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ORIGINAL PAPER

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

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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, and the moss species *Racomitrium lanuginosum, Sanionia uncinata,* and *Straminergon stramineum* from the polygonal tundra, initial cyanobacteria-moss wet tundra, snow bed cyanobacteria-moss tundra, and flow water moss tundra alimented by melting ice or snow. The observed higher concentrations of Cu and lower concentrations of Hg in mosses, lichens, and vascular plants compared with values observed 20 years earlier were apparently associated with changes in the atmospheric deposition of contaminants over Spitsbergen due to changes in the long-distance transport of anthropogenic emissions from industrialized areas. *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

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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 (Gulińska 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 (Drbal 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 Szymański et al. (2013). According to Walker et al. (2005), Svalbard belongs to a bioclimatc 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, Racomitrium lanuginosum, Sanionia uncinata, Straminergon stramineum, Tetraplodon*

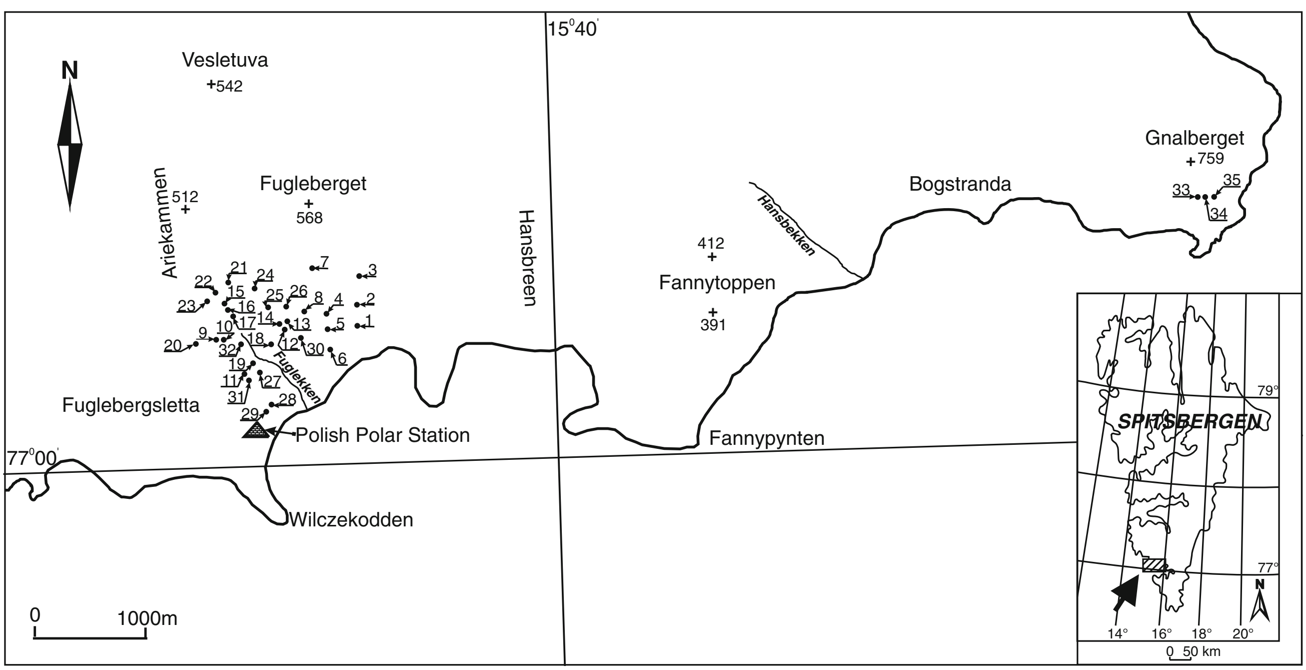

Fig. 1 Map showing study areas and sampling locations

Table 1 Type of tundra and number of species collected from sampling sites

Type of tundra (sites)	Habitat characterization	Species (*N*—number of samples)
Geophytic initial dry tundra (1–3)	Dry sites on lateral moraine	*Saxifraga oppositifolia* ($N = 15$), *Racomitrium lanuginosum* ($N = 15$), *Sanionia uncinata* ($N = 15$)
Initial cyanobacteria-moss wet tundra (4–6)	Wet sites on lateral moraine	*S. uncinata* ($N = 15$), biological soil crust (BSC) ($N = 15$)
Epilithic moss-lichen tundra (7–11)	Dry sites on acid rocks	*Salix polaris* ($N = 20$), *R. lanuginosum* ($N = 25$), *Cladonia rangiferina* ($N = 25$), *Flavocetraria nivalis* ($N = 25$)
Polygonal tundra (12–14)	Moderately wet sites on patterned ground	*R. lanuginosum* ($N = 15$), BSC ($N = 15$)
Wet moss tundra (15–20)	Habitats with standing fresh water	*Aulacomnium palustre* ($N = 5$), *Bryum pseudotriquetrum* ($N = 5$), *S. uncinata* ($N = 15$), *Straminergon stramineum* ($N = 15$), *Tetraplodon mnioides* ($N = 10$)
