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Elemental chemistry of four lichen species from the Apostle Islands, Wisconsin, 1987, 1995 and 2001

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Abstract

Four lichen species sampled three times over a 15-year time span at four of the Apostle Islands, Wisconsin were analyzed for 16 chemical elements in order to determine time trends and spatial patterns. Factor analyses of the data revealed that elements associated with soils (Al, Cr, Fe, Na, Ni and S) have increased over the study period, while nutrient and pollutant elements (Cu, K, P, Pb and Zn) have decreased. Four other elements (Ca, Cd, Mg and Mn) were unchanged over time. *Cladina rangiferina*, a terricolous species, contained the lowest concentrations of all elements, while the corticolous species *Evernia mesomorpha* was highest in soil elements, *Hypogymnia physodes* was highest in Ca, Cd, Mg and Mn, and *Parmelia sulcata* was highest in the nutritional elements. Lichens on islands within 3–4 km of the mainland were highest in soil elements, which decreased with distance from the mainland. Elements that were 18–43% greater on the nearest islands were significantly different between near and far islands. Eight elements (Al, Ca, Cd, K, Mg, Mn, P and S) exceeded enrichment levels for *Hypogymnia physodes*, suggesting possible contamination problems for this species. Although Pb has decreased significantly over the time period, other elements have increased in the lichens while decreasing in the atmosphere, suggesting that accumulation in the environment is continuing.

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1. Introduction

Previously we have documented spatial and temporal trends in chemical elements in lichen species from the upper Midwestern US, which could be explained by changes over regional scales. For example, in Isle Royale National Park in Lake Superior, toxic elements increased more

than non-toxic elements in two lichen species over a nine-year time span (Bennett, 1995). In northern Minnesota, a suite of elements representing dust sources from lichens sampled over an 11-year time span decreased over time and from west to east, while a suite of nutritional elements increased across the same factors (Bennett and Wetmore, 1999). The inverse relationship found between these two factors could have been the result of changes in climate and wind-blown dust in recent

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decades in the upper Midwestern US. Lichens sampled in western North Dakota over a 16-year time span revealed elevated concentrations of soil elements in a soil lichen compared to an epiphytic species, and 30% decreases in Cd and Hg in both species over the time period of the study (Bennett and Wetmore, 2000). For the three upper Great Lakes studies, when combined together there are eight sample years from 1983 to 2001, with four in the 1980s, three in the 1990s, and one in 2000.

Other studies of changes in element concentrations in lichens through time usually compare a contemporary sample with a herbarium sample collected earlier. Schutte (1977) found Cr increases in two *Parmelia* species in Ohio and West Virginia over 100 years by analyzing herbarium samples. *Cladonia alpestris* herbarium samples from the 1880s to the 1970s showed increases in Pb (Persson, 1974). However, Lawrey and Hale (1988), and Lawrey (1993) found decreases in Pb in herbarium samples of *Flavoparmelia baltimorensis* collected in 1983, 1988 and 1992. Unidentified *Xanthoparmelia* species collected in Arizona over 25 years showed decreases in Pb and increases in Zn (Zschau, 1999). In Italy, samples of *Parmelia sulcata* collected and analyzed in 1978 and 1993 (no herbarium samples) showed no significant changes in element concentrations even though they were sampled 16 years apart (Loppi and De Dominicis, 1996). This may be due to the measurements being performed only on lobe tips rather than whole thalli, a method that can lead to underestimations of concentrations. In Antarctica, field samples of *Umbilicaria decussata* collected 11 years apart showed no changes on average between 1989 and 1999 (Bargagli et al., 2000). Finally, field samples of *Cetraria nivalis* collected nine times over an 11 year time span (1979–1990) in Greenland decreased in Pb content by half (Pilegaard, 1994). The overall picture that emerges from these studies is that of an increase of Pb in lichens up to the 1980s, followed by decreases as Pb was phased out of gasoline, increases of some anthropogenic elements over time spans approaching 100 years, and ambiguous changes in other elements over time spans of a few decades.

