Trace elements and polychlorinated biphenyls (PCBs) in terrestrial compartments of Svalbard, Norwegian Arctic

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HIGHLIGHTS

- Concentrations of Al, As, Cr, Cu, Fe, Pb and Ni were associated with the geology of the studied area.
- Concentrations of Cd and PCBs were influenced by atmospheric deposition.
- Concentrations of Cd and PCBs were significantly greater in vegetation than in underlying organic soils.

GRAPHICAL ABSTRACT
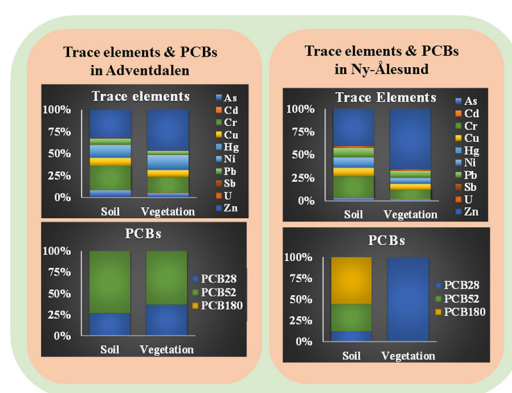
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ABSTRACT

Despite being a remote location, the Arctic is a major receptor for anthropogenic pollution transported from the mid-latitudes. Vegetation and underlying organic soils in the Norwegian Arctic, Svalbard were used to study the occurrences of polychlorinated biphenyls (PCBs) and trace elements. In this study, current concentrations of PCBs and trace elements, namely, Al, As, Cd, Cr, Cu, Fe, Hg, Mn, Ni, Pb, S, Sb, U and Zn in the terrestrial compartments of Svalbard are presented. Samples were collected from Adventdalen near Longyearbyen and from areas in proximity to Ny-Ålesund. There was significant variability in soil organic matter (SOM) among the soils analysed (5.0%–72.1%), with the highest values detected in Ny-Ålesund. The concentrations of Al, As, Cr Cu, Fe, Pb and Ni were associated with the geology of the local bedrock. The concentrations of all elements, except for Cd, Hg and Zn, were higher in soils than those in the overlying vegetation layers. Mean concentrations of $\sum$PCBs were significantly higher in vegetation (6.90 ± 0.81 ng g^{-1} dw) than the underlying organic soils (3.70 ± 0.36 ng g^{-1} dw). An inverse correlation of PCBs with the elements originating from the local bedrock indicated that their concentrations were potentially impacted by atmospheric deposition. PCBs and Cd were strongly associated, proposing a potential concomitant source of origin in Svalbard. Concentrations of PCBs and trace elements measured herein were below the proposed guidelines for Norwegian soil quality.

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1. Introduction

The Arctic is a pristine environment impacted by pollution, and therefore has become an area of great concern. Direct human activity in the Arctic is limited compared to the distant human activity occurring in temperate and industrial areas; nonetheless, the latter has significantly influenced the polar environment. Persistent organic pollutants (POPs) such as polychlorinated biphenyls (PCBs) and toxic elements are of great concern in the Arctic environment. PCBs and toxic elements have been detected in all compartments of the Arctic ecosystem and, among others, pose adverse health risks for the indigenous Arctic populations (AMAP, 2011; Kallenborn et al., 2013; Macdonald et al., 2005; Turetta et al., 2016; Brown et al., 2018).

Toxic elements occur naturally in all ecosystems; their concentrations vary based on the local geology (Halbach et al., 2017), while their release into the environment involves weathering of rocks, volcanic activities, forest fires, mining activities, non-ferrous metal industry, metal processing and recycling, fossil fuel combustion and waste incineration (AMAP, 1997; Tabelin et al., 2018). Mercury (Hg) has attracted significant scientific attention throughout the years, since it is accumulating in the Arctic food chain (AMAP, 2005; Jaeger et al., 2009; Ruus et al., 2015). On the contrary, concentrations of specific elements, including arsenic (As), cadmium (Cd), copper (Cu) and vanadium (V) have shown a decrease in the Arctic atmosphere (AMAP, 2005).

Emissions of Cd from natural sources are significant (AMAP, 1998, 2005; Nriagu, 1989); however, anthropogenic emissions are estimated to be two to three times higher than those from natural sources (AMAP, 2005; Tabelin et al., 2018). Cd is emitted from high-temperature sources in the form of aerosols with particle sizes in the submicron range (≤ 1 µm) (Allen et al., 2001; Dillner et al., 2005; Kuloglu and Tuncel, 2005; Milford and Davidson, 1985; Molnár et al., 1995; Pakkanen et al., 2001), and upon their entrance into the atmosphere, they follow air trajectories that can lead to the Arctic (AMAP, 2005). Transport of Cd in the atmosphere depends on several factors including, aerosol particle size, temperature, height of release (in the air column), wind speed and precipitation conditions (AMAP, 2005).

Polychlorinated biphenyls (PCBs) are ubiquitous environmental contaminants that do not readily breakdown in the environment (Jones and de Voogt, 1999). PCBs were widely used as flame retardants and dielectric fluids in transformers and capacitors in the past, but their production was banned in the late 1970s (Choi et al., 2008; Ockenden et al., 2003). Waste dumps, decommissioning sites and even older equipment containing PCBs could be serving as primary sources of contamination in Svalbard (Granberg et al., 2017; Kallenborn et al., 2013).

Even though several reports of new environmental pollutants and their decomposition products have been previously reported, PCBs account for more than half of the total pollutant loads in Svalbard for a number of living organisms (Kallenborn et al., 2013). A strong decline of PCBs levels was measured in Svalbard (in air and sediment matrices) from the mid-1990s to 2004 (AMAP, 2011; Carlsson et al., 2018; Evenset et al., 2007). However, this decline in PCBs concentrations did not remain consistent after 2004, since thereafter, an increase of PCBs concentrations was measured in the Svalbard atmosphere (AMAP, 2011; Hung et al., 2016; Kallenborn et al., 2013). In addition, with the ongoing climate change, the Arctic is expected to receive higher concentrations of PCBs in future (Carlsson et al., 2018; Wang et al., 2019). Long-range atmospheric transport to the Arctic from the Northern Hemisphere mid-latitudes (Hung et al., 2001, 2005, 2010) is estimated as the major source of PCBs in Svalbard (AMAP, 2011). PCBs travel through the atmosphere via a sequence of deposition and re-volatilization, also known as "the grasshopper effect" (Ockenden et al., 2003). Higher temperatures at lower latitudes favour volatilization of PCBs, while lower temperatures at higher latitudes favour deposition. Temperature therefore plays a key role in determining the behaviour of POPs in the environment, including emissions (primary and secondary emissions) and

degradation rates (Hansen et al., 2015; Lamon et al., 2009; Wöhrnschimmel et al., 2013).

To date, most of the reported studies have focused either on the distribution profile of organic (e.g., Eggen et al., 2008, 2011; Jartun et al., 2007, 2009a, 2009b, 2010; Ma et al., 2019; Zhang et al., 2014; Zhu et al., 2015) or inorganic (e.g., Halbach et al., 2017; Krajcarová et al., 2016; Singh et al., 2013; Steinnes and Jacobsen, 1994) pollutants in Arctic terrestrial compartments (such as soils and vegetation), while knowledge of the relationship between organic and inorganic pollutants for the Arctic ecosystem is scarce. This study addresses this challenge by simultaneously measuring the concentrations of both trace elements and PCBs in vegetation and underlying organic soils across a wide area of the Svalbard, Norwegian Arctic. The knowledge of naturally occurring background concentrations of organic and inorganic pollutants alongside with their distribution profile in permafrost-affected soils is a prerequisite for the evaluation of anthropogenic impacts in the Arctic ecosystem. The aim of this study was to provide current data on the background concentrations of trace elements (with a special focus on Cd) and PCBs in vegetation and underlaying organic soils from Svalbard. Our objectives were to: (1) identify possible pollution sources for Cd and PCBs leading to the current concentrations of those in Svalbard vegetation and soils; (2) investigate the associations of those to the soil organic matter (SOM); (3) examine spatial variation of concentrations; and 4) study relationship between trace elements and PCBs.

