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Bioindication of atmospheric heavy metal deposition in the Southeastern US using the moss *Thuidium delicatulum*

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Abstract

Ectohydric mosses are known accumulators of atmospheric heavy metals. Reliable bioindication of atmospheric heavy metals in the Southern Appalachians using moss has been limited by poor species distribution in moss used in analogous studies. In this study, Pb, Cu, Cr, and Ni concentrations were quantified in the tissue of fern moss *Thuidium delicatulum* in the central Blue Ridge of Virginia. The objectives of the study were to evaluate the suitability of fern moss for moss-monitoring studies in the Southern Appalachians, to compare local terrestrial metal concentrations, and to test the effects of several geographical and environmental variables on deposition.

Fern moss was sampled over four mountains in Virginia following the standard protocol of the German moss-monitoring method. Sampling was standardized for monitoring in deciduous forests, and analysis was performed by graphite furnace-atomic absorption spectrophotometry. Overall concentrations of two metals were significantly different depending on the presence of *Pinus* spp. in the canopy. Positive and negative correlations of heavy metal concentrations with elevation were also observed, suggesting a need for comprehensive sampling at high and low elevations in mountainous areas. A role for similar moss-monitoring is suggested as a complement to current precipitation analysis techniques and as a compendium for landscape-scale metal monitoring projects. The applications of heavy metal bioindication with this particular species throughout the physiographic province of the Blue Ridge and the Appalachians in future heavy metal deposition studies are discussed.

Keywords: Biomonitoring; Bryophyte; Trace metals; Mosses; Appalachian

1. Introduction

Determining concentrations of heavy metals in the environment is an important part of understanding biogeochemical processes and gauging ecosystem health. Current metal fluxes from the atmosphere to the biosphere can be significantly increased as a result of anthropogenic inputs from fossil fuel consumption, agricultural dust, and metallurgy (Yunus et al., 1996). A combination of physical, chemical, and environmental conditions determine total metal deposition, the extent of biological uptake, and the subsequent effects of these metals on biological communities (Egan, 1982; Gifford, 1982). Although modeling the transport of trace metals from emission source to the biological point of uptake is important for understanding transport, and precise chemical analysis of input sources is necessary for predicting levels of elemental flux, it is also important to quantify actual deposition into the biosphere that is subsequently taken up by living organisms.

Mosses have frequently been used to monitor time-integrated bulk deposition of metals as a combination of wet, cloud, and dry deposition, thus eliminating some of the complications of precipitation analysis due to the

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heterogeneity of precipitation (Markert et al., 1996). Ectohydric mosses in particular draw negligible amounts of water and minerals from the soil, and instead depend almost entirely on atmospheric inputs of nutrients (Ruhling and Tyler, 1968; Ross, 1990). Because mosses have a high cation exchange capacity (CEC), they act as hyperaccumulators of metals and metal complexes. The metals are bound to the tissue with minimal translocation within the plant due to a lack of vascular tissue (Ruhling and Tyler, 1968). This results in biological tissue that can be analyzed to reveal time-integrated deposition (Zechmeister, 1998).

Additional advantages of using mosses as heavy metal biomonitors include their stationary nature, widespread geographic distribution, and low genetic variability between populations (Richardson, 1981). It has been shown, however, that there is some experimental error due to heterogeneity in morphological characteristics and microenvironments among different populations (Zechmeister, 1995, 1998). There is also an incomplete understanding of the degree of mineral uptake by ectohydric mosses in direct contact with substrate (Okland et al., 1999). Despite the accuracy and precision of precipitation analysis techniques, however, mosses offer an efficient, low-cost complement for determining metal concentrations at a large number of locations and offer analyses of biologically relevant fluxes at multiple scales.

Beginning with the research of Ruhling and Tyler (1968, 1970, 1971), ectohydric mosses have been employed primarily as a means for making intersite comparisons and for creating relative deposition isopleths for heavy metals. Most studies have been carried out in Europe or the Northeastern US, and the majority of large scale projects have successfully employed the mosses *Hylocomium splendens* (Hedw.) and *Pleurozium schreberi* (Brid.) (Ruhling and Tyler, 1970; Groet, 1976; Ross, 1990; Zechmeister, 1995; Markert et al., 1996; Okland et al., 1999). In North America, these and other mosses used for similar smaller-scale studies are only prolific in northern temperate forests and boreal ecosystems, thus confining such studies to northern latitudes (Groet, 1976; Barclay-Estrup and Rinne, 1979; Percy, 1982).

