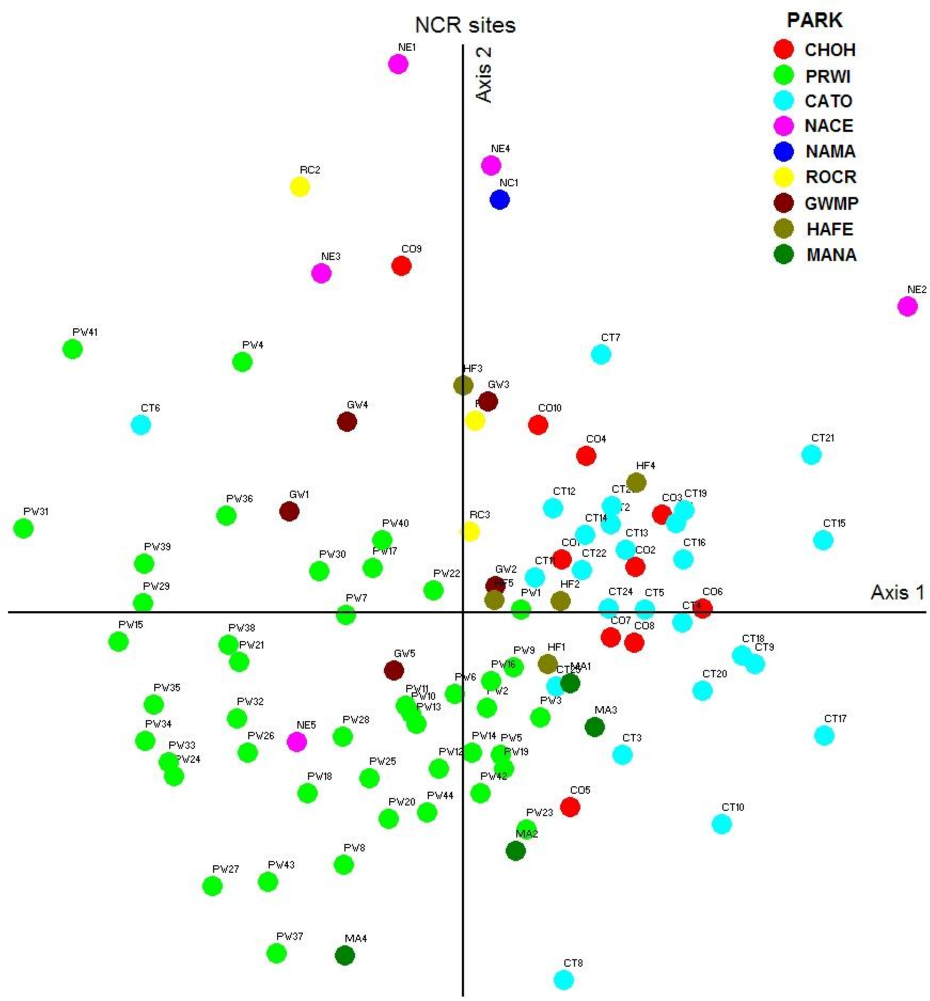

Figure 2. NMS ordination of lichen floristic data obtained at each of the 102 plots established in the NCR.

Multivariate statistical approaches are useful for integrating large floristic datasets and providing a basis for assessing change in floristic patterns over time. An approach similar to that of McCune et al. (1997) was used to assign gradient scores to each plot based its lichen community composition. Dominant community gradients are extracted using nonmetric multidimensional scaling (NMS) in the program PC-ORD v.5 (McCune & Mefford 1999). NMS has been shown to be especially well-suited to data that are nonnormal or are on arbitrary, discontinuous, or otherwise questionable scales (McCune and Mefford 1999, Clarke 1993). NMS ordination of plots for the combined 2004/2005 lichen community dataset in NCR indicated that lichen communities in PRWI and CATO are especially distinct, with each having species not found in the other parks Figure 2). Some of the patterning seen here likely reflects differences in the geographic locations of these park units (axis 1), but may also indicate effects of past pollution. Communities of the three most urban parks (NAMA, NACE, ROCR) are also distinct, likely a reflection of their low species diversity (axis 2).

Table 1. Summary of macrolichen collections. Collections were made in sampling plots established within the nine park units participating in the study. Sensitivity of species is based on the literature.

Park Unit	Species	Sensitive species	Notes
CATO (25 plots)	26 macrolichens, 2 lichenicolus parasites	Cetrelia olivetorum, Collema furfuraceum, Leptogium cyanescens	Mountain flora (northern Allocetraria oaksiana and western Flavopunctelia soredica); Peltigera canina collected off-frame.
CHOH (10 plots)	20 macrolichens, 2 lichenicolus parasites	Coccocarpia palmicola	Historical floristic data available for Plummers Island, Maryland (CHOH09).
GWMP (5 plots)	15 macrolichens, 0 lichenicolus parasites	Usnea sp.	Historical collections from Great Falls, Maryland, available in the U.S. National Herbarium.
HAFE (5 plots)	12 macrolichens, 0 lichenicolus parasites	None	
MANA (4 plots)	20 macrolichens, 0 lichenicolus parasites	Leptogium cyanescens, Parmelia squarrosa, Tuckermannopsis ciliaris	
NACE (5 plots)	10 macrolichens, 0 lichenicolus parasites	None	Tolerant nitrophilous species dominant (Physcia millegrana, Candelaria concolor, Punctelia rudecta).
NAMA (1 plot)	6 macrolichens, 1 lichenicolus parasite	None	Tolerant nitrophilous species dominant (Physcia millegrana, Candelaria concolor, Punctelia rudecta).
PRWI (44 plots)	30 macrolichens, 0 lichenicolus parasite	Leptogium cyanescens, Parmelia squarrosa, Tuckermannopsis ciliaris, Usnea ceratina	Collema furfuraceum, Peltigera canina collected off-frame.
ROCR (3 plots)	10 macrolichens, 0 lichenicolus parasites	None	Historical collections available in the U.S. National Herbarium.

Table 2. Lichen indicator categories. Certain species of lichens collected in the NCR study have been tentatively assigned to indicator categories based on published reports. These categories include the indicator and functional groups listed above. It should be noted that a specific lichen may be assigned to more than one grouping**.**

Allocetraria oaksiana S[1]	Heterodermia speciosa	Parmotrema stuppeum	Punctelia rudecta NT
Anaptychia palmulata	Hypotrachyna livida S	Parmotrema tinctorum	Punctelia subrudecta NT
Candelaria concolor N	Leptogium cyanescens CS	Phaeophyscia adiastola	Pyxine caesiopruinosa
Canoparmelia caroliniana	Myelochroa aurulenta	Phaeophyscia orbicularis N	Pyxine sorediata
Cetrelia olivetorum S	Myelochroa galbina	Phaeophyscia pusilloides	Rimelia reticulata
Coccocarpia palmicola CS	Parmelia squarrosa S	Phaeophyscia rubropulchra N	Tuckermannopsis ciliaris AS
Collema furfuraceum CS	Parmelia sulcata NT	Phaeophyscia squarrosa	Usnea ceratina AS
Dirinaria aegialita	Parmelinopsis horrescens	Physcia aipolia N	Usnea strigosa A
Flavoparmelia caperata N	Parmelinopsis minarum	Physcia americana	Usnea sp. AS
Flavopunctelia flaventior N	Parmotrema dilatatum	Physcia millegrana NT	Athelia arachnoidea para
Flavopunctelia soredica	Parmotrema hypotropum T	Physcia stellaris	Marchandiomyces corallinus para
Heterodermia obscurata	Parmotrema michauxianum	Physconia detersa	Nectriopsis parmeliae para

[1]Key: S = sensitive; T = tolerant; N = nitrophilous; A = acidophilous; C = cyanolichen; para = lichenicolous fungi.

Table 3. Bark-inhabiting macrolichens collected at Plummers Island, Maryland, at various times during the past century. Pollution-sensitive species are in red (also indicated by S).

Collections from 1917-1935:	Collections from 1982-2004:
Anaptychia palmulata	Candelaria concolor
Coccocarpia palmicola	Dirinaria aegialita
Collema leptaleum (S)	Flavoparmelia caperata
Collema subflaccidum (S)	Flavopunctelia flaventior
Dirinaria picta	Parmotrema dilatatum
Flavoparmelia caperata	Parmotrema hypotropum
Fuscopannaria leucosticta (S)	Phaeophyscia adiastola
Leptogium azureum (S)	Phaeophyscia rubropulchra
Leptogium corticola (S)	Physcia millegrana
Leptogium cyanescens (S)	Punctelia rudecta
Myelochroa aurulenta	Pyxine caesiopruinosa
Parmelia squarrosa (S)	Pyxine sorediata
Parmotrema cetratum	
Parmotrema reticulatum	
Phaeophyscia erythrocardia	
Phaeophyscia adiastola	
Phaeophyscia rubropulchra	
Physcia americana	
Physcia millegrana	
Punctelia rudecta	
Pyxine sorediata	
Usnea sp. (S)	

Table 4. Summary of element concentrations (mean µg/g ± S.D.) measured in *Flavoparmelia caperata. S*amples were collected in 2004 (top values, clear) and 2009 (lower values, shaded). For HAFE and MANA, first samples were collected in 2006. All element data for each study plot are available in the appendices.