2. Material and methods

2.1. Study area

Sampling was performed in Spitsbergen, Svalbard in August 2016. Sampling sites were selected from two geologically different locations Adventdalen, Longyearbyen and in the proximity to Ny-Ålesund (Fig. 1). Svalbard is an archipelago located between 74° to 81° north latitude, and from 10° to 35° east longitude with a total landmass of 61,000 km² (Lydersen et al., 2010). Svalbard is favoured for the measurements of background levels of pollutants in the Arctic, as it is considered to be largely devoid of local sources (Jartun et al., 2009b). At present, Svalbard has a population of 2085 inhabitants, mainly situated in Longyearbyen, followed by the Russian settlement Barentsburg (Statistics Norway, 2019). Glaciers cover 60% of the landmass, while <10% has vegetation (Lydersen et al., 2010; Nilsen, 2018). The landscape of Svalbard is characterized by permafrost and tundra, and has poorly developed soils (Halbach et al., 2017).

Longyearbyen is the largest populated settlement and, its resident number can increase massively during tourist seasons (Statistics Norway, 2019). The northernmost settlement of Ny-Ålesund on the other hand is populated for research purposes only. Svalbard has a long history (of >100 years) of coal mining, but the only active mine today is Mine 7 in Longyearbyen (Evenset, 2013). Runoffs from mine 7 and other shut-down mines are characterized by high concentrations of toxic elements such as nickel (Ni), Cu and As (Granberg et al., 2017). Other possible sources of local pollution are solid waste and ash, mainly from the coal-fired power station, garbage disposal facilities, cruise ships, snowmobiles, and air and road traffic (Halbach et al., 2017; Lyche and Nedland, 2012). Samples were collected from Foxdalen, Jansondalen and Jansonhaugen areas in Adventdalen, located 20 to 25 km from Longyearbyen (Fig. 1). Overall, Foxdalen showed highest soil development, which spread along the riverbed. In Jansondalen, the ground was merely glacially influenced and lithoidal with a low soil development. Jansonhaugen sites had good soil development; samples were collected from the valley and had the highest chance to be impacted by local mining activities.

All sampling sites from Ny-Ålesund were in shore proximity. Samples were collected from Gåsebu and Bayelva located at the east side (~3 km from Ny-Ålesund) and Leinstranda located on the west coast of the Brøggerhalvøya (~10 km from Ny-Ålesund) (Fig. 1). Soils from
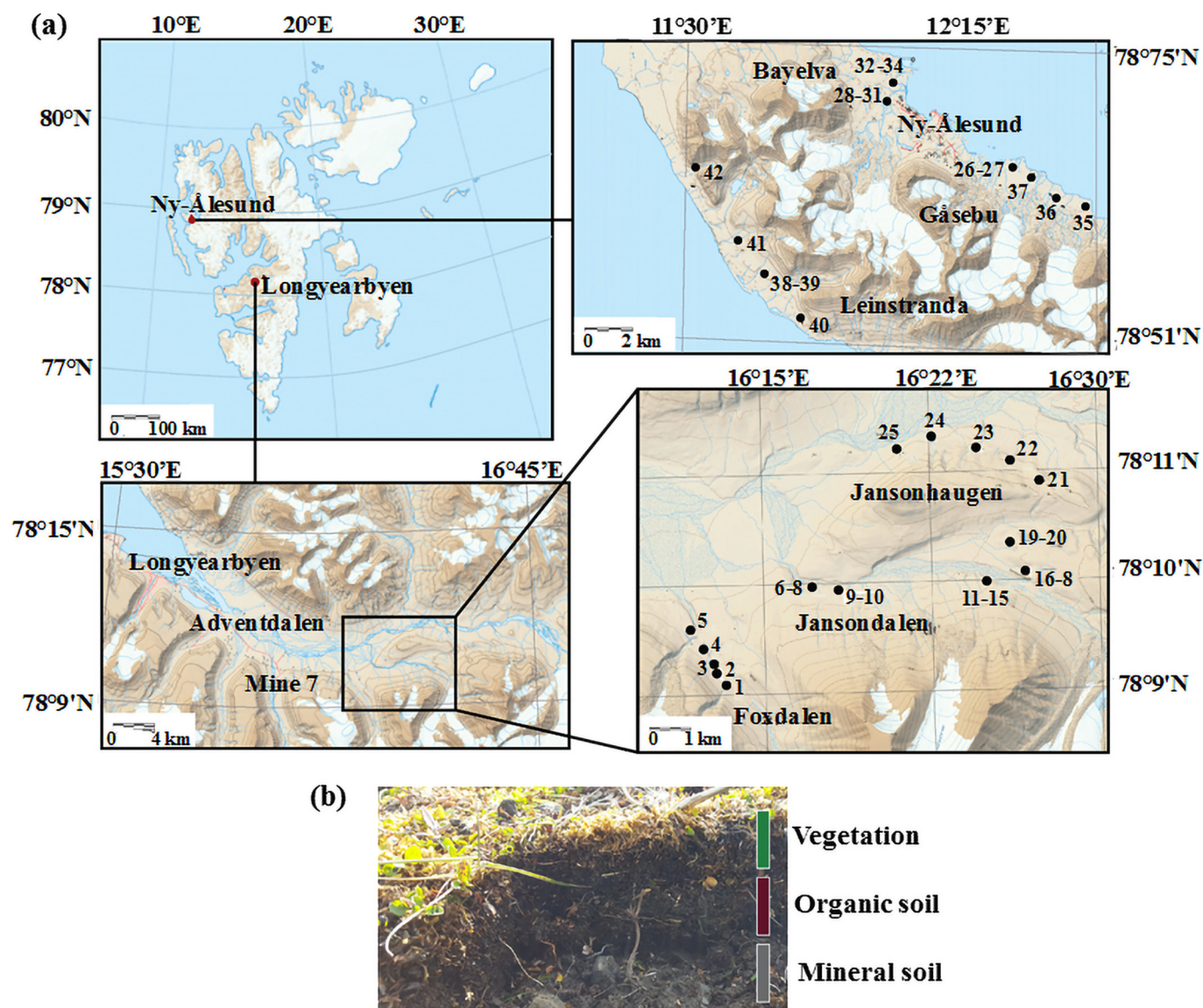
Fig. 1. (a) Maps of Svalbard (left) showing the sampling sites near Ny-Ålesund (top right) and Adventdalen (bottom right). (b) Profile of the top soil in Svalbard. Topographic map was used with the courtesy of the Norwegian Polar Institute. Sampling of inorganic soil layer (A) was not done in this study.

Ny-Ålesund were characterized by silty clay and sand gley soil with a thin organic soil cover. In general, soil development was more pronounced at the sampling sites in Adventdalen than in Ny-Ålesund.

2.2. Sample collection

Sample locations were selected at least >100 m away from the seashore, based on the remoteness from local anthropogenic pollution sources, the full coverage of surface soil with vegetation and the state of the soil layer development. For each site, two samples were collected within a radius of ~10 m. A total of 63 and 46 samples were collected from Adventdalen (41 soil and 22 vegetation samples), and in proximity of Ny-Ålesund (33 soil and 13 vegetation samples), respectively (Supp. Table A.1). Soil samples were collected by cutting squares with an area of 18 × 18 cm and ~5 cm deep (thickness) in the soil together with the vegetation cover using a normal stainless-steel bread knife. The thickness of the vegetation layer varied from 0.5 to 3 cm; while the organic soil layer varied from 0 to 3 cm. The main appearing vegetation type was moss: generally, an accumulation of several old moss layers over each other, with some root fibre content. Samples were kept intact (without removing the vegetation) after collection. In order to reduce

the risk of post-collection contamination, samples were sealed with layers of aluminium foil (at least three layers) and were stored in paper bags immediately after collection. Samples were transported to the lab at ambient temperature.

A small hole was pierced in one corner of the aluminium foil wrapping of the samples for air exchange, and samples were air dried for 3 days. To avoid any possible contamination from air, ~0.5 cm of soil matter was removed from each side, and then the vegetation layer was sliced carefully. Samples that showed presence of moisture (mainly from Ny-Ålesund) were freeze-dried (Alpha 1–2 LDplus - Martin Christ). Dried samples were then homogenised in a Retsch mill SM100 with a 3 mm sieve. All samples were stored at −25 °C until further analysis was performed.