Ornithocoprophilous tundra under influence of *Alle alle* (21–23)	Dry rocky debris on slopes	*Cerastium arcticum* ($N = 15$), *S. polaris* ($N = 15$), *Poa alpina* ($N = 10$), *Plagiomnium ellipticum* ($N = 15$), *S. uncinata* ($N = 15$), *T. mnioides* ($N = 15$)
Flow water moss tundra (24–26)	Habitats with flowing fresh water	*B. pseudotriquetrum* sp. ($N = 5$), *S. uncinata* ($N = 15$), *S. stramineum* ($N = 15$), *Warnstorfia sarmentosa* ($N = 5$), BSC ($N = 10$)
Snow bed cyanobacteria-moss tundra (27–29)	Damp, loamy habitats on level ground	*S. uncinata* ($N = 15$), BSC ($N = 15$)
Prostrate shrub lichen tundra (30–32)	Dry sites on level to gently sloping ground	*S. polaris* ($N = 15$), *S. oppositifolia* ($N = 15$), *Cetrariella delisei* ($N = 15$)
Ornithocoprophilous tundra under influence of *Uria lomvia* and *Rissa tridactyla* (33–35)	Rocky debris on slopes	*Cochlearia groenlandica* ($N = 15$), *C. arcticum* ($N = 15$), *P. alpina* ($N = 15$), *Prasiola crispa* ($N = 15$)

Type of tundra modified based on Kuc (1998) and Szymański et al. (2013)

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 $35 \times 5 = 175$.

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 2 Minimum (min), maximum (max) values, median (med) of concentrations of elements (Carbon in % all other elements in mg kg^{-1}) in soil of Spitsbergen of various types of tundra sites

Type of tundra	C			Cd			Co			Cr			Cu			Fe		
	Min	Max	Med	Min	Max	Med	Min	Max	Med	Min	Max	Med	Min	Max	Med	Min	Max	Med
Geophytic initial dry tundra	0.9	1.3	1.1	0.04	0.06	0.05	20	26	23	19	26	23	44	50	48	33,927	47,643	41,420
Initial cyanobacteria-moss wet tundra	0.7	1.0	1.0	0.03	0.10	0.06	21	28	25	20	28	24	35	49	40	33,116	47,006	41,410
Epilithic moss-lichen tundra	8.9	31.9	30	0.08	0.14	0.12	13	15	13	12	18	16	13	25	17	33,032	36,743	34,760
Polygonal tundra	0.8	1.0	1.0	0.11	0.17	0.14	29	35	32	18	24	21	12	22	17	46,377	67,504	53,430
Wet moss tundra	1.9	39.3	34.2	0.25	0.46	0.35	12	23	17	14	26	19	26	64	43	66,582	85,219	75,270
Ornithocoprophilous tundras under influence of *Alle alle*	14.4	27.9	17.7	0.30	0.40	0.36	56	66	60	23	27	24	82	99	92	79,719	90,546	85,090
Flow water moss tundra	1.7	11.1	2.9	0.50	1.35	1.20	30	45	38	32	49	38	51	58	53	40,940	44,327	42,043
Snow bed cyanobacteria-moss tundra	1.6	3.7	3.0	0.09	0.12	0.11	25	32	29	19	22	20	35	47	41	57,234	67,245	61,670
Prostrate shrub lichen tundra	3.8	17.9	4.1	0.09	0.13	0.11	22	23	22	21	24	23	52	60	56	16,270	19,665	18,086
Ornithocoprophilous tundras under influence of *Uria lomvia* and *Rissa tridactyla*	21.5	24.5	22.3	0.14	0.27	0.21	44	50	46	46	48	47	85	97	92	70,887	78,744	75,519

