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Bryophytes and lichens as fallout originated radionuclide indicators in the Svalbard archipelago (High Arctic)

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ABSTRACT

Arctic environment is very sensitive to anthropogenic pollutants, especially in terms of radionuclide contamination which persists in polar regions due to very slow biological turnover rate. The main aim of the study was to determine concentrations of ^{137}Cs in selected cryptogamic species (bryophytes and lichens) in different areas of Svalbard archipelago in the period of 1985–2017 and thus recognize the level of ^{137}Cs contamination in Svalbard as well as to indicate the best fallout originated radionuclide bioindicators in the Arctic region. The ^{137}Cs activity was measured in 31 samples of cryptogams (*Cetraria islandica* (L.) Ach., *Cetrariella delisei* (Bory ex Schaer.) Kärnefelt & A. Thell, *Flavocetraria nivalis* (L.) Kärnefelt & A. Thell, *Ptilidium ciliare* (L.) Hampe, *Racomitrium lanuginosum* (Hedw.) Brid., *Sanionia uncinata* (Hedw.) Loeske, and *Sphaerophorus globosus* (Huds.) Vain.) collected between 1985 and 2017 at six different locations in Svalbard: Adventdalen, Bellsund, Kaffiøyra, Ny-Ålesund, Petuniabukta, and Sørkapp Land. Analyses showed that species *R. lanuginosum* and *C. delisei* can be recommended as the best bioindicators of changes in radioactivity level in the Arctic region.

1. Introduction

The Arctic environment is affected by radionuclides from multiple sources, which contribute to various degree of contamination of terrestrial and maritime ecosystems. The majority of contaminants is transported to Arctic by atmospheric circulation, marine currents, rivers and sea ice (Zaborska et al., 2010). This part of globe has been especially contaminated by anthropogenic radionuclides as a result of nuclear weapons tests during the 1950s and 1960s, Chernobyl accident in 1986, Fukushima accidents in 2011 and international discharge of radioactivity waste from industrial plant producing and processing radioactive material, such as Sellafield, la Hague, Mayak, Tomsk, Krasnoyarsk (Johannessen et al., 2010; Thakur et al., 2013; UNSCEAR, 2000). The primary source of radionuclides in the Arctic region was stratospheric fallout from atmospheric nuclear weapons testing, which accounts for over 80% of the total fallout (Macdonald et al., 2000). Novaya Zemlya was one of the Soviet sites for atmospheric nuclear weapon testing in Arctic where the tests started in 1957 and ended in 1990 with a total explosive energy equivalent to 265 megatons of TNT. In this part of Arctic about 130 tests were carried out. In period 1957–1962, 83 purely atmospheric test, 3 over the water and one from a tower were carried out (Johannessen et al., 2010). Between 1972 and 1990 only underground tests took place (Johannessen et al., 2010; Khalturin et al., 2005). It was estimated that from all the nuclear weapons tests in the world 950 PBq ^{137}Cs was released (UNSCEAR, 2008), from which 30 PBq was deposited in Arctic region (Aarkrog, 1994). Another important source of ^{137}Cs in terrestrial ecosystem was tropospheric fallout after Chernobyl accident. During this accident 85 PBq of ^{137}Cs was released and the deposition to the Arctic was estimated to be 4.1 PBq (Aarkrog, 1994; Livingston and Povinec, 2002). The last evident source of ^{137}Cs for Svalbard Archipelago were the Fukushima accidents. The atmospheric release from the Fukushima accident started on March 12, 2011. It was estimated that atmospheric release of ^{137}Cs was in the range of 13–15 PBq but the total deposition on the Svalbard archipelago is indeterminate (Povinec et al., 2013). One of the main reasons why Svalbard environment is still contaminated with anthropogenic radionuclides is that the polar environments are characterized by a very slow biological turnover rate (Svoboda and Taylor, 1979; Hutchison-Benson et al., 1985).