2.3. Measurement of soil organic matter (SOM)

SOM contents were determined by loss on ignition (LOI) as described by Halbach et al. (2017). Briefly, samples (3–4 g) were dried (in pre-weighed crucibles) at 105 °C overnight and were then combusted in a muffle furnace (L3/12, Nabertherm, Germany) at 500

°C for 3 h. Organic contents could not be measured in the vegetation layer due to the limited amount of material.

2.4. Elemental analysis

Prior to ICP-MS analysis, soil samples were mineralised with nitric acid (50% v/v) using UltraCLAVE (Milestone) as described by Halbach et al. (2017).

Elemental composition was determined by ICP MS using a Thermo Scientific ELEMENT 2 high resolution ICP-MS instrument. A calibration curve consisting of five different concentrations was made from multi-element standards. Method detection limits for the studied elements are given in Supp. Table A.2. Accuracy and reproducibility were ensured by measuring replicates of certified calibration solutions, and the frequent analysis of the customised reference soil material GBW 07408 (GSS-8) (Chinese National Center for Standard Materials).

2.5. PCBs analysis

PCBs concentrations were determined by SINTEF Molab, Oslo Norway in accordance to the method D00835, which is approved by the Norwegian Accreditation system (NS-EN ISO / IEC 1725). Samples were analysed for the presence of 7 PCBs congeners (IUPAC numbers 28, 52, 101, 118, 138, 153 and 180). Briefly, homogenised samples (20-30 g) were extracted twice with a mixture of methanol:mili-Q water:dicholoromethane (1:1:2, v/v; 40 mL) using sonication (15 min per cycle) followed by shaking (1 h in first cycle and 30 min in second cycle). Internal standards (1 μg of PCB30 and PCB204) were added to each sample prior to extraction to measure the recovery efficiency of the entire procedure. Organic phase was separated and was acidified (pH 2) with diluted H_2SO_4 (aq.). Extracts were combined and were dried with anhydrous Na_2SO_4. Samples were concentrated under a gentle stream of nitrogen at 45 °C (TurboVap II, Zymark, Hopkinton, USA), followed by SPE (Isolute SI, Biotage, Uppsala, Sweden) clean up using hexane. The hexane eluent was concentrated again under a gentle stream of nitrogen at 45 °C (Pierce Reacti-Term Pierce, Rockford, IL, USA). Separation of compounds was performed by GCMS (Clarius 600, Perkin Elmer) equipped with a DB-5 column (30 m × 0.25 mm id with 0.25 μm film thickness, Agilent Technologies). The temperature programming was as follows: 60 °C held for 1 min., then 60–180 °C (25 °C min.$^{-1}$) and finally 180–280 °C (15 °C min.$^{-1}$) for 15 min. Accuracy and reproducibility were ensured by frequent analysis of the reference sediment material CNS329 (Resource Technology Corporation of Laramie, USA). Recoveries of individual compounds ranged from 88% to 122% and were 103% for $\sum_7$PCBs.

2.6. Data and statistical analysis

Normality and homogeneity of variances were tested with Shapiro-Wilk and Levene's tests, respectively. Mann–Whitney U test was performed to test significant differences in PCBs and elemental concentrations in between sample types (soils and vegetation) and sampling locations (Ny-Ålesund and Adventdalen). Analysis of variance (Kruskal-Wallis test adjusted using the Bonferroni correction for pairwise comparison) was used for evaluating the significant differences of PCBs and elemental concentrations in soil and vegetation samples collected from different sampling locations (Ny-Ålesund and Adventdalen). The coefficient of variation (CV) was used to show the extent of variability in relation to the mean of elemental concentrations and SOM. Spearman's correlation was used to investigate relationships between different variables. Similarities among different elemental concentrations in the terrestrial compartments of Svalbard were explored with Factor Analysis (FA). The extraction of factors was done through principal component analysis (PCA) and rotation using the Varimax

method (Schaug et al., 1990). Statistical analysis for comparison of different variables and FA were performed with SPSS® V25 (IBM Corp., Armonk, NY, USA).

The elemental profile of soil and vegetation in the Svalbard sampling locations (Ny-Ålesund and Adventdalen) were explored with PCA based on Spearman's correlation matrix. The association of PCBs with trace elements in terrestrial compartments of Svalbard was investigated using hierarchical clustering based on Spearman's correlation matrix. PCA and hierarchical cluster analysis was performed with XLStat software (Addinsoft 2018, Paris). All statistically significant differences quoted were at $p < 0.05$. Standard error (SE) is presented as a measure of variability for all samples.

3. Results and discussion

Vegetation and underlying organic soils were used to identify contributions of PCBs and trace elements to the terrestrial compartments of the Arctic ecosystem. Arctic soils are generally characterized by low SOM due to the low degree of vegetation (Drew and Tedrov, 1962), permafrost and climate influences (Halbach et al., 2017). Overall, SOM content showed high spatial variability (5.0% to 72.1%) among all investigated samples (Fig. 2, Table 1). Levels of SOM content were generally related to the soil features; soil samples collected from the sites with pronounced soil development and full vegetation cover had high SOM content (Table 1). Overall, SOM contents were higher in Ny-Ålesund (26.9% ± 3.1; 67.3% CV) compared to Adventdalen (19.6% ± 1.5; 47.7% CV) soils; however, the differences were not statistically significant. The organic content measured in this study was in agreement with the findings of Halbach et al. (2017), where SOM was reported in similar ranges (22–84%) for Svalbard surface soils. However, SOM contents were lower than the levels reported for natural surface soils from the Norwegian mainland (Nygård et al., 2012).

3.1. Elemental profile in Svalbard vegetation and underlying organic soils

The mean concentrations of trace elements were present in the decreasing order of Mn > Zn > Cr > Ni > Cu > Pb > As > U > Cd > Hg > Sb in both soil and vegetation samples (Fig. 2, Table 2). For most of the elements studied, the differences in elemental concentrations between the sample types were significant (Fig. 2). In general, the concentration of most elements (Al, As, Cr, Cu, Fe, Pb, Sb and U) were significantly ($p < 0.05$) higher (≥ 2 fold) in soil samples than in overlaying vegetation (Fig. 2). Elemental concentrations measured in this study were consistent with those reported earlier for soils (Allen-Gil et al., 2003; Hao et al., 2013; Halbach et al., 2017) and vegetation (Singh et al., 2013; Wojtuń et al., 2013) in the Arctic region.

Several studies conducted in mainland Norway have reported elemental distribution profiles in surface organic soils (e.g., Låg and Steinnes, 1978a, 1978b; Nygård et al., 2012; Steinnes and Andersson, 1991; Steinnes and Lierhagen, 2018). Concentrations of Zn and Cu presented herein were comparable to those reported for soils from mainland Norway. In contrast, As, Cr and Ni concentrations were higher in Svalbard soils. Higher concentrations of these elements in the studied areas can be attributed to both local pollution sources and natural geological conditions (Halbach et al., 2017). Mean values of elements known to be associated with long-range transportation, such as Sb and Pb (Steinnes and Friedland, 2006; Steinnes et al., 2016), were lower than those reported for the corresponding Norwegian mainland soils.

