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 Metals in some dominant vascular plants, mosses, lichens, algae, and the biological soil crust in various types of terrestrial tundra, SW Spitsbergen, Norway

B. Wojtuń · A. Samecka-Cymerman · K. Kolon · A. J. Kempers · G. Skrzypek

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Abstract Arctic environments are commonly considered to be relatively pristine because of minimal local human activity. However, these areas receive air pollution from lower latitude regions. Our goal was to determine concentrations of metals (Cd, Co, Cr, Cu, Fe, Hg, Mn, Ni, Pb, and Zn) in dominant species of vascular plants, mosses, lichens, algae, and in the biological soil crust (BSC), and topsoil (0–3 cm) from various types of tundra in the southwestern part of Spitsbergen, Norway. Results indicate that mosses are more efficient bioaccumulators of Cd, Co, Cr, Cu, Fe, Mn, and Zn than lichens. The highest levels of Co, Cr, Cu, Fe, Hg, Mn, Ni, and Pb were found in the BSC, Prasiola crispa and Salix polaris may be useful bioindicators of Cd and Zn, and the BSC, R. lanuginosum, S. uncinata, and S. stramineum as bioindicators of Co, Cr, Cu, Fe, Hg, Mn, Ni, and Pb. These results may be extrapolated across other areas of Spitsbergen with similar climates.

Keywords Arctic · Svalbard · Anthropogenic emissions · Bioindication · Long-distance transport

Introduction

Arctic environments are commonly considered to be relatively pristine and stable because of the absence of intensive local human activities and of significant local atmospheric contamination sources. However, these areas receive air pollution from lower latitude regions (Headley 1996; Bard 1999; Simões and Zagorodnov 2001). Especially in the northern hemisphere, where anthropogenic sources are concentrated in Europe, North America, and Siberia, the natural cycles are strongly influenced by anthropogenic emissions containing toxic elements (Savinov et al. 2003). Ecosystems in the Arctic are highly sensitive to human
impacts. Because of relatively simple food webs, even a minor amount of contamination can exert extensive impacts throughout the ecosystem (Gulin'ska et al. 2003). Svalbard is a unique area in Europe where local atmospheric pollution sources are very restricted. It is far removed from major sources of atmospheric pollution but is recognized to be one of the areas most affected by anthropogenic pollution transported from industrialized areas (Dribal et al. 1992; Birks et al. 2004). These high pollutant concentrations result from specific atmospheric circulation patterns, which bring emissions from oil and coal combustion, non-ferrous metal production, and other sources of anthropogenic pollutants from Europe to Svalbard. Several studies have shown that the atmosphere over Svalbard during winter is heavily loaded with a variety of anthropogenic pollutants, including metals (Heintzenberg et al. 1981; Simões and Zagorodnov 2001). There have also been some indications that polluted air reaches this area during summer (Heintzenberg et al. 1991). Another study demonstrated that contamination of Arctic air led to the bioaccumulation of metals in each trophic level, including terrestrial biota (Xie et al. 2006). Bryophytes, as well as lichen and algae, are abundant in the Arctic, particularly in the wet and low tundra (Smith 1982). They live in ecosystems considered to be extremely severe because of low temperatures, low nutrient availability, and a short growing season; hence, abiotic factors are supposed to be largely responsible for the restrictions imposed upon the distribution of populations (Davey 1997; Hoshino et al. 1999). The aim of this study was to investigate the level of metal contaminants (Cd, Co, Cr, Cu, Fe, Hg, Mn, Ni, Pb, and Zn) in dominant higher plants, mosses, lichens, algae, and the BSC collected from various types of terrestrial tundra in the southwestern part of Spitsbergen. We tested the hypothesis that terrestrial mosses are the best bioindicators of contamination in comparison with other plant species, lichens, algae, and the BSC in the various types of the terrestrial tundra.

