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Concentrations of Metals in Tissues of Lowbush Blueberry (*Vaccinium angustifolium*) near a Copper-Nickel Smelter at Sudbury, Ontario, Canada: A Factor Analytic Approach

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Ecosystems damaged by emissions from the copper-nickel smelters of Inco and Falconbridge Ltd. near Sudbury, Ontario, Canada have provided a unique opportunity to study the effects of metal particulates and sulphur dioxide fumigations on plant and animal communities. History and details of the environmental degradation in the region are given by Freedman and Hutchinson (1980) and Winterhalder (1984). Examples of studies undertaken in this industrially damaged ecosystem are given in Bagatto and Shorthouse (1991).

The most infamous terrain in the Sudbury region is nearest the smelters (two active and one closed), where nearly all vegetation has been destroyed and soils eroded and contaminated. However, over the past twenty years, some species of plants have developed a tolerance to polluted soils and some denuded lands have been naturally and artificially revegetated (Winterhalder 1984). Furthermore, a series of unique anthropogenic forests have developed away from the smelters (Amiro and Courtin 1981).

Several studies have been undertaken on the accumulation of metals in plant tissues near the Sudbury smelters and, as one would expect, the levels of metals are usually highest closest to the smelters. Consequently, several studies have reported high correlations between plant concentrations of certain metals with distance from the source of pollution (Freedman and Hutchinson 1980; Taylor and Crowder 1983; Gignac and Beckett 1986; Bagatto and Shorthouse 1991). However, tissue metal burdens are not always correlated with distance from the emission source, even though atmospheric emission of metals is above normal (Chan and Lusis 1986), suggesting that other biological and physico-chemical factors may influence tissue metal burdens in the Sudbury habitat.

The present study provides further information on the metal burdens in another plant, lowbush blueberry (Vaccinium angustifolium), which grows near the smelters and some distance away. Although we have already reported on the levels of copper and nickel within the tissues of this plant, and an insect gall induced by a chalcid wasp on its vegetative shoots (Bagatto and Shorthouse 1991), our purpose here is to assess the apparent influence of the Sudbury smelting operations on plant tissue burdens of five additional elements, along with copper and nickel, by using a factor analytic approach. We have assumed that this approach will allow us to ascertain underlying factors which govern tissue metal burdens in a polluted

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environment and helps to refine the future direction of research in the Sudbury ecosystem.

MATERIALS AND METHODS

Six sampling sites were chosen, ranging from 6.5 to 74 km away from the Inco smelter along a northwest transect. A detailed description of each site can be found in Bagatto and Shorthouse (1991). Five randomly chosen clumps of lowbush blueberry with attached roots and rhizomes were collected from each of the six sites in June of 1988. The plants were divided into leaves, stems and roots. The roots were thoroughly washed with tap water and all tissues were stored at -20°C. Mature berries were collected from near the previous clones at each site in July of 1988. All plant samples were taken at least 100 m from roads to minimize influence from vehicles.

Plant tissues were washed twice in double-distilled deionized water and allowed to air dry for 2 days. Air dried tissues were ground in a plant mill, oven dried for 48 h at 90°C and subsamples of approximately 0.5 g digested in concentrated aqua regia. The digests were then analyzed for Cu, Ni, Zn, Fe, Mn, Mg and Ca by flame atomic absorption spectrophotometry, using a Perkin-Elmer atomic absorption spectrophotometer model 303. Procedural blanks not containing biological materials and citrus leaf standard reference material were also analyzed with each experimental run to evaluate analytical reliability of the methods used.

Tissue concentrations of all metals were factor analyzed using a principal components factor analysis with varimax rotation. Factors were deemed significant if their corresponding eigenvalues were greater than one. Items loading greater than $|0.4|$ were used to define the factors. Tissue concentrations were then reduced to scores on each of the factors. Each of these factor scores was then regressed with distance from the Sudbury smelter to determine the underlying association between each factor and distance. Various transformations of the data were performed to maximize the percent variance explained.