We have continued to study elemental chemistry of lichens in this same region, and have recently completed sampling of lichens at Apostle Islands National Lakeshore. While the study was done to add to our knowledge of regional effects, the data indicated a local effect of considerable interest. Smaller scale changes are probably nested within regional scale effects and are worthy of investigation for local patterns. This paper describes a local effect unknown previously.

Apostle Islands National Lakeshore is a national park in Lake Superior that consists of 21 islands and a strip of land bordering the lake. The terrestrial portion of the park is a little over 16 300 acres, but the islands are spread out over the western end of Lake Superior in an area spanning approximately 50 km west to east. The islands are uninhabited, and there are no sources of pollution on any islands. Some islands, however, are visited regularly by tourists using motorized watercraft because of the presence of docking facilities. These islands presented an opportunity to study local effects of air pollution because the islands were assumed to be influenced by emissions on the mainland in relation to their distance. However, the same factor makes studying them difficult because accessibility is a problem. We attempted to study this phenomenon by sampling lichens three times over a 15-year time span at the same localities on four of the islands. We hypothesized that element concentrations in lichens would decrease with an increase in distance from the mainland.

2. Materials and methods

Lichens were sampled for elemental chemistry in three years: 1987, 1995 and 2001. Four species were sampled in the last 2 years of sampling: *Cladonia rangiferina* (terricolous), *Evernia mesomorpha*, *Hypogymnia physodes* and *Parmelia sulcata* (all three epiphytic). The last species was not sampled in 1987. In 1987, 27 samples were collected, 54 in 1995, and 47 in 2001, for a total of 128 samples.

Four sampling localities were used: Raspberry Island (46°58'15"N, 90°47'25"W), Long Island (46°43'38"N, 90°47'4"W), Stockton Island

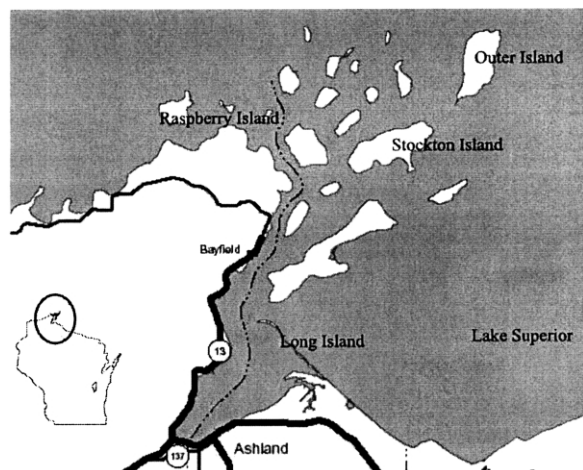


Fig. 1. Map of the Apostle Islands National Lakeshore, Wisconsin in western Lake Superior. Raspberry Island is the small island above the 'n' in 'Island'.

(46°55'36"N, 90°33'10"W) and Outer Island (46°59'46"N, 90°27'55"W) (Fig. 1). Raspberry and Long islands are close to the mainland, while Stockton and Outer are far off from the mainland. Long Island was only sampled in 1995 and 2000. The shortest straight line distance to the mainland for each island is: Raspberry, 3 km; Long, 4 km; Stockton, 8 km; and Outer, 17 km. Long Island is southeast of the mainland, while the other three islands are east. The total number of samples collected from each island across species and years was: Raspberry, 33; Long, 23; Stockton, 33; and Outer, 39.

Lichens were collected at each locality in aggregate samples from several host trees and the soil and stored in porous plastic sample bags and air dried. They were manually cleaned of debris and other plant material in the lab, then ground to a powder in a mill, and analyzed for elements by ICP-OES. They were not washed prior to analysis.