In the Southeastern US, samples of *H. splendens* and *P. schreberi* for use in bioindication have been confined to post-glacial relic plant communities at relatively high altitudes for background comparison to northern samples (Groet, 1976). As no species used in other large-scale projects is common or generally available in most southeastern ecosystems (Crum and Anderson, 1981; Breil, 1994, unpublished checklist), there is a need to employ an alternate species for monitoring in areas like the Southern piedmont and Appalachians.

The focus of this research is on the use of the species *Thuidium delicatulum* (Hedw.) for monitoring atmospheric heavy metal deposition in the central Blue Ridge of Virginia (Fig. 1). The Blue Ridge, on the eastern edge of the Appalachian mountains, incorporates a multitude of physical, climatic, and chemical environments, and effectively represents the geographic diversity found in the mountain environments of the Southeastern US

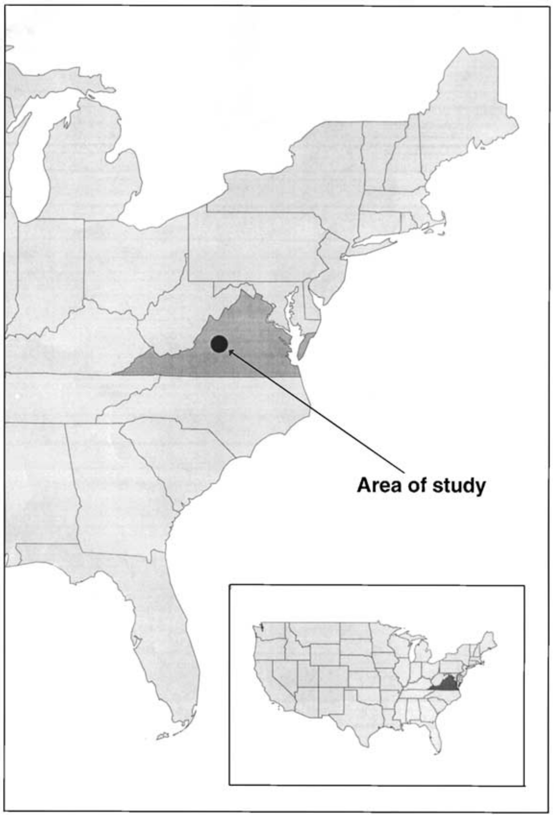

Fig. 1. Study area. The Blue Ridge of Central Virginia, US.

T. delicatulum occupies a substantial range, and exhibits typical characteristics of an ectohydric, mat-forming moss (Crum and Anderson, 1981). Sharing the same common name "fern moss" with other monitoring mosses, this species similarly has extensive branching allowing for a large exposed surface area for ion exchange. These features make *T. delicatulum* a likely candidate for use as a biomonitor.

The primary objective of this study was to evaluate the suitability of *T. delicatulum* as a bioindicator of heavy metals on a regional landscape scale in the Southern Appalachians. To accomplish this objective we tested the availability of *T. delicatulum* in a variety of habitats and analyzed tissue samples for the metals Pb, Cu, Cr, and Ni known to be efficiently monitored using the moss technique (Groet, 1976; Okland et al., 1999). We also examined the effects of several topographical features (slope, aspect, altitude) and site variables (canopy vegetation, soil metal concentration) on the metal concentrations found in moss tissue. Additionally, this study contributes to the current information on atmospheric deposition and metal concentrations in North American ecosystems by providing data and an alternative monitoring technique for the Southeastern US.

