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The influence of seabirds on the concentration of selected heavy metals in organic soil on the Bellsund coast, western Spitsbergen

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ABSTRACT

Seabirds are an important factor affecting the chemical properties of the arctic soil environment. The objective of this work was to study the differences in content and distribution of heavy metals in organic soils resulting from the differential influence of seabirds. Studies were conducted in two stations in the southwest part of Spitsbergen—the first without the influence of seabirds and the second directly affected by an avian colony. Basic properties of soils as well as total content of Ca, Na, Mg, K, Fe, Al, Cu, Zn, Ni, Mn, Pb, Cd, Co, and Cr were determined. Reference was made to the previously published contents of different forms of phosphorus (P) for these locations. The studies showed that Zn, Mn, Cu, and Cd contents were higher in the soils that had been in the vicinity of the seabird colony. High statistically positive correlations of Cd, Cu, and Zn were noted with particular P forms. In the case of Pb, Cr, Co, and Ni content, the seabird influence was not dominant; probably other factors were more relevant (the processes of weathering, denudation, leaching, and atmospheric pollutants transported in the form of dust or gases). Clear segregation was observed of individual positions conditioned by selected soil features and by heavy metals content.

Introduction

The arctic soil environment is subjected to changes, wherein natural processes play a fundamental role. Cryogenic processes influenced the current state of the Spitsbergen soil cover to the greatest extent, as well as humidity and weathering (Forman and Miller, 1984; Mann et al., 1986; Blümel et al., 1993; Melke and Chodorowski, 2006; Witkowska-Walczak et al., 2014; Bockheim, 2015). In the Bellsund region (southwestern Spitsbergen), organic and mineral-organic soils are relatively common, but they only cover small areas. Peat soils form under very moist tundra habitats, in areas of water stagnation, such as in local depressions of coastal plains, on hillsides, and at the bottom of slopes. Peat soil profiles are generally shallow and very shallow (Eurola, 1971; Zelikson, 1971; Låg, 1980; Göttlich and Hornburg, 1982; Klimowicz et al., 1997). They are characterized by organic matter that is poorly decomposed, and the peat layer is deposited on rock debris or heavy clay. The chemical composition of organic deposits in Spitsbergen has been poorly examined; only a few publications have reported on it (Dobrovolsky, 1990; Jóźwik and Magierski, 1992; Klimowicz et al., 1997; Melke, 1999; Melke and Chodorowski, 2006; Chmiel et al., 2009).

Polar land ecosystems, including soil cover, greatly depend on nutrients originating from the sea. Seabirds are the key organisms in the Arctic acting as biovectors and influencing energy and nutrient transportation from marine to land ecosystems (Tatur, 1989; Godzik, 1991; Headley, 1996; Ligęza and Smal, 2003; Michelutti et al., 2009, 2010; Mallory et al., 2015). From marine areas of foraging, birds carry nutrients to breeding areas, where they release them through defecation, regurgitation, dropping food, or mortality (Blais et al., 2005; Ellis et al., 2006; Mulder et al., 2011; Bauer and Hoye, 2014). In polar regions, the amount of nutrients delivered with avian excrement is much higher than from alternate sources and on a local scale it enriches the ecosystem significantly (Bildstein et al., 1992; Bokhorst et al., 2007). Introducing nutrients to the land food chain influences the chemical properties of soil and directly influences the flora in the proximity of avian colonies (Breuning-Madsen et al., 2008; Zwolicki et al., 2013, 2015; Ziółek and Melke, 2014).

In the bio-transportation of organic materials, transportation of pollutants and their concentration in the proximity of breeding areas can also be observed (Blais et al., 2005; Brimble et al., 2009; Mallory et al., 2015). Seabirds are the main source of the terrestrial environment's pollution because their food consists of organisms that are high in the food chain. As a result of bioaccumulation and biomagnification, these organisms contain a high concentration of pollutants, including heavy metals originating from the marine environment (Buckman et al., 2005; Campbell et al., 2005; Mallory and Braune, 2012). Enrichment of the terrestrial environment with heavy metals in the proximity of seabird breeding areas is documented for the polar (Godzik, 1991; Headley, 1996; Bargagli et al., 1998; Sun et al., 2004; Zhu et al., 2005; Evenset et al., 2007; Mallory et al., 2015) and temperate zones, as well as the tropical zone (Otero Perez, 1998; Hawke et al., 1999; Garcia et al., 2002; Liu et al., 2006). The efficiency of pollutant introduction to the terrestrial environment by seabirds is also visible in terms of the heavy metal content in flora. Plants in the proximity of avian colonies show higher concentrations than the same species growing in similar habitats distant from avian colonies (Godzik, 1991; Blais et al., 2005; Evenset, 2007).

Increased soil pollution is most often observed in areas subjected to direct pressure from human activity (Makuch, 2014). Nevertheless, the surveyed region's significant distance from any industrial areas does not exclude the influence of anthropogenic factors on the arctic environment. It is mostly manifested by deposition of gas and dust pollutants transferred over great distances (Pacyna, 1995; Law and Stohl, 2007; Ruman et al., 2013; Kozak et al., 2015). Local sources, such as coal mines, also have a small influence on the pollution of Svalbard's soil environment (Headley, 1996; Gulińska et al., 2003; Lewińska-Preis et al., 2009).

The objective of this research was to study the role of birds in the transport of pollutants, visible in the content and distribution of heavy metals in Spitsbergen organic soils. The presented results show a new perspective on the diverse accumulation of contaminants in organic soils and are useful for determining changes in the environment of the Arctic.

Study Area

The study was conducted at two stations in the northwest part of Wedel Jarlsberg Land, southwestern Spitsbergen (Fig. 1).

Within the area of the first station (Skilvika profile), there were organic soils not directly subjected to the influence of seabirds. The station is located on Calypsostranda plain in the direct neighborhood of a cliff coast on Sklivika Bay. In geological terms, it is a part of a system of elevated marine terraces with average height of 40–65 m a.s.l. where tundra polygons formed under the influence of frost weathering. The station area is covered with mossy flora with sparsely occurring clumps of grass and the *Salix polaris* willow.