RESULTS AND DISCUSSION

Principal component analysis (PCA) of tissue metal concentrations resulted in a three factor solution for the combined tissue, root and berry data sets and a two factor solution for the leaf and stem data sets (Table 1). The PCA classification explained approximately 54% of the variation for all of the tissue metal concentrations except for berries where the three factors explained 60% of the variation.

The factor solution of metal concentrations for the combined tissues (All Tissues) indicates that three distinct patterns of covariation occur among blueberry plant concentrations of various elements (Table 1). Mn, Mg and Ca covary together, Cu, Ni and Zn follow a second pattern of covariation and Fe does not covary with any of the other elements examined in this study. Regression of these three factors with distance from the Inco smelter (Table 2) indicates that only Factor 2, which groups Cu, Ni and Zn together, shows a significant relationship with distance and points to the Inco smelter as the source of metal emission. This holds true despite the heterogeneous nature of the bedrock in the region; however, it is well known that the Inco smelter has released vast quantities of Cu and Ni into the environment (Chan and Lusis 1986). Although the factors produced by PCA are unnamed

Table 1. Factor solutions of metal concentrations for blueberry plant tissues.

	All Tissues			Root		
Variable	Factor1	Factor 2	Factor 3	Factor 1	Factor 2	Factor 3
Cu	.027	.898*	.119	.911*	.158	-.156
Ni	.050	.909*	.166	.664*	-.142	.598*
Zn	.603*	-.460*	.247	-.403*	.027	-.567*
Fe	.097	.170	.891*	-.160	.813*	-.257
Mn	.819*	.088	.322	-.130	-.078	.949*
Mg	.695*	-.159	-.286	.219	.825*	.101
Ca	.871*	.322	.099	.848*	-.004	.221
Eigenvalue	2.482	2.058	.852	2.656	1.679	1.03

	Leaf		Stem		Berries		
Variable	Factor 1	Factor 2	Factor 1	Factor 2	Factor 1	Factor 2	Factor 3
Cu	-.880*	.360	-.798*	-.523*	.123	.020	.968*
Ni	-.919*	.214	-.926*	-.134	-.825*	-.148	-.049
Zn	.936*	-.076	.918*	.094	.534*	.393	.610*
Fe	-.097	-.868*	-.715*	.343	.437*	-.701*	-.376
Mn	.944*	.097	.200	.920*	-.864*	-.152	-.383
Mg	.545*	.255	.741*	.017	.342	.895*	.024
Ca	.662*	.408*	.643*	-.656*	.476*	.814	.038
Eigenvalue	4.132	1.176	3.862	1.682	3.517	1.355	1.146

* Factor loadings greater than |0.4|

Table 2. Regression equations for factor scores (y) in various plant tissues versus distance (x) from the Sudbury smelting centre.

	Equation of Best Fit	r coefficient	probability
All Tissues			
F1	$y = -0.578 - 0.392 \log(x)$	0.139	0.3210
F2	$y = 3.115 - 2.188 \log(x)$	0.753	0.0001
F3	$y = -0.317 + 0.007\ x$	0.149	0.2858
Root			
F1	$y = 3.94 - 2.79 \log(x)$	0.896	0.0001
F2	$y = -0.61 + 0.019\ x$	0.429	0.1645
F3	$y = 0.352 - 0.01\ x$	0.231	0.4693
Leaf			
F1	$y = -3.457 + 2.467 \log(x)$	0.868	0.0003
F2	$y = 1.135 - 0.654 \log(x)$	0.249	0.4554
Stem			
F1	$y = -3.34 + 2.432 \log(x)$	0.924	0.0001
F2	$y = -1.115 + 0.721 \log(x)$	0.264	0.3825
Berry			
F1	$y = -0.474 + 0.016\ x$	0.448	0.082
F2	$y = -3.137 + 2.207 \log(x)$	0.699	0.0026
F3	$y = -0.092 + 0.001\ x$	0.019	0.9455

hypothetical underlying factors, we have assigned descriptive terms to these factors based on the PCA and regression of the factor scores. We have termed a smelter insensitive base cation (Mn, Mg, Ca) Factor 1, a smelter sensitive (Cu, Ni, Zn) Factor 2 and a smelter insensitive (Fe) Factor 3. Examination of factor loadings of tissue metal concentrations in individual plant organs comprising the root, leaf, stem and berry tissues allows us to further refine the general patterns of elemental covariation observed in the PCA of all tissues combined (Table 1 and 2).