Sixteen elements were measured in the samples: Al, B, Ca, Cd, Cr, Cu, Fe, K, Mg, Mn, Na, Ni, P, Pb, S and Zn. Boron levels in all species at Long Island in 2001 were below the detection limit and were not available. Six other below detection limits values in other elements were substituted with 0.7 times the detection limit because the number of values were less than one third of the total data

Table 1

Three-year chemical element averages for *Cladina rangiferina*

<i>Cladina</i>					
Element	1987	1995	2001	Grand average	% Change 1987–2001
Al	205.2	223.6	316.1	251.1	54.0
B	5.6	0.6	0.7	1.8	–87.0
Ca	525.1	626.0	765.6	651.5	45.8
Cd	0.2	0.2	0.1	0.1	–20.7
Cr	0.3	0.4	0.6	0.5	73.3
Cu	3.4	2.3	1.7	2.3	–51.0
Fe	212.9	306.7	497.6	351.3	133.7
K	1672.0	1420.9	1292.4	1432.1	–22.7
Mg	280.7	259.0	303.0	278.8	8.0
Mn	38.5	82.1	40.2	58.2	4.5
Na	23.0	19.8	27.0	23.0	17.6
Ni	0.4	0.5	0.6	0.5	75.9
P	424.8	443.2	393.2	422.1	–7.4
Pb	2.0	1.7	1.4	1.7	–27.1
S	565.0	427.9	561.8	503.7	–0.6
Zn	14.0	15.0	15.5	15.0	10.6

Elements that were significantly different between years are shown in bold print, as determined by *F* probabilities less than 0.05 in one-way analyses of variance. Percent changes from 1987 to 2001 are shown in the last column.

Table 2

Three-year chemical element averages for *Evernia mesomorpha* (see Table 1 for details)

<i>Evernia</i>					
Element	1987	1995	2001	Grand average	% Change 1987–2001
Al	552.7	504.4	478.0	508.9	–13.5
B	7.1	2.2	2.3	3.7	–67.5
Ca	707.7	942.9	1375.5	1025.5	94.4
Cd	0.3	0.3	0.3	0.3	–5.1
Cr	1.0	1.4	1.0	1.1	4.9
Cu	8.2	5.4	3.3	5.5	–59.3
Fe	727.0	900.7	1054.8	904.8	45.1
K	2547.1	2300.9	2133.3	2312.6	–16.2
Mg	372.9	363.8	357.4	364.2	–4.1
Mn	45.6	44.8	45.9	45.4	0.6
Na	40.1	39.8	35.2	38.3	–12.3
Ni	0.9	1.2	1.3	1.1	49.7
P	622.3	586.7	601.8	601.9	–3.3
Pb	7.3	4.4	3.6	4.9	–50.2
S	1241.1	1089.5	1384.3	1233.5	11.5
Zn	31.3	32.8	30.1	31.5	–3.9

Table 3

Three-year chemical element averages for *Hypogymnia physodes* (see Table 1 for details)

<i>Hypogymnia</i>					
Element	1987	1995	2001	Grand average	% Change 1987–2001
Al	613.3	600.3	570.7	593.8	–6.9
B	6.6	2.1	2.5	3.6	–62.3
Ca	13 998.3	16 612.7	18 511.3	16 530.0	32.2
Cd	1.0	1.4	1.1	1.2	17.2
Cr	1.1	1.4	1.1	1.2	5.8
Cu	10.5	8.3	5.6	8.0	–46.7
Fe	706.5	944.2	1025.9	905.4	45.2
K	3355.8	3035.3	2732.4	3021.3	–18.6
Mg	824.2	778.8	850.5	816.2	3.2
Mn	240.2	214.6	205.4	218.7	–14.5
Na	33.6	31.3	33.8	32.8	0.8
Ni	1.3	1.7	1.7	1.6	29.8
P	754.8	703.9	788.4	747.3	4.4
Pb	15.8	14.0	9.3	12.9	–41.5
S	1020.6	972.0	1206.3	1066.2	18.2
Zn	65.6	81.4	66.0	71.6	0.6

available for that element (Bennett et al., 2000). There were a total of 2048 data points across all years, species and elements.

Statistical analyses of the data were performed as follows. The effects of years of sampling and

species were analyzed with a two-way factorial analysis of variance for each element. One-way analyses of variance of the effect of year of sampling were performed for each element for each species for tabular presentation, but are not discussed in detail. Comparison of the two near (Raspberry and Long islands) vs. the two far-off (Stockton and Outer) islands were performed using *t*-tests for each element using a near/far dummy variable. Differences among islands were tested with one-way analyses of variance of each element across years and species. A factor analysis was performed on the three-way data matrix (species, years, and islands) using varimax rotation. Boron was excluded from the factor analysis because of missing data in the matrix. Factor coefficients were used to calculate factor values for analyses of variance and *t*-tests. All statistics were computed using the latest version of *Systat*.