The second station (Dunderdalen transect) is located on the southern slope of Dundrabeisen (435 m a.s.l.), at a height of around 30–90 m a.s.l. (Fig. 2.). There is a shallow, sloping peatland of less than 1 ha located here, formed on an alluvial cone, with a tilt of around 30°. Above the peatland, there is a very steep and plantless rock wall with bird nests, mostly blacklegged kittiwake, *Rissa tridactyla*. The number of nests was estimated at several hundred, and the share of other species was negligible. The influence of the avian colony can be seen in the whole area of the station (lush vegetation), with an obvious intensification directly under the nesting zone (organic remains: dry plants, bird droppings, and feathers). The research station's area is covered with mossy flora.

The average air temperature in the area of study is around 5 °C in the summer and between –8 and –16 °C in the winter. Temperatures over 15 °C are recorded sporadically. The average annual temperature is around –5 °C. There is very little precipitation; the annual sum is below 400 mm. The highest amount of precipitation is observed in the fall season.

Materials and Methods

The Dunderdalen transect was designated along the fall of the alluvial cone and the peatland that formed on it. The material collection points were placed in an approximately 25-m sequence; the first one was located directly under the avian nesting zone and the last one on the flattening at the bottom of the cone. The thick-

FIGURE 1. Location of study area and survey points. Topographic map was used with the courtesy of the Norwegian Polar Institute.

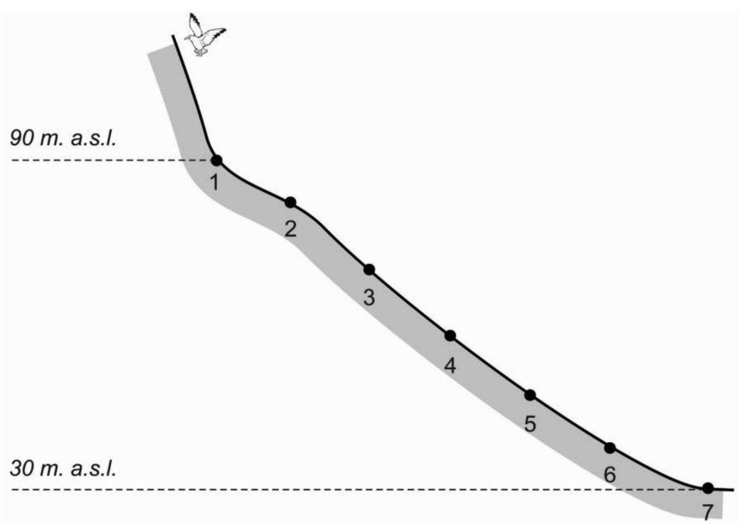

FIGURE 2. The location of sample collection points at the Dunderdalen transect.

ness of the organic material was diversified, and one to three samples were collected from each individual point (15 in total).

The Sklivika profile was described in the wedge between tundra polygons filled with peat moss. The depth of the wedges reached over 50 cm at the permafrost boundary. The station has an ombryogenic character. Peat, along with mineral substrate, was collected to a depth of 67 cm and divided into samples of 1.5–2.5 cm thickness (27 in total).

A detailed morphological description and results of basic properties (organic matter [OM] and pH) for the Skilvika profile and the Dunderdalen transect can be found in the work by Ziółek and Melke (2014).

The material was dried and ground in an agate mortar for further studies. The following basic analyses were carried out: soil organic matter content by burning at 550 °C, carbonate content using the volumetric method, and pH in 0.01 M $CaCl_2$. Samples incinerated at 550 °C were dissolved in a solution of concentrated HF and $HClO_4$ acids, evaporated to dryness, and then treated with 6 M HCl. Assessment of the total content of Fe, Al, Cu, Zn, Ni, Mn, Pb, Cd, Co, and Cr was carried out using the AAS method (Sparks et al., 1996). Analytical data were supplemented with data concerning the content of individual P forms in the studied soils (Ziółek and Melke, 2014).

The average values for the respective Skilvika profile depths were calculated for comparison with each other, and those depths refer directly to the depths from which samples along the Dunderdalen transect were collected, creating a summary of data referring to each other in terms of depth. Subsequently, the data were subjected to statistical analysis. Their purpose was to answer the following questions: (1) Do the concentrations of the individual components analyzed differ among sites? If so, what is the difference? To solve this problem, both single-variable and multi-variable statistical tests were used. Their more detailed description is provided below. (2) The difference between the posts may be because of not only the concentrations of the individual components, but also their specific combination. So, in the analyzed data, what specific classes are there and what are their characteristics? The multi-variable grouping methodology (described below) was used to answer this question. (3) Is there a relationship between the concentrations of the heavy metals tested and the concentrations of the different forms of P that may be seen as an indicator of the impact of the bird colony on the properties of the soils tested? Pearson correlations between individual parameters were calculated, and significance was adjusted by Holm's method (Holm, 1979). The results were confirmed by Spearman's rank correlation analysis.

Because of the small size of both study groups separated on the basis of location ($n < 30$), nonparametric methods were used to assess the significance of their differences. The following methods were used: U Mann-Whitney test (evaluation of the lack of differences in average), Brown-Forsythe test (assessment of the significance of differences in data variability), Wald-Wolfowitz runs test (conformity assessment of data distribution in populations). Typically, testing the significance of the differences among samples is limited to the mean values. It happens, however, that although the samples do not differ in average values, they may vary in terms of the variability (scattering of values around the mean) and/or the shape of the distribution (for example, its symmetry/skewness). Wald-Wolfowitz runs test is a nonparametric test that examines whether two populations differ in central tendency, variances, skewness, or any other distribution pattern. The above statistical tests allowed us to verify the assumptions about differences among particular (individual) variables in the populations from which the samples were derived. However, they did not allow us to determine the degree of similarity of the population resulting from the combination of many features. For multivariate assessment of similarity/dissimilarity of positions complementary methods: ANOSIM (one-way ANOSIM–ANalysis Of Similarities) and Simper (Similarity Percentage) were used (Clarke, 1993). The calculations were performed using PAST software (Hammer et al., 2001, Hammer and Harper, 2006) using Euclidean distance to the standardized data.

The similarity of individual soil samples was also determined, regardless of the place of collection. Similarity was determined from three perspectives: for all analyzed components of the soil, the macronutrients and pH (OM, Ca, Mg, Na, K, Al, and H^+) and heavy metals only (Fe, Mn, Cu, Cb, Cd, Pb, Zn, Ni, Cr). Grouping using the Ward method in the Euclidean space was performed, on the basis of standardized data. A distance for which inflection of the connecting (agglomeration) curve followed was taken as a criterion for grouping. Such a collapse of the agglomeration curve indicated the start of grouping of objects of small similarity (above this level objects of low similarity are combined). In each case, similarity of variables was analyzed in addition to the similarity among the analyzed samples, because high similarity among variables may indicate their similar origins in the soil.