Ny-Ålesund is a remote area and is devoid of local activities; therefore, the area around Ny-Ålesund is often used for background pollution measurements. Elemental concentrations measured in the soils from Ny-Ålesund were compared with the samples from Adventdalen to assess the current pollution pressures in this area (Table 2, Supp. Table A.3). Soils from Adventdalen were characterized by higher ($p < 0.05$) concentrations (≥ 2 fold in both soil and
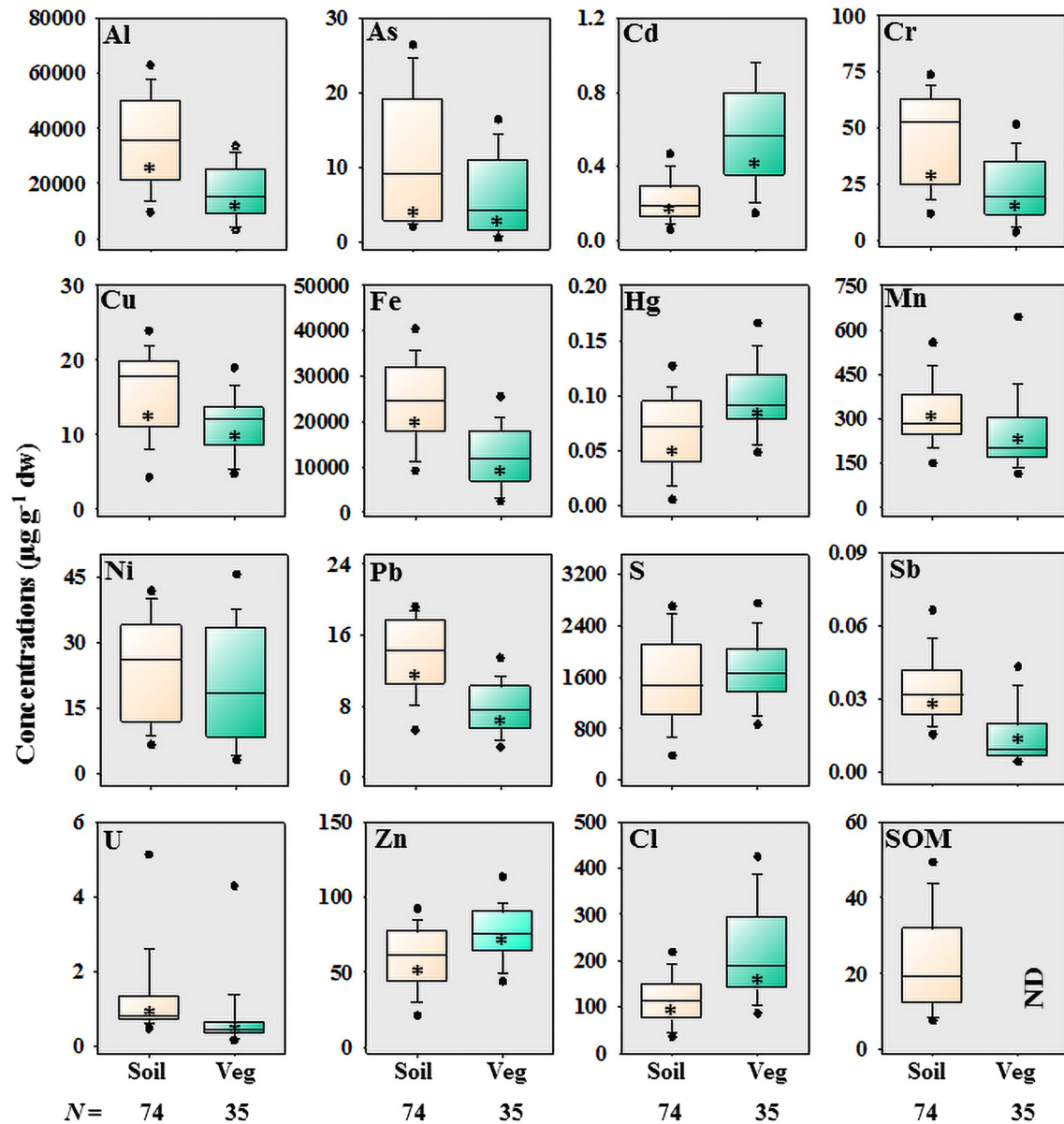
Fig. 2. Concentrations (µg g^{-1} dw) of elements in vegetation (Veg) and underlying organic soil (Soil) layers. Boxes: median and 25/75 percentiles; bars: minima and maxima. Asterisk (*) symbols represent the significance differences ($p < 0.05$) between concentrations in soil and vegetation. N represent number of samples for each sample type used for analysis, whereas ND represent not determined.

vegetation) of most of elements (Al, As, Cr, Cu, Fe, Hg, Ni and S) except from Cd, Mn, Pb, Zn and Sb than those from Ny-Ålesund (Table 2). In contrast, concentration of U was significantly greater ($p < 0.05$) in soils and vegetation from Ny-Ålesund (Table 2). Distribution profiles of elements between soil and vegetation were similar for both sampling locations (Fig. 3). PCA was performed to compare samples collected from Ny-Ålesund and Adventdalen (Supp. Fig. A.1). Samples from the Adventdalen site separated from those of Ny-Ålesund due to the higher concentrations of Mn, Hg, Z, S, Zn, Cu, Ni, Pb, Cr, Al and Fe (Supp. Fig. A.1). The elevated elemental concentrations at Adventdalen potentially been driven by local activities (inputs from air and marine traffic, coal mining, coal combustion). Moreover, ~1054 tons of waste were deposited on the landfill close to Gruve 6 (Mine 6) in Adventdalen, Longyearbyen during 2008–2010 (Lyche and Nedland, 2012), and consequently, waste leaching from the landfill can be contributing to the elemental concentrations in this area (Kallenborn et al., 2013; Lyche and

Nedland, 2012; Ottesen et al., 2010). Concentrations of all elements measured herein were below the reported guidelines for Norwegian soil quality (Hansen and Danielsberg, 2009); hence, these concentrations can be characterized as background pollution concentrations in Svalbard.

In order to identify sources of elemental origin in different environmental compartments, Factor Analysis has been used previously (Halbach et al., 2017; Nygård et al., 2012; Schaug et al., 1990; Steinnes and Lierhagen, 2018). A similar approach was used here to pinpoint the sources of trace elements in the terrestrial compartments of Svalbard (Table 3). Four extracted factors are shown in Table 3 and only loadings greater than −0.5 and 0.5 are shown herein. Factor 1 (F1) revealed a strong association between six trace elements, namely, Al, As, Cr, Cu, Fe and Ni in organic surface soils, indicating a common source of origin, potentially reflecting the influence of geology of the studied area. These findings are in good agreement with Halbach et al. (2017), where concentrations

Table 1
General profile of sampling sites (mean ± SE). Significant differences ($p < 0.05$) among sampling sites are shown by different letter codes (there is no significant difference between data with same letter code). Numbers of samples are given within parentheses.

General parameters	Adventdalen			Ny-Ålesund		
	Foxdalen	Jansondalen	Jansonhaugen	Gasebu	Bayelva	Leinstranda
Air temp (°C)	8.1 ± 0.3[ab] (6)	8.7 ± 0.3[ab] (3)	10.3 ± 0.8[ab] (14)	7.8 ± 0.3[a] (8)	7.9 ± 0.26[a] (13)	9.8 ± 0.3[b] (8)
Soil temp (°C)	5.8 ± 0.2[ab] (6)	6.3 ± 0.3[ab] (3)	7.1 ± 0.2[a] (14)	5.6 ± 0.2[b] (8)	6.0 ± 0.2[b] (13)	6.5 ± 0.8[ab] (8)
Soil thickness (cm)	2.5 ± 0.4[ab] (6)	2.4 ± 0.32[ab] (15)	3.2 ± 0.38[a] (20)	2.9 ± 0.18[ab] (10)	1.68 ± 0.2[b] (12)	3.35 ± 0.3[a] (10)
Vegetation thickness (cm)	2.0 ± 0.5[a] (4)	1.3 ± 0.2[a] (9)	1.39 ± 0.2[a] (9)	1.8 ± 0.2[a] (5)	1.7 ± 0.3[a] (6)	1.2 ± 0.3[a] (2)
SOM (%)	31.2 ± 3.4[ab] (6)	16.7 ± 2.1[a] (15)	18.3 ± 1.8[a] (20)	23.6 ± 5.3[ab] (10)	33.2 ± 2.2[b] (13)	21.8 ± 8.3[a] (10)

of Al, As, Cr Cu, Fe and Ni in Svalbard soils were indicated as influenced by mineral soils and bedrock. Further evidence of association of these elements with local bedrock comes from the inverse correlation of these elements with SOM ($\rho = 0.371$, 0.403, 0.325, 0.422 and 0.319 at $p < 0.01$ for Al, As, Cr, Fe and Pb respectively). In contrast to the findings of Halbach et al. (2017), a strong association of Pb with elements of geogenic origin (Al, As, Cr Cu, Fe and Ni) was observed here, indicating a significant input from the geology of the studied area on the concentration of Pb in Svalbard terrestrial compartments rather than from long-range atmospheric transport.