2. Methods

2.1. Bioindicator availability and site selection

To test the availability of the chosen bioindicator moss, *Thuidium delicatulum* (Hedw.), two mountains in the central Blue Ridge rising 1174 m (3851 ft) and 978 m (3208 ft) were sampled randomly in late winter of 2000 at altitudes ranging from 213 m to the peaks of each mountain. Species presence and absence for all viable ectohydric mosses, including *T. delicatulum*, were recorded in 21 randomly established 100 m^2 circular plots on each mountain. Mosses were identified according to Crum and Anderson (1981), and five randomly collected specimens of *T. delicatulum* were verified by the University of Michigan Herbarium in order to maintain the distinction from a similar species, *T. recognitum* (Hedw.).

After testing moss relative abundances, four mountains were sampled along east–west transects. In order from Southwest to Northeast, the mountains sampled were Thunder Ridge (1195 m, 3920 ft), Bald Knob (1216 m, 3989 ft), Devils Knob (1174 m, 3851 ft), and Massanutten (978 m, 3208 ft). Along the transects, sites were established on both eastern and western aspects at altitudes of 610 m (2000 ft), 762 m (2500 ft), 914 m (3000 ft), and the top of each mountain. At each site, three 100 m^2 plots were established, for a total of 21 sample plots per mountain. The slope, aspect, altitude, and canopy assemblage were recorded for each plot. Sites were at least 40 m apart, but never more than 400 m apart, and were located at least 200 m from any traveled road. Of the 84 plots sampled (21 per mountain $\times$ 4 mountains), seven plots had no canopy trees, 14 had *Pinus* spp. canopy trees, and 63 had hardwood canopies.

Massanutten mountain and Bald Knob both lie directly east of cities reporting point-source and fugitive air emissions in the year prior to this study. Within 9 km of Massanutten, one industry reported Pb emissions, 6 industries reported Cu, 1 reported Cr, and 2 reported Ni emissions (DEQ, 2000). West of Bald Knob, one industry reported airborne Cu emissions and 3 reported airborne Cr emissions (DEQ, 2000). Devils Knob has one major source of copper emissions directly to the west, however, this mountain and Thunder Ridge are otherwise lacking local metal emission sources to the west.

2.2. Collection and preparation of samples

Adapting from the protocol of Markert et al. (1996), mosses were collected in late winter as composite samples. Composites were comprised of five sub-samples of moss per plot, with sub-samples approximately 7 cm in diameter and representing five distinct populations. Samples were collected at least 5 m from the base of any tree to avoid stemflow and from areas unaffected by stream overflow or water pooling.

Each sub-sample was collected with disposable latex gloves and transported for analysis in sterile Whirl-pak bags. After air drying the moss tissue for 24 h, new growth was clipped with plastic forceps at a distance no longer than 1.5 cm from the tip, totaling 150.0 mg from each of the five sub-samples. The sub-samples were homogenized in an unglazed ceramic ball-mill, and 100.0 mg of the moss powder was digested inside a polytetraflouroethylene (PTFE) insert in a 23 ml acid digestion bomb (140°C for 4 h) with 1.5 ml of 7.2 M HNO_3. After 2 h cooling, each digested moss sample was filtered through a 0.2 μm syringe filter and stored in sterile polyethylene tubes. NIST Standard Reference Materials (pines needles 1575) were subjected to the same digestion procedure to verify accuracy of the extraction protocol for Pb, Cu, and Cr. Reference material was not available at the time of analysis for Ni, and although Ni is a reliably extractable metal, this discrepancy is notable prior to conclusions. Negative controls of 7.2 M HNO_3 without digestible moss material were also run at the beginning, end, and midway through the digestion of the 84 moss samples and indicated that there was no significant contamination or memory effect of the digestion bomb.

O-horizon soil samples from the 21 plots on Massanutten mountain were collected near each moss sample location with a polyethylene trowel. The soil samples were air dried and sieved through a 2 mm screen. Metals were extracted from 5 g of the soil by shaking overnight in 25 ml of 1% HCl (Shaw et al., 1987). The samples were then filtered to 11 μm and were analyzed in the same manner as moss tissue extracts.

2.3. Sample analysis

All liquid samples were analyzed by graphite furnace-atomic absorption spectrophotometry on a series 800 Perkin-Elmer AA. Pb, Cu, Cr, and Ni were analyzed after calibrating with preformulated spectroscopic standards. Appropriate matrix modifiers for these metals were used to optimize sample ionization, and quality control standard analyses were performed every ten samples with instrument recalibration every 23 samples.