Physical Description

The organic soils of the studied stations are diversified in terms of morphological structure, organic matter content, and acidity. In the peat soil of Skilvika, the organic part of the profile reaches a depth of 57.5 cm, below which there is a mineral clay substrate. The organic part of the profile consists of peat moss in varying degrees of decomposition. In the upper part, it is very weakly decomposed and with the increase of depth its decomposition rises to the level of well-decomposed in the lower part.

In Dunderdalen, all samples in the seven points of the transect consisted of organic material deposited on rock debris. The first point of the transect—the surface sample—consisted of dry floral remains, avian excrement, and feathers. Samples of subsequent points consisted of peat moss at different degrees of decomposition: from weakly to mid-decomposed in samples at depths of 0–10 cm and 0–5 cm, and mid- to well-decomposed in deeper samples. Generally, the degree of peat decomposition rises along the transect and with depth.

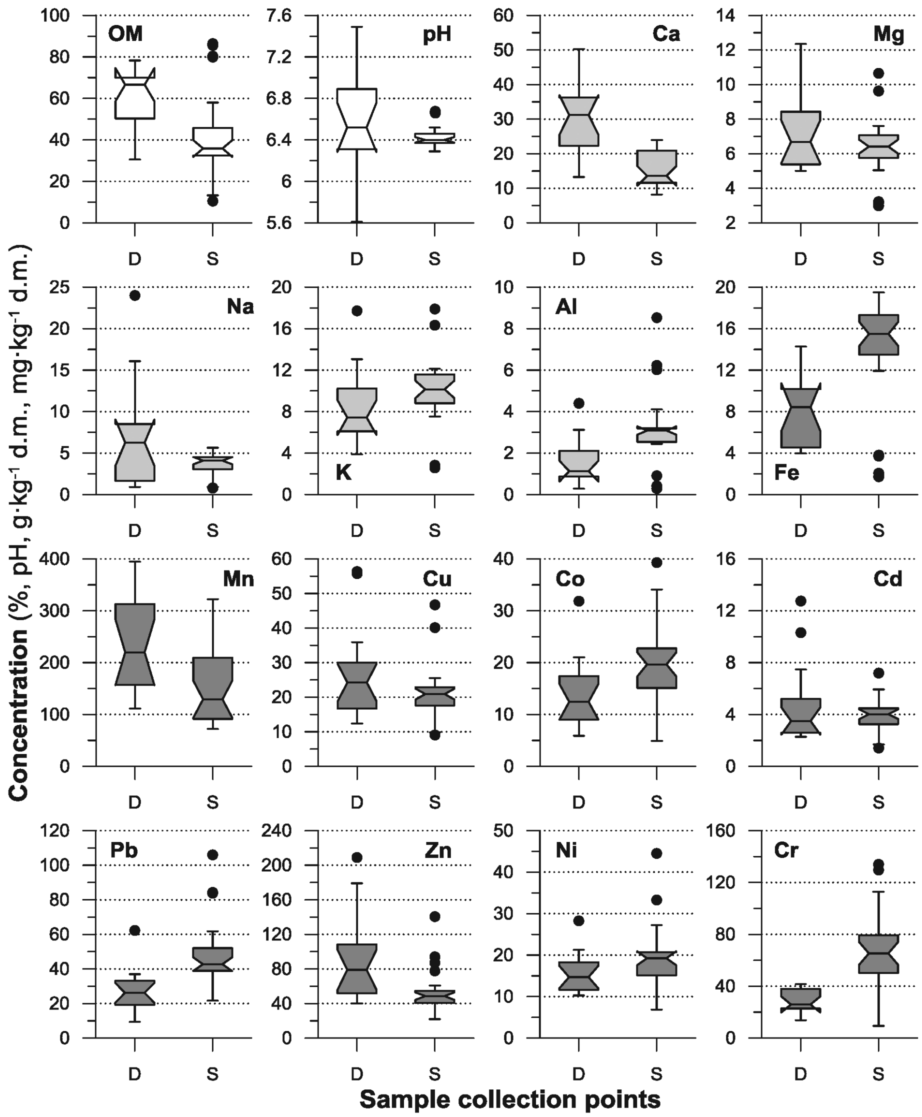

FIGURE 3. Box plot for particular elements in soil samples from surveyed locations. D—Dunderdalen, S—Sklivika. Indents of boxes represent the range of 95% confidence interval for the median. White and gray filling of boxes was used to distinguish the groups of parameters (organic matter [OM] and pH macronutrient/light metal [i.e., Ca, Mg, Na, K, and Al] and heavy metals [i.e., Fe, Mn, Cu, Co, Cd, Pb, Zn, Ni, and Cr]). The dots represent data outliers, defined as greater than 3 quartile or less than 1 quartile more than 1.5 IQR (interquartile interval). Units for particular components are listed in Table 1.

Results

For the most of the parameters analyzed, the differences between the positions were very significant and applied to the averages (medians), dispersion of data, and the general character of the distribution. Charts (Fig. 3) also showed a significantly higher incidence of outlier values in Skilvika (38 cases to 11 in Dunderdalen). Most of these samples were observed by reference to the Al concentrations (6 cases), and Mg, Fe, and Zn (4 cases). Large differences in medians for OM, Ca, Al, Fe, Pb, and Cr are visible. Mg, pH, Na, Zn, and Cr were very differentiated in terms of variability.

In the studied organic soils of Spitsbergen, samples from Dunderdalen transect were characterized by a much greater amount of Ca, Na, Zn, Mn, and Cu. The reverse situation occurred in the case of Fe, Al, Cr, Pb, and Co, where a significantly higher level was recorded for the Skilvika profile. There were only slight differences in the content of Mg, K, Cd, and Ni between Dunderdalen and Skilvika; the determined amounts of these elements were in a similar range (Table 1, Fig. 4).

The heavy metal content was inconsistently correlated with particular forms of P (Table 4). Zn, Cd, and Cu showed positive correlations with individual forms of P. Fe, Co, Ni, Pb, and Cr were not correlated with P.