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One of the most widespread plant species in the Arctic that can be considered as bioindicators are bryophytes and lichens, whose abundance in polar region is higher than in other world biomes (Matveyeva and Chernov, 2000). Both bryophytes and lichens, due to their specific features (i.e. long live spans, slow metabolic activity, slow growth rate, lack of roots, waxy cuticles or specialized structures for water and gas exchange), easy absorb and accumulate contaminants and radionuclides from wet and dry atmospheric deposition, and due to that they are considered as useful bioindicators of air pollution (Conti and Cecchetti, 2001; Nimis et al., 2002). ^{137}Cs can be especially easily incorporated into the biological structure of plant due to its similarity to potassium ions (Nimis et al., 2002). Similar to other heavy metal, mobility of ^{137}Cs can be affected by environmental conditions, such as altitude, wind exposure, substrate pH, soil texture, snow cover, as well as presence of glaciers as additional radionuclide sources (Pinglot et al., 1994; Pinglot et al., 1999; Nimis et al., 2002; Wallace et al., 2012).

The main aim of presented studies was to determine concentrations of ^{137}Cs in selected species of lichen and bryophytes collected in different areas of Svalbard archipelago in the period 1985–2017. This allows to recognize the level of ^{137}Cs contamination in Svalbard and propose the fallout originated radionuclide bioindicators in the Arctic region.

2. Material and methods

2.1. Study area and sample collection

Samples of four lichen species (*Cetraria islandica* (L.) Ach., *Cetrariella delisei* (Bory ex Schaer.) Kärnefelt & A. Thell, *Flavocetraria nivalis* (L.) Kärnefelt & A. Thell, *Sphaerophorus globosus* (Huds.) Vain.) and three bryophyte species (*Ptilidium ciliare* (L.) Hampe, *Racomitrium lanuginosum* (Hedw.) Brid., *Sanionia uncinata* (Hedw.) Loeske), have been collected between 1985 and 2017 from areas of Svalbard archipelago: Adventdalen (Paleogene bedrock; mesic slope *Cassiope tetragona* community), Bellsund (Proterozoic bedrock; mesic slope *Luzula confusa* community), Kaffiøyra (Paleogene bedrock; mesic plain *Luzula confusa* community), Ny-Ålesund (Carboniferous and Permian bedrocks; mesic plain *Luzula nivalis* community), Petuniabukta (Devonian bedrock; mesic *Cassiope tetragona* community), and Sørkapp Land (Carboniferous and Permian bedrocks; mesic *Luzula nivalis* community) (Fig. 1); Dubiel and Olech (1991); Elvebakk (1994), 2005; Węgrzyn and Wietrzyk (2015); Elling et al., (2016). Altogether, thirty-one samples have been collected. Table 1 presents detailed list of species collected in particular location and year. Specimens in good condition with no signs of decay and fungal diseases were collected in the same type of dry tundra habitat of plains and slopes in above-mentioned locations (Dubiel and Olech, 1991; Elvebakk, 1994, 2005; Dallmann, 1999; Węgrzyn and Wietrzyk, 2015). In the case of lichens, fruticose species were collected, that form compact, cushion-like structures. Similarly, cushion of *Racomitrium lanuginosum* was collected, while in the case of two other bryophytes, the fragments of their mats were obtained. Each sample weighed approximately 100 g. After collection, samples were cleaned of soil and other plant debris in the field and air-dried.

2.2. Laboratory analysis

After homogenization, the ^{137}Cs activity was measured using a gamma spectrometry system: Extended Range Coaxial Ge Detectors (XtRa) with a relative efficiency of 40% and a resolution of 1.8 keV for the 1332 keV peak of ^{60}Co. The detector was coupled to an 8192-channel computer analyser and GENIE 2000 spectroscopy software. The measurements for each sample was 80,000 s. The reliability and accuracy of