3. Results

Of the 16 elements, 11 have changed significantly ($P < 0.05$) over time: B, Cd, Cr, Cu, Fe, K, Mn, Ni, Pb, S and Zn (Tables 1–4). Al, Ca, Mg, Na and P have not changed significantly. Of those that have changed significantly, B, Cd, Cu, K, Mn,

Table 4

Two-year chemical element averages for *Parmelia sulcata* (see Table 1 for details)

<i>Parmelia</i>				
Element	1995	2001	Grand average	% Change 1995–2001
Al	667.1	667.1	667.1	0.0
B	4.0	3.9	3.9	–1.3
Ca	2790.5	3543.7	3150.7	27.0
Cd	0.6	0.5	0.6	–9.9
Cr	1.1	1.1	1.1	4.6
Cu	11.4	6.8	9.2	–39.8
Fe	918.8	1036.2	974.9	12.8
K	3549.1	2835.9	3208.0	–20.1
Mg	532.7	560.0	545.8	5.1
Mn	173.2	134.4	154.6	–22.4
Na	30.5	27.9	29.3	–8.4
Ni	1.4	1.6	1.5	10.6
P	1224.3	1075.5	1153.2	–12.2
Pb	13.1	10.9	12.1	–17.2
S	1266.3	1254.3	1260.6	–0.9
Zn	89.1	80.2	84.9	–9.9

Pb and Zn have all decreased, while Cr, Fe, Ni and S have increased. Significant increases ranged from 5 to 134% and averaged 39.6%, while significant decreases ranged from 1 to 87% and averaged 39.2%.

All elements were significantly ($P < 0.05$) different among species. *Cladina* was always lowest in all elements with one exception (Mn in 1995 was lowest in *Evernia*). For the three other species, usually either *Hypogymnia* or *Parmelia* was highest in concentration of all elements.

For some elements there was a significant ($P < 0.05$) year by species interaction: Al, Cd, Cr, Cu, Na, Pb, S and Zn. Usually this meant that the change over time of the element varied among species, with some species decreasing while others increased.

Some elements varied significantly ($P < 0.05$) among the four islands (using data across species and years): B, Cr, Fe, K, Mg, Na, Ni, P and Pb (Table 5). With one exception, these elements were highest at Raspberry Island, and generally decreased from west to east. The exception was Pb, which was highest at Long and Stockton islands.

Seven elements were significantly ($P < 0.05$) higher on the two near islands compared to the

Table 6

Element concentrations at two near to the mainland and two far from the mainland Apostle Islands averaged across lichen species and years of sampling

Element	Near	Far	% Change (far to Near)
Al	504.3	453.9	+11
B	2.93	3.20	−8
Ca	4919	5354	−8
Cd	0.553	0.496	+11
Cr	1.04	0.85	+22
Cu	5.99	5.58	+7
Fe	809.4	686.5	+18
K	2714	2100	+29
Mg	556.5	424.8	+31
Mn	105.3	118.0	−11
Na	34.7	27.0	+29
Ni	1.25	1.01	+24
P	819.3	571.1	+43
Pb	7.46	6.93	+8
S	979.0	950.1	+3
Zn	47.9	44.2	+8

two far islands: Cr, Fe, K, Mg, Na, Ni and P (Table 6). No elements were significantly lower on the near islands.

The factor analysis extracted three factors that explained 83% of the variation in the data (Fig.

Table 5

Element concentrations at four Apostle Islands averaged across lichen species and years of sampling

Element	Raspberry	Long	Stockton	Outer	% Change (outer to Raspberry)
Al	535.2	460.1	478.8	432.9	+24
B	3.55	1.56	3.78	2.71	+31
Ca	6159	3141	5344	5362	+15
Cd	0.592	0.498	0.348	0.622	−5
Cr	1.09	0.97	0.91	0.81	+35
Cu	5.78	6.30	5.37	5.76	0
Fe	899.5	680.0	769.0	616.7	+46
K	2796	2597	2157	2051	+36
Mg	652.4	419.1	435.6	415.7	+57
Mn	117.2	88.2	137.2	101.8	+15
Na	35.3	33.8	26.0	27.8	+27
Ni	1.31	1.18	1.07	0.96	+36
P	861.8	758.5	585.7	558.8	+54
Pb	6.35	9.04	8.71	5.43	+17
S	1065	855.3	993.9	913.0	+17
Zn	48.5	47.0	52.8	36.9	+31