The vertical distribution of the most studied heavy metals within the Skilvika profile indicated some relation with the ash content. The lowest content was observed in the surface part of the profile in the very weakly decomposed peat moss, with the highest content of organic matter (over 80%). The exceptions were Pb, which saw an increase in content between 2 and 5 cm, and Ni, for which a slight accumulation was observed in the surface sample (0–2 cm; Fig. 4). From the depth of 7 cm, where the ash content rises to over 40%, there was

TABLE 1

Basic descriptive statistics of individual components in soil samples of surveyed stations. OM = loss combustion of organic matter. Prior to the calculation of the statistics for soil reaction pH values were converted to a concentration of hydrogen ion (H^+). The results are restated in the pH scale.

		Dunderdalen transect						Skilvika profile					
Component	Unit	*n*	Mean	Med.	Min.	Max.	Std.Dev.	*n*	Mean	Med.	Min.	Max.	Std.Dev.
OM	%	15	60.5	66.6	30.5	78.3	14.97	27	42.2	35.9	10.5	86.4	19.70
Reaction	pH	15	6.26	6.52	5.61	7.49	0.38	27	6.41	6.40	6.29	6.69	0.08
Ca	$g \cdot kg^{-1}$ d.m.	15	29.5	31.2	13.3	50.3	10.47	27	15.3	13.6	8.2	23.9	4.81
Mg	$g \cdot kg^{-1}$ d.m.	15	7.2	6.7	5.0	12.3	2.11	27	6.3	6.4	3.0	10.6	1.76
Na	$g \cdot kg^{-1}$ d.m.	15	6.8	6.3	0.9	24.0	6.30	27	3.6	4.1	0.8	5.7	1.37
K	$g \cdot kg^{-1}$ d.m.	15	8.4	7.4	3.9	17.7	3.69	27	9.7	10.1	2.6	17.9	3.68
Fe	$mg \cdot kg^{-1}$ d.m.	15	8.5	8.4	4.0	14.3	3.38	27	14.0	15.5	1.7	19.5	5.09
Al	$mg \cdot kg^{-1}$ d.m.	15	1.6	1.1	0.3	4.4	1.13	27	3.1	3.1	0.3	8.5	1.70
Mn	$mg \cdot kg^{-1}$ d.m.	15	226.5	220.0	111.5	394.6	83.56	27	157.2	129.3	72.2	322.4	77.34
Cu	$mg \cdot kg^{-1}$ d.m.	15	26.8	24.2	12.4	56.3	13.62	27	21.5	20.9	9.1	46.7	7.45
Co	$mg \cdot kg^{-1}$ d.m.	15	13.8	12.4	5.9	31.8	6.75	27	19.1	19.7	4.9	39.3	7.99
Cd	$mg \cdot kg^{-1}$ d.m.	15	4.8	3.5	2.3	12.7	3.11	27	3.9	4.0	1.4	7.2	1.32
Pb	$mg \cdot kg^{-1}$ d.m.	15	27.8	26.2	9.4	62.2	12.15	27	49.0	42.8	21.6	106.0	17.86
Zn	$mg \cdot kg^{-1}$ d.m.	15	91.4	79.0	40.0	209.0	48.32	27	52.9	48.6	22.0	140.5	24.34
Ni	$mg \cdot kg^{-1}$ d.m.	15	15.6	14.7	10.3	28.3	4.86	27	19.4	19.3	6.9	44.5	7.32
Cr	$mg \cdot kg^{-1}$ d.m.	15	29.6	25.9	13.8	41.5	8.40	27	62.8	65.3	9.4	134.0	32.05

an increase in the occurrence of all studied elements, with a distinct accumulation at the depth of 15–17.5 cm. However, the maximal content for all studied microelements (Cu, Co, Cd, Pb, Zn, and Ni) was found in the well-decomposed peat moss at a depth of 52.5–55 cm. Mn and Cr are the exceptions; the highest content of Mn was reported in the upper part of the profile at a depth of 7–8.5 cm, whereas Cr reached its maximum content in the mineral substrate (Fig. 4).

The positioning of microelements in the Dunderdalen transect was more diversified both along the transect and in the respective points. Their maximum content was characteristic for some elements (Mn, Zn, Cu, and Cd) at point 2, just below the surface sample under the avian colony in the weakly decomposed peat moss (Fig. 4). This point also had the lowest pH in the whole transect. Ni, Co, and Cr also had heightened concentrations here, but their maximum content occurred at the final seventh point of the transect (Co and Ni in the 20–25 cm sample; Cr in the 5–15 cm sample of that point). The content of Pb exhibited a different trend, and its maximum occurred in the surface sample of the transect's fifth point (Fig. 4).

Of the 16 parameters taken into consideration, in 10 cases a statistically significant difference was found in averages, in 5 in variances, and in 9 in the whole distribution of the variables (Table 2). Two data sets—concentrations of Ca and Cr—were the most differentiated, because they differed in each analyzed aspect, and the probability of error was very low ($p \leq 0.01$). The content of OM and concentrations of Fe, Al, and Pb differed significantly among stations because of average values and data distribution. In particular, concentrations of Fe and Pb differentiated the two groups, because the probability of error was less than 0.001. Reaction (pH) and concentration of Na and Cu were different in variances and the distribution of values. Concentrations of Mn, Co, Zn, and Ni were different only in mean values, and in the case of K and Cd there was no reason to reject a hypothesis of the lack of differences. It should also be noted that the test results for Cu and Ni were close to the threshold of statistical significance ($0.035 < p < 0.049$), so they should be interpreted with caution.

The results of the tests described above allowed us to evaluate the significance of differences in the statistics of individual variables. However, they did not allow us to determine the degree of differentiation resulting from the combination of many features simultaneously. For this purpose, ANOSIM and SIMPER methods were used. These calculations confirmed the difference between the two locations. For the data of all components analyzed, average rank of the intra-group distance in ANOSIM test was 368.3 (rb), and intergroup was 501.6 (rw). R test statistic calculated on their basis had a value of 0.309, and the probability (p) that the differences between the groups are random was only 0.0002. If ANOSIM used only the concentrations of heavy metals, the value of rb was 495.8, rw = 373.4, $R = 0.2842$, and $p = 0.0006$. The differences between soil in the studied positions, connected with the content of heavy metals, were also highly statistically significant, although somewhat