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			Mn			Ni			Pb			Zn		
	Min	Max	Med	Min	Max	Med	Min	Max	Med	Min	Max	Med	Min	Max	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 *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	10	16	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 *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			Co			Cr			Cu		
		Min	Max	Med	Min	Max	Med	Min	Max	Med	Min	Max	Med
Biological soil crust													
1	BSC	0.05	0.6	0.2	8.0	18	13	12	45	27	10	44	25
Algae													
2	*Prasiola crispa*	1.5	1.9	1.7	1.2	1.4	1.3	3.4	4.2	3.9	27	30	27
Lichens													
3	*Flavocetraria nivalis*	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	*Cetrariella delisei*	0.07	0.1	0.09	0.1	0.3	0.14	0.4	1.4	0.8	1.1	2.0	1.4
5	*Cladonia rangiferina*	0.03	0.08	0.05	0.01	0.4	0.3	0.3	0.7	0.6	0.9	1.0	1.2
Mosses													
6	*Aulacomnium palustre*	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	*Bryum pseudotriquetrum*	0.2	0.4	0.3	1.4	1.9	1.6	1.5	2.4	2.0	10	15	12
8	*Plagiomnium ellipticum*	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	*Racomitrium lanuginosum*	0.02	0.1	0.04	0.2	11	3.0	0.2	19	1.9	1.6	20	3.6
10	*Sanionia uncinata*	0.03	0.9	0.1	0.3	16	6.0	0.8	22	6.0	2.1	29	9.0
11	*Straminergon stramineum*	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	*Tetraplodon mnioides*	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	*Warnstorfia sarmentosa*	0.1	0.3	0.2	9.0	11	10	14	16	15	16	18	17
Vascular plants													
14	*Cerastium alpinum*	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	*Cochlearia groenlandica*	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	*Poa alpina*	0.02	1.1	0.1	0.1	0.2	0.1	0.3	2.0	0.8	1.7	12	5.1
17	*Salix polaris*	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

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			Hg			Mn		
		Min	Max	Med	Min	Max	Med	Min	Max	Med
Biological soil crust										
1	BSC	12,490	32,150	22,430	0.02	0.3	0.04	142	1,520	440
Algae										
2	*Prasiola crispa*	2,400	3,420	2,990	0.17	0.19	0.18	84	117	95
Lichens										
3	*Flavocetraria nivalis*	120	190	160	0.03	0.05	0.04	13	20	16
4	*Cetrariella delisei*	540	1,000	750	0.06	0.09	0.08	15	23	20
5	*Cladonia rangiferina*	410	698	440	0.02	0.05	0.04	8.0	12	9.0
Mosses										
6	*Aulacomnium palustre*	140	3,410	220	0.02	0.04	0.03	12	120	19
7	*Bryum pseudotriquetrum*	1,290	2,160	1,720	0.02	0.03	0.02	90	94	92
8	*Plagiomnium ellipticum*	170	770	350	0.01	0.03	0.02	55	92	74
9	*Racomitrium lanuginosum*	320	15,910	2,590	0.03	0.10	0.04	7.0	320	70
10	*Sanionia uncinata*	250	15,890	5,760	0.03	0.10	0.05	17	850	130
11	*Straminergon stramineum*	110	4,840	480	0.02	0.05	0.04	10	440	33
12	*Tetraplodon mnioides*	80	520	120	0.01	0.03	0.02	8.0	31	18
13	*Warnstorfia sarmentosa*	13,380	13,400	13,395	0.04	0.05	0.04	420	440	430
Vascular plants										
14	*Cerastium alpinum*	114	323	164	0.01	0.03	0.02	28	190	140
15	*Cochlearia groenlandica*	115	130	124	0.01	0.02	0.01	27	29	28
16	*Poa alpina*	90	190	120	0.01	0.02	0.01	27	60	40
17	*Salix polaris*	130	660	240	0.01	0.09	0.02	140	280	210
18	*Saxifraga oppositifolia*	150	460	380	0.01	0.02	0.02	16	46	23