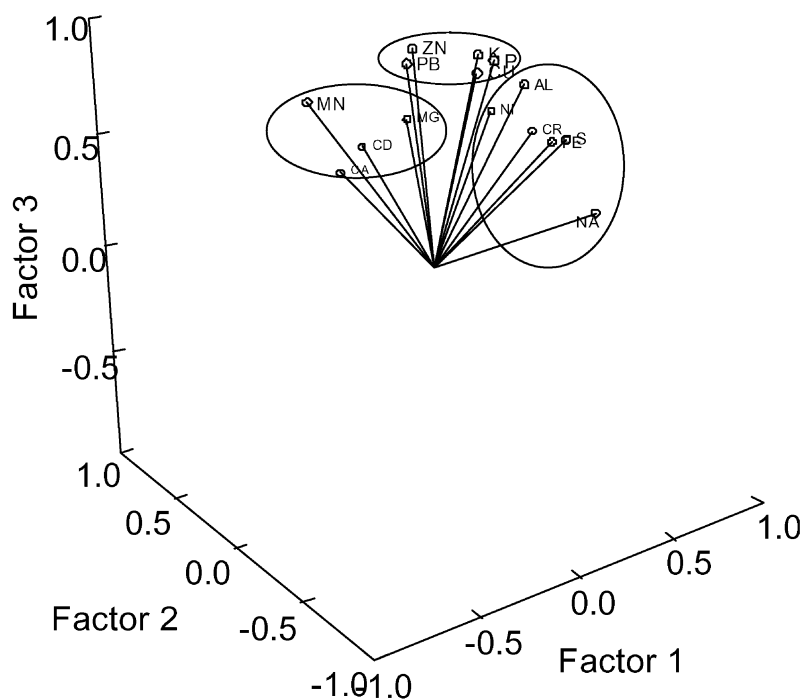


Fig. 2. Loading plot of three varimax rotated factors extracted from 15 chemical elements found in four lichen species of Apostle Islands National Lakeshore. Ellipses are drawn around the elements most loaded on Factor 2, 3 and 1, left to right in the figure.

2). Factor 1 was highly loaded with Al, Cr, Fe, Na, Ni and S and explained 29% of the variation. Most of these elements are associated with soil enrichment. The second factor explained 25% of the variation and was highly loaded with Ca, Cd, Mg and Mn. This factor contains two alkali earth metals (Ca and Mg) and two transition metals (Cd and Mn). The third factor explained another 29% of the variation and was loaded with Cu, K, P, Pb and Zn. This factor contains a mixture of nutrient elements (P, K and Zn) and some heavy metals (Cu and Pb).

The factor means were analyzed by *t*-tests and analyses of variance for the same four treatments as above (Table 7). This presents a clearer picture of the results of the study. Factor 1 clearly increased over the three years of sampling, while Factor 3 decreased (Fig. 3). Factor 2 was not significantly affected by year. Factor 1 decreased from Raspberry Island east towards Outer Island, but the other two factors were not affected significantly. Factor 2 is clearly dominated by *Hypogym-*

nia, Factor 3 by *Parmelia*, while Factor one is evenly divided by *Cladina* and *Evernia* in opposition (Fig. 4). Factor 1 is the only factor with a clear near vs. far distance to the mainland effect: the factor is highest at the near islands and lowest on the far islands (Fig. 5).

4. Discussion

Of those elements that have significantly decreased over time, only B, Cu, K, Pb and possibly Mn have consistently decreased for all four species. Other elements that decreased did not do so consistently among species. The decrease in Pb is probably due to lead being phased out of gasoline and agrees with other studies (Lawrey and Hale, 1988; Lawrey, 1993; Pilegaard, 1994). Copper may have decreased because of the decline in Cu mining in the upper Great Lakes. No plausible explanation for the decline in the other elements can be suggested at this time.