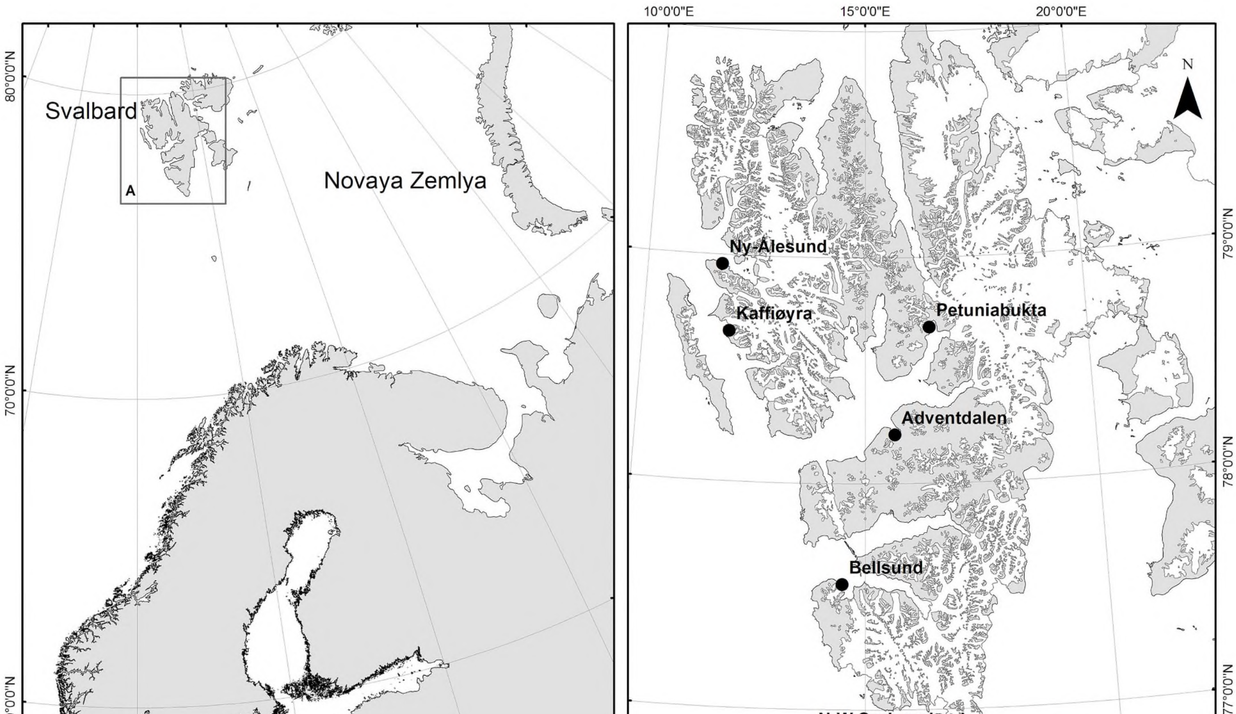

Fig. 1. Locations of sample collection © Norwegian Polar Institute, 2019 (npolar.no).

Table 1
Detailed list of species collected in particular location and year (including geographical coordinates in WGS 1984).