Materials and methods

Sampling design

The study site was conducted in the southwestern area of Spitsbergen on Wedel Jarlsberg Land, on the northwest side of Hornsund fjord, in the vicinity of the Polish Polar Station (77°00'N; 15°33'E), and investigated during the summer of 2011 (Fig. 1). The region is a typical Arctic tundra ecosystem and is located in the Fuglebekken catchment area. A total of 35 sites were selected (Fig. 1) representing ten types of tundra (Table 1) modified based on Kuc (1998) and Szyman'ski et al. (2013). According to Walker et al. 2005, Svalbard belongs to a bioclimatic subzone of the Arctic, and this part of Spitsbergen is classified as a physiognomic category of sedge/grass moss wetland. We collected vascular plants: Cerastium arcticum, Cochlearia groenlandica, Poa alpina, Salix polaris, and Saxifraga oppositifolia; mosses: Aulacomnium palustre, Bryum pseudotriquetrum, Plagiomnium ellipticum, Racotritium lanuginosum, Sanionia uncinata, Straminergon stramineum, Tetraplodon

![Fig. 1 Map showing study areas and sampling locations](image-url)
mnioides, and Warnstorfia sarmentosa; lichens: Flavocetraria nivalis, Cetrariella delisei, and Cladonia rangiferina; algae: Prasiola crispa; and the biological soil crust (BSC). At each site within a 25 m × 25 m square, five replicates per species were randomly collected. Dead material, soil particles, and litter were manually removed from the samples. In addition, topsoil samples (depth of 0–3 cm) in five replicates were collected from each square. Each sample consisted of a mixture of three subsamples. Plant remains and stones were removed from the soil. The total number of soil samples collected was 35 × 5 = 175.

Soil and plant analysis

Soil and plant samples were dried at 50 °C until a constant weight was reached. According to Krishna et al. (2003), this temperature is low enough to prevent the loss of mercury. Soil samples were homogenized with a mortar and pestle after the coarse material was removed using a 2-mm sieve. Plant samples were homogenized to a fine powder in an IKA Labortechnik M20 laboratory mill. Dried soil and plant samples (300 mg of dry weight, in triplicate) were digested with 3 mL of nitric acid (ultra pure, 65 %) and 2 mL of perchloric acid (ultra pure, 70 %) in a CEM Mars 5 microwave oven. Samples were then diluted with deionized water to a total volume of 50 mL, and the soil and plant digests were analyzed for Fe, Mn, and Zn using FAAS and Cd, Co, Cr, Cu, Ni, and Pb using ETAAS with Graphite Furnace GF3000 (AVANTA PM Atomic Absorption Spectrophotometry from GBC Scientific Equipment). Mercury was analyzed using an AMA 254 Advanced Mercury Analyzer. All elements were assayed against Atomic Absorption Standard Solution from Sigma Chemical Co. and blanks containing the same matrix as the samples and were processed and analyzed as samples. Results of metal concentrations for the plants were calculated on a dry weight basis. The accuracy of the methods applied for the determination of the metal concentrations in plant and soil samples was checked against certified reference materials: moss M2 and M3 (Finnish Forest Research Institute), DC73348 LGC standards of bush branches and leaves, NCS DC73350 poplar leaves, and RTH 907 Dutch Anthropogenic Soil (Wageningen Evaluating Programs for Analytical Laboratories, WEPAL). The coefficient of variance (CV) was calculated for the measured metal concentrations in the reference materials (Online resource 1).
Statistical analysis

Differences among sampling sites in concentrations of elements in soil, higher plants, mosses, lichens, algae, and the BSC were evaluated by nonparametric ANOVA Kruskal–Wallis analysis. Multiple comparisons of mean ranks for soil, higher plants, mosses, lichens, algae, and the BSC were then calculated.

The matrix of concentrations of 10 metals (Cd, Co, Cr, Cu, Fe, Hg, Mn, Ni, Pb, and Zn) in plant, lichen, algae, and BSC samples from 35 sites after Box–Cox transformation and standardization was subjected to ordination to reveal possible gradients of element levels by means of the principal component and classification analysis (PCCA). Plots of PCCA ordination of the plant, lichen, algae, and BSC samples, and projection of the concentrations of elements on the factor plane give information about similarities between samples and shows correlations between the original variables and the first two factors. (Legendre and Legendre 1998). All calculations were done with the Statistica 10 program Statsoft (2011).

Results

The ranges of metal concentrations in soil, plant, lichen, algae, and BSC samples are displayed in Tables 2, 3, 4, 5, and 6. The mean concentrations of metals in soil and biota differed significantly (ANOVA, Kruskal–Wallis $P < 0.05$).