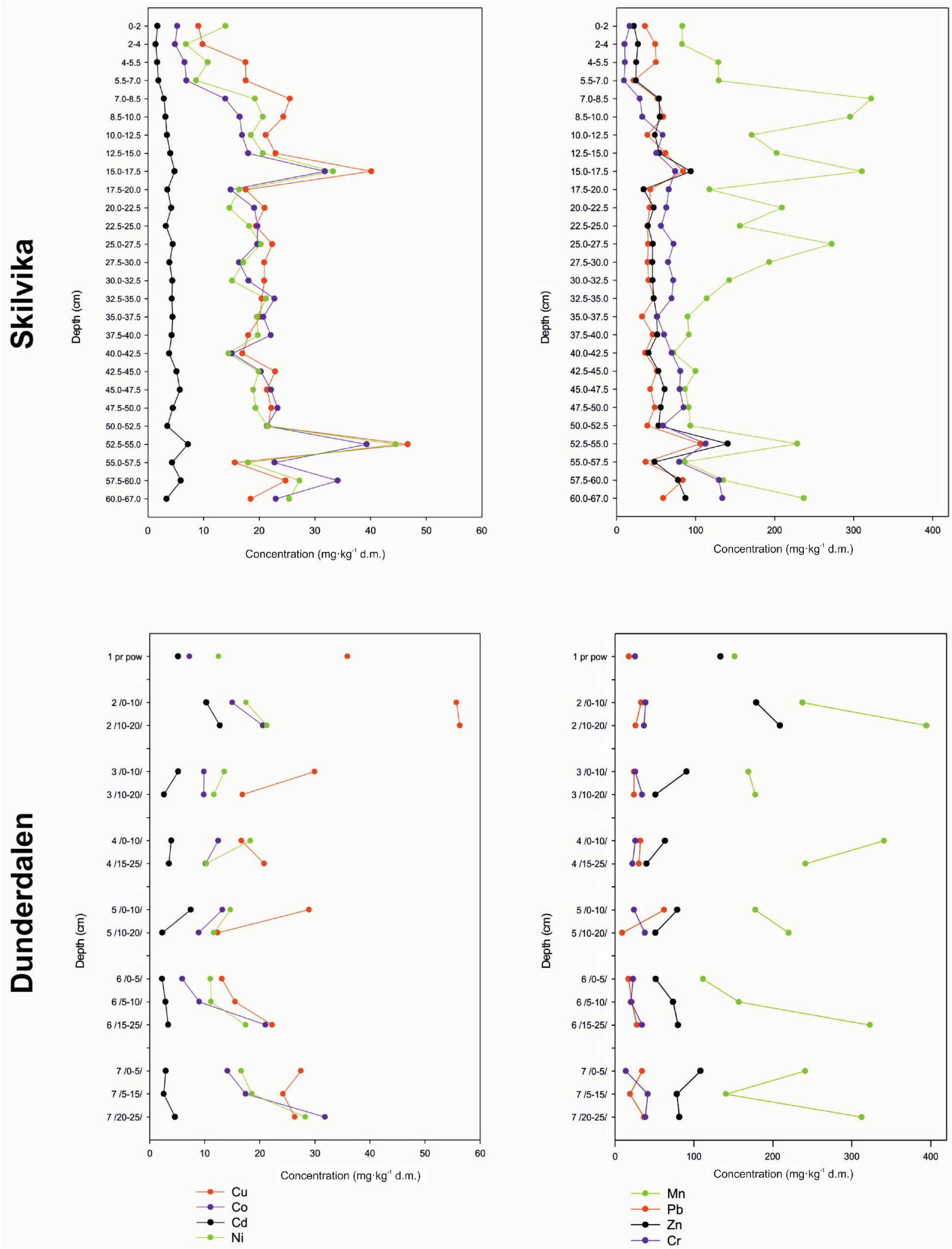

FIGURE 4. The distribution of heavy metals in the profile Skilvika and along Dunderdalen transect.

weaker than in the other analyzed parameters (differences in *R* values: 0.309 vs. 0.284).

Results of SIMPER indicated that all the parameters determined in the soil samples showed fairly equal conditions of dissimilarity of soils at both positions (Table 3). The ratio of difference between the Ca that most affects the dissimilarity, and Ni, the effect of which was the smallest, was only like 1.69:1. The

TABLE 2

Test statistics and significance levels for comparison of the components in soil samples taken from the Dunderdalen and Skilvika stations. Explanations: M.-W. U = U test (Mann-Whitney), Brn-Fors. = Brown-Forsythe test, W.-W. = Wald-Wolfowitz runs test. Calculations for soil reaction (pH) were done on the basis of the data converted to hydrogen ion concentration. Cases with $p < 0.05$ are marked by gray background.

Component	M.-W. U	*p*-value	Brn-Fors.	*p*-value	W.-W.	*p*-value
OM	2.599	0.0094	0.091	0.7641	2.996	0.0027
Reaction	–1.682	0.0926	6.093	0.0179	2.314	0.0207
Ca	4.252	0.0000	12.158	0.0012	2.655	0.0079
Mg	0.840	0.4009	0.901	0.3482	0.609	0.5426
Na	1.732	0.0832	13.136	0.0008	3.337	0.0008
K	–1.654	0.0982	0.073	0.7880	0.950	0.3422
Fe	–3.439	0.0006	0.261	0.6119	3.678	0.0002
Al	–2.966	0.0030	0.182	0.6724	2.655	0.0079
Mn	2.756	0.0058	0.144	0.7067	0.609	0.5426
Cu	1.076	0.2818	4.692	0.0363	1.973	0.0485
Co	–2.336	0.0195	0.196	0.6600	0.950	0.3422
Cd	0.105	0.9164	3.707	0.0613	1.291	0.1968
Pb	–4.279	0.0000	0.634	0.4307	3.337	0.0008
Zn	3.202	0.0014	3.630	0.0640	1.291	0.1968
Ni	–2.100	0.0357	0.229	0.6352	0.268	0.7888
Cr	–3.386	0.0007	7.195	0.0106	4.360	0.0000

heavy metals' share in total dissimilarity was 54.8% (21,296/38,891) and was roughly proportional to their number in relation to all analyzed variables (9 of 16). Among them, the most important were Zn, Cd, and Pb, and the least, Ni and Co.

A dendrite of sample similarity constructed with the use of all parameters divided soils into five groups (Fig. 5). The division was made at a bond distance of 9.5, for which the agglomeration curve showed a distinct shoulder. Distinguished groups had from 2 to 17 objects. In classes 3 and 1, soil samples from only one station (S or D) were connected; in the other classes there were combinations of various samples. Nonetheless, even in the latter groups, on the lowest level of the dendrite (single branches), samples from different stations varied—there was no situation in which the sample of "S" was the most similar to the sample of "D" and vice versa. The largest class 3 was the most homogeneous one; it was characterized by a relatively small variation of all the parameters and values lying in the central part of their total range. The minimum concentrations of Ca and Mn were outstanding among the other classes.