Table 7

Factor means for year, island, species and distance to mainland; means in columns that are significantly different ($P < 0.05$) are shown in bold print

Variable	Factor 1 Al, Cr, Fe, Na, Ni, S	Factor 2 Ca, Cd, Mg, Mn	Factor 3 Cu, K, P, Pb, Zn
<i>Year</i>			
1987	−0.239	−0.123	0.128
1995	−0.143	0.016	0.185
2001	0.302	0.052	−0.286
<i>Island</i>			
Raspberry	0.528	0.100	0.027
Long	0.037	−0.314	0.260
Stockton	−0.267	−0.006	0.147
Outer	−0.243	0.105	−0.300
<i>Species</i>			
<i>Cladina</i>	−0.981	−0.418	−0.719
<i>Evernia</i>	1.007	−0.706	−0.466
<i>Hypogymnia</i>	0.169	1.584	0.185
<i>Parmelia</i>	0.113	−0.477	1.673
<i>Distance</i>			
Near	0.326	−0.070	0.123
Far	−0.254	0.054	−0.095

The four elements that have increased over time have not done so consistently. Iron is the exception, however, as all four species have increased from year to year. Chromium has increased for all four species when 2001 is compared with 1987, but *Evernia* and *Hypogymnia* actually peaked in 1995. Nickel has increased but appears to be leveling off for *Hypogymnia* and *Evernia*. Sulfur has increased for three of the species, but appears to be level for *Parmelia*. These four elements could be increasing from soil dust exposure, but also from air pollution, although sulfur has been decreasing in recent years as sulfur emissions have been controlled.

Nine elements were 17 to 57% higher at Raspberry Island than at Outer Island, with one exception. This may be due to an effect of longitude, or it may be proximity to the mainland, as suggested by the near vs. far island comparisons. Lead was higher at Long and Stockton islands, and this might be due to mainland proximity for Long Island, and boat engine emissions at Stockton Island (our sample locality is approx. 1 mile north of the boat dock). Note that the near islands

average 3.5 km from the mainland, while the two far islands average 13 km from the mainland.

The factor analysis showed clearly that elements associated with soils (Factor 1) have increased with time, while those which are nutrients (Factor 3) have decreased. The species means show that *Cladina* is lowest in all the elements because it is lowest on all three factors. This is probably due to it being terricolous while the other three species are epiphytic. Presumably terricolous species are less exposed to atmospheric deposition in this area than epiphytic species. *Evernia* is highest in Factor 1 elements, *Hypogymnia* is highest for Factor 2 elements, and *Parmelia* is highest for Factor 3 elements. It is generally thought that foliose species accumulate more elements than fruticose species (Garty, 2001). That is true in this study when *Hypogymnia* (foliose) is compared to *Cladina* (fruticose), but that comparison is confounded by the habitat differences between the two species (epiphytic and terricolous, respectively). Comparing *Hypogymnia* with *Evernia*, which are both epiphytic, however, shows that for some elements the fruticose species (*Evernia*) is higher than the foliose species (*Hypogymnia*). This would suggest that there are localized exceptions to the Garty's generalization.

Raspberry Island is highest in Factor 1 elements, followed by Long, Stockton and Outer islands in that order. There were little differences between

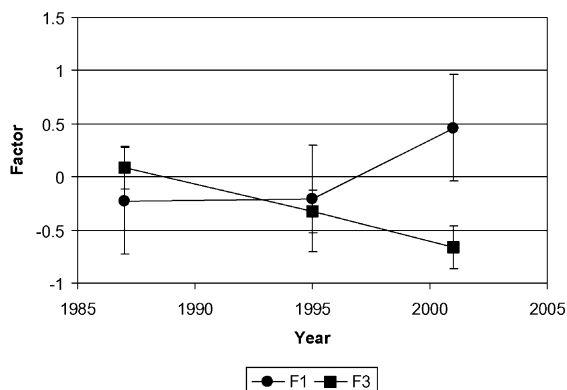


Fig. 3. Line graph showing median values of factors 1 (F1) and 3 (F3) plotted against year of sampling. Whisker lines above and below medians represent 95% confidence intervals.