Soil

Large difference in the carbon percentage (Table 2) in the examined soils depends on the variability of the organic matter content. For example, the geophytic initial dry tundra and initial cyanobacteria-moss wet tundra are growing on a substrate consisting of wet, very fine sand mixed with many rock fragments. However, the epilithic moss–lichen tundra and wet moss tundra are growing on a substrate consisting of dead shoots of mosses on rocky debris (Szymański et al. 2013).

The comparison of metal concentrations observed in the Svalbard soils with pristine soils from the Russian Arctic (in mg kg$^{-1}$: Cd 0.2, Cu 23, Pb 9.1, Zn 29) by Zhulidov et al. (1997) and from much drier tundra soils of the maritime lowland Kaffiöyra in western Spitsbergen (in mg kg$^{-1}$: Cd 0.1, Co 7.4, Cu 23, Fe 29000, Mn 392, Ni 24, Pb 12, Zn 75) by Plichta and Kuczyńska (1991) revealed that only the concentration of Co and Fe was higher than background concentrations in all types of tundras (Tables 2, 3). Multiple comparisons of mean ranks for soils revealed that the two ornithocoprophilous tundras did not differ in concentrations of each of the examined metals.
Table 3 Minimum (min), maximum (max) values, median (med) of concentrations of elements (mg kg\(^{-1}\)) in soil of Spitsbergen of various types of tundra sites

| Type of tundra                                    | Hg Min | Hg Max | Hg Med | Mn Min | Mn Max | Mn Med | Ni Min | Ni Max | Ni Med | Pb Min | Pb Max | Pb Med | Zn Min | Zn Max | Zn Med |
|--------------------------------------------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| Geophytic initial dry tundra                      | 0.009  | 0.01   | 0.01   | 394    | 503    | 450    | 37     | 41     | 39     | 10     | 13     | 11     | 60     | 73     | 65     |
| Initial cyanobacteria-moss wet tundra             | 0.03   | 0.06   | 0.04   | 324    | 501    | 411    | 29     | 35     | 32     | 8      | 11     | 9      | 54     | 81     | 72     |
| Epilithic moss-lichen tundra                      | 0.05   | 0.54   | 0.25   | 252    | 403    | 316    | 19     | 27     | 23     | 15     | 25     | 19     | 55     | 83     | 70     |
| Polygonal tundra                                  | 0.05   | 0.47   | 0.20   | 531    | 923    | 704    | 41     | 46     | 43     | 20     | 24     | 22     | 72     | 92     | 81     |
| Wet moss tundra                                   | 0.05   | 0.32   | 0.15   | 417    | 1,268  | 886    | 11     | 31     | 23     | 10     | 18     | 14     | 52     | 185    | 120    |
| Ornithocoprophilous tundras under influence of \(\text{Alle alle}\) | 0.03   | 0.10   | 0.05   | 1,105  | 1,375  | 1,231  | 75     | 84     | 78     | 34     | 38     | 36     | 213    | 249    | 236    |
| Flow water moss tundra                            | 0.17   | 0.36   | 0.24   | 201    | 298    | 242    | 53     | 59     | 56     | 34     | 37     | 35     | 229    | 345    | 296    |
| Snow bed cyanobacteria-moss tundra                | 0.03   | 0.04   | 0.04   | 706    | 1,006  | 910    | 39     | 47     | 43     | 16     | 10     | 14     | 71     | 75     | 73     |
| Prostrate shrub lichen tundra                     | 0.15   | 0.23   | 0.18   | 242    | 643    | 452    | 8      | 15     | 12     | 10     | 14     | 12     | 81     | 96     | 89     |
| Ornithocoprophilous tundras under influence of \(\text{Uria lomvia and Rissa tridactyla}\) | 0.09   | 0.15   | 0.12   | 1,217  | 1,626  | 1,450  | 58     | 62     | 59     | 30     | 44     | 38     | 174    | 184    | 180    |