($P < 0.05$). 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 1.3, Cr 1.9, Cu 10, Fe 1556, 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, Hg, Ni, and Pb had decreased (Tables 4, 5, 6).

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 0.2, Mn 24, Ni 2.4, 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 0.6, Cu 6.0, Ni 4.3, Pb 7.1, Zn 21). 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). 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 6 Minimum (min), maximum (max) values, median (med) of concentrations (mg kg^{-1}) of Ni, Pb, and Zn in vascular plants, mosses, lichens, and algae and biological soil crust (BSC) of various types of tundra of Spitsbergen

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
Algae										
2	*Prasiola crispa*	4.3	5.1	4.7	5.8	6.7	5.9	117	130	125
Lichens										
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
Mosses										
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	*Racomitrium 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 mnioides*	0.01	0.9	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
Vascular plants										
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

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

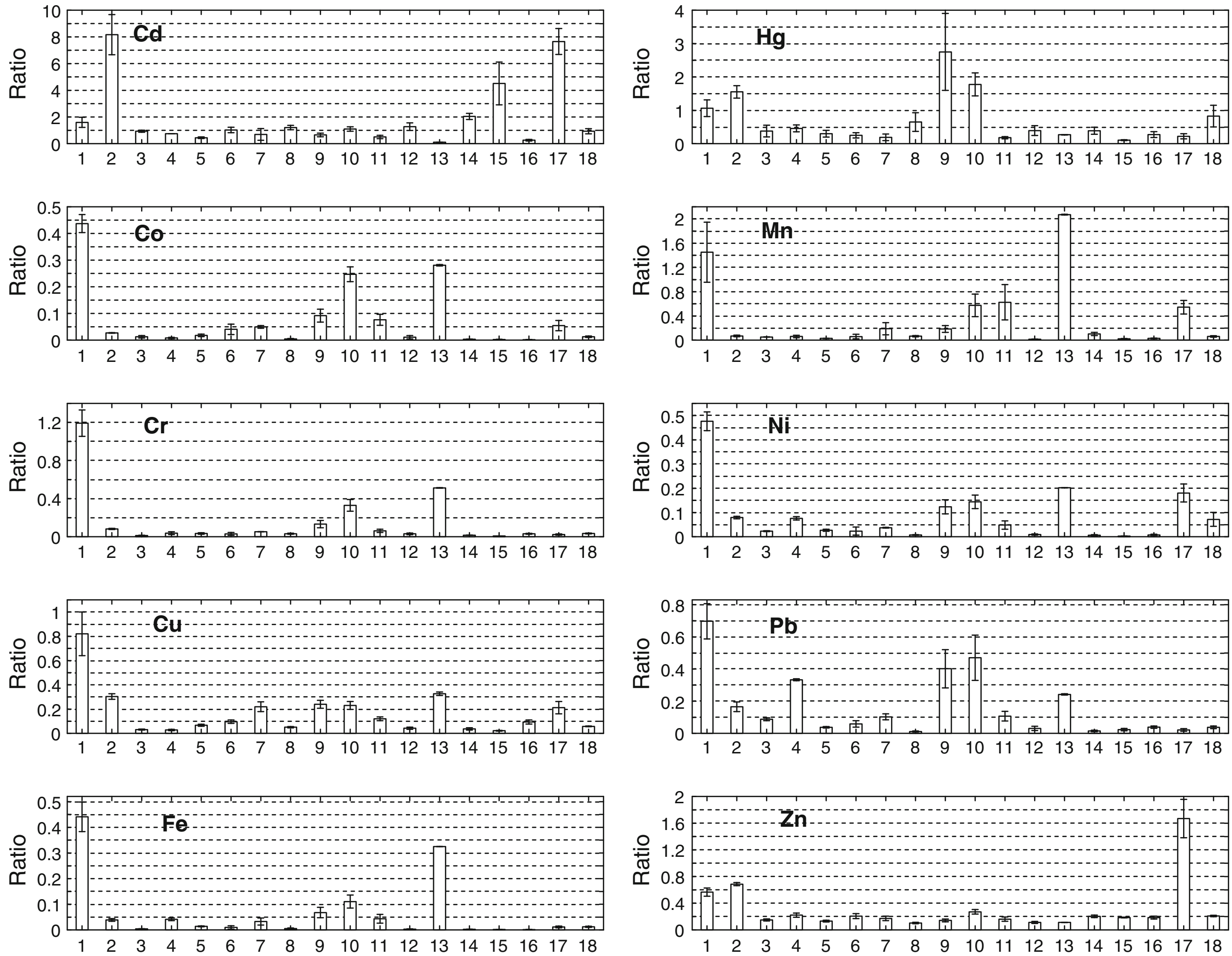

Fig. 2 Ratio for concentration of metals in biota divided by concentration of metals in soil (numbers of BSC, algae, vascular plants, mosses, lichens in the Tables 4, 5, and 6), *bar*: mean, ⌶: standard error