Factor 2 (F2) suggested a different source of origin, other than geological material for Cd, Hg, and Zn. It is most likely that atmospheric deposition is leading to the accumulation of these elements in terrestrial compartments of Svalbard. Further evidence of atmospheric deposition of these elements stems from significantly higher concentrations ($p < 0.01$) of Cd, Hg and Zn in vegetation layers than in underlying organic soils (Fig. 2). It is important to note that the vegetation layer studied here comprised mainly mosses, and mosses absorb chemicals efficiently from the atmosphere due to lack of root system (Rühling and Tyler, 1971; Steinnes et al., 1994, 2016). A number of nationwide surveys conducted in Norway have also proposed atmospheric deposition for the enrichment of these elements (Cd, Hg and Zn) in mosses (Berg et al.,

1995; Berg and Steinnes, 1997; Christensen et al., 2018; Nickel et al., 2015; Schaug et al., 1990; Steinnes et al., 1992, 1994, 2016). A linear relationship between wet deposition rate and concentrations in moss has been reported previously for Cd, Hg and Zn (Berg et al., 1995; Berg and Steinnes, 1997).

3.2. Cd in the terrestrial compartments of Svalbard

Unlike most of the elements studied here, Cd did not show spatial variability, and concentrations were similar for both studied locations (Table 2); therefore, current concentrations of Cd in Svalbard soils are not shown to be influenced by local activities.

Cd enrichment in organic surface soils has been reported in the Arctic (Allen-Gil et al., 2003; Halbach et al., 2017; Krajcarová et al., 2016; Marquès et al., 2017), Norway (Steinnes and Lierhagen, 2018) and other European countries (Heinrichs and Maye, 1980; Saur and Juste, 1994). Cd concentrations ranged from 0.03 to 2.16 µg g^{-1} dw (mean concentration 0.34 ± 0.03 µg g^{-1} dw in soils) in this study and were found in the same order of magnitude as previously reported for Svalbard soils (Gulińska et al., 2003; Hao et al., 2013; Halbach et al., 2017; Marquès et al., 2017; Wojtuń et al., 2013). However, Cd concentrations were higher compared to the background level (0.17 µg g^{-1} dw)

Table 2
Concentrations (µg g^{-1} dw, mean ± SE), minimum (Min), maximum (Max) and coefficient of variation (%CV) of elements in vegetation and underlying organic soils collected from Adventdalen and Ny-Ålesund. Significant differences ($p < 0.05$) between samples from sampling locations are shown by different letter codes (there is no significant difference between data with same letter code). Number of samples (N) is given within parentheses underneath the location name.

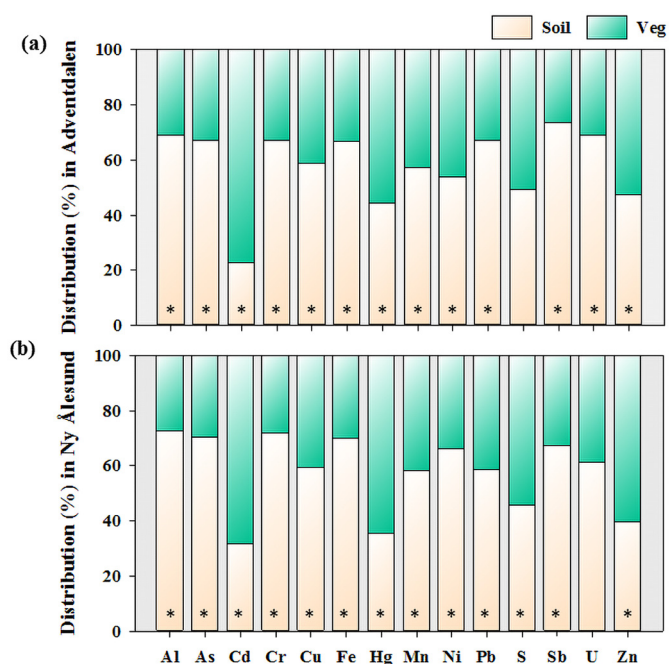| Elements		Vegetation		Organic soils	
		Adventdalen (N = 41)	Ny-Ålesund (N = 33)	Adventdalen (N = 22)	Ny-Ålesund (N = 13)
Aluminium (Al)	Mean ± SE	21,666.47 ± 1896.37[b]	7896.18 ± 1140.13[c]	47,715.81 ± 1607.84[a]	20,895.47 ± 1632.63[b]
	Min – Max (%CV)	4119.00–34,753.53 (41.1)	1868.79–16,049.26 (52.1)	27,631.92–68,509.33 (21.6)	5029.48–46,976.43 (44.9)
Arsenic (As)	Mean ± SE	8.89 ± 1.00[c]	1.36 ± 0.21[b]	18.03 ± 0.94[a]	3.22 ± 0.24[b]
	Min – Max (%CV)	1.71–17.66 (52.7)	0.32–3.26 (54.6)	7.50–28.39 (33.2)	1.95–6.99 (42.4)
Cadmium (Cd)	Mean ± SE	0.63 ± 0.09[b]	0.54 ± 0.06[b]	0.18 ± 0.02[a]	0.25 ± 0.03[a]
	Min – Max (%CV)	0.15–2.16 (69.9)	0.13–0.96 (43.0)	0.03–0.54 (52.2)	0.005–0.59 (57.6)
Chromium (Cr)	Mean ± SE	30.19 ± 2.66[b]	10.59 ± 1.43[c]	61.58 ± 1.44[a]	26.70 ± 1.99[b]
	Min – Max (%CV)	6.88–52.38 (41.3)	2.79–19.29 (48.6)	40.50–81.36 (15.0)	9.00–54.82 (42.8)
Copper (Cu)	Mean ± SE	14.06 ± 0.63[b]	7.30 ± 0.61[c]	19.91 ± 0.35[a]	10.54 ± 0.74[bc]
	Min – Max (%CV)	9.63–23.06 (21.0)	4.73–11.64 (30.3)	16.24–26.36 (11.1)	3.03–22.62 (40.2)
Iron (Fe)	Mean ± SE	15,301.65 ± 1302.19[b]	6742.5 ± 981.7[c]	30,520.59 ± 950.49[a]	15,664.58 ± 1064.08[b]
	Min – Max (%CV)	3226.08–27,846.66 (39.9)	1619.3–12,460.7 (52.5)	19,482.74–46,292.62 (19.9)	3322.32–33,021.46 (39.0)
Mercury (Hg)	Mean ± SE	0.11 ± 0.01[c]	0.08 ± 0.01[ab]	0.091 ± 0.003[ac]	0.04 ± 0.01[b]
	Min – Max (%CV)	0.06–0.21 (30.0)	0.05–0.12 (26.3)	0.05–0.15 (24.3)	0.02–0.13 (75.1)
Manganese (Mn)	Mean ± SE	277.26 ± 31.52[b]	200.27 ± 23.50[b]	367.36 ± 29.58[a]	275.93 ± 13.13[ab]
	Min – Max (%CV)	115.64–698.58 (53.3)	78.29–366.68 (42.3)	96.19–1254.31 (51.6)	148.97–496.22 (27.3)
Nickel (Ni)	Mean ± SE	28.85 ± 2.54[a]	6.46 ± 0.71[b]	33.44 ± 0.92[a]	12.52 ± 0.85[b]
	Min – Max (%CV)	11.59–66.94 (41.4)	2.78–10.4 (39.6)	22.68–43.72 (17.7)	4.90–24.65 (39.0)
Lead (Pb)	Mean ± SE	7.68 ± 0.54[c]	8.37 ± 1.09[bc]	15.46 ± 0.46[a]	11.84 ± 0.89[b]
	Min – Max (%CV)	3.38–12.16 (33.2)	3.33–18.59 (47.2)	8.80–19.31 (19.0)	3.84–25.77 (43.0)
Sulfur (S)	Mean ± SE	1955.11 ± 101.73[a]	1322.63 ± 104.40[b]	1885.98 ± 97.32[a]	1111.03 ± 107.18[b]
	Min – Max (%CV)	1052.38–3311.44 (24.4)	741.72–2133.17 (28.5)	814.87–3947.81 (33.0)	141.02–2698.72 (55.4)
Antimony (Sb)	Mean ± SE	0.010 ± 0.002[b]	0.020 ± 0.003[a]	0.040 ± 0.002[a]	0.040 ± 0.004[a]
	Min – Max (%CV)	0.00–0.06 (98.3)	0.004–0.04 (63.4)	0.01–0.08 (38.2)	0.01–0.12 (69.2)
Uranium (U)	Mean ± SE	0.37 ± 0.03[c]	1.52 ± 0.63[ab]	0.83 ± 0.09[a]	2.38 ± 0.57[b]
	Min – Max (%CV)	0.17–0.76 (38.9)	0.13–8.60 (149.0)	0.49–4.42 (71.0)	0.25–15.81 (136.6)
Zinc (Zn)	Mean ± SE	79.80 ± 3.99[a]	69.86 ± 5.20[a]	71.83 ± 1.82[a]	45.70 ± 3.68[b]
	Min – Max (%CV)	46.57–125.47 (23.4)	33.76–96.66 (26.9)	51.51–99.14 (16.3)	11.62–95.55 (46.3)