Table 4 Minimum (min), maximum (max) values, median (med) of concentrations (mg kg\(^{-1}\)) of Cd, Co, Cr, and Cu in vascular plants, mosses, lichens, and algae and biological soil crust (BSC) of various types of tundra of Spitsbergen

| No | Species                          | Cd Min | Cd Max | Cd Med | Co Min | Co Max | Co Med | Cr Min | Cr Max | Cr Med | Cu Min | Cu Max | Cu Med |
|----|----------------------------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| 1  | Biological soil crust            | 0.05   | 0.6    | 0.2    | 8.0    | 18     | 13     | 12     | 45     | 27     | 10     | 44     | 25     |
| 2  | Algae                            | 1.5    | 1.9    | 1.7    | 1.2    | 1.4    | 1.3    | 3.4    | 4.2    | 3.9    | 27     | 30     | 27     |
| 3  | Lichens                          | 0.08   | 0.13   | 0.11   | 0.01   | 0.3    | 0.3    | 0.1    | 0.4    | 0.2    | 0.3    | 1.0    | 0.5    |
| 4  | Flavocetraria nivalis            | 0.07   | 0.1    | 0.09   | 0.1    | 0.3    | 0.3    | 0.14   | 0.4    | 0.8    | 1.1    | 2.0    | 1.4    |
| 5  | Cetrariella delisei              | 0.03   | 0.08   | 0.05   | 0.01   | 0.4    | 0.3    | 0.3    | 0.7    | 0.6    | 0.9    | 1.0    | 1.2    |
| 6  | Mosses                           | 0.2    | 0.6    | 0.3    | 0.1    | 2.6    | 0.4    | 0.2    | 1.4    | 0.3    | 2.3    | 7.0    | 3.4    |
| 7  | Aulacomnium palustre             | 0.2    | 0.4    | 0.3    | 1.4    | 1.9    | 1.6    | 1.5    | 2.4    | 2.0    | 10     | 15     | 12     |
| 8  | Bryum pseudorhizotum             | 0.4    | 0.6    | 0.5    | 0.1    | 0.4    | 0.3    | 0.7    | 1.0    | 0.7    | 3.8    | 6.0    | 4.7    |
| 9  | Plagiomnium ellipticum           | 0.02   | 0.1    | 0.04   | 0.2    | 11     | 3.0    | 0.2    | 19     | 1.9    | 1.6    | 20     | 3.6    |
| 10 | Racotriitrium lanuginosum         | 0.03   | 0.09   | 0.1    | 0.3    | 16     | 6.0    | 0.8    | 22     | 6.0    | 2.1    | 29     | 9.0    |
| 11 | Sanionia uncinata                | 0.06   | 0.4    | 0.2    | 0.2    | 6.0    | 0.6    | 0.3    | 5.0    | 0.7    | 2.1    | 9.0    | 4.4    |
| 12 | Straminergon stramineum          | 0.2    | 0.8    | 0.4    | 0.1    | 0.4    | 0.2    | 0.5    | 1.1    | 0.6    | 0.9    | 4.0    | 3.2    |
| 13 | Warnstorffia sarmentosa          | 0.1    | 0.3    | 0.2    | 9.0    | 11     | 10     | 14     | 16     | 15     | 16     | 18     | 17     |
| 14 | Vascular plants                  | 0.3    | 1.0    | 0.7    | 0.1    | 0.3    | 0.2    | 0.4    | 0.6    | 0.5    | 1.2    | 5.0    | 3.4    |
| 15 | Cerastium alpinum                | 0.5    | 0.8    | 0.6    | 0.01   | 0.03   | 0.02   | 0.2    | 0.4    | 0.3    | 1.7    | 2.0    | 1.9    |
| 16 | Cochlearia groenlandica          | 0.02   | 1.1    | 0.1    | 0.1    | 0.2    | 0.1    | 0.3    | 2.0    | 0.8    | 1.7    | 12     | 5.1    |
| 17 | Poa alpina                       | 0.6    | 2.3    | 1.1    | 0.4    | 3.0    | 0.7    | 0.1    | 1.5    | 0.4    | 4.0    | 7.0    | 5.6    |
| 18 | Saxifraga oppositifolia          | 0.02   | 0.2    | 0.1    | 0.1    | 0.4    | 0.3    | 0.4    | 1.1    | 0.8    | 2.4    | 4.0    | 3.0    |
The high levels of metals found in Spitsbergen sites influenced by birds nesting were reported earlier (Savinov et al. 2003).