Park Units	S	Pb	Hg	Cu	Ni	Zn	Cd	Cr
CATO (25 plots)	1611.9 ± 18.7	22.82 ± 0.89	0.14 ± 0.01	14.11 ± 0.68	NR[1]	45.42 ± 1.28	NR	NR
	1640.94 ± 99.05	17.07 ± 2.94	—	14.79 ± 2.12	2.71 ± 0.89	52.50 ± 7.69	NR	NR
CHOH (10 plots)	1585.5 ± 56.3	21.93 ± 1.53	0.14 ± 0.00	18.47 ± 1.37	2.72 ± 0.23	51.99 ± 2.61	NR	2.16 ± 1.45
	1691.69 ± 122.50	28.03 ± 22.30	—	16.43 ± 4.70	2.87 ± 0.83	49.46 ± 12.11	NR	NR
GWMP (5 plots)	1700.3 ± 54.4	28.54 ± 1.83	0.15 ± 0.01	22.97 ± 3.39	3.10 ± 0.41	54.28 ± 4.54	NR	1.99 ± 1.25
	1762.90 ± 52.47	20.07 ± 3.80	—	13.84 ± 1.08	2.69 ± 0.39	47.65 ± 4.14	NR	NR
HAFE (5 plots)	1839.81 ± 104.33	11.26 ±2.73	—	11.22 ± 3.29	2.10 ± 0.76	49.74 ± 4.84	NR	NR
	1849.16 ± 85.37	9.98 ± 3.58	—	13.01 ± 4.52	2.37 ± 1.22	48.71 ± 11.37	NR	NR
MANA (4 plots)	1703.01 ± 236.07	8.04 ± 3.99	—	13.54 ± 4.82	2.28 ± 0.61	36.94 ± 10.57	NR	NR
	1542.44 ± 76.27	5.66 ± 3.35	—	9.95 ± 0.81	1.36 ± 0.20	33.81 ± 4.10	NR	NR
NACE (5 plots)	1570.3 ± 80.7	23.76 ± 2.89	0.15 ± 0.01	14.15 ± 1.82	2.27 ± 0.41	40.21 ± 3.84	NR	NR
	1707.27 ± 143.84	18.75 ± 2.59	—	14.47 ± 1.90	2.88 ± 0.52	49.13 ± 7.94	NR	NR
NAMA (1 plot)	1626.2 ± 199.3	40.63 ± 3.53	0.12 ± 0.02	24.68 ± 19.3	4.53 ± 1.69	63.88 ± 5.62	< 0.54	3.10 ± 1.55
	1790.95 ± 17.93	47.26 ± 40.16	—	18.95 ± 7.35	2.86 ± 0.01	59.46 ± 20.12	NR	NR
PRWI (44 plots)	1320.5 ± 14.2	12.28 ± 0.61	0.13 ± 0.01	11.37 ± 0.51	NR	38.97 ± 1.54	NR	NR
	1471.82 ± 97.13	11.53 ± 6.46	—	13.75 ± 5.75	2.30 ± 0.97	41.14 ± 8.38	NR	NR
ROCR (3 plots)	1503.3 ± 58.2	23.36 ± 1.58	0.13 ± 0.01	20.57 ± 4.41	2.19 ± 0.14	40.91 ± 0.65	NR	NR
	1686.66 ± 76.77	18.03 ± 2.73	—	14.63 ± 0.93	2.71 ± 0.16	52.27 ± 4.70	NR	2.66 ± 0.56

[1]Not resolvable.

2005 and 2009 Elemental Data

Concentrations of sulfur and metals were measured in the test lichen *Flavoparmelia caperata*, collected from each of the 102 plots (Table 4). Data collected in 2004 are for seven of the participating park units; data from HAFE and MANA were collected in 2006. A resampling of selected plots was also done in 2009.

Element concentrations varied little throughout the study area and no significant 'hot spots' were detectable in the individual plot results. Data from the initial (2004/2006) sampling indicated that lichens from PRWI plots had significantly lower mean concentrations of sulfur, Pb and Cu. This trend continued in the resampled sites in 2009. No significant differences in mean concentration of Hg or Zn were observed throughout the study area. Concentrations of Cd and Cr were either very low or below detectable limits.

A comparison of the 2004 and 2009 element data showed no significant differences for any element or site for which data were available. However, nonmetric multidimensional scaling revealed significant patterns in both the 2004 and 2009 elemental datasets (Figure 2). Based on these analyses PRWI plots were clustered separately from the others, a result consistent with the summary data shown in Table 3. Increasing concentrations of elements on the ordination axes can be visualized with reference to the S concentrations (red line on the ordination), which are correlated with the axes as shown.

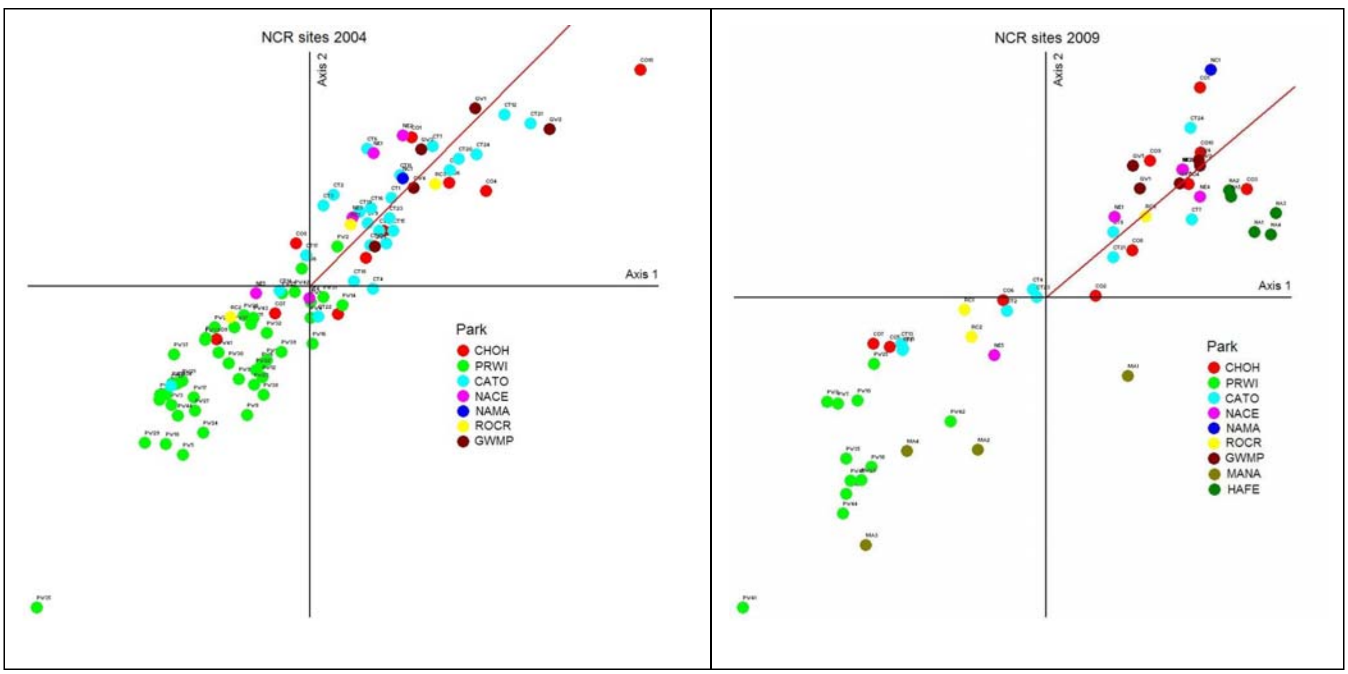

Figure 3. NMS ordination of lichen elemental data. Data are from each of the plots established in the NCR for which element data were collected in 2004 (left) and 2009 (right). For reference, the red lines indicate the specific correlation of S concentration with the axes in each ordination.

Discussion

Taken together, the floristic and element data suggest that nitrophilous, relatively pollution-tolerant lichen communities have developed over time in the NCR, probably the result of poor air quality in the past and only slight improvement since. Results are consistent with those of a recent study (McCune et al. 1997) that analyzed lichen community patterns throughout the southeastern U.S. as a part of the Forest Health Monitoring Program. The authors found two major gradients in the data, a macroclimatic gradient from the coast to the Appalachian Mountains primarily related to temperature, and another correlated with reduced air quality caused by nitrogen- and sulfur-based acidifying and fertilizing pollutants. Dominant lichens were similar to those observed in the present study (*Punctelia rudecta*, *Flavoparmelia caperata*, *Usnea strigosa*, *Rimelia reticulata*, *Parmotrema hypotropum*, *Hypotrachyna livida*, *Parmelinopsis minarum*, *Phaeophyscia rubropulchra*).
There are few comprehensive floristic studies of east coast lichen communities, but those that are available (e.g., Lawrey 1993 for Monongahela National Forest, West Virginia and Flenniken 2003 for Rhode Island) report similar floristic results.

Comparative studies of U.S. lichen element status indicate that present-day concentrations of S and metals in NCR samples of *F. caperata* are not unusually elevated. Chromium concentrations in the NCR are generally less than 3 µg/g, which is low compared to values measured in other studies. For example, Schutte (1977) consistently found values exceeding 20 µg/g, up to a maximum concentration of 69.5 µg/g, in *F. caperata* samples collected in industrial areas of Ohio. In the same study, lichens from rural areas had values less than 10 µg/g, but seldom as low as 3 µg/g.