2.4. Data analysis

Data for moss samples were analyzed by ANOVA, regressions, Pearson product-moment correlations, and Tukey-Kramer means comparisons using the JMP Statistical Package (SAS Institute, Inc., 1995). Statistical significance was based on an alpha of 0.05.

3. Results

The decision to use *T. delicatulum* as our bioindicator species was reinforced by availability studies which indicated that *T. delicatulum* was the most common easily identifiable moss species on the randomly selected plots. On plots containing *T. delicatulum*, it is notable that 43% also contained *Leucobryum* spp., 29% *Climacium* spp., 21% *Mnium* spp., and 14% *Dicranum scoparium* (Hedw.). Data from the sample plots on all four mountains used in our main study showed only slightly higher co-occurrence percentages for most of these moss species (50%, 39%, 36%, and 11% respectively).

Atomic absorption analysis of moss tissue samples revealed hyperaccumulated concentrations of Pb, Cu, Cr, and Ni (Table 1). Metal concentrations found in the Massanutten soil samples were not significantly correlated to the concentrations in the moss samples collected from the same locations. Soil Pb concentrations were, however, positively correlated with elevation. ANOVA for the combined data set of all plots ($n = 84$) showed no significant effect of slope or aspect on the metal concentrations found in moss tissue samples (data from "top of mountain" plots were excluded for aspect analyses). Aspect effects on Cu concentrations, however, were nearly significant ($p = 0.0543$), with an average concentration ($\pm$SE) of $8.130 \pm 1.118\,\mu g\,g^{-1}$ on western mountain faces and $11.225 \pm 1.118\,\mu g\,g^{-1}$ on eastern mountain faces.

ANOVA for the combined data set did show a significant effect of canopy vegetation on Pb and Cr concentrations in moss samples. Tukey-Kramer means comparisons were used post-hoc to evaluate differences. Few open canopy sites were available at sampled mountain locations. Among the gaps that were sampled, open-canopy plots ($n = 7$) did not show a significant relative difference in any metal concentration when compared to plots under hardwood canopy within the same site ($n = 5$) or when compared to all hardwood canopy sites ($n = 63$). Means comparisons revealed significant differences between sites with *Pinus* spp. in the canopy ($n = 14$) and sites without *Pinus* in the canopy ($n = 70$). The mean Pb concentration ($\pm$SE) found in moss tissues was significantly higher in plots with a pine canopy (14.33 ± 2.18 vs. $5.79 \pm 0.29\,\mu g\,g^{-1}$ for canopies without pine), and Cr concentrations were significantly lower (0.30 ± 0.11 vs. $0.76 \pm 0.10\,\mu g\,g^{-1}$ for canopies without pine).

Table 1
Composite sample mean heavy metal concentrations and ranges expressed as dry weights ($\mu g\,g^{-1}$) SE. Pine presence refers to *Pinus* spp. canopy trees. Sample size *(n)* is based on composite samples

	Pb	Cu	Cr	Ni
Thunder R.	5.683 ± 0.115	7.509 ± 0.296	1.433 ± 0.224	1.538 ± 0.093
w/Out pine ($n = 20$)	5.679 ± 0.554	7.582 ± 0.302	1.505 ± 0.223	1.585 ± 0.096
Under pine ($n = 1$)	5.761	6.061	0.04	1.182
Bald Knob	6.609 ± 1.023	8.757 ± 0.481	0.354 ± 0.146	1.778 ± 0.178
w/Out pine ($n = 18$)	5.752 ± 0.589	8.728 ± 0.554	0.383 ± 0.170	1.730 ± 0.160
Under pine ($n = 3$)	11.750 ± 6.336	8.886 ± 0.710	0.181 ± 0.061	2.069 ± 0.926
Devils Knob	6.517 ± 1.004	9.031 ± 0.990	0.603 ± 0.085	1.793 ± 0.284
w/Out pine ($n = 21$)	6.517 ± 1.004	9.031 ± 0.990	0.603 ± 0.085	1.793 ± 0.284
Under pine ($n = 0$)	NA	NA	NA	NA
Massanutten	11.147 ± 1.545	12.924 ± 2.418	0.368 ± 0.089	2.294 ± 0.260
w/Out pine ($n = 11$)	6.776 ± 0.725	15.700 ± 4.500	0.368 ± 0.112	2.178 ± 0.417
Under pine ($n = 10$)	15.956 ± 2.366	9.870 ± 0.756	0.364 ± 0.147	2.421 ± 0.317
All Sites	7.450 ± 0.589	8.955 ± 0.352	0.685 ± 0.088	1.855 ± 0.112
w/Out pine ($n = 80$)	5.791 ± 0.286	8.859 ± 0.412	0.762 ± 0.103	1.775 ± 0.121
Under pine ($n = 14$)	14.327 ± 2.180	9.387 ± 2.253	0.301 ± 0.109	2.257 ± 0.294
Range	2.63–29.13	4.34–23.91	0.10–3.35	0.44–4.73