**Vascular plants**

Of the vascular plants, *P. alpina* contained the highest concentrations of Cr, Cu, and Pb. *S. polaris* contained the highest concentrations of Cd, Co, Mn, Ni, and Zn (Tables 4, 5, 6). Askaer et al. (2008) demonstrated that native graminoid plants of Svalbard in the industrialized area contained phytotoxic concentrations of some metals. In this investigation, only the highest concentrations of Cu and Zn in *P. alpina* were higher than average values typical of plants from unpolluted areas (Kabata-Pendias 2001). A comparison of median metal concentrations of vascular plants observed in this study with those reported for the vascular *Cassiope tetragona* (in mg kg \(^{-1}\): Cd 0.2, Co 0.8, Cr 1.4, Cu 3.1, Fe 1205, Hg 0.14, Mn 106, Ni 4.1, Pb 1.6, Zn 33.5) in the same area 20 years earlier (Drbal et al. 1992) revealed that concentrations of Co, Cr, Cu, Fe, Mn, and Ni have increased in this species. Concentrations of Cu, Ni, and Zn have increased, and concentrations of Cd and Pb have decreased in *S. uncinata* (Tables 4, 5, 6). The lower concentrations of Hg and Pb observed in vascular plants, and mosses are in agreement with decreases in Hg emissions in the past two decades throughout Europe. This finding further emphasizes the susceptibility of the Arctic region to the long-range transport of contaminants from industrialized areas (Pacyna and Keeler 1995; Poikolainen

### Table 5 Minimum (min), maximum (max) values, median (med) of concentrations (mg kg \(^{-1}\)) of Fe, Hg, and Mn in vascular plants, mosses, lichens, and algae and biological soil crust (BSC) of various types of tundra of Spitsbergen

| No | Species                   | Fe Min | Fe Max | Fe Med | Hg Min | Hg Max | Hg Med | Mn Min | Mn Max | Mn Med |
|----|---------------------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| 1  | Biological soil crust     |        |        |        |        |        |        |        |        |        |
| 2  | Algae                     |        |        |        |        |        |        |        |        |        |
| 3  | Lichens                   |        |        |        |        |        |        |        |        |        |
| 4  | Mosses                    |        |        |        |        |        |        |        |        |        |
| 5  | Vascular plants           |        |        |        |        |        |        |        |        |        |
| 6  | *Biological soil crust*   |        |        |        |        |        |        |        |        |        |
| 7  | *Algae*                   |        |        |        |        |        |        |        |        |        |
| 8  | *Lichens*                 |        |        |        |        |        |        |        |        |        |
| 9  | *Mosses*                  |        |        |        |        |        |        |        |        |        |
| 10 | *Vascular plants*         |        |        |        |        |        |        |        |        |        |
| 11 | *Biological soil crust*   |        |        |        |        |        |        |        |        |        |
| 12 | *Algae*                   |        |        |        |        |        |        |        |        |        |
| 13 | *Lichens*                 |        |        |        |        |        |        |        |        |        |
| 14 | *Mosses*                  |        |        |        |        |        |        |        |        |        |
| 15 | *Vascular plants*         |        |        |        |        |        |        |        |        |        |

\((P < 0.05)\). The high levels of metals found in Spitsbergen sites influenced by birds nesting were reported earlier (Savinov et al. 2003).

### Mosses

Median metal concentrations of *R. lanuginosum* observed in this study were also compared with those observed by Drbal et al. (1992) in mg kg \(^{-1}\): Cd 0.2, Co 0.8, Cr 1.4, Cu 3.1, Fe 1205, Hg 0.14, Mn 106, Ni 4.1, Pb 7.3, Zn 11.5) and those observed by Grodzińska and Godzik (1991) in mg kg \(^{-1}\): Cd 0.3, Cu 2.3, Ni 2.4, Pb 4.9, Zn 13). Median metal concentrations of *S. uncinata* were compared with those observed by Grodzińska and Godzik (1991) in the same area (in mg kg \(^{-1}\): Cd 0.3, Cu 2.3, Ni 2.4, Pb 4.9, Zn 13). Concentrations of Cd, Hg, and Pb have decreased in *R. lanuginosum*, while concentrations of Co, Cr, Cu, Fe, Mn, and Ni have increased in this species. Concentrations of Cu, Ni, and Zn have increased, and concentrations of Cd and Pb have decreased in *S. uncinata* (Tables 4, 5, 6).
et al. 2004). Multiple comparisons of mean ranks for mosses revealed that there was no significant difference in concentration of metals between species.