In both the 2004 and 2009 samples, sulfur concentrations in *F. caperata* average 1500 µg/g and are always less than 2000 µg/g. These are comparable to values observed in other lichen studies in the region. For example, at Plummers Island (CHOH09), S content in *F. baltimorensis* (a rock-inhabiting relative of *F. caperata*) has declined steadily since 1983 when the concentration was 2500 µg/g. Samples collected from the same location during the present study had concentrations of 1660 µg/g in 2004, and 1673 µg/g in 2009 (Table 5). Comparable values were observed in lichens collected from Bear Island located approximately 6 km upstream from Plummers Island (and the American Legion Memorial Bridge).

S values for *Flavoparmelia caperata* obtained in other studies are similar to those observed in CHOH. For example, at Whitetop Mountain in southwest Virginia, Kinsman (1990) found an average S concentration of 1500 µg/g for *F. caperata*, with values generally less than 2000 µg/g at all elevations and azimuths. A study done in Shenandoah National Park in the mid-1980's found that S concentrations in *F. caperata* and *F. baltimorensis* were generally less than 2000 µg/g except in rare cases (Lawrey 1985). Sites where both species had elevated concentrations were always in the Northern District of the Park at high elevations (Lawrey and Hale 1988). In Monongahela National Forest, West Virginia, mean S values in *F. caperata* were 1450 µg/g at Otter Creek Wilderness and 1570 µg/g at Dolly Sods Wilderness in 1992 (Lawrey 1993).

Pb values in 2004 samples are generally low (consistently less than 50 µg/g) throughout the NCR. Lichens collected at Plummers Island (CHOH09 site) for the past 100 years document dramatic increases in atmospheric Pb deposition prior to the early 1980's. The highest values were observed after the completion of the American Legion Memorial Bridge just above the Island and carries traffic on Interstate 495. At about this time, leaded gasoline was also phased out in the U.S. and subsequent measurements of Pb concentrations in lichens declined sharply.

Table 5. Concentrations of S (mean µg/g ± SE) measured in the rock-inhabiting lichen *Flavoparmelia baltimorensis* collected at Plummers Island (CHOH09), Bear Island (CHOH08) and at Stony Man Mountain summit in SHEN.

Year	Plummers Is	Bear Is	Stony Man
1983	2500 ± 50.0		
1988	1860 ± 15.0	2070 ± 6.0	1340 ± 11.0
1992	1560 ± 3.0	1800 ± 0.0	1300 ± 5.0
2000	1500 ± 4.0	1580 ± 1.0	1330 ± 2.0
2004	1660 ± 19.0	1660 ± 49.0	1250 ± 17.0
2009	1673 ± 44.1	1677 ± 73.5	1307 ± 48.8

Table 6. Concentrations of Pb (mean µg/g ± SE) measured for the rock-inhabiting lichen *Flavoparmelia baltimorensis* collected at Plummers Island (CHOH09), Bear Island (CHOH08) and at Stony Man Mountain summit in SHEN.

Year	Plummers Is	Bear Is	Stony Man
1907	82.3 ± 8.2		
1938	127.8 ± 14.8		
1958	327.9 ± 12.6		
1970	1160.5 ± 148.8		
1979	1131.0 ± 179.3	273.0 ± 50.6	218.5 ± 100.9
1982	787.2 ± 25.3	174.0 ± 53.2	
1988	418.3 ± 44.8	123.4 ± 18.6	66.7 ± 1.0
1992	136.8 ± 7.21	49.4 ± 3.2	25.5 ± 2.3
2000	72.8 ± 13.2	29.0 ± 5.4	18.6 ± 7.1
2004	30.7 ± 4.7	26.4 ± 2.7	15.5 ± 0.7
2009	76.7 ± 0.8	14.9 ± 3.1	12.4 ± 1.9

Similar trends have been observed for other elements (N, Cd, Cr, Ni, Zn) and in other lichen species (Lawrey 1993).

Hg levels in lichens are generally moderate (average 0.15 µg/g) and probably reflect background levels for the eastern U.S. However, there are few comparative data available. No obvious hot spots were detected. A study in southwestern Pennsylvania (Davis et al. 2002) of Hg uptake by the lichen *Punctelia rudecta* showed concentrations of Hg ranging from 0.15 - 0.20 µg/g. Higher Hg levels were measured for the lichen *Letharia vulpina* in Yellowstone National Park (up to 0.243 µg/g, average 0.11 µg/g), probably a result of geyser emissions (Bennett and Wetmore 1999).

To summarize, the floristic and elemental data collected in the National Capital Region during the study (2004 and 2009) generally indicate:

1. There are presently no pollution "hot spots" in any of the park units where permanent plots were established.
2. Bark-inhabiting macrolichen communities are dominated by nitrophilous, pollution-tolerant species with pollution-sensitive species found in most park units only infrequently.
3. Lichen communities in plots from the urban parks closest to the Washington, D.C. city center are lowest in species diversity and coverage, with no pollution-sensitive species.
4. Lichens in PRWI plots are consistently higher in species richness, highest in coverage of pollution-sensitive species, and lower in element concentration than those from other park units.

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Appendix I

The following tables contain species lists and abundance scores for all permanent plots in each of the nine park units visited during the study. Abundance scores are from McCune et al. (1997), and use a 4-step scale: 1 = < 3 individuals in plot; 2 = 4-10 individuals in plot; 3 = > 10 individuals in plot; 4 = more than half boles and branches in the plot have the subject species present.

CHOH species listing, with abundance scores. 2004.

Lichen species	01	02	03	04	05	06	07	08	09	10
Anaptychia palmulata								1		
Candelaria concolor	3	2	3	2			3		3	2
Coccocarpia palmicola								1		
Dirinaria aegialita									1	
Flavoparmelia caperata	4	4	3	3	4	4	4	4	4	4
Flavopunctelia flaventior									2	
Heterodermia obscurata								2		
Myelochroa aurulenta	4	4	4	3	4	4	4	4		
Parmelia sulcata		3								
Phaeophyscia adiostola								1	2	
Phaeophyscia orbicularis					2					
Phaeophyscia pusilloides		1	3				2			
Phaeophyscia rubropulchra	2	4	2	3	4	3	3	3		3
Physcia aipolia			1				3			
Physcia millegrana	4	4	4	3		4	4	4	3	3
Physconia detersa							1			
Punctelia rudecta	4	4	4	3	4		4	4	2	4
Punctelia subrudecta	3	3	3			3		2		
Pyxine caesiopruinosa		1			2		2	2	2	
Pyxine sorediata	1				3				2	
Marchandiomyces corallinus									1	
Nectriopsis parmeliae							1			

PRWI species listing, with abundance scores. 2004.

Lichen species	PRWI sites																																										
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44
Candelaria concolor	1		1																2															1										
Canoparmelia caroliniana		1																																										
Flavoparmelia caperata	4	4	4	2	4	4	4	4	4	4	4	4	4	4	3	4	3	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	3	4	3	4	4	4
Heterodermia obscurata			2	1	2							1												2	2	3		3									3					3	3	
Heterodermia speciosa																			1						1																	1		
Hypotrachyna livida							2	2													3					1					3			2		2		2			1	3		
Leptogium cyanescens		1																																										
Myelochroa aurulenta	4	4	4	2	4	4	2	3	3	3	3	3	3	3		4	3	4	3	4		4	4		2	2		1		2		1					3			1		4	2	3
Parmelia squarrosa	1							2				2					2										2						2											
Parmelia sulcata	2							2																												2								
Parmelinopsis horrescens																											2										2							
Parmelinopsis minarum																																					3						3	
Parmotrema dilatatum		2	1	1	4	2	2			3	3	2	3		2	2		3	2	2	3									2			1	2	3	2								
Parmotrema hypotropum	2	3	3	1	4	2	2	4	4	4	3	3	3	3	3	3	3	4	4	4	3	2	2	3	1	3	3	3	1	1		4	3	3	3	3	3	3	2			4	3	4
Parmotrema michauxianum																			1										2							1								3
Parmotrema stuppeum											2		2																															
Parmotrema tinctorum																								2																				
Phaeophyscia pusilloides			2			1			2		2					2																												3
Phaeophyscia rubropulchra	3	3	3	2	4	4			3	3	3	3	3	4		4			4						2		2	3												3		3		2
Phaeophyscia squarrosa																						2																						
Physcia aipolia	1	3	3		2				2		1	2				2		4	3		2	2	3	2	3			2		3					3	1		3	2	3				
Physcia americana					1					2				1					2								3	3		3				2			2							
Physcia millegrana	3	2	2		4		3		3	2	1					3	3		3		3	3	2					1		2						3		4				3		1
Punctelia rudecta	4	4	4	2	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	3	4	4	4
Punctelia subrudecta		2	4	1			1	3	3			3	2	2						3			4						2	2						3			1					
Pyxine caesiopruinosa	1	1	1							1			1														2									2	2	3			1			
Pyxine sorediata		2	2	1	2		2	2	3	2				2		2			3	3	3		3	2	2	1	3		2			2	3	2				3				3	3	3
Rimelia reticulata								2				2							2				1								3						2		1			2	2	
Tuckermannopsis ciliaris														2									3																					
Usnea ceratina	1	1	1		1															2			2				1		2															

CATO species listing, with abundance scores. 2004.