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

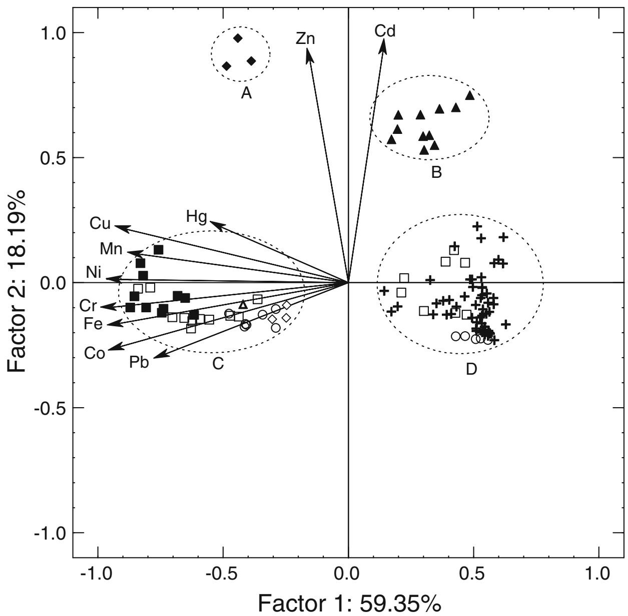

Fig. 3 Ordination plot of higher plants, mosses, lichens, algae, and BSC based on concentrations of the 10 metals Cd, Co, Cr, Cu, Fe, Hg, Mn, Ni, Pb, and Zn and projection of metal concentrations on the component plane. Filled square biological soil crust, open square *S. uncinata*, open circle *R. lanuginosum,* open triangle *W. sarmentosa,* open diamonds *S. stramineum*, filled diamonds *P. crispa,* filled triangle *S. polaris,* plus sign remaining species

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-biogenic elements. Peer et al. (2010) confirmed that the BSC acts as captors for atmogenic 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 ornithocoprophilous 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 (Grodzińska 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 vicinity 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 ornithocoprophilous 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 ornithocoprophilous 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 ornithocoprophilous 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 alimented by melting ice or snow. This implicates the probability that metal contaminants observed to bioaccumulate 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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References