Lichens

A comparison of median metal concentrations of Flavocetraria nivalis with those reported by Drbal et al. (1992) for this species (in mg kg\(^{-1}\): Cd 0.1, Co < 0.5, Cr 0.9, Cu 1.4, Fe 237, Hg 0.1, Mn 14.9, Ni 1.6, Pb 4.9, Zn 13.4) revealed that concentrations of Cr, Cu, Fe, Hg, Ni, Pb, and Zn have decreased (Tables 4, 5, 6). Multiple comparisons of mean ranks for lichens revealed that C. delisei contained significantly higher concentrations of Mn, Pb, and Zn (\(P < 0.05\)) than C. rangiferina and significantly higher concentrations of Cr, Cu, and Fe (\(P < 0.05\)) than F. nivalis. The comparison of the metal concentrations between mosses and lichens by the Mann–Whitney U Test (\(P < 0.05\)) revealed that mosses contained significantly higher concentrations of Cd, Co, Cr, Cu, Fe, Mn, and Zn. There was no difference in concentration of Hg, Ni, and Pb.

Algae

Compared with metal concentrations (mg kg\(^{-1}\)) in algae from Spitsbergen given by Drbal et al. (1992), the highest concentrations of Cd (0.2), Co (1.3), Cr (1.1), Cu (5.5), Fe (255), Hg (0.06), Mn (10), Ni (3.3), Pb (0.5), and Zn (12) in all P. crispa samples were higher than those observed 20 years ago (Tables 4, 5, 6).

Biological soil crust

As we did not find any publications containing data on metal concentrations in the BSC in Arctic regions, we compared our results to the average metal concentrations (mg kg\(^{-1}\)) in BSC from Hohe Tauern, Austria given by Peer et al. (2010). The BSC from Spitsbergen contained higher concentrations of Cd (0.41), Cu (11.5), and Ni (22.4); and lower concentrations of Pb (107) and Zn (62) than those reported in Peer et al. (2010).

The ratio of metal concentration in biota to metal concentration in soil (Fig. 2) showed that the accumulation of all metals (except Hg and Zn) was highest in the BSC. The

| No | Species | Ni | Pb | Zn |
|----|---------|----|----|----|
|    |         | Min| Max| Med| Min| Max| Med| Min| Max| Med|
|    | Biological soil crust |  |    |    |    |    |    |    |    |    |
| 1  | BSC     | 11 | 26 | 20 | 2.4| 22 | 11 | 32 | 74 | 54 |
| 2  | Prasiola crispa | 4.3| 5.1| 4.7| 5.8| 6.7| 5.9| 117| 130| 125|
| 3  | Flavocetraria nivalis | 0.4| 0.7| 0.6| 1.4| 2.1| 1.5| 9.0 |13  |10  |
| 4  | Cetrariella delisei | 0.6| 1.2| 1.0| 3.3| 4.6| 4.2| 17  |25  |19  |
| 5  | Cladonia rangiferina | 0.4| 0.8| 0.6| 0.6| 0.9| 0.7| 7.0 |11  |8.0 |
|    | Lichens |    |    |    |    |    |    |    |    |    |
| 6  | Aulacomnium palustre | 0.01| 2.2| 0.1| 0.3| 1.9| 0.6| 17  |22  |20  |
| 7  | Bryum pseudotriquetrum | 0.9| 2.2| 1.6| 2.1| 2.7| 2.4| 35  |43  |39  |
| 8  | Plagiomnium ellipticum | 0.5| 0.7| 0.5| 0.2| 0.7| 0.4| 22  |27  |24  |
| 9  | Racocmitrium lanuginosum | 0.5| 12 | 4.0| 0.9| 23 | 3.0| 4.0 |37  |11  |
| 10 | Sanionia uncinata | 0.01| 17 | 5.0| 0.7| 32 | 3.2| 15  |48  |26  |
| 11 | Straminergon stramineum | 0.02| 6.1| 0.3| 0.3| 9.4| 1.1| 16  |25  |22  |
| 12 | Tetraplodon minioides | 0.01| 9.0| 0.8| 0.4| 0.9| 0.6| 12  |27  |24  |
| 13 | Warnstorfia sarmentosa | 12 |14  |13  |7.0 |9.0 |8.0 |35  |38  |36  |
|    | Mosses  |    |    |    |    |    |    |    |    |    |
| 14 | Cerastium alpinum | 0.3| 0.9| 0.4| 0.2| 0.8| 0.4| 36  |52  |44  |
| 15 | Cochlearia groenlandica | 0.1| 0.2| 0.2| 1.4| 1.6| 1.5| 34  |36  |35  |
| 16 | Poa alpina | 0.01| 0.8| 0.4| 0.4| 2.6| 1.0| 27  |40  |38  |
| 17 | Salix polaris | 2.6| 7.0| 3.4| 0.1| 1.2| 0.3| 61  |180 |160 |
| 18 | Saxifraga oppositifolia | 0.01| 1.8| 1.1| 0.3| 0.7| 0.4| 13  |20  |15  |
ratio for Hg was highest in *R. lanuginosum* and for Zn was *S. polaris* (Fig. 2).