Lichen species	CT1	CT2	CT3	CT4	CT5	CT6	CT7	CT8	CT9	CT10	CT11	CT12	CT13	CT14	CT15	CT16	CT17	CT18	CT19	CT20	CT21	CT22	CT23	CT24	CT25
Allocetraria oakesiana						2		3																	
Candelaria concolor	2	2		3	3		2						3	2	2	3		4		3	3		3		
Cetrelia olivetorum															2										
Collema furfuraceum															3			2		2					
Flavoparmelia caperata	4	3	4	4	4	4	4	4	4	3	3	4	4	4	4	4	4	4	4	3	3	4	4	3	4
Flavopunctelia flaventior	3	2		3	3				3	3					3	3	3		3					3	
Flavopunctelia soredica				2								1						2							
Heterodermia obscurata			3							3															
Hypotrachyna livida									3																
Leptogium cyanescens															3			2		2					
Myelochroa aurulenta	3	3	3	4	3			4		4	3	4	4	3		4	4	4	4	4	4	4	3	4	4
Myelochroa galbina						2		3									3								
Parmelia sulcata	3			3					3									3		2					
Parmelinopsis minarum										3															
Parmotrema hypotropum				3													3			2					3
Phaeophyscia adiostola										2							2								
Phaeophyscia pusilloides																				2					3
Phaeophyscia rubropulchra	3	3	4	4	4				4	4	3		4	3	4	4	4	3		3	4	4	4	3	3
Phaeophyscia squarrosa							3	3			2				2		3	2		2		2	3		
Physcia aipolia		2	3		2	2		2	2						3		2	3							3
Physcia millegrana	3	2		3	4		4		3		3	3	4	4	4	4	3	3	4	4	4	3	3	3	4
Physcia stellaris																					1				
Punctelia rudecta	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4		4	4	4		4	4	4	4
Punctelia subrudecta	3	3	4	4	3	4	3		3	4		4	3	3	4	4	4	4	4						4
Pyxine sorediata					3				4	3	3							3		4				3	4
Rimelia reticulata																			2						
Lichen-associated species (parasites):																									
Athelia arachnoidea						1																			
Nectriopsis parmeliae	1																								

NACE species listing, with abundance scores. 2004.

Lichen species	01	02	03	04	05
Candelaria concolor	1	3	1	2	
Flavoparmelia caperata	2	2	2	2	3
Myelochroa aurulenta				1	3
Parmotrema hypotropum			1		
Phaeophyscia pusilloides		3			
Phaeophyscia rubropulchra		4			
Physcia aipolia			2		
Physcia millegrana	2	3	2	2	
Punctelia rudecta	2		3	2	4
Punctelia subrudecta		3	1		

NAMA species listing, with abundance scores. 2004.

Candelaria concolor (3)
Myelochroa aurulenta (1)
Flavoparmelia caperata (2)
Parmotrema hypotropum (2)
Physcia millegrana (3)
Punctelia rudecta (2)
Nectriopsis parmeliae (1)

ROCR species listing, with abundance scores. 2004.

Lichen species	01	02	03
Flavoparmelia caperata	2	2	3
Myelochroa aurulenta	3		3
Parmotrema hypotropum			2
Phaeophyscia pusilloides	1		
Phaeophyscia rubropulchra	2		
Physcia millegrana	2	2	3
Punctelia rudecta	3	3	4
Punctelia subrudecta			3
Pyxine caesiopruinosa	1		
Pyxine sorediata	2		

GWMP species listing, with abundance scores. 2004.

Lichen species	01	02	03	04	05
Candelaria concolor				2	
Flavoparmelia caperata	3	3	3	3	3
Myelochroa aurulenta	1	3			3
Parmelia sulcata	3				
Parmotrema hypotropum	2			3	3
Phaeophyscia pusilloides	2				
Phaeophyscia rubropulchra	3	3	3		3
Physcia aipolia				1	
Physcia millegrana		2	3	4	
Punctelia rudecta	4	4	4	4	4
Punctelia rudecta	4	4	4	3	4
Punctelia subrudecta	3	3	3		
Pyxine caesiopruinosa	1			2	
Pyxine sorediata		3			
Usnea sp.					1

HAFE species listing, with abundance scores. 2006.

Lichen species	01	02	03	04	05
Flavoparmelia caperata	4	4	4	4	4
Heterodermia obscurata				3	
Myelochroa aurulenta	2	3			3
Parmotrema hypotropum					2
Phaeophyscia pusilloides	2				
Phaeophyscia rubropulchra	3	3		4	4
Physcia aipolia				2	
Physcia millegrana			3	4	3
Punctelia rudecta	4	4	4	4	4
Punctelia subrudecta	4	4	4	4	
Pyxine caesiopruinosa					1
Pyxine sorediata	2				

MANA species listing, with abundance scores. 2006

Lichen species	01	02	03	04
Candelaria concolor	3		3	
Flavoparmelia caperata	4	4	4	4
Heterodermia speciosa		2		
Hypotrachyna livida	2			
Leptogium cyanescens		3		
Myelochroa aurulenta	3	4	4	4
Parmelia squarrosa				2
Parmelia sulcata	2			
Parmelinopsis minarum			3	3
Parmotrema hypotropum	3	3	3	4
Parmotrema michauxianum			2	
Phaeophyscia rubropulchra	4	4	4	
Physcia aipolia	3	4		3
Physcia americana				2
Physcia millegrana	4		3	
Punctelia rudecta	4	4	4	4
Punctelia subrudecta	2			
Pyxine caesiopruinosa			3	3
Pyxine sorediata	3		3	3
Tuckermannopsis ciliaris				2

Appendix II

The following tables contain element concentrations (µg/g ± SD) measured in the lichen *Flavoparmellia caperata* collected in each permanent plot in each of the nine park units visited during the study. GPS readings and names assigned to each plot are provided in the tables and are also available on the project website http://mason.gmu.edu/~jlawrey/CUE/

CHOH sites. Element concentrations (µg/g ± SD) measured in the lichen Flavoparmelia caperata collected in 2004 (top values, black) and 2009 (bottom values, red).

			Cd	Cu	Cr	Pb	Ni	Zn	S	Hg
CHOH01	Cumberland	38.9702N 77.1782W	< 0.52 < 0.50	11.26 ± 1.78 19.58 ± 6.72	1.62 ± 0.95 3.39 ± 0.63	33.82 ± 5.09 35.97 ± 28.9	1.90 ± 0.33 2.95 ± 0.57	38.69 ± 7.03 52.14 ± 12.1	1729.6 ± 219.2 1767.6 ± 144.1	0.14 ± 0.03 —
CHOH02	Oldtown	39.5373N 78.5948W	0.61 ± 0.18 < 0.50	9.55 ± 2.53 9.81 ± 0.41	2.90 ± 2.25 3.38 ± 0.36	9.79 ± 3.63 19.86 ± 0.63	3.68 ± 0.94 3.69 ± 0.52	49.99 ± 9.43 49.83 ± 4.06	1507.1 ± 273.8 1651.95 ± 189.4	0.14 ± 0.02 —
CHOH03	Little Tonoloway	39.6967N 78.1721W	< 0.54 < 0.50	27.92 ± 13.2 18.52 ± 3.38	4.81 ± 1.12 2.17 ± 0.51	30.31 ± 8.39 15.28 ± 2.46	5.15 ± 1.06 1.95 ± 0.33	76.19 ± 16.1 72.44 ± 1.87	1530.7 ± 172.7 1725.23 ± 117.4	0.15 ± 0.01 —
CHOH04	Williamsport	39.6080N 77.8359W	< 0.54 < 0.50	14.71 ± 1.95 13.14 ± 3.18	1.76 ± 0.58 2.20 ± 0.81	17.23 ± 1.93 19.90 ± 4.95	2.38 ± 0.81 2.26 ± 0.71	65.91 ± 3.01 43.34 ± 8.01	1756.9 ± 254.2 1751.85 ± 132.9	0.13 ± 0.01 —
CHOH05	Sharpsburg	39.4396N 77.7968W	< 0.54 < 0.50	22.02 ± 4.99 16.78 ± 4.08	1.44 ± 0.19 3.57 ± 0.86	25.16 ± 5.81 18.32 ± 2.56	2.29 ± 0.52 3.56 ± 0.71	56.21 ± 12.12 43.05 ± 0.78	1573.60 ± 145.6 1546.12 ± 0.38	0.16 ± 0.00 —
CHOH06	Weverton	39.3246N 77.6885W	0.68 ± 0.07 < 0.50	16.72 ± 1.63 13.78 ± 3.42	1.27 ± 0.75 1.42 ± 0.16	17.80 ± 0.65 21.68 ± 23.5	1.58 ± 0.19 2.65 ± 1.90	45.73 ± 3.24 48.35 ± 14.6	1717.6 ± 279.1 1617.1 ± 60.23	0.13 ± 0.01 —
CHOH07	Point of Rocks	39.2885N 77.5545W	< 0.54 < 0.50	23.95 ± 1.63 15.13 ± 0.41	1.34 ± 0.71 3.74 ± 0.52	17.45 ± 6.54 19.73 ± 0.41	2.67 ± 0.71 3.69 ± 0.38	44.41 ± 2.17 44.14 ± 0.28	1378.6 ± 108.8 1533.60 ± 2.64	0.12 ± 0.02 —