The signs on the factor loadings indicate that Cu and Ni accumulate in higher concentrations in plants closest to the Inco smelter and decline logarithmically with increasing distance; whereas, tissue concentrations of Zn increase in plant tissues as a function of distance. Covariation among Cu, Ni and Zn suggests that the high levels of Cu and Ni within the blueberry plant or soil tend to reduce or inhibit the uptake of Zn. Zn is emitted from the Inco smelter as part of the aerosol fraction of particulate emissions; however, it is far less abundant than Cu, Ni, and Fe (Chan and Lusis 1986). The atmospheric concentrations of Zn are known to decrease with increasing distance from the smelter and consequently Zn concentrations are elevated within the Sudbury soils. Thus the lower concentrations of Zn in plants closest to the smelter suggests that competitive inhibition by the relatively higher concentrations of Cu and Ni lowers the levels of Zn. Payne et al. (1988) showed that there is competition between Cu and Zn for adsorption sites within the soil and this appears to be the case in Sudbury soils.

When individual plant organs are examined for mineral concentrations, all tissues except for the berries contain a smelter sensitive (Cu, Ni, Zn) factor and depending on the plant tissue, Mn, Fe, Mg and Ca covary to different degrees. Thus metal concentrations within the various blueberry organs are governed by the nutritional requirements and physiology of the plant and the physico-chemical factors associated with the soil which determines the plant availability of any particular element. For example, Fe is emitted in large quantities from the Inco smelter (1,454 T/yr) and it has been estimated that up to 52% is deposited within a 60 km radius (Chan and Lusis 1986, Freedman and Hutchinson 1980). A significant correlation of Fe with distance from the smelter is only evident in the stem tissue indicating that the effects of aerial deposition are masked by the higher concentrations from the surrounding soils and the nutritional physiology associated with uptake of Fe by the plant. Verry (1975) and Semkin and Kramer (1976) found that the geochemistry of the Sudbury basin is the most important factor influencing the occurrence and accumulation of Fe in plant tissues and the importance of soil chemistry on the uptake of Fe in plants near Sudbury has been shown in several studies (Taylor and Crowder 1983; Gignac and Beckett 1986; Burns and Parker 1988). In addition to soil characteristics, several studies have shown the inherent tolerance of ericaceous plants to potentially toxic levels of Fe and also the ability of the plant to regulate Fe by the mycorrhizal endophyte associated with the roots (Leake et al. 1990).

As is the case with Fe, the base cations (Mn, Mg and Ca) are also emitted from the Inco smelter; however, their concentrations within blueberry plants are inconsistent with emission patterns. Our study has shown that concentrations of these elements are lower in plants closest to the smelter than those further away indicating that aerial deposition and the acidic gradient associated with the Sudbury region are not the most important factors determining accumulation by these plants.

In this study we have not attempted a full interpretation of the factor solutions. Instead, we have used the factor analytic approach to more fully define those variables or characters which best represent distinct variation in tissue metal burdens as a function of distance from the industrially disturbed region near Sudbury. Cu and Ni tissue burdens show expected patterns of accumulation given their high emissions from the Sudbury smelter and also have an important influence on tissue accumulations of Zn. Tissue accumulations of base cations (Mn, Mg, Ca) and Fe did not reflect emission patterns of these elements and it is apparent that a greater percentage of the variation associated with tissue burdens of these elements in blueberry plants near Sudbury will be explained once various characteristics of soil, plant nutrition and genetic tolerance are included in the analysis. The variables examined in this study along with other soil and plant variables can then be factor analyzed to more fully define underlying factors which affect the observed tissue metal burdens.

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