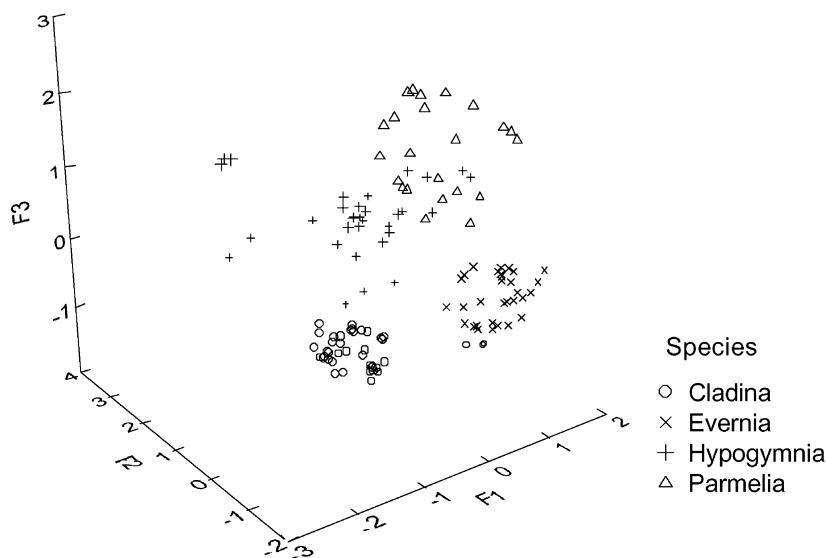


Fig. 4. Species groupings of three factor element space for lichens collected in Apostle Islands.

islands for Factor 2 and 3 elements. Factor 1 was also the only factor affected by the near vs. far category of islands, with near islands having elevated levels of these elements, and far islands decreased levels.

Half of the elements were measured with values that exceeded the enrichment thresholds for *Hypogymnia physodes* in the literature (Bennett, 2000): Al, Ca, Cd, K, Mg, Mn, P and S. Maximum elevated values for Al, K, Mn and S were observed in 1987, for Ca and Cd in 1995, and for Mg and P in 2001. These time trends have little meaning because the second highest values were observed in other years for these elements. There may be a pattern to these elevated elements: Al, Cd and S may be elevated due to pollution, inducing stress in the lichen, which counteracts the stress by taking up more nutritional elements, including Ca, K, Mg and P. Conversely, elevated Ca may indicate accumulation of excess calcium oxalate, a compound thought to be involved in water balance, light attenuation, and sulfur reduction. These elevated elements should be studied in the future to monitor the situation.

The same four species of lichen were studied over an 11-year time span at the Boundary Waters

Canoe Area Wilderness in northern Minnesota (Bennett and Wetmore, 1999). The four elements that increased in time at Apostle Islands decreased at the Boundary Waters. Boron is the only element that decreased in both studies. However, approximately the same elements decreased or increased

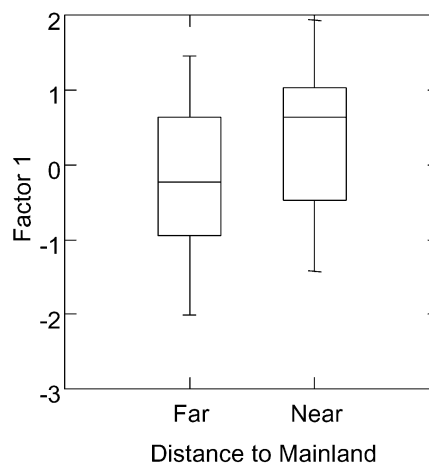


Fig. 5. Boxplots of distance from mainland effects on factor 1. Near islands were 3–4 km, and far islands were 8 and 17 km from the mainland.