Analysis of data from each individual mountain showed some significant effects of topographical characteristics on the metal concentrations found in moss tissues on only one of the four mountains. Pb concentrations were directly related to altitude on Massanutten [$-8.03+0.01$(elev.), $p=0.0269$, $r^2=0.232$], but statistical significance was lost when data from plots with a *Pinus* canopy were excluded from the analysis. A significant quadratic trend on Massanutten [31.49–0.02 (elev.) $+4.27\times10^{-6}$ (elev.)^2, $p=0.0104$, $r^2=0.364$] for Ni concentrations ($\mu g\,g^{-1}$) showed a stronger linear trend [8.67–0.003 (elev.), $p=0.0009$, $r^2=0.725$] after the exclusion of plot data influenced by a pine canopy (Fig. 2). All Massanutten mountain peak plots had pine canopies and their exclusion eliminated the highest altitude site.

Though initial analyses of data from all plots showed higher mean concentrations of Pb and Cu on Massanutten than on all other mountains, Pb differences were no longer significant when pine canopy plots were excluded. Thunder Ridge showed significantly higher levels of Cr than all other mountains, regardless of analysis with or without pine canopy plots (Table 1).

Pearson product-moment coefficients for Pb, Ni, and Cu show a significant positive correlation over all individual plots. The coefficients were as follows: Pb/Cu (0.356), Pb/Ni (0.490), and Cu/Ni (0.569). Cr was not significantly correlated with any of the other metals.

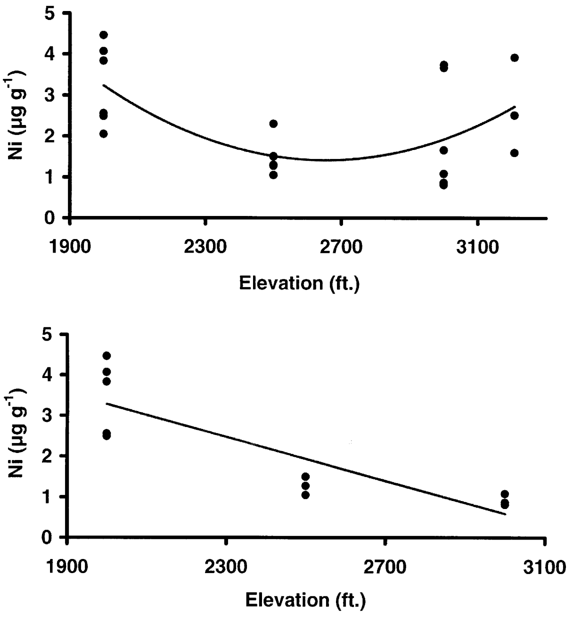

Fig. 2. Nickel by elevation on Massanutten before (quadratic) and after (linear) the exclusion of plots with *Pinus* spp. canopy trees.