Fig. 3. Relative distribution of elements between vegetation (green) and underlying organic soils (light yellow) in Ny-Ålesund and Adventdalen. Asterisk (*) symbols represent the significance differences ($p < 0.05$) between concentrations in soil and vegetation. Number of samples (N) for soil = 6, 15, 20, 10, 13, 10 and vegetation = 4, 9, 9, 5, 6, 2 for Foxdalen, Janssondalen, Jansonhaugen, Gasebu, Bayelva and Leinstranda, respectively.

previously suggested for organic surface soils, which were collected from north of the Arctic circle (Andersson et al., 1991), and Greenland soils (0.04–0.10 µg g^{-1} dw) (AMAP, 2005).

Nationwide Norwegian moss and soil surveys have shown a gradient of Cd concentration in organic surface soils from south to north (Berg and Steinnes, 1997; Christensen et al., 2018; Nygård et al., 2012; Steinnes et al., 2016; Steinnes and Lierhagen, 2018). The magnitude of Cd concentrations reported herein are comparable to, or to some extent lower than those reported for the organic surface soils of mainland Norway (Nygård et al., 2012; Steinnes and Lierhagen, 2018). Geographical distribution of Cd is strongly related to atmospheric deposition in natural soils in mainland Norway (Nickel et al., 2015; Nygård et al., 2012; Steinnes et al., 1997; Steinnes and Lierhagen, 2018) and the Arctic region (AMAP, 2005). Therefore, also herein a strong association of Cd with SOM ($\rho = 0.652$ at $p < 0.01$), and the inverse correlation with

Table 3
Rotated component matrix for Svalbard samples.

	F1	F2	F3	F4
Al	0.980			
As	0.925			
Cd		0.764		
Cr	0.981			
Cu	0.922			
Fe	0.959			
Hg		0.781		
Mn				0.749
Ni	0.831			
Pb	0.798			
S		0.551		−0.597
Sb			0.725	
U			0.792	
Zn		0.588		
Cl		0.793		
Variance explained	45.0	19.2	8.8	7.8

Extraction Method: Principal Component Analysis. Rotation Method: Varimax with Kaiser Normalization. Rotation converged in 8 iterations.
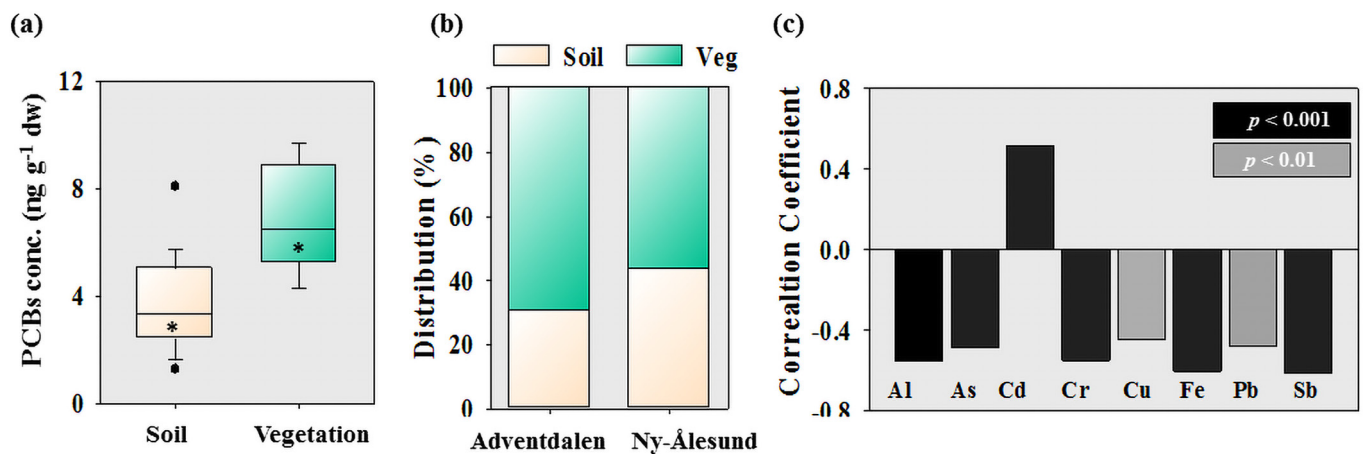
soil thickness ($\rho = -0.494$ at $p < 0.01$) along with significantly higher accumulation of Cd in vegetation strongly indicates atmospheric deposition of Cd in the studied area.

3.3. PCBs profile in Svalbard vegetation and underlying organic soils

There is no evidence of any recent emission of PCBs from any local source in Svalbard; nonetheless, landfill sites that are in use or shut down are potential sources. Outdoor paint used in Barentsburg, Colesbukta, Grumant, Isfjord Radio and Longyearbyen was reported as a primary source of local pollution in Svalbard (Jartun et al., 2010). In addition, de novo production of PCBs from thermal processes has been reported previously (Schoonenboom et al., 1995; Ishikawa et al., 2007), hence the coal power stations (in Longyearbyen and Barentsburg) and other combustion facilities could be a potential source of PCBs emissions in Svalbard. Previous studies have reported a strong correlation between SOM and PCBs (Meijer et al., 2002, 2003; Zhang et al., 2014); however, no relationship was observed between PCBs and SOM in this study.

The concentrations of $\sum$PCBs ranged from 1.3 to 8.1 ng g^{-1} dw in soils (Fig. 4a, Supp. Table A.4). PCBs levels in mainland Norway soils are reported with max. of 17.5 and 9.5 ng g^{-1} dw for south and north Norway, respectively (Lead et al., 1996). Earlier studies have reported high concentrations of PCBs in Svalbard soils than mainland Norway (Kallenborn et al., 2013); while in this study, PCBs concentrations were on the same order of magnitude as those reported for north Norwegian soils. Several studies have measured PCBs concentrations in Svalbard soils and reported varying PCBs concentrations from different settlements of Svalbard (Table 4). The highest levels of PCBs (up to 28,700 ng g^{-1}) were reported from Barentsburg (Jartun et al., 2010). On the contrary, levels as low as <1 ng g^{-1} were reported for several settlements including Longyearbyen and Ny-Ålesund (Breedveld, 2000; Harris, 2008; Schlabach and Steinnes, 1999a, 1999b). Mean concentrations of $\sum$PCBs measured herein are consistent with the recently published reports for the same region (Zhang et al., 2014; Zhu et al., 2015), high Arctic (Cabrerizo et al., 2018) and the background levels (1–5 ng g^{-1} dw) reported for Svalbard soil (Kallenborn et al., 2013). Mean concentrations of $\sum$PCBs presented here were significantly lower than those reported by Jartun et al. (2010) for Longyearbyen and Ny-Ålesund, where soils samples were collected during 2007–2009 from contaminated sites.

The mean concentrations of $\sum$PCBs ranged from 4.30 to 9.70 ng g^{-1} dw in vegetation (Fig. 4a, Supp. Table A.4). Higher concentrations of PCBs (in the range of 6.1 to 52 ng g^{-1} dw) were previously reported in vegetation collected from remote areas of Norway between 1977 and 1990 (Lead et al., 1996). However, mean concentrations of $\sum$PCBs for vegetation (6.90 ± 0.81 ng g^{-1} dw) presented herein are an order of magnitude greater than those reported in a recently published nationwide moss-based survey conducted in Norway (Schlabach et al., 2016), indicating higher concentrations of PCBs in Svalbard environment than in mainland Norway. PCBs concentrations were in the same range as recently reported (Σ_{70}PCBs ranging from 0.19 to 4.82 ng g^{-1} dw) for vegetation from the high Arctic (Cabrerizo et al., 2018). PCBs concentrations measured in this study are below the reported guidelines for Norwegian soil quality (recommended Σ_{7}PCBs < 10 ng g^{-1} dw) (Hansen and Danielsberg, 2009), and therefore display solely background pollution.