No	Species	Group	Region	Year	Longitude	Latitude
1	*Flavocetraria nivalis*	lichens	N-W Sørkapp Land	1985	15°35'20,247"E	76°53'13,591"N
2	*Cetrariella delisei*	lichens	N-W Sørkapp Land	1985	15°31'15,742"E	76°52'59,071"N
3	*Cetraria islandica*	lichens	N-W Sørkapp Land	1985	15°36'22,314"E	76°52'50,276"N
4	*Sphaerophorus globosus*	lichens	N-W Sørkapp Land	1985	15°36'24,414"E	76°52'29,941"N
5	*Sanionia uncinata*	bryophytes	N-W Sørkapp Land	1985	15°40'04,601"E	76°52'14,461"N
6	*Racomitrium lanuginosum*	bryophytes	N-W Sørkapp Land	1985	15°34'02,285"E	76°53'26,612"N
7	*Flavocetraria nivalis*	lichens	Bellsund	1988	14°08'23,425"E	77°32'31,634"N
8	*Cetrariella delisei*	lichens	Bellsund	1988	14°08'06,507"E	77°31'49,753"N
9	*Cetraria islandica*	lichens	Bellsund	1988	14°08'06,507"E	77°31'49,753"N
10	*Sphaerophorus globosus*	lichens	Bellsund	1988	14°02'54,866"E	77°30'49,384"N
11	*Sanionia uncinata*	bryophytes	Bellsund	1988	13°59'19,883"E	77°30'22,997"N
12	*Sanionia uncinata*	bryophytes	Bellsund	1988	14°01'05,281"E	77°31'53,871"N
13	*Ptilidium ciliare*	bryophytes	Bellsund	1988	14°01'05,281"E	77°31'53,871"N
14	*Racomitrium lanuginosum*	bryophytes	Bellsund	1988	14°00'27,416"E	77°32'48,365"N
15	*Flavocetraria nivalis*	lichens	N-W Sørkapp Land	2008	15°34'04,403"E	76°54'09,757"N
16	*Cetrariella delisei*	lichens	N-W Sørkapp Land	2008	15°34'07,278"E	76°53'31,153"N
17	*Cetraria islandica*	lichens	N-W Sørkapp Land	2008	15°35'07,081"E	76°53'28,352"N
18	*Sphaerophorus globosus*	lichens	N-W Sørkapp Land	2008	15°31'57,861"E	76°51'56,117"N
19	*Sanionia uncinata*	bryophytes	N-W Sørkapp Land	2008	15°33'44,444"E	76°53'31,772"N
20	*Ptilidium ciliare*	bryophytes	N-W Sørkapp Land	2008	15°33'44,444"E	76°53'31,772"N
21	*Racomitrium lanuginosum*	bryophytes	N-W Sørkapp Land	2008	15°33'09,762"E	76°53'21,092"N
22	*Cetrariella delisei*	lichens	Kaffiøyra	2012	11°49'48,711"E	78°40'39,188"N
23	*Ptilidium ciliare*	bryophytes	Kaffiøyra	2012	11°56'56,729"E	78°40'49,709"N
24	*Racomitrium lanuginosum*	bryophytes	Kaffiøyra	2012	11°56'56,729"E	78°40'49,709"N
25	*Flavocetraria nivalis*	lichens	E Sørkapp Land	2016	15°36'24,414"E	76°52'29,941"N
26	*Cetrariella delisei*	lichens	Bellsund	2016	14°30'21,612"E	77°33'22,715"N
27	*Flavocetraria nivalis*	lichens	Petuniabukta	2017	16°21'37,456"E	78°43'47,777"N
28	*Cetrariella delisei*	lichens	Ny-Ålesund	2017	11°47'03,711"E	78°55'56,083"N
29	*Cetrariella delisei*	lichens	Petuniabukta	2017	16°25'27,486"E	78°43'11,242"N
30	*Racomitrium lanuginosum*	bryophytes	Ny-Ålesund	2017	11°47'03,711"E	78°55'56,083"N
31	*Racomitrium lanuginosum*	bryophytes	Adventdalen	2017	15°46'02,556"E	78°11'39,952"N

the measurements as well as comparability were verified by the participation in 2018 in the intercalibrations organized within the National Atomic Energy Agency in Poland (PAA) and analysis organized yearly by IAEA-MEL Monaco (Table 2). Activity concentrations of ^{137}Cs were recalculated for decay corrected back to the time of sampling.

3. Results and discussion

In 1985, before the accident of the Chernobyl nuclear power plant, the highest ^{137}Cs activity concentrations in the lichens were measured in *C. delisei* (391.3 Bq kg^{-1} dw) and in *S. globosus* (229.3 Bq kg^{-1} dw) (Table 3). Lower values were found in specimens of *F. nivalis* (148.9 Bq kg^{-1} dw) and *C. islandica* (129.7 Bq kg^{-1} dw). Much wider range of activity concentrations of ^{137}Cs was observed in bryophytes. The highest activity was found in sample of *R. lanuginosum* (698.6 Bq kg^{-1} dw) – it was almost twice as high a value as in *C. delisei*. The lowest values were measured in the samples of *S. uncinata* (41.4 Bq kg^{-1} dw) (Table 3). Relatively high activity concentrations of ^{137}Cs in lichens (from 129.7 Bq kg^{-1} dw to 391.3 Bq kg^{-1} dw, with the average 224.8 Bq kg^{-1} dw) and in bryophytes (from 41.4 Bq kg^{-1} dw to 698.6 Bq kg^{-1} dw, with the average 370.0 Bq kg^{-1}) collected in N-W Sørkapp Land in 1985 were probably still connected with fallout from atmospheric tests conducted in Novaya Zemlya in 1961 and 1962 (Fig. 2). Hallstadius et al. (1986) estimated that the deposition after nuclear weapons testing was 2.2 kBq m^{-2}, so total load of ^{137}Cs direct on Svalbard was about 0.13 PBq. Obtained results are comparable to concentrations of ^{137}Cs found in lichen and moss collected from northwest Canada in 1986, which stayed in the range from 228 Bq kg^{-1} to 986 Bq kg^{-1} (Taylor et al., 1988).