CHOH08	Bear Island	38.9821N 77.2366W	< 0.54 < 0.50	22.16 ± 3.31 13.35 ± 6.47	1.93 ± 0.45 2.68 ± 1.14	26.40 ± 2.40 14.93 ± 5.34	2.41 ± 0.52 2.42 ± 0.99	51.46 ± 5.63 61.66 ± 9.96	1474.7 ± 126.8 1677.4 ± 147.5	0.13 ± 0.02 —
CHOH09	Plummers Island	38.9702N 77.1782W	< 0.55 < 0.50	16.15 ± 1.56 22.79 ± 0.79	2.35 ± 1.80 4.08 ± 0.41	30.70 ± 4.70 76.72 ± 1.47	2.46 ± 1.93 2.55 ± 0.10	35.85 ± 8.22 38.47 ± 14.4	1191.0 ± 91.5 1673.3 ± 76.55	0.11 ± 0.02 —
CHOH10	Chain Bridge	38.9326N 77.1148W	< 0.54 < 0.50	18.81 ± 0.25 15.00 ± 1.96	2.20 ± 0.61 3.63 ± 0.60	16.60 ± 0.80 21.32 ± 3.46	2.52 ± 0.35 3.34 ± 0.43	55.17 ± 1.93 43.80 ± 2.17	1993.2 ± 122.1 1819.6 ± 66.41	0.16 ± 0.01 —

PRWI sites. Element concentrations (µg/g ± SD) measured in the lichen Flavoparmelia caperata collected in 2004 (top values, black) and 2009 (bottom values, red).

			Cd	Cu	Cr	Pb	Ni	Zn	S	Hg
PRWI01	Birch Bluff Tr	38.5639N 77.3463W	0.64 ± 0.16	6.92 ± 1.21	0.66 ± 0.13	5.18 ± 1.22	1.18 ± 0.37	43.29 ± 9.78	1525.2 ± 55.2	0.13 ± 0.05
PRWI02	Birch Bluff & Crossing Tr	38.5628N 77.3419W	0.72 ± 0.24 < 0.50	15.38 ± 6.12 12.19 ± 1.44	1.35 ± 0.26 2.25 ± 1.00	25.97 ± 4.13 20.50 ± 0.78	1.67 ± 0.34 2.43 ± 0.94	40.96 ± 14.26 41.55 ± 11.25	1524.3 ± 75.9 1434.7 ± 74.64	0.16 ± 0.01 —
PRWI03	So Valley Tr & Turkey Run Tr	38.5697N 77.3642W	< 0.54	6.86 ± 0.88	0.74 ± 0.08	6.56 ± 0.66	0.97 ± 0.12	31.56 ± 0.29	1249.0 ± 45.3	0.11 ± 0.01
PRWI04	Old Blacktop Rd south	38.5953N 77.3882W	0.64 ± 0.14	13.68 ± 1.26	3.48 ± 1.97	18.32 ± 4.75	3.68 ± 1.55	45.46 ± 12.38	1421.8 ± 112.2	0.16 ± 0.01
PRWI05	Oak Ridge Tr	38.5953N 77.3875W	< 0.54	16.17 ± 7.95	0.60 ± 0.08	8.20 ± 0.68	1.41 ± 0.08	31.50 ± 6.75	1135.4 ± 162.1	0.11 ± 0.03
PRWI06	Old Blacktop Rd south	38.5897N 77.3875W	0.66 ± 0.20	21.91 ± 2.96	1.53 ± 0.73	19.73 ± 1.58	1.74 ± 0.54	49.71 ± 9.31	1207.9 ± 152.8	0.12 ± 0.01
PRWI07	Taylor Farm Rd	38.5816N 77.3792W	0.69 ± 0.12 < 0.50	8.43 ± 4.14 15.07 ± 0.45	1.54 ± 1.51 3.61 ± 0.45	12.26 ± 0.50 11.79 ± 6.39	1.72 ± 0.83 3.47± 0.16	29.54 ± 13.35 44.22 ± 2.53	1181.6 ± 86.2 1427.6 ± 197.2	0.13 ± 0.02 —
PRWI08	High Meadows Tr south	38.9817N 77.2375W	< 0.54	12.62 ± 2.49	3.99 ± 3.00	20.95 ± 6.38	4.00 ± 2.73	43.30 ± 11.95	1136.7 ± 192.7	0.15 ± 0.03
PRWI09	North Parking Area F	38.6046N 77.3837W	< 0.54	12.34 ± 1.22	1.66 ± 0.99	10.47 ± 0.90	2.06 ± 1.06	39.42 ± 7.24	1293.5 ± 106.7	0.17 ± 0.02
PRWI10	North Parking Area F west	38.6142N 77.3889W	0.73 ± 0.31 < 0.50	6.83 ± 3.71 12.93 ± 2.66	0.71 ± 0.28 1.40 ± 0.14	12.69 ± 1.21 16.62 ± 0.46	1.39 ± 0.83 2.09± 0.78	26.50 ± 10.80 46.99 ± 16.46	1384.3 ± 29.1 1415.1 ± 47.6	0.16 ± 0.01 —
PRWI11	North Parking Area F NW	38.6182N 77.3891W	< 0.54	11.36 ± 1.20	1.02 ± 0.24	11.13 ± 2.35	1.63 ± 0.07	35.39 ± 3.14	1408.6 ± 51.3	0.16 ± 0.02
PRWI12	Mawavi Rd	38.5871N 77.4100W	0.57 ± 0.04	13.01 ± 4.91	2.09 ± 1.32	15.58 ± 4.91	2.67 ± 2.10	71.58 ± 28.18	1249.9 ± 23.9	0.14 ± 0.02
PRWI13	Mawavi Rd S Valley Tr	38.5875N 77.4219W	< 0.54	7.54 ± 0.38	0.67 ± 0.16	9.76 ± 3.33	1.08 ± 0.13	29.48 ± 3.69	1238.5 ± 126.4	0.12 ± 0.02
PRWI14	Parking Area D south	38.5743N 77.3621W	< 0.54	9.81 ± 3.53	0.66 ± 0.22	4.88 ± 1.72	1.19 ± 0.12	90.01 ± 38.0	1568.2 ± 112.4	0.16 ± 0.02

PRWI15	Pyrite Mine Rd	38.5687N 77.3532W	0.64 ± 0.18	14.38 ± 6.10	2.69 ± 2.10	18.08 ± 6.51	2.96 ± 1.78	45.13 ± 6.89	1295.7 ± 152.2	0.13 ± 0.00
PRWI16	So Valley Orenda Mine	38.5690N 77.3509W	0.59 ± 0.07 < 0.50	8.98 ± 0.96 10.07 ± 5.93	0.58 ± 0.07 2.57 ± 0.97	7.23 ± 2.39 5.52 ± 0.46	2.87 ± 2.63 2.61 ± 1.00	81.64 ± 27.52 39.15 ± 4.10	1492.6 ± 112.2 1397.9 ± 78.91	0.15 ± 0.02 —
PRWI17	Parking Area E east	38.5867N 77.3614W	0.59 ± 0.06	8.53 ± 1.60	0.67 ± 0.12	8.41 ± 1.31	1.09 ± 0.39	33.07 ± 13.28	1270.3 ± 127.6	0.12 ± 0.02
PRWI18	Parking Area E west	38.5891N 77.3770W	< 0.54 < 0.50	16.08 ± 3.83 12.98 ± 0.95	0.67 ± 0.13 2.31 ± 1.43	8.86 ± 4.81 10.70 ± 8.95	1.26 ± 0.41 2.35 ± 1.49	28.08 ± 5.23 38.60 ± 4.92	1148.0 ± 28.9 1470.4 ± 68.11	0.13 ± 0.02 —
PRWI19	Parking Area I SE	38.5683N 77.3733W	< 0.54	10.67 ± 2.86	0.72 ± 0.18	12.73 ± 4.39	0.98 ± 0.22	29.39 ± 2.14	1215.2 ± 118.6	0.11 ± 0.01
PRWI20	Liming Lane Parking Area I	38.5695N 77.3887W	< 0.54	7.18 ± 0.80	0.70 ± 0.13	18.01 ± 4.83	1.26 ± 0.07	34.92 ± 3.37	1350.6 ± 135.3	0.12 ± 0.01
PRWI21	Near Goodwill Cabin Camp	38.5962N 77.3623W	< 0.54	7.70 ± 2.97	1.02 ± 0.38	4.94 ± 1.53	1.26 ± 0.45	27.08 ± 6.69	1330.0 ± 130.3	0.10 ± 0.04
PRWI22	Burma Rd east	38.6038N 77.3650W	0.77 ± 0.27	9.58 ± 3.14	0.75 ± 0.19	8.53 ± 2.78	1.68 ± 0.06	45.76 ± 11.87	1368.8 ± 108.7	0.12 ± 0.01
PRWI23	Burma Rd south	38.6041N 77.3764W	< 0.54 < 0.50	14.52 ± 0.20 13.80 ± 2.56	1.22 ± 0.09 2.31 ± 1.43	9.23 ± 3.27 8.54 ± 6.95	1.76 ± 0.14 2.35 ± 1.49	45.66 ± 0.60 38.60 ± 4.92	1313.9 ± 24.9 1470.4 ± 68.11	0.14 ± 0.01 —
PRWI24	Burma Rd and Scenic Dr	38.5958N 77.3756W	< 0.54	11.79 ± 2.31	1.83 ± 0.64	12.05 ± 3.70	2.49 ± 0.79	37.85 ± 9.66	1129.4 ± 104.3	0.12 ± 0.02
PRWI25	Oak Ridge Tr/ S Valley Tr	38.5983N 77.4121W	0.59 ± 0.08 < 0.50	9.36 ± 3.73 11.68 ± 3.22	0.96 ± 0.40 1.65 ± 0.60	17.67 ± 6.59 15.11 ± 3.67	1.28 ± 0.60 1.75 ± 0.81	39.22 ± 12.71 38.02 ± 9.35	1459.8 ± 164.3 1448.1 ± 71.23	0.15 ± 0.01 —
PRWI26	S Valley Tr North	38.5955N 77.4211W	0.73 ± 0.22	9.02 ± 4.45	0.65 ± 0.10	8.47 ± 2.21	1.24 ± 0.14	26.86 ± 4.09	1458.5 ± 28.7	0.15 ± 0.02
PRWI27	West Gate Rd	38.6039N 77.4171W	< 0.54	7.02 ± 1.49	0.93 ± 0.17	9.14 ± 3.47	1.35 ± 0.09	36.89 ± 8.50	1228.5 ± 84.0	0.15 ± 0.02
PRWI28	West Gate Rd north 1 km	38.6108N 77.4185W	0.56 ± 0.02	16.62 ± 1.12	1.09 ± 0.58	24.12 ± 3.47	1.66 ± 0.39	35.72 ± 4.03	1280.2 ± 86.78	0.12 ± 0.01
PRWI29	West Gate Rd north 2 km	38.6203N 77.4219W	< 0.54	8.24 ± 2.64	0.58 ± 0.06	9.93 ± 3.75	1.36 ± 0.41	26.93 ± 3.84	1146.8 ± 94.3	0.10 ± 0.01
PRWI30	Farms to Forest Tr	38.6055N 77.4109W	0.55 ± 0.01	10.99 ± 2.46	1.84 ± 0.52	10.49 ± 1.96	2.14 ± 0.72	37.34 ± 9.24	1337.6 ± 206.8	0.16 ± 0.02
PRWI31	NNE of PW30	38.6135N	< 0.54	8.62 ± 1.01	0.82 ± 0.28	16.07 ± 5.69	1.93 ± 1.19	45.53 ± 13.90	1497.1 ± 36.0	0.12 ±