Class number 5 showed high variability among its samples, in the case of most of the analyzed parameters. Its diversity was the result of a minimum content of OM and the highest concentrations of up to eight analyzed components (Mg, K, Fe, Al, Co, Pb, Ni, and Cr).

Class 1 varied the most from the other classes, having highest concentrations of Ca, Na, Mn, Cu, Cd, and Zn, and the lowest pH. The other two classes, 2 and 4, contained the samples of the two stations and had a rather complex internal structure. Class 2 was characterized by the highest mean content of OM and lowest concentrations of most of the other components (Mg, Na, K, Fe, Al, Cu, Co, Cd, Pb, Zn, Ni, and Cr). The highest average pH and relatively high variability of the other soil parameters (with average level of concentration) were specific for class 4.

Using the same methods, analyzed variables were also grouped on the basis of similarity (Fig. 6); four groups were distinguished. In the smallest one, OM content and the concentration of Ca were combined. The dendrite branch including this group also included groups consisting of Mn, Na, and Mg, and Cd, Zn, Cu, and H^+. The last group, consisting of Pb, Cr, Al, Ni, Co, Fe, and K, was very dissimilar to both previous groups.

Additionally, we created a dendrite of similarity of soil samples, using only data for heavy metals (Fig. 7). Five groups were also distinguished, which tended to almost concurrently demonstrate a similar homogeneity as in the analysis of all parameters (Fig. 5). Only

TABLE 3

Results of SIMPER analysis for all soil parameters analyzed and only for heavy metals.

Component	Av. dissim all	Contrib. % all	Cumulative % all	Contrib. % heavy metals	Cumulative % heavy metals
Ca	3.28	8.43	8.429		
Na	2.86	7.36	15.79		
Zn	2.78	7.15	22.95	13.07	13.07
H+	2.76	7.09	30.04		
Cd	2.50	6.43	36.47	11.75	24.82
Pb	2.50	6.42	42.90	11.73	36.55
Cu	2.42	6.23	49.13	11.39	47.94
Fe	2.39	6.15	55.28	11.23	59.16
Mn	2.34	6.01	61.29	10.98	70.14
Cr	2.31	5.94	67.23	10.85	80.99
OM	2.29	5.88	73.11		
Al	2.22	5.70	78.81		
Mg	2.17	5.59	84.40		
Co	2.11	5.48	89.83	9.91	90.90
K	2.02	5.19	95.02		
Ni	1.94	4.98	100	9.10	100
Overall dissimilarity	38.89				

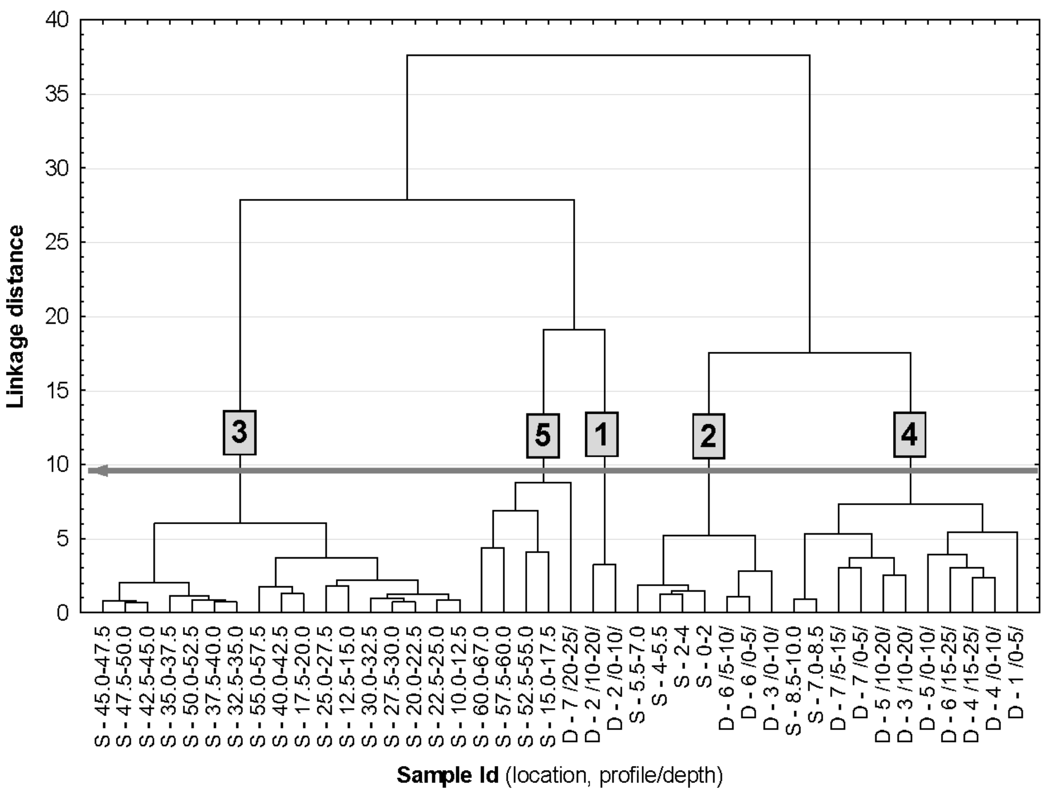

FIGURE 5. Dendrite of similarities among soil samples, determined on the basis of all the components analyzed. Numbers (1–5) specify classes described in the text.