4. Discussion

4.1. Evaluation of bioindicator moss

The abundance and ease of identification of *T. delicatulum* over the test sites is promising for its use as a bioindicator. The relative abundances of other species is also useful for planning future studies utilizing comparisons of accumulated concentrations in several moss species. Some of these mosses have been utilized occasionally in other US studies (Groet, 1976; Jackson and Ehrle, 1994). The lack of correlation between the metal concentrations observed in moss and the respective O-horizon soil samples suggests that although there may be metal cation inputs from the soil for these particular metals, they are relatively insignificant compared to the hyperaccumulated atmospheric fluxes. A positive correlation between Pb and elevation for soil samples is also notable, and supports the findings of Weathers et al. (2000). The lack of a soil/moss concentration correlation suggests minimal sample error resulting from cation inputs from alternate sources (Okland et al., 1999).

The observed mean metal concentrations found in *T. delicatulum* in this study are comparable to previous reports (Groet, 1976; Ross, 1990; Jackson and Ehrle, 1994; Markert et al., 1996). The concentration ranges for each metal also generally correspond, although there were some values that were slightly lower than previously reported. The lowest recorded Cr concentration in this study was $0.4\,\mu g\,g^{-1}$ lower than Ross (1990) reported, and the lowest Ni concentration was $0.14\,\mu g\,g^{-1}$ lower than Markert et al. (1996) reported.

The lower concentrations could be due to a cation exchange discrepancy between *T. delicatulum* and other well-studied mosses. *T. delicatulum* may be a less efficient metal accumulator. Groet (1976), however, analyzed one *T. delicatulum* sample and three *T. recognitum* samples. Although the sample sizes were small, the concentrations in the *Thuidium* spp. were comparable to the concentrations found in the other species included in his study. A species-specific CEC experiment, such as the studies by Ruhling and Tyler (1969, 1970), would be a rational next step for quantifying the actual accumulation rate in this moss.

The lower observed concentrations of Cr and Ni could also simply be due to lower overall levels. Airborne concentrations of some metals may be generally lower in Virginia as compared with the northeastern US or Europe.

4.2. Canopy assemblage effects

A significant finding of this study was the difference in Pb and Cr concentrations in moss based on the canopy type of sample plots. Moss collected in plots where *Pinus* spp. were present in the canopy contained higher Pb concentrations and lower Cr concentrations than mosses collected from plots where *Pinus* was absent. Other studies (Hasselrot and Grennfelt, 1987; Kerstiens, 1996; Okland et al., 1999) have suggested that physical structure and leaching disparities can allow differential deposition below various canopy trees. This includes differences between evergreen conifers such as pines. On these Blue Ridge sites, pines such as *Pinus strobus*, *P. virginiana*, and *P. pungens* were common canopy constituents, and were the dominant conifers. As leaching inputs and physical differences at the atmosphere–biosphere interface complicate interpretations, monitoring should be standardized taking into consideration canopy assemblage.

Open sites were uncommon ($n = 7$) in this study, reflecting the lack of natural openings on these mountains. Means comparisons suggested that metal deposition is not significantly higher or lower in open areas compared to under a hardwood canopy. A study designed to specifically answer this question would be in order; however, caution must be exercised when input ratios of cloud, wet, and dry deposition are variable as well as forest gap area (Weathers et al., 2000). In this southern study, it was assumed that the frequency of open sites that support moss populations is too low to allow landscape-scale moss sampling away from the hardwood canopy.

4.3. Comparisons between mountains

The higher Pb concentrations on Massanutten are probably an artifact of the large number of pine canopy plots, as differences were no longer significant when these plots were excluded. The persistently higher Cu concentrations, however, seem to reflect an actual difference in Cu deposition on this mountain. It is possible that this difference reflects the large number of local industries reporting Cu emissions to the west of Massanutten (DEQ, 2000), though other environmental differences between mountains might also be responsible. Reasons for the higher Cr levels observed on Thunder Ridge are unknown, as they do not correspond to any known differences in local emission sources. Overall, differences in moss metal concentrations were not well explained by local emission sources.

4.4. Topographical effects

Neither slope nor aspect had any significant effect on metal concentrations in sample mosses. This observation applied when data were compiled into a single data set or examined individually for each mountain, and suggests a lack of aspect-dependence for metal deposition. Variability in the data, however, could allow aspect-independence to be interpreted as a natural result of moss genotype heterogeneity or as a result of smaller-scale atmosphere–biosphere interactions. Metal cation concentrations might also be too low, even when exchanged and accumulated, to emphasize concentration differences. A nearly significant effect of aspect on copper concentrations, may suggest that deposition of this metal is influenced by precipitation or prevailing wind patterns. Further study would be required to examine this possibility.