		77.4111W								0.02
PRWI32	N of PW31	38.6218N 77.4106W	< 0.54	11.74 ± 2.65	1.90 ± 1.41	12.33 ± 4.58	1.28 ± 0.72	41.56 ± 9.93	1396.4 ± 126.3	0.13 ± 0.03
PRWI33	Mawavi Rd SW	38.5817N 77.4106W	< 0.54	6.29 ± 1.79	< 0.54	10.71 ± 8.01	0.98 ± 0.20	24.25 ± 4.24	1399.3 ± 57.4	0.09 ± 0.04
PRWI34	S Valley Tr South	38.5707N 77.4032W	< 0.54	6.75 ± 2.59	0.95 ± 0.35	6.16 ± 3.06	0.94 ± 0.16	22.65 ± 3.23	1341.0 ± 76.17	0.08 ± 0.03
PRWI35	S. Valley Tr S downstream	38.5721N 77.3921W	< 0.54 < 0.50	7.49 ± 1.40 11.57 ± 3.63	0.60 ± 0.10 2.44 ± 1.46	6.11 ± 1.17 4.96 ± 0.38	1.36 ± 0.25 3.12 ± 0.34	22.82 ± 1.39 41.95 ± 12.9	991.48 ± 98.7 1413.9 ± 185.6	0.08 ± 0.01 —
PRWI36	Parking Area H SE	38.5780N 77.3857W	0.78 ± 0.23	30.83 ± 7.36	0.84 ± 0.17	27.95 ± 2.85	1.26 ± 0.29	51.52 ± 6.42	1436.5 ± 121.7	0.16 ± 0.01
PRWI37	Parking Area H SW	38.5864N 77.3993W	< 0.54	10.02 ± 2.30	0.77 ± 0.01	19.93 ± 4.34	1.73 ± 0.85	26.58 ± 2.24	1239.2 ± 116.1	0.13 ± 0.02
PRWI38	N Valley Tr S	38.5871N 77.3543W	< 0.54	22.40 ± 8.82	0.56 ± 0.01	6.42 ± 1.43	2.73 ± 1.07	49.14 ± 12.52	1301.3 ± 147.4	0.10 ± 0.01
PRWI39	NE near Travel Trailer Village	38.5991N 77.3545W	0.63 ± 0.13	8.73 ± 1.00	0.64 ± 0.16	6.33 ± 2.39	1.92 ± 1.42	45.98 ± 10.07	1426.9 ± 97.6	0.12 ± 0.01
PRWI40	Pleasant Camp area	38.5947N 77.3548W	< 0.54 < 0.50	6.86 ± 4.34 12.23 ± 1.04	< 0.54 1.83 ± 1.48	3.60 ± 0.64 9.56 ± 5.54	0.76 ± 0.01 2.09 ± 1.18	19.33 ± 2.59 39.62 ± 5.09	1323.6 ± 128.5 1388.3 ± 15.54	0.05 ± 0.03 —
PRWI41	N Valley Quantico Falls	38.5885N 77.3464W	0.64 ± 0.11 < 0.50	9.46 ± 3.23 8.04 ± 2.24	0.72 ± 0.29 2.47 ± 0.33	9.32 ± 2.83 8.52 ± 4.17	1.26 ± 0.30 2.03 ± 0.44	30.00 ± 6.34 34.05 ± 8.49	1377.1 ± 130.5 1318.8 ± 18.14	0.13 ± 0.02 —
PRWI42	Oak Ridge Campground	38.6202N 77.4333W	0.57 ± 0.04 < 0.50	13.67 ± 1.15 10.96 ± 1.12	1.17 ± 0.41 1.27 ± 0.19	18.56 ± 6.74 17.19 ± 0.78	1.75 ± 0.81 1.41 ± 0.07	40.23 ± 6.28 32.42 ± 2.14	1448.4 ± 121.2 1578.9 ± 89.24	0.13 ± 0.01 —
PRWI43	Cabin Camp 2	38.5805N 77.4194W	< 0.54	11.36 ± 2.37	0.86 ± 0.21	16.84 ± 3.43	1.17 ± 0.21	39.51 ± 11.3	1384.4 ± 30.5	0.13 ± 0.02
PRWI44	South Orenda Rd	38.5619N 77.3535W	< 0.54 < 0.50	11.59 ± 6.02 11.39 ± 1.20	< 0.54 1.82 ± 0.54	7.66 ± 2.51 4.96 ± 0.55	1.66 ± 0.30 1.78 ± 0.41	33.59 ± 2.93 37.90 ± 3.34	1183.6 ± 122.7 1387.1 ± 204.4	0.09 ± 0.02 —

CATO sites. Element concentrations (µg/g ± SD) measured in the lichen Flavoparmelia caperata collected in 2004 (top values, black) and 2009 (bottom values, red).

			Cd	Cu	Cr	Pb	Ni	Zn	S	Hg
CATO01	Brown's Farm Tr S	39.6468N 77.4870W	0.57 ± 0.04 < 0.50	8.52 ± 0.53 14.92 ± 0.72	1.29 ± 0.11 2.64 ± 0.38	8.61 ± 1.05 16.55 ± 0.38	0.87 ± 0.11 2.69 ± 0.18	31.71 ± 0.77 51.79 ± 1.50	1704.5 ± 84.2 1557.36 ± 9.98	0.13 ± 0.01 —
CATO02	Chestnut Picnic Area S	39.6373N 77.4779W	< 0.54 < 0.50	10.42 ± 0.35 14.37 ± 0.80	1.25 ± 0.23 3.32 ± 0.46	36.80 ± 0.42 19.43 ± 0.95	2.31 ± 1.40 3.29 ± 0.35	38.57 ± 0.10 45.02 ± 2.31	1591.0 ± 59.6 1611.34 ± 133.5	0.16 ± 0.01 —
CATO03	Catoctin Tr N	39.6412N 77.4782W	0.66 ± 0.22	8.28 ± 0.41	1.08 ± 0.07	31.45 ± 0.49	1.34 ± 0.22	32.75 ± 0.63	1592.8 ± 94.8	0.14 ± 0.01
CATO04	Thurmont Vista area	39.6456N 77.4380W	0.97 ± 0.14 < 0.50	15.75 ± 5.05 14,79 ± 0.57	0.65 ± 0.22 2.12 ± 0.28	13.98 ± 3.81 16.96 ± 0.74	1.90 ± 0.47 2.13 ± 0.16	79.33 ± 1.11 55.74 ± 1.32	1566.4 ± 144.6 1630.76 ± 30.03	0.13 ± 0.00 —
CATO05	Wolf Rock	39.6350N 77.4401W	< 0.54	9.04 ± 0.57	0.69 ± 0.17	21.27 ± 2.49	1.49 ± 0.35	45.20 ± 0.72	1612.6 ± 29.1	0.13 ± 0.01
CATO06	Chimney Rock	39.6306N 77.4288W	0.67 ± 0.15	10.32 ± 0.47	1.47 ± 0.33	44.03 ± 2.27	1.16 ± 0.31	40.15 ± 1.90	1666.1 ± 63.5	0.16 ± 0.01
CATO07	Crow's Nest	39.6251N 77.4318W	< 0.54 < 0.50	14.33 ± 0.86 12.41 ± 2.21	0.67 ± 0.23 1.96 ± 0.62	28.23 ± 1.03 14.36 ± 0.85	1.58 ± 0.08 1.92 ± 0.37	40.02 ± 0.96 50.47 ± 10.71	1728.1 ± 120.7 1729.76 ± 55.14	0.14 ± 0.01 —
CATO08	Park Central and Park Hdqrs	39.6290N 77.4416W	< 0.54 < 0.50	10.22 ± 0.41 15.26 ± 0.87	1.27 ± 0.12 3.71 ± 1.03	20.19 ± 1.19 16.86 ± 0.94	1.87 ± 0.12 2.79 ± 0.64	61.47 ± 1.27 57.95 ± 1.80	1610.2 ± 30.0 1678.70 ± 44.99	0.15 ± 0.01 —