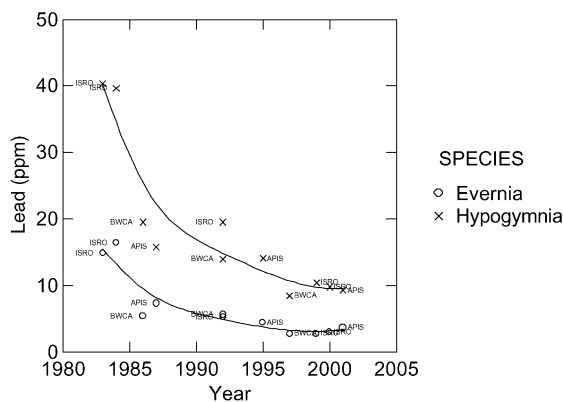


Fig. 6. Changes in lead concentrations in *Evernia mesomorpha* and *Hypogymnia physodes* over time. Lines represent distance weighted least squares regressions. APIS=Apostle Islands National Seashore, BWCA=Boundary Waters Canoe Area, and ISRO=Isle Royale National Park.

from west to east in both studies across the four species. Thus the two studies resulted in comparable geographic patterns, but not comparable time trends. The Boundary Waters study spanned 1986 to 1997, and the Apostle Islands study 1987 to 2001. Perhaps the extra four years in the latter study explains the differences in time trends. The two study areas are approximately 150 miles apart.

The five elements in *Parmelia sulcata* that changed in this study compared fairly well with the changes in the same species at Theodore Roosevelt National Park over an earlier 16-year time span (Bennett and Wetmore, 2000), even though the study areas are approximately 600 miles apart. Actual concentrations, however, were only comparable for K and S. Al, B, Ca, Cr, Fe, Mg, Na and Ni were higher at Theodore Roosevelt, while Cd, Cu, Mn, P, Pb and Zn were higher at Apostle Islands. The higher elements at Apostle Islands are elements more associated with anthropogenic emissions, which may have had a longer history at this park than at Theodore Roosevelt. Many of the elements that are higher at Theodore Roosevelt are associated with soils, indicating there is a higher degree of dust deposition on lichens there compared to Apostle Islands. This is to be expected because Theodore Roosevelt is

much drier climatically and has more exposed soil surfaces.

Pooling the Apostle Islands *Evernia* and *Hypogymnia* data with that from Isle Royale and the Boundary Waters studies allows the evaluation of time trends over the period 1983–2001. Lead has decreased significantly throughout this period in both species (Fig. 6), which is probably due to the reduction of lead in gasoline. The period of decrease corresponds with the decrease in Pb deposition to the Great Lakes (US Environmental Protection Agency, 2000). Sulfur, however, has increased in both species over the time period, which is contrary to the decline seen in atmospheric concentrations (Baumgardner et al., 2002; Kelly et al., 2002; Nilles and Conley, 2001) Fig. 7. Other elements have also increased over the time period, including Ca, Cd, Cr and P. All of these except P are decreasing in atmospheric concentrations, but appear to be remaining in the environment and accumulating in lichens.

Lichen chemistry at Apostle Islands is complex. It is a positive sign that Pb and Cu are decreasing overall, but the increases in S and Cr are troubling. When coupled with the observations that elements tend to be higher near the mainland or near anthropogenic activities, and that some elements are enriched in *Hypogymnia*, a picture emerges of a growing problem for lichens. The Apostle Islands

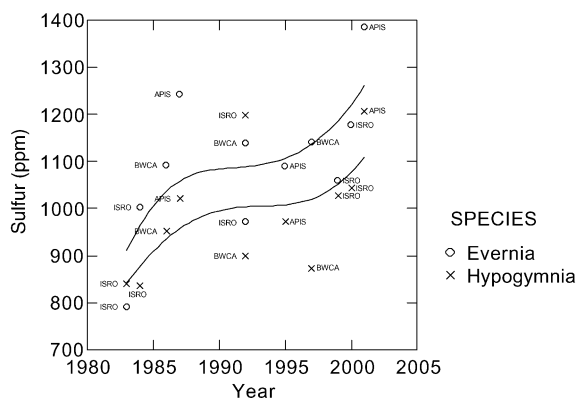


Fig. 7. Changes in sulfur concentrations in *Evernia mesomorpha* and *Hypogymnia physodes* over time. Lines represent distance weighted least squares regressions. Labels as in Fig. 6.

may not be as pristine as is thought. These warning signs suggest that a more detailed study of some islands is needed.

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