Askaer L, Schmidt LB, Elberling B, Asmund G, Jónsdóttir IS (2008) Environmental impact on an Arctic soil–plant system resulting from metals released from coal mine waste in Svalbard (78°N). Water Air Soil Pollut 195:99–114

Baddeley JA, Woodin SJ, Alexander IJ (1994) Effects of increased nitrogen and phosphorus availability on the photosynthesis and nutrient relations of three arctic dwarf shrubs from Svalbard. Funct Ecol 8:676–685

Bard SM (1999) Global transport of anthropogenic contaminants and the consequences for the Arctic marine ecosystem. Mar Pollut Bull 38:356–379

Bargagli R, Sanchez-Hernandez JC, Martella L, Monaci F (1998) Mercury, cadmium and lead accumulation in Antarctic mosses growing along nutrient and moisture gradients. Polar Biol 19:316–322

Bashkin VN, Howarth RW (2002) Modern biogeochemistry. Kluwer Academic Publishers, Dordrecht

Beraldi-Campesi H, Hartnett HE, Anbar A, Gordon GW, Garciapichel F (2009) Effect of BSC on soil elemental concentrations: implications for biogeochemistry and as traceable biosignatures of ancient life on land. Geobiology 7:348–359

Birks HJB, Jones VJ, Rose NL (2004) Recent environmental change and atmospheric contamination on Svalbard as recorded in lake sediments: an introduction. J Paleolimnol 31:403–410

Davey MC (1997) Effects of short-term dehydration and rehydration on photosynthesis and respiration by Antarctic bryophytes. Environ Exp Bot 37:187–198

Dowdall M, Gwynn JP, Gabrielsen GW (2005) Assessment of elevated radionuclide levels in soils associated with an avian colony in a High Arctic environment. Soil Sediment Contam 14:1–11

Drbal K, Elster J, Komárek J (1992) Heavy metals in water, ice and biological material from Spitsbergen, Svalbard. Polar Res 11:99–101

Elberling B, Søndergaard J, Jensen LA, Schmidt LB, Hansen BU, Asmund G, Zunić TB, Hollesen J, Hanson S, Jansson PE, Friborg T (2007) Arctic vegetation damage by winter-generated coal mining pollution released upon thawing. Environ Sci Technol 41:2407–2413

Grodzińska K, Godzik B (1991) Heavy metals and sulphur in mosses from Southern Spitsbergen. Polar Res 9:133–140

Gulińska J, Rachlewicz G, Szczuciński W, Barałkiewicz D, Kózka M, Bulska E, Burzyk M (2003) Soil contamination in high Arctic areas of human impact, central Spitsbergen, Svalbard. Pol J Environ Stud 12:701–707

Headley AD (1996) Heavy metal concentrations in peat profiles from the high Arctic. Sci Total Environ 177:105–111

Heintzenberg J, Hansson H-C, Lannefors H (1981) The chemical composition of arctic haze at Ny-Alesund, Spitsbergen. Tellus 33(2):162–171

Heintzenberg J, Strom J, Ogren JA, Fimpet HP (1991) Vertical profiles of aerosol properties in the summer troposphere of central Europe, Scandinavia and the Svalbard region. Atmos Environ A 25:621–627

Hoshino T, Tojo M, Okada G, Kanda H, Ohgiya S, Ishizaki K (1999) A filamentous fungus, *Pythium ultimum* Trow var. *ultimum*, isolated from moribund moss colonies from Svalbard, northern islands of Norway. Polar Biosci 12:68–75

Kabata-Pendias A (2001) Trace elements in soils and plants. CRC Press, Boca Raton

Krishna MVB, Karunasagar D, Arunachalam J (2003) Study of mercury pollution near a thermometer factory using lichens and mosses. Environ Pollut 124:357–360