CATO09	Owens' Creek campground	39.6642N 77.4812W	0.67 ± 0.21	16.22 ± 1.41	0.78 ± 0.26	17.86 ± 0.85	1.61 ± 0.23	40.20 ± 2.04	1601.3 ± 60.6	0.14 ± 0.01
CATO10	Sawmill Exhibits	39.6554N 77.4832W	< 0.54	20.32 ± 2.45	0.96 ± 0.09	23.71 ± 1.56	1.89 ± 0.07	48.29 ± 2.28	1704.8 ± 137.2	0.14 ± 0.01
CATO11	Deerfield Nature Tr	39.6667N 77.4933W	0.76 ± 0.18	9.74 ± 0.21	1.39 ± 0.16	23.83 ± 2.49	1.22 ± 0.21	41.65 ± 1.41	1682.4 ± 19.8	0.14 ± 0.01
CATO12	Catoctin Tr NE/Mt Zion Rd	39.6738N 77.4904W	0.62 ± 0.08	9.41 ± 0.25	1.68± 0.45	20.05 ± 2.24	1.97 ± 0.21	33.27 ± 0.71	1881.5 ± 102.0	0.15 ± 0.01
CATO13	NW corner of Park	39.6797N 77.4850W	< 0.54 < 0.50	13.46 ± 1.45 16.44 ± 0.06	0.77 ± 0.40 2.89 ± 0.34	14.49 ± 4.19 16.41 ± 0.18	0.91 ± 0.15 3.06 ± 0.33	27.79 ± 2.73 51.44 ± 1.60	1183.4 ± 106.9 1559.70 ± 3.18	0.10 ± 0.01 —
CATO14	Horse Tr NW corner	39.6728N 77.4833W	0.55 ± 0.03	22.38 ± 0.43	1.93 ± 0.28	17.04 ± 0.86	2.11 ± 0.41	41.42 ± 2.18	1408.5 ± 110.0	0.14 ± 0.01
CATO15	Deerfield Nature Tr loop	39.6581N 77.4934W	< 0.54 < 0.50	9.13 ± 0.83 16.41 ± 0.64	0.60 ± 0.06 2.81 ± 0.32	11.65 ± 1.62 16.36 ± 0.13	1.45 ± 0.22 2.87 ± 0.17	50.91 ± 3.92 49.21 ± 0.80	1657.6 ± 188.8 1555.40 ± 18.19	0.11 ± 0.02 —
CATO16	Hog Rock parking S	39.6496N 77.4479W	< 0.54	11.72 ± 1.02	1.94 ± 0.37	25.68 ± 1.13	2.34 ± 0.28	41.18 ± 1.71	1606.7 ± 97.0	0.14 ± 0.01
CATO17	Near Sabillasville Rd	39.6526N 77.4436W	< 0.54	15.09 ± 8.54	< 0.54	24.64 ± 3.66	2.94 ± 2.56	37.81 ± 1.13	1482.3 ± 58.4	0.11 ± 0.00
CATO18	Hog Rock overlook S	39.6390N 77.4625W	< 0.54	22.12 ± 2.53	7.90 ± 1.25	19.69 ± 3.93	7.17 ± 0.95	50.31 ± 0.71	1482.8 ± 14.2	0.15 ± 0.01
CATO19	Hog Rock/Falls Nature Tr	39.6334N 77.4649W	0.56 ± 0.04	13.23 ± 0.85	2.64 ± 0.50	21.97 ± 1.29	2.31 ± 0.28	39.40 ± 0.99	1595.3 ± 134.6	0.13 ± 0.01

CATO20	Blue Blazes Still exhibit	39.6378N 77.4503W	0.61 ± 0.13	16.48 ± 2.32	1.81 ± 0.41	25.02 ± 0.97	3.01 ± 0.57	48.25 ± 2.10	1731.1 ± 34.5	0.15 ± 0.01
CATO21	Hog Rock parking N	39.6512N 77.4530W	< 0.54 < 0.50	13.81 ± 1.01 14.48 ± 1.54	1.12 ± 0.20 2.42 ± 0.48	20.41 ± 1.14 17.01 ± 1.35	2.04 ± 0.40 2.43 ± 0.33	45.44 ± 2.94 45.25 ± 17.1	1874.10 ± 88.9 1669.54 ± 87.18	0.13 ± 0.01 —
CATO22	Poplar Grove campground	39.6563N 77.4721W	0.63 ± 0.14	12.66 ± 1.12	2.53 ± 1.94	18.47 ± 0.53	2.78 ± 1.68	61.33 ± 12.91	1453.3 ± 106.2	0.14 ± 0.02
CATO23	Manahan Road	39.6620N 77.4730W	1.02 ± 0.25 < 0.50	32.93 ± 7.18 16.28 ± 1.44	< 0.54 1.92 ± 0.55	22.16 ± 1.46 14.68 ± 6.63	0.99 ± 0.07 2.26 ± 0.44	59.31 ± 6.40 56.66 ± 4.77	1592.9 ± 162.5 1629.81 ± 66.23	0.14 ± 0.01 —
CATO24	Lantz Marsh	39.6690N 77.4569W	< 0.54 < 0.50	11.50 ± 1.64 12.56 ± 4.98	2.47 ± 0.34 4.76 ± 4.17	26.02 ± 0.31 22.04 ± 3.05	2.17 ± 0.31 3.70 ± 2.50	47.18 ± 1.60 61.43 ± 4.37	1772.4 ± 204.2 1787.81 ±159.8	0.13 ± 0.01 —
CATO25	Lantz Marsh south	39.6637N 77.4570W	0.61 ± 0.15	19.52 ± 2.77	3.63 ± 0.93	26.78 ± 1.73	4.23 ± 0.46	51.10 ± 0.31	1531.9 ± 112.2	0.12 ± 0.01

NACE sites. Element concentrations (µg/g ± SD) measured in the lichen Flavoparmelia caperata collected in 2004 (top values, black) and 2009 (bottom values, red).

			Cd	Cu	Cr	Pb	Ni	Zn	S	Hg
NACE01	Ft. Dupont	38.8781N 76.9553W	< 0.52 < 0.50	10.19 ± 5.14 15.15 ± 0.67	1.13 ± 0.55 3.19 ± 0.58	39.74 ± 10.8 19.51 ± 3.47	1.70 ± 0.73 3.04 ± 0.66	39.45 ± 10.8 48.90 ± 7.90	1671.1 ± 299.6 1688.4 ± 137.0	0.16 ± 0.03 —
NACE02	Kenilworth Gardens	38.9137N 76.9416W	< 0.54 < 0.50	21.21 ± 6.20 15.57 ± 1.57	2.25 ± 0.97 3.43 ± 0.67	55.27 ± 11.6 20.44 ± 2.67	3.89 ± 1.33 3.09 ± 0.37	55.28 ± 11.67 52.51 ± 8.06	1666.8 ± 24.60 1743.8 ± 189.7	0.14 ± 0.02 —
NACE03	Greenbelt Park	38.9781N 76.9046W	< 0.54 < 0.50	17.69 ± 3.96 13.30 ± 0.42	0.98 ± 0.35 3.06 ± 0.21	18.60 ± 9.33 16.64 ± 0.83	1.48 ± 0.62 2.70 ± 0.03	32.18 ± 6.13 45.77 ± 0.09	1606.8 ± 273.5 1761.6 ± 41.45	0.13 ± 0.03 —
NACE04	Oxon Hill	38.8055N 77.0078W	0.61 ± 0.08 < 0.50	11.71 ± 2.76 13.69 ± 2.53	0.83 ± 0.03 3.37 ± 0.21	21.82 ± 4.56 18.81 ± 0.11	2.74 ± 0.93 2.62 ± 0.03	45.63 ± 7.63 59.35 ± 2.98	1444.3 ± 119.0 1737.5 ± 181.6	0.17 ± 0.01 —
NACE05	Marshall Hall	38.6797N 77.0870W	0.73 ± 0.17 < 0.50	9.96 ± 6.45 12.59 ± 2.66	< 0.54 2.62 ± 1.19	15.86 ± 2.99 17.69 ± 3.10	1.50 ± 0.95 2.78 ± 0.92	28.44 ± 11.72 41.41 ± 4.91	1461.3 ± 73.9 1599.6 ± 84.76	0.16 ± 0.02 —

NAMA01 site. Element concentrations (µg/g ± SD) measured in the lichen Flavoparmelia caperata collected in 2004 and 2009.