**Discussion**

Multiple comparisons of mean ranks for all BSC, algae, lichens, mosses, and higher plant samples revealed that *P. crispa* contained significantly higher (*P* < 0.05) concentrations of Cu than all other samples, except for the BSC, *S. uncinata*, and *R. lanuginosum*, while the BSC contained significantly higher (*P* < 0.01) concentrations of Co and Ni than all other samples, except for *P. crispa*. These results are in contrast to Drbal et al. (1992) who found lower metal concentrations in algae than in higher plants.

Our results are supported by the PCCA ordination (Fig. 3). The first principal component discriminates between all BSC samples from initial cyanobacteria-moss wet tundra, polygonal tundra, snow bed cyanobacteria-moss tundra, and flow water moss tundra; mosses: *R. lanuginosum* of geophytic initial dry tundra and polygonal tundra; *S. uncinata* of geophytic initial dry tundra, initial cyanobacteria-moss wet tundra, snow bed cyanobacteria-moss tundra, and flow water moss tundra; *W. sarmentosa* of flow water moss tundra; *S. stramineum* of flow water moss tundra (negative scores); and all moss species, lichens, and higher plants of other sampling sites (positive scores). The second principal component is correlated (positive scores) with all *P. crispa* and *S. polaris*. The projection of the variables on the factor plane showed that the BSC, *R. lanuginosum*, *S. uncinata*, *S. stramineum*, and *W. sarmentosa* with negative scores of factor one were highly correlated with the highest concentrations of Co, Cr, Cu, Fe, Hg, Mn, Ni, and Pb in their tissues. *P. crispa* and *S. polaris* from all sites with positive scores of factor two were correlated with the highest concentrations of Cd and Zn. The highest
concentrations of metals were found in the BSC, *R. lanuginosum*, *S. uncinata*, *S. stramineum*, and *W. sarmentosa* from types of tundra which, except for geophytic initial dry tundra, receive water from melting ice or snow. Spring runoff water alimenting these tundras contains elevated concentrations of metals, and soil–water interactions in tundra soils are a potential source of nutrients for surrounding ecosystems (Elberling et al. 2007; Tye and Heaton 2007). Additionally, water from melting glaciers containing an additional portion of metals deposited from the air should be taken into account (Drbal et al. 1992). Of the moss species examined, *S. uncinata* appeared to be an efficient bioindicator of metal pollution (Samecka-Cymerman et al. 2011). The reason for the elevated concentrations of metals in *R. lanuginosum* and *S. uncinata* from the geophytic initial dry tundra became clearer when we consider elevation. Although the difference in altitude between this tundra site and the other sites was only 26 m, *S. uncinata* and *R. lanuginosum* at this site were likely more exposed to pollution transported by wind. Svalbard is located very far from major sources of atmospheric pollution. However, some long-range transport of pollutants has been reported, and atmospheric deposition is a significant source of metals in Arctic ecosystems (Bashkin and Howarth 2002; Birks et al. 2004; Samecka-Cymerman et al. 2011). The supply of sea salts and trace metals via precipitation also appears to contribute to high metal concentrations observed in Spitsbergen biota (Bard 1999; Bashkin and Howarth 2002).