A wide variety of PCBs congeners (> 80 congeners) have been previously detected from Svalbard soils, demonstrating a wide variation among the concentrations of the congeners (Breedveld, 2000; Harris, 2008; Jartun et al., 2010; Kallenborn et al., 2013; Schlabach and Steinnes, 1999a, 1999b; Zhang et al., 2014; Zhu et al., 2015). Out of seven studied PCBs congeners (PCB28, 52, 101, 118, 138, 153 and 180) the presence of three (PCB28, 52 and 180) was confirmed in soils, while only two of them (PCB52 and PCB180) were confirmed in vegetation (Table 5).

Fig. 4. (a) Concentrations (ng g^{-1} dw) of polychlorinated biphenyls ($\sum$PCB) in vegetation and underlying organic soils. Boxes: median and 25/75 percentiles; bars: minima and maxima. (b) Relative distribution of $\sum$PCBs between vegetation and underlying organic soils in Ny-Ålesund and Adventdalen. (c) Spearman correlation coefficients (ρ) between concentrations of $\sum$PCBs and trace elements ($N = 25$).

The presence of PCB28 in Svalbard (Ny-Ålesund) is influenced by emissions mainly from Western Russia and to some extent from Scandinavia and Eastern Europe (Ubl et al., 2012). High concentrations of PCB28, even greater than those in mainland Norway and other Svalbard areas have been detected in Ny-Ålesund (Ubl et al., 2012). However, in this study PCB28 was the least abundant congener compared to the others (Table 5, Supp. Table A.4). PCB28 is principally transported in the gas phase from mid latitude to the Arctic areas and can remain in a gaseous phase in the climatic conditions that prevail in Svalbard (Kallenborn et al., 2013). Consequently, concentrations of PCB28 are generally higher in the Svalbard atmosphere during the summer when air arrives mainly from the oceans compared to the winter season, when air arrives mainly from the continents (Ubl et al., 2017). PCB28 is highly correlated with temperature (Eckhardt et al., 2007), which may indicate re-volatilization of PCB28 from the surface into the atmosphere when temperatures are high (Wania et al., 1998). Hence, at the time of sampling PCB28 was potentially present in the gaseous form (since sampling was conducted during summer). Given that PCB28 is semi-volatile, future studies on soil–air flux are needed.

PCB52 was the major and most abundant congener at the Adventdalen area, accounting for 66% to 100% ΣPCBs concentrations and it was detected in almost all samples (except from the vegetation layer from Foxdalen) (Table 5, Supp. Table A.4). Concentrations of PCB52 ranged from <1 to 9.70 ng g^{-1} dw, and were comparable with previously reported concentrations of this congener (<10 ng g^{-1} dw) in Svalbard soils (Kallenborn et al., 2013 and references cited therein). PCB52 is generally present in most of commercial PCBs formulations (Ivanov and Sandell, 1992; Frame et al., 1996), and has been reported as a dominating congener in Svalbard's atmosphere (Eckhardt et al., 2007). Low to medium chlorinated congeners are generally enriched in the Arctic atmosphere and terrestrial compartments compared to mid-latitudes (Carlsson et al., 2018). It is anticipated that with ongoing climate change, the concentration of lighter PCBs congener such as PCB52 will increase in the Arctic due to re-emissions of previously deposited PCBs from the oceans and ice (Hung et al., 2016). Recently Bartlett et al. (2019) found PCB52 as one of the dominating congeners in Svalbard snow samples and documented that its flux increased by 80% in snow samples compared to previous years. Another source of PC52 enrichment in Adventdalen area can be the microbial degradation of heavier PCBs as shown earlier in a study where the enrichment of PCB52 was observed from the dechlorination pathways of Aroclor 1260 (Fagervold et al., 2007).

The concentration of PCB180 has shown a declining trend after 2007 in Svalbard's atmosphere (Hung et al., 2016). Zhang et al.

(2014) has reported the presence of *hepta*-chloro PCBs in Ny-Ålesund air and soil. Concentrations of PCB180 < 1 ng g^{-1} dw were detected by Schlabach and Steinnes (1999a) in Svalbard soils, whereas concentrations as high as 100 ng g^{-1} dw were previously reported in a Svalbard survey report (Kallenborn et al., 2013). Concentrations of PCB180 were below the detection limit (< 1 ng g^{-1}) in soil and vegetation samples collected from the Adventdalen area and were detected only in Ny-Ålesund soils (Table 5, Supp. Table A.4).

Atmospheric deposition (both wet and dry deposition) is the dominant process for the input of PCBs into the terrestrial Arctic environments (Carlsson et al., 2018; Garmash et al., 2013; Kallenborn et al., 2007). In case of atmospheric transportation, deposition is generally uniform across a large geographic area. Similar trends were found in this study, as values of mean concentrations of ΣPCBs were similar for Ny-Ålesund (5.40 ng g^{-1} dw) and Adventdalen (4.30 ng g^{-1} dw). Average concentrations of ΣPCBs in vegetation were ~2 fold higher ($p < 0.01$) than in underlying organic soils (Fig. 4, Table 5), indicating that PCBs in the vegetation samples resulted from aerosol deposition or ice/snow melting on the surface of the vegetation layer, rather than being absorbed from soil. In contrast to PCB28 (found only in the vegetation layers) and PCB52 (found 2 fold greater in vegetation than corresponding soils), PCB180 was not detected in vegetation samples, indicating that this congener was potentially not being atmospherically deposited to Ny-Ålesund.

For substances transported to the Arctic environment by long-range transport, previous studies have reported an inverse relationship between latitudes and concentrations (Meijer et al., 2002, 2003); however, no such relationship was observed in this study. The assessed area herein was potentially not large enough to observe this relationship; therefore, a study area with broader latitude scale should be considered for future studies. PCBs can make their way to the Arctic in pathways other than long-range transportation, for example marine transport, which generally accounts for 30% total transportation of PCBs to the Arctic (Kallenborn et al., 2013). Arctic seabirds are also known to transport persistent organic pollutants to the Arctic soils (Blais et al., 2005). Earlier studies have reported the presence of PCB180 in Arctic seabird species (Eckbo et al., 2019; Warner et al., 2019) and have found high concentrations of PCBs in the soils in vicinity of avian breeding areas (Blais et al., 2005). Most of the study sites in Ny-Ålesund were in proximity to shoreline; thus, avian influence on current PCBs levels cannot be excluded. In future studies, transects of sampling sites from ocean to land and, nearby the avian breeding

Table 4

Comparison of the concentrations (ng g^{-1} dw) of PCBs previously reported for Svalbard organic soils and threshold levels for clean soils (according to Norwegian classification system) with the current study. Number of samples or sites* are given within parentheses for each study.