2004 samples	***2009 samples***
Cd < 0.54	Cd < 0.50
Cu 24.68 ± 19.26	Cu 18.95 ± 7.35
Cr 3.10 ± 1.55	Cr 4.07 ± 1.61
Pb 40.63 ± 3.53	Pb 39.00 ± 12.73
Ni 4.53 ± 1.69	Ni 2.86 ± 0.81
Zn 63.88 ± 5.62	Zn 59.46 ± 20.12
S 1626.2 ± 199.3	S 1790.9 ± 17.93
Hg 0.12 ± 0.02	Hg NR

ROCR sites. Element concentrations (µg/g ± SD) measured in the lichen Flavoparmelia caperata collected in 2004 (top values, black) and 2009 (bottom values, red).

			Cd	Cu	Cr	Pb	Ni	Zn	S	Hg
ROCR01	Peirce Mill	38.9469N 77.0477W	< 0.52 < 0.50	14.20 ± 0.63 15.02 ± 1.57	2.28 ± 0.21 2.83 ± 1.05	27.03 ± 3.30 19.59 ± 1.58	1.98 ± 0.35 2.69 ± 0.28	41.92 ± 0.15 55.52 ± 2.77	1557.8 ± 47.6 1599.2 ± 27.5	0.14 ± 0.02 —
ROCR02	Nature Center	38.9748N 77.0432W	< 0.54 < 0.50	9.30 ± 0.50 12.95 ± 2.56	1.85 ± 0.12 2.72 ± 0.16	25.13 ± 1.08 20.02 ± 1.58	2.34 ± 0.38 2.69 ± 0.33	39.29 ± 1.50 46.59 ± 1.93	1319.7 ± 49.7 1594.1 ± 254.7	0.11 ± 0.01 —
ROCR03	North End	38.9869N 77.5713W	0.67 ± 0.10 < 0.50	37.96 ± 1.05 16.94 ± 3.54	2.20 ± 0.78 2.43 ± 0.10	17.86 ± 0.69 15.84 ± 3.48	2.24 ± 0.40 2.78 ± 0.05	41.47 ± 2.00 54.71 ± 1.95	1631.8 ± 152.5 1696.6 ± 24.18	0.15 ± 0.01 —

GWMP sites. Element concentrations (µg/g ± SD) measured in the lichen Flavoparmelia caperata collected in 2004 (top values, black) and 2009 (bottom values, red).

			Cd	Cu	Cr	Pb	Ni	Zn	S	Hg
GWMP01	Great Falls	38.9879N 77.2495W	0.65 ± 0.09 < 0.50	16.61 ± 2.70 14.39 ± 1.02	2.75 ± 1.87 3.01 ± 0.71	30.59 ± 10.8 21.95 ± 5.23	2.77 ± 0.80 2.82 ± 0.68	39.95 ± 8.52 52.39 ± 4.83	1787.4 ± 31.7 1710.6 ± 62.61	0.16 ± 0.02 —
GWMP02	Turkey Run	38.9656N 77.1565W	< 0.54 < 0.50	45.13 ± 8.59 14.11 ± 0.41	2.73 ± 1.19 2.73 ± 0.22	25.52 ± 5.50 16.63 ± 0.94	5.41 ± 1.34 2.70 ± 0.07	70.67 ± 11.6 46.75 ± 0.22	1815.4 ± 181.3 1795.47 ± 8.95	0.14 ± 0.02 —
GWMP03	Theodore Roosevelt Island	38.8981N 77.0625W	< 0.54 < 0.50	19.31 ± 5.89 14.15 ± 1.55	1.58 ± 0.05 2.42 ± 0.56	34.30 ± 5.75 21.05 ± 5.05	1.91 ± 0.13 2.58 ± 0.55	49.92 ± 8.98 48.23 ± 2.23	1685.4 ± 144.3 1741.0 ± 32.72	0.16 ± 0.02 —
GWMP04	Dyke Marsh	38.7742N 77.0510W	0.61 ± 0.08 < 0.50	12.58 ± 3.50 12.71 ± 0.38	1.36 ± 0.15 2.86 ± 0.13	26.52 ± 4.65 20.63 ± 0.86	2.12 ± 0.32 2.67 ± 0.15	58.34 ± 12.54 43.24 ± 1.10	1674.2 ± 183.2 1804.5 ± 32.52	0.15 ± 0.01 —
GWMP05	Fort Hunt	38.7122N 77.0546W	< 0.54 < 0.50	21.53 ± 4.11 17.90 ± 2.69	1.54 ± 0.97 3.09 ± 0.44	25.71 ± 7.91 28.00 ± 6.61	2.99 ± 0.71 2.89± 0.06	51.70 ± 15.5 48.74 ± 2.91	1538.2 ± 156.8 1701.1 ± 10.03	0.15 ± 0.01 —

HAFE sites. Element concentrations (µg/g ± SD) measured in the lichen Flavoparmelia caperata collected in 2006 (top values, black) and 2009 (bottom values, red).

			Cd	Cu	Cr	Pb	Ni	Zn	S	Hg
HAFE01	Maryland Heights	39.3327N 77.7214W	< 0.50 < 0.50	9.06 ± 1.70 9.97 ± 2.82	1.64 ± 0.21 1.16 ± 0.36	10.82 ± 0.90 13.76 ± 3.70	1.98 ± 0.18 1.60 ± 0.12	49.61 ± 2.58 48.97 ± 7.73	1917.8 ± 19.3 1906.3 ± 45.2	— —
HAFE02	Stone Fort	39.3429N 77.7165W	< 0.50 < 0.50	8.80 ± 0.40 13.40 ± 5.02	1.08 ± 0.05 1.63 ± 0.72	15.43 ± 0.31 14.50 ± 0.71	1.75 ± 0.08 1.66 ± 0.57	53.15 ± 2.65 37.46 ± 3.91	1913.2 ± 182.6 1812.2 ± 104.7	— —
HAFE03	Miltary Road East	39.3288N 77.7205W	< 0.50 < 0.50	12.40 ± 0.69 11.41 ± 0.00	1.80 ± 0.05 2.06 ± 0.26	12.57 ± 0.49 12.32 ± 3.79	2.03 ± 0.01 3.89 ± 2.01	55.61 ± 1.59 61.36 ± 21.8	1822.3 ± 75.4 1893.1 ± 5.10	— —
HAFE04	Loudoun Heights	39.3160N 77.7328W	< 0.50 < 0.50	9.12 ± 0.64 10.64 ± 1.18	1.25 ± 0.15 1.61 ± 0.05	8.19 ± 0.20 9.75 ± 0.26	1.47 ± 0.06 1.98 ± 0.19	44.49 ± 0.61 48.37± 5.30	1812.8 ± 102.1 1890.2 ± 103.4	— —
HAFE05	Loudoun Heights Blue Trail	39.3175N 77.7270W	< 0.50 < 0.50	16.71 ± 0.82 20.16 ± 2.73	2.20 ± 0.52 1.58 ± 0.35	9.31 ± 0.90 8.45 ± 0.77	3.29 ± 1.12 2.71 ± 1.25	45.84 ± 2.58 47.37 ± 2.65	1732.8 ± 12.6 1743.9 ± 56.76	— —

MANA sites. Element concentrations (µg/g ± SD) measured in the lichen Flavoparmelia caperata collected in 2006 (top values, black) and 2009 (bottom values, red).

			Cd	Cu	Cr	Pb	Ni	Zn	S	Hg
MANA01	Stone Bridge	38.8267N 77.5083W	< 0.50 < 0.50	14.41 ± 7.21 10.16 ± 0.60	3.02 ± 0.97 1.44 ± 0.00	7.84 ± 0.63 4.39 ± 0.02	2.67 ± 0.80 1.15± 0.02	43.14 ± 16.46 36.20 ± 1.36	1807.7 ± 408.4 1647.1 ± 124.3	— —
MANA02	First Manassas Tr.	38.8306N 77.5158W	< 0.50 < 0.50	13.72 ± 1.52 10.84 ± 0.73	1.51 ± 0.48 1.31 ± 0.22	5.80 ± 2.15 4.10± 0.42	1.70 ± 0.34 1.20 ± 0.17	37.88 ± 2.51 36.05 ± 0.14	1639.2 ± 140.9 1581.5 ± 82.7	— —
MANA03	Chinn Ridge	38.8090N 77.5380W	< 0.50 < 0.50	8.90 ± 0.97 9.14 ± 0.60	2.21 ± 0.12 1.17 ± 0.03	6.36 ± 2.66 4.84± 0.17	1.77 ± 0.23 1.29 ± 0.03	28.93 ± 4.23 30.44 ± 7.33	1563.6 ± 87.1 1483.0 ± 70.1	— —
MANA04	NY Monuments	38.8083N 77.5415W	< 0.50 < 0.50	12.55 ± 2.19 9.67 ± 0.37	1.89 ± 0.68 1.14 ± 0.19	7.24 ± 2.66 9.00± 0.71	2.02 ± 0.23 1.40 ± 0.33	34.70 ± 4.23 32.53 ± 3.86	1749.1 ± 23.9 1558.0 ± 134.2	— —

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National Park Service
U.S. Department of the Interior

Natural Resource Program Center
1201 Oakridge Drive, Suite 150
Fort Collins, CO 80525

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