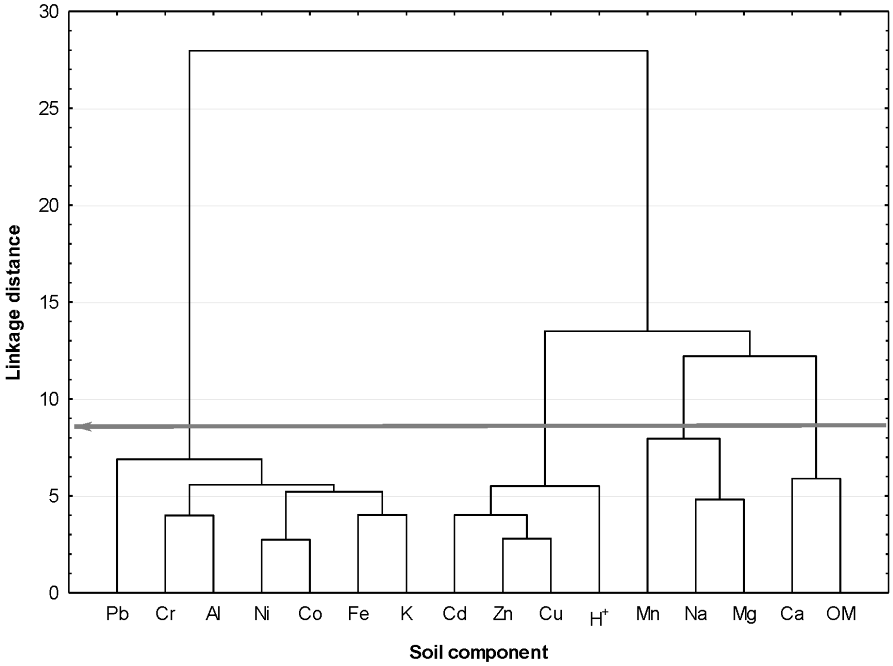

FIGURE 6. Similarity of all variables (components in soil samples).

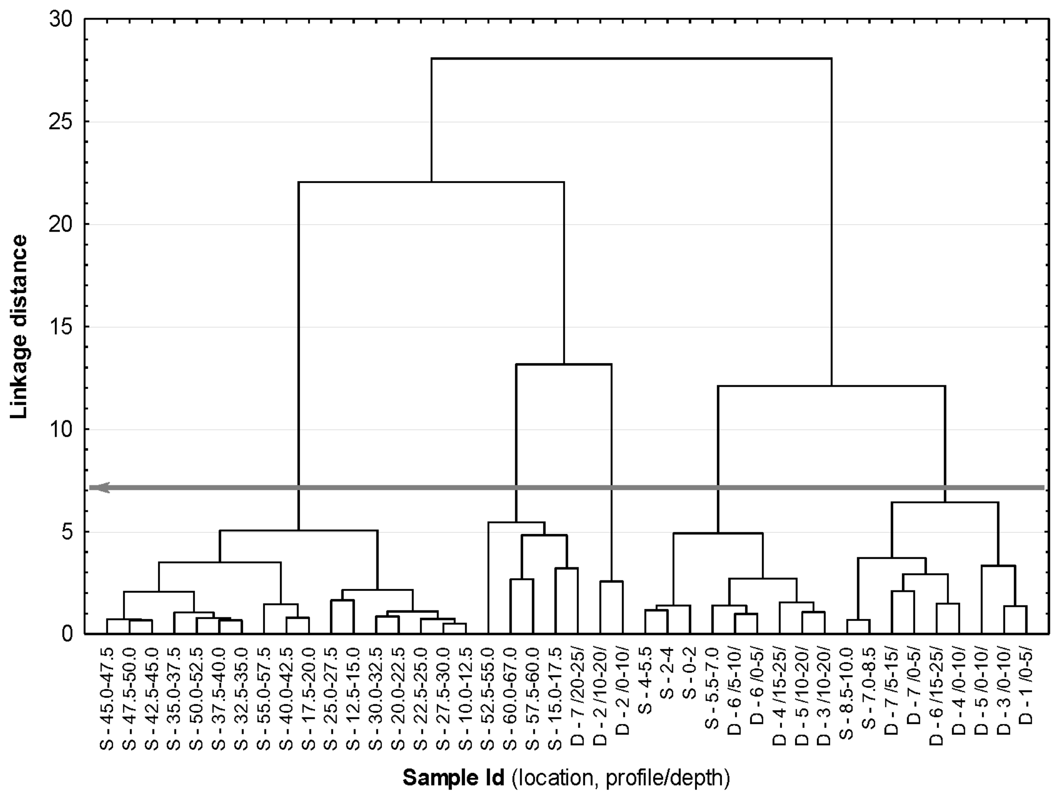

FIGURE 7. Dendrite of similarities among soil samples, determined on the basis of only heavy metals concentrations (Fe, Mn, Cu, Co, Cd, Pb, Zn, Ni, and Cr).

four samples from Dunderdalen: 3 (0–10), 3 (10–20), 4 (15–25), and 5 (10–20) were included in the other branch than in the first case. A dendrite of similarity of variables (Fig. 8) showed clear differentiation of heavy metals, which were combined into two groups consisting essentially of the elements having a higher concentration in Dunderdalen (Zn, Cu, and Mn) or Skilvika (Pb, Co, Cr, and Fe).

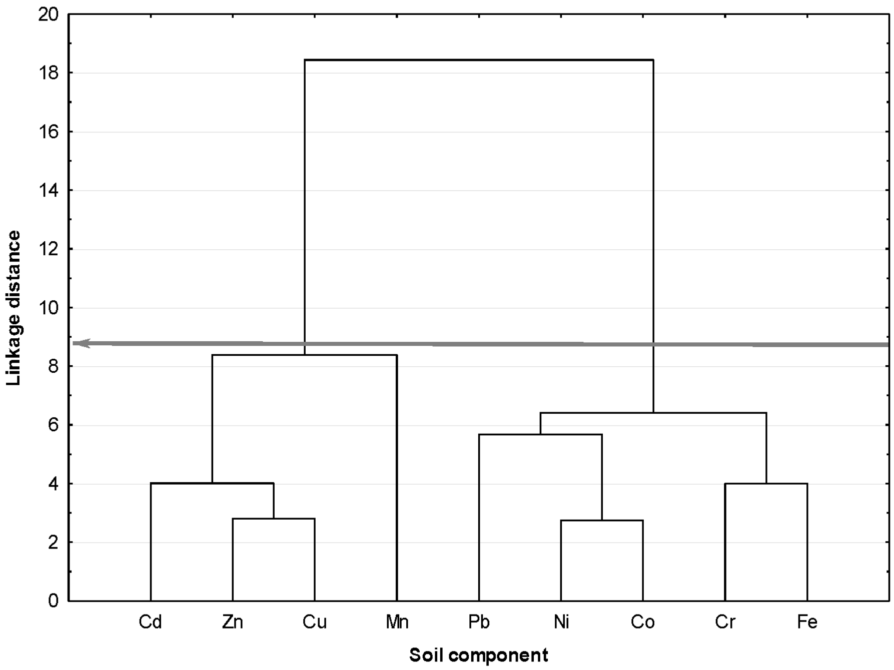

FIGURE 8. Similarity in the group of variables of heavy metals.