Lead concentrations in moss tissues were significantly positively correlated with elevation on Massanutten; however, significance was lost with the exclusion of the pine canopy plots. This suggests that the initial trend could be a reflection of the higher Pb concentrations found under pine canopies on high elevation plots. Also, precipitation gradients and clinal variations in plant communities in the Blue Ridge are probably less pronounced than in higher altitude mountainous areas sampled during other similar studies that resulted in deposition/altitude correlations (Zechmeister, 1995). It is possible that altitude may be less important in determining metal deposition when canopy features and precipitation gradients are less dramatic.

When data was standardized to the hardwood canopy, the quadratic trend for Ni concentrations previously seen with sites including the pines on Massanutten, however, became linear (Fig. 1) with an increase in the r^2-value from 0.364 to 0.725. Although Ni concentrations were not significantly correlated with canopy-type, the pine canopy appears to add a great deal of variability in these data. Under standardized canopy, accumulated Ni concentrations in moss tissues were clearly higher in the low altitude plots. Ni may be settling at lower elevations as a result of a lack of air circulation, as a result of thermal inversions, as an artifact of differences in the duration of winter snowpack, or by another natural or anthropogenic mechanism. Because this trend was not seen on other mountains, however, generalizations are simply mountain-specific, and are more safely interpreted as localized variability in deposition process dynamics. For general elevational trends, precipitation analysis may be more appropriate (Weathers et al., 2000).

4.5. Metal correlations

Significant correlations between metals within the same moss composite samples suggest general deposition trends. Such correlations have the possibility of reflecting overall concentration similarities as an artifact of the age of the parent tissue. It is notable, as well, that *T. delicatulum* has indistinguishable growth segments, and although the method for sampling this kind of tissue has been standardized (Markert et al., 1996), age-dependency could influence metal concentration disparities between sites. The thorough homogenization of spatially distinct population samples into a representative composite sample is designed to eliminate some of this concern. Accepting this assumption, the correlations between Pb, Cu, and Ni can be viewed instead as a reflection of general metal fluxes at particular plots and as an indication that deposition at discrete locations depends on a number of local complexities including microenvironmental factors, precipitation variability, and vegetation composition and density. Furthermore, the correlations suggest that bioindication with moss is reflecting these general patterns in local deposition.

Chromium revealed no significant trends based on any variable other than canopy assemblage. It must be noted that during graphite furnace-AA analysis, Cr classically exhibits uneven drying and splattering in the graphite tube and is easily trapped in residue that builds in the tube after individual firings. Graphite furnace-AA may not be the most efficient analytical method for Cr analysis (Berman, 1980). QC and recalibrations on this instrument should keep contamination minimal, and although there was no statistically significant correlation between Cr levels and progressing sample analysis in this study, memory effect for Cr should be monitored in future similar studies using graphite furnace-AA spectrometry.

5. Conclusion

T. delicatulum is worthy of further study as a passive accumulator and bioindicator for ground-level deposition rates of heavy metals in the Blue Ridge and in the Southern Appalachians. Future studies concerning the quantification of the actual CEC and the details of its growth rate and translocation of cations would allow a more comprehensive picture of local deposition histories. However, the results of this study show that this species is readily available, can be efficiently analyzed for certain heavy metals, and shows landscape and canopy-dependent accumulations that generally correspond to expected concentrations. The results also suggest that smaller scale, local deposition patterns are variable and could be completely studied using moss tissue.

Due to time and financial restraints, trace metal monitoring has often played a secondary role to various atmospheric non-metal cation and acidic inputs. Heavy metal monitoring projects have therefore been relatively infrequent in the United States (Munger and Eisenreich, 1982). Moss-monitoring not only offers a more cost-efficient method available to researchers with less available technology, it also allows a more time-efficient way to reveal qualitative and quantitative differences in metal concentrations at discrete locations and on local and landscape scales.

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