Kuc M (1998) Environs of the Polish Polar Station (Isbjörnhamna, North Hornsund, Spitsbergen) as survey in 1958 by vegetation mapping and related methods. In: Głowacki P, Bednarek J (eds) Polish polar studies. Twenty-fourth international polar symposium. Institute of Geophysics of the Polish Academy of Sciences, Warszawa, pp 141–157

Legendre P, Legendre L (1998) Numerical ecology, second English ed. Developments in environmental modelling. Elsevier, Amsterdam

Liu X, Zhao S, Sun L, Yin X, Xie Z, Honghao L, Wang Y (2006) P and trace metal contents in biomaterials, soils, sediments and plants in colony of red-footed booby (*Sula sula*) in the Dongdao Island of South China Sea. Chemosphere 65:707–715

Olech M (1996) Human impact on terrestrial ecosystems in west Antarctica. NIPR Symp Polar Biol 9:299–306

Olech M, Węgrzyn M, Lisowska M, Słaby A, Angiel P (2011) Contemporary changes in vegetation of polar regions. Papers Glob Change IGBP 18:35–51

Pacyna JM, Keeler GJ (1995) Sources of mercury in the Arctic. Water Air Soil Poll 80:621–632

Peer T, Türk R, Gruber JP, Tschaikner A (2010) Species composition and pedological characteristics of biological soil crusts in a high alpine ecosystem, Hohe Tauern, Austria. Eco Mont J Prot Mt Areas Res Manag 2:23–30

Plichta W, Kuczyńska I (1991) Metal contents in soils of Kaffiöyra, Spitsbergen. Pol. Polar Res 12(2):183–193

Poikolainen J, Kubin E, Piispanen J, Karhu J (2004) Atmospheric heavy metal deposition in Finland during 1985–2000 using mosses as bioindicators. Sci Total Environ 318:171–185

Rate AW, Lee KM, French PA (2004) French Application of biosolids in mineral sands mine rehabilitation: use of stockpiled topsoil decreases trace element uptake by plants. Bioresour Technol 91:223–231

Samecka-Cymerman A, Wojtuń B, Kolon K, Kempers AJ (2011) *Sanionia uncinata* (Hedw.) loeske as bioindicator of metal pollution in polar regions. Polar Biol 34:381–388

Savinov VM, Gabrielsen GW, Savinova TN (2003) Cadmium, zinc, copper, arsenic, selenium and mercury in seabirds from the Barents Sea: levels, inter-specific and geographical differences. Sci Total Environ 306:133–158

Simões JC, Zagorodnov VC (2001) The record of anthropogenic pollution in snow and ice in Svalbard, Norway. Atmos Environ 35:403–413

Smith AJE (ed) (1982) Bryophyte ecology. Chapman and Hall Ltd., New York

StatSoft Inc (2011) STATISTICA (data analysis software system), version 10. http://www.statsoft.com

Szymański W, Skiba S, Wojtuń B (2013) Distribution, genesis, and properties of Arctic soils: a case study from the Fuglebekken catchment, Spitsbergen. Pol Polar Res 34:3. doi:10.2478/popore-2013-0017

Tye AM, Heaton THE (2007) Chemical and isotopic characteristics of weathering and nitrogen release in non-glacial drainage waters on Arctic tundra. Geochim Cosmochim Acta 71(17):4188–4205

Walker DA, Raynolds M K, Daniëls FJA, Einarsson E, Elvebakk A, Gould WA, Katenin A E, Kholod SS, Markon CJ, Melnikov ES, Moskalenko MNG, Talbot SS, Yurtsev BA, CAVM Team (2005) The Circumpolar Arctic Vegetation Map. J Veg Sci 16:267–282

Xie Z, Sun L, Blum JD, Huang Y, He W (2006) Summertime aerosol chemical components in the marine boundary layer of the Arctic Ocean. J Geophys Res 111, D10, 309: 1–11

Zhulidov AV, Headley JV, Robarts RD, Nikanorov AM, Ischenko AA, Champ MA (1997) Concentrations of Cd, Pb, Zn and Cu in pristine wetlands of the Russian Arctic. Mar Pollut Bull 35:242–251