TABLE 4

Pearson correlation coefficients between heavy metals concentration and particular phosphorus forms. Marked values are significant at $p < 0.05$ (p values were adjusted using Holm's method). Explanations: PT = total P, OP = organic P, IP = inorganic P, Pi-L = labile inorganic P, Pi-FeAl = inorganic P associated with Fe and Al, Pi-CaMg = inorganic P associated with Ca and Mg, Po-HuAc = organic P associated with humic acids, Po-Res = residual organic P.

	Cd	Co	Cr	Cu	Fe	Mn	Ni	Pb	Zn
TP	0.720	–0.016	–0.055	0.755	–0.109	0.228	0.004	–0.364	0.819
IP	0.700	–0.038	–0.062	0.736	–0.135	0.192	–0.009	–0.333	0.792
OP	0.607	0.208	0.037	0.624	0.194	0.489	0.134	–0.513	0.737
Pi-CaMg	0.877	0.044	–0.013	0.855	–0.062	0.317	0.058	–0.276	0.878
Pi-FeAl	0.324	–0.045	–0.076	0.458	–0.119	0.034	–0.012	–0.380	0.556
Pi-L	0.304	–0.190	–0.136	0.397	–0.252	–0.047	–0.146	–0.317	0.481
Po-HuAc	0.265	0.355	0.061	0.315	0.373	0.341	0.275	–0.222	0.402
Po-Res	0.683	0.070	0.013	0.676	0.039	0.470	0.016	–0.579	0.779

Discussion

Our study has shown that seabird colonies, as a consequence of bio-transportation processes, play an important role in increasing the content of and changing the distribution of heavy metals in arctic soils, and that this is a widely described phenomenon (Godzik, 1991; Headley, 1996; Blais et al., 2005; Michelutti et al., 2010; Mallory et al., 2015). This is indicated by the highest scores of Zn, Mn, Cu, and Cd contents in the peat under the avian colony, which is the direct receiver of those inputs (the second point of the transect), and is in agreement with other studies (e.g., Brimble et al., 2009; Michelutti et al., 2009). Moreover, the surface part of the peatland, not subjected to the direct influence of birds, exhibited lower contents of all heavy metals in relation to the substrate under the avian colony (with the exception of Pb).

The process of bio-transportation does not, however, increase the contents of all heavy metals. One of the surprising results is the higher contents of Pb, Cr, and Co found in the soil profile not subjected to the direct influence of birds. Apart from the influence of seabirds, organic soils of Spitsbergen are exposed to the accumulation of heavy metals from other sources. The supply and loss of the particular analyzed elements in the sediment can be (a) the processes of weathering/type and composition of the in situ bedrock; (b) denudation (surface runoff erosion, mass movements, deflation), leaching, accumulation, and other agencies (Gulińska et al., 2003; Mallory et al., 2015); (c) accumulation of atmospheric pollutants transported in the form of dust or gases (Plichta and Kuczyńska, 1991; Steinnes and Friedland, 2006; Rumam et al., 2013; Kozak et al., 2015); (d) biogenic accumulation (in the case of Spitsbergen, mainly related to birds). Each type of delivery is related to specific relationships among the elements. The dominant system of similarities arising from the elemental composition of the minerals that build bedrock and the relative mobility of individual elements can be modified when there is a significant supply or loss from other sources listed above. In the case of a comparison between the positions of Dunderdalen and Skilvika, significant differences in geomorphology of both objects should be noted—in the first case the slope, in the second, uplifted marine terrace. However, the material in which the designations were performed is peat, characterized by a permanent bonding of heavy metals, notwithstanding some environmental differences. Sampling along the slope profile enables the balancing of local (point) effects of erosion and accumulation processes. In addition, the relatively small distance between the positions allows the conclusion that the differences cannot be more the result of modern atmospheric input of pollutants (dusts and gases).

Results indicate the evident influence of the avian colony on heightened soil pollution concentration in the Dunderdalen region, though the influence is not the same for all cases of heavy metals. In the context of seabirds' influence, attention is especially drawn to the low correlation of most metals with individual forms of P—generally only Cu and Zn, and Cd to a smaller extent, correlate with P. The dependence of these elements on seabirds' influence was already indicated by researchers (Godzik, 1991; Brimble et al., 2009; Mallory et al., 2015). Seabirds' activity increases the amount of P in soils (Ziółek and Melke, 2014), so there is a clear impact of seabirds on the concentration of elements mentioned above.

Significantly lower concentrations of Pb in soil samples from Dunderdalen were determined, which excludes the influence of avian colonies on the content of this element in soil, what is also indicated by not significant correlation (Table 4). A similar observation was presented by Mallory et al. (2015) and was explained as a high natural content of lead. In the discussed case, probably the age of Skilvika peat (2040 ± 80 yr B.P., at a depth of 55 cm, Ziółek, not published) was of great importance, in connection with long-distant transport of pollutants in the past, presented in literature (Weiss et al., 1999; Liang and Mao, 2015).

The dendrite of similarity based on all analyzed environmental variables (Figs. 5, 6) depicts the relatively distinctive segregation of the research stations subjected to the pressure of seabirds and those without it. On the basis of test statistics (Table 2), it should be stated that parameters associated with macro-elements had a high input into dissimilarity, and there is an evident occurrence of organic matter as well. To verify to what extent the dissimilarity of both localizations is associated with heavy metals, an additional analysis was conducted, with the exclusion of the remaining features (Figs. 7, 8). The segregation, although less evident, is still clearly visible.

Conclusions

Studies show that the concentrations of Zn, Mn, Cu, and Cd in the organic soils of Spitsbergen are higher within the range of influence of seabird colonies. However, seabirds are not always the greatest vectors of heavy metals—for the concentrations of Pb, Cr, Co, and Ni, the influence of seabirds is not dominant; other factors are more relevant, for example, atmospheric pollution (current and historical) and geological substrate.

High correlation of certain heavy metal contents (Cu, Cd, and Zn) with various forms of P is a strong evidence for birds' influence. In the case of Co, Ni, Cr, and Pb, no significant correlation was observed.

Significant differences between the locations subjected to the influence of birds and those not influenced by seabirds were determined. Individual points show a clear dissimilarity, conditioned more or less equally by all analyzed parameters. Segregation of positions also remains clear, taking into account only heavy metal concentrations as variables determining the dissimilarity of two groups of soils.

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