Area studied	PCBs levels	References
Nordauslandet (1)	$\sum_7$ 0.175	Schlabach and
Kongsfjord, Ny Alesund (3)	$\sum_7$ 0.23 – 0.48	Steinnes, 1999a
Longyearbyen (3)	$\sum_7$ 0.41 – 0.78	
Longyearbyen &	$\sum_6$ 0.21 – 0.67	Schlabach and
Ny-Ålesund (9)*		Steinnes, 1999b
Platåfjellet (7)	$\sum_7$ <0.4	Breedveld, 2000
Bjørnøya	$\sum_{27}$ 4.4 – 17.2	Ockenden et al., 2003
Barentsburg	$\sum_7$ <4 – 28700	Jartun et al., 2007
Longyearbyen	$\sum_7$ <4 – 130	
Pyramiden	$\sum_7$ <4 – 1390	
Barentsburg (20)	$\sum_7$ <20 – 1990	Eggen et al., 2008.
Colesbukta (13)	$\sum_7$ <20 – 1890	
Grumant (5)	$\sum_7$ <20	
Isfjord radio (9)	$\sum_7$ <20 – 3500	
Longyearbyen (3)	$\sum_7$ <20	
Ny-Ålesund (12)	$\sum_7$ <20 – 40	
Svea (14)	$\sum_7$ <20	
Nordauslandet (4)	$\sum_7$ <1	Harris et al., 2008
Barentsburg (87)	$\sum_7$ <20 – 9200	Jartun et al., 2009a
Longyearbyen (46)	$\sum_7$ <20 – 55	
Pyramiden (51)	$\sum_7$ <20 – 18400	
Barentsburg (22)	$\sum_7$ 52 – 28700	Jartun et al., 2009b
Longyearbyen (30)	$\sum_7$ <4 – 131	
Pyramiden (31)	$\sum_7$ <4 – 13900	
Barentsburg (127)	$\sum_7$ <20 – 28700	Jartun et al., 2010
Bjørnøya (9)	$\sum_7$ <20 – 121	
Colesbukta (13)	$\sum_7$ <20 – 1890	
Fuglehuken lighthouse (1)	$\sum_7$ 39	
Longyearbyen (79)	$\sum_7$ <4 – 130	
Ny-Ålesund (20)	$\sum_7$ <4 – 42	
Pyramiden (83)	$\sum_7$ <4 – 18400	
Grumant (5), Hopen (1), Hornsund (1), Isfjord Radio (16) & Svea (14)	$\sum_7$ <20	
Prins Karls Forland (12)*	$\sum_7$ 3.1 – 5.5	Eggen et al., 2011
St. Johnsfjorden (12)*	$\sum_7$ 1.6 – 1.7	
The PCB project/Iowa State Univ. (23) *	$\sum_{209}$ 7.11	Geological Survey of Norway (NGU) reference in Kallenborn et al., 2013
Ny-Ålesund (12)	$\sum_8$ 2.76 – 10.8	Zhang et al., 2014
Ny-Ålesund (5) London Island (7)	$\sum_{25}$ 0.56 – 2.52	Zhu et al., 2015
Longyearbyen (19)	1.3 – 5.5	Present study
Ny-Ålesund (6)	3.2 – 8.1	
Background levels for Svalbard soils	$\sum_7$ 1 – 5	Kallenborn et al., 2013
Threshold levels for clean soils (according to Norwegian classification system for polluted ground)	$\sum_7$ <10	Hansen and Danielsberg, 2009 (TA-2553/2009)

areas are needed to evaluate the influence of ocean and migratory birds on the current PCBs concentrations in the Svalbard terrestrial ecosystem.

Table 5

PCBs levels (ng g^{-1} dw) in vegetation and underlaying organic soils. Numbers of samples (N) are given within parenthesis.

	Vegetation		Soil	
	Adventdalen	Ny-Ålesund	Adventdalen	Ny-Ålesund
PCB28	3.60 (1)	6.70 (1)	1.10 (1)	< 1 ng (11)
PCB52	6.20 ± 1.10 (6)	< 1 ng	3.00 ± 0.40 (13)	2.90 ± 0.40 (2)
PCB101	< 1 ng (8)	< 1 ng (7)	< 1 ng (14)	< 1 ng (11)
PCB118	< 1 ng (8)	< 1 ng (7)	< 1 ng (14)	< 1 ng (11)
PCB138	< 1 ng (8)	< 1 ng (7)	< 1 ng (14)	< 1 ng (11)
PCB153	< 1 ng (8)	< 1 ng (7)	< 1 ng (14)	< 1 ng (11)
PCB180	< 1 ng (8)	< 1 ng (7)	< 1 ng (14)	4.90 ± 0.40 (4)
$\sum$ PCB	6.80 ± 0.80 (6)	6.70 (1)	3.10 ± 0.40 (13)	5.10 ± 0.90 (5)

3.4. Are Cd and PCBs related to each other in Arctic terrestrial compartments?

It is worth reporting that both Cd and PCBs although different chemicals showed similar distribution patterns in Svalbard terrestrial compartments. Hierarchical cluster analysis was performed to investigate relationship of PCBs with the trace elements in terrestrial compartments of Svalbard (Fig. 5). Cluster analysis revealed three main groupings, with most elements clustered together in two groups. PCBs and Cd were grouped together, reflecting a strong association of those in the terrestrial compartments of Svalbard. Strong association indicates a potential concomitant source of origin. Association of Cd with Cl (ρ = 0.620 at $p < 0.01$) indicates that Cd is potentially present as chloride ($CdCl_2$). $CdCl_2$ is volatile in nature and the predominant chemical form released (as vapour) from waste incineration (AMAP, 1998). Similarly, waste incineration can release PCBs into the environment (Kallenborn et al., 2013). However, there is no official record of any local waste incineration unit in Svalbard area. Biomass burning is also known to release PCBs (mostly the lighter congeners, PCB28 and PCB52) (Eckhardt et al., 2007) and trace elements (McConnell and Edwards, 2008) in the Arctic environment. It is also possible that different sources are releasing Cd and PCBs simultaneously in Svalbard atmosphere and, therefore, a strong association was observed in the present study. Further research should be performed for a better understanding of source contributions to the occurrence of Cd and PCBs in Svalbard.

PCBs and Cd can be found in many environmental settings. These pollutants are persistent and share some common properties such as toxicity, carcinogenicity, bioaccumulation and act as endocrine disruptors (Corsolini and Sarà, 2017; Hamid et al., 2019; Reddy et al., 2019; Sabir et al., 2019). Although the concentrations measured in Arctic soils are below the limits recommended for Norwegian soil quality, yet they can be very toxic for biota in the Arctic ecosystem. There is growing evidence that the mixture toxic effect of Cd and PCBs is more pronounced in living organisms than their individual toxicities (Buha et al., 2013; Danis et al., 2006; den Besten et al., 1991; Petrosino et al., 2018; Sures et al., 2006). Generally, researchers study one class of the pollutants in environmental samples, while different types of pollutants (chemically different in nature) are present in complex compositions in environment. Studying a single group of chemicals does not provide enough information on how they impact nature when combined to other chemicals. It is therefore important to design larger studies to investigate both organic and inorganic pollutants concurrently in different components of the Arctic ecosystem.

4. Conclusion

Results presented herein provide insights on the distribution profile of trace elements and PCBs in Svalbard vegetation and underlying
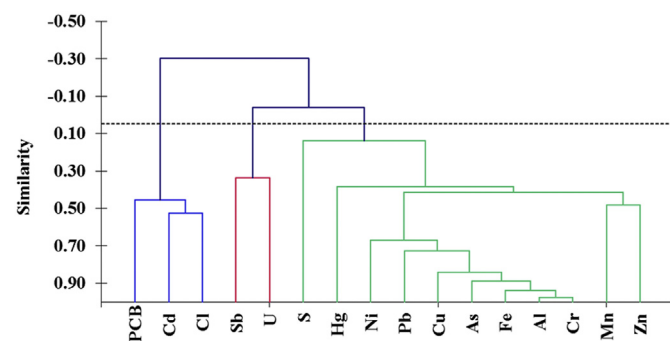
Fig. 5. Relationship of PCBs with elements in terrestrial compartment of Svalbard. Dendrogram showing the similarity between PCBs and elements.

organic soils. Current concentrations of Al, As, Cr Cu, Fe and Pb in the terrestrial compartments of Svalbard seemed to be influenced by the crustal material, while concentrations of Hg, Zn and Cd and PCBs appeared to be affected by atmospheric deposition. The present study provides background concentrations of both trace elements and PCBs in the terrestrial compartments of Svalbard. The presence of only two congeners (PCB52 and PCB180) in vegetation and three congeners (PCB28, 52 and 180) in underlying organic soils was confirmed. Concentrations of Cd and PCBs did not show pronounced spatial variability in the studied area. PCBs and Cd were strongly associated, proposing a potential concomitant source of origin in Svalbard.

Author contributions

Shazia N. Aslam: Data curation, Software, Writing- Original draft preparation, Reviewing and Editing. Carolin Huber: Methodology, Investigation. Alexandros G. Asimakopoulos: Writing- Reviewing and Editing. Eiliv Steinnes: Conceptualization, Supervision, Reviewing and Editing. Øyvind Mikkelsen: Conceptualization, Funding Acquisition, Supervision, Reviewing and Editing.

Declaration of Competing Interest

Authors certify that there is no conflict of interest with any financial or nonfinancial organisation regarding the subject matter or materials discussed in this manuscript.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2019.06.060.

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