The high concentrations of metals in the BSC support the suggestion by Beraldi-Campesi et al. (2009) that the BSC plays a role in soil fertility and influences the metal budgets of associated soil and biota. These authors observed that soils underneath the crusts showed depletion of non-biothetic elements. Peer et al. (2010) confirmed that the BSC acts as captors for atmogentic heavy metals. The very high concentrations of metals in the indicator species *P. crispa* for soils fertilized with wastes (Olech 1996) may be connected with the fact that in this investigation, *P. crispa* grew only in ornthocoprophilous tundra in the vicinity of colonies of *Uria lomvia* and *Rissa tridactyla* feeding on marine fishes and molluscs. As these birds breed on land, they transport contaminants (among them a significant amount of trace metals) to coastal areas in levels that may affect those ecosystems (Grodzinska and Godzik 1991; Dowdall et al. 2005). Seabirds act as a vector for the transport of metals between the marine and terrestrial ecosystems (Headley 1996). Their excretions are the most probable sources of metals to *P. crispa* that grow in the vicinities of bird colonies (Bargagli et al. 1998). It is important to note, however, that other species growing under the influence of bird colonies, *C. groenlandica* and *C. arcticum*, contained low concentrations of metals. The Mann–Whitney U test comparing the concentration of metals in *S. polaris* indicated that this species collected from both epilithic moss-lichen tundra and prostrate shrub lichen tundra contained significantly higher concentrations of Zn and Cu (*P < 0.05*) than *S. polaris* collected from ornthocoprophilous tundra. This phenomenon may be attributed to metal dilution by higher biomass production. In areas characterized by low primary production and very slow decomposition processes, the availability of soil nutrients is almost negligible. However, additional sources of macroelements, by the presence of numerous seabirds whose excrements fertilize the area around their breeding colonies, affect development of the specific plant communities of ornthocoprophilous tundra receiving extremely high loadings of nitrogen and phosphorus (Olech et al. 2011). According to Baddeley et al. (1994) *S. polaris* in particular was very responsive to nitrogen and phosphorus inputs, showing an increase in biomass. Concentration (mg kg⁻¹) of nitrogen and phosphorus in soil of ornthocoprophilous tundra was as high as 9,000–18,100 and 600–700, respectively, and in *S. polaris* was as high as 30,000 and 5,630, respectively. In comparison, nitrogen and phosphorus concentrations (mg kg⁻¹) in soil of initial tundra were 300–390 and 300–370, respectively. Rate et al. (2004) reported that plant uptake of all elements increased with increasing biosolid application, suggesting that the dilution effect by increased plant biomass was responsible for erratic metal concentrations.
Conclusions

In this study, mosses were better bioindicators of Cd, Co, Cr, Cu, Fe, Mn, and Zn than lichens. PCCA analysis revealed that the BSC, *R. lanuginosum*, *S. uncinata*, and *S. stramineum* accumulated the highest concentrations of Co, Cr, Cu, Fe, Hg, Mn, Ni, and Pb in their tissues growing in polygonal tundra, initial cyanobacteria-moss wet tundra, snow bed cyanobacteria-moss tundra, and flow water moss tundra almented by melting ice or snow. This implicates the probability that metal contaminants observed to bio-accumulate in these species originate from atmospheric deposits; therefore, a high degree of metal accumulation can be linked to greater wetness of habitats. *P. crispa* and *S. polaris* were the best accumulators of Cd and Zn. Mosses are known to be bioindicators in Spitsbergen, as they accumulate significantly higher concentrations of metals than lichens. These results therefore suggest that the observed higher concentrations of Cu in mosses and lower concentrations of Hg in mosses, lichens, and vascular plants in 2011, compared with values observed in 1992, are associated with changes in the atmospheric deposition of contaminants over Spitsbergen, likely because of changes in the long-distance transport of anthropogenic emissions from industrialized areas.

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