In 1988, two years after Chernobyl accident, no uniform pattern was observed for studied organisms collected in Bellsund in terms of radionuclides content. There is no clear evidence for increase in ^{137}Cs concentrations as compared to species collected in 1985 and thus for the impact of Chernobyl fallout. Only in the case of *S. uncinata* the increase of ^{137}Cs activity was observed: from 41.4 Bq kg^{-1} dw to approximately 390 Bq kg^{-1} dw. In *F. nivalis* ^{137}Cs concentration even dropped from 148 Bq kg^{-1} dw to 55 Bq kg^{-1} dw, but it should be emphasized that samples were gathered in different locations. The activities of ^{137}Cs in other species stayed at the similar level (Table 3). Fallout of ^{137}Cs from the Chernobyl accident was rather negligible and amounted to roughly 20 Bq m^{-2} (Pinglot et al., 1994). This suggest that the failure of the Chernobyl nuclear power plant might be a negligible source of the studied isotope.

In 2008 the samples of the same species were collected again in N-W Sørkapp Land and the obtained results clearly indicate concentrations decrease in the studied organisms as compared to 1985. ^{137}Cs activity in lichens ranged from 17.4 Bq kg^{-1} dw (*F. nivalis*) to 190.1 Bq kg^{-1} dw (*C. delisei*), while in bryophytes it varied from 16.6 Bq kg^{-1} dw (*R. lanuginosum*) to 99.3 Bq kg^{-1} dw (*P. ciliare*) (Table 3). Obtained result are comparable with the limited number of data previously reported. ^{137}Cs activity concentrations varied from 29 Bq kg^{-1} dw to 292 Bq kg^{-1} dw in bryophytes, 30 Bq kg^{-1} dw to 140 Bq kg^{-1} dw in lichen, collected in 2001 and 2002 in Svalbard (Gwynn et al., 2004). Dowdall et al. (2005) reported the activities of ^{137}Cs in samples collected in 2001 and 2002 from Kongsfjorden at similar levels: in bryophytes (*Racomitrium ericoides* - 292 Bq kg^{-1} dw, *S. uncinata* from 37 Bq kg^{-1} dw to 117 Bq kg^{-1} dw, *Amphidium lapponum* - 29 Bq kg^{-1} dw and *Bryum sp.* from 11 Bq kg^{-1} dw to 216 Bq kg^{-1} dw) and in lichen (*F. nivalis* from 75 Bq kg^{-1} dw to 140 Bq kg^{-1} dw).

The decrease in ^{137}Cs activity observed in 2008 as compared to 1985

Table 2
The reliability and accuracy of the measurements of laboratory.

	Reported Laboratory Value [Bq dm^{-3}]	Assigned value [Bq dm^{-3}]	Accuracy	Precision	Overall	
^{137}Cs	0.235 ± 0.012	0.2599 ± 0.0026	Pass	Pass	Accepted	IAEA
^{137}Cs	18.52 ± 0.52	18.784 ± 0.564	Pass	Pass	Accepted	PAA

Table 3
Activity of^{137}Cs (Bq kg^{-1} dw) in samples of cryptogam species collected in Svalbard in the years 1985–2017.

		Lichens				Bryophytes		
Locality	Year	*Flavocetraria nivalis*	*Cetrariella delisei*	*Cetraria islandica*	*Sphaerophorus globosus*	*Sanionia uncinata*	*Ptilidium ciliare*	*Racomitrium lanuginosum*
N-W Sørkapp Land	1985	148. ± 4.6	391.3 ± 7.4	129.7 ± 5.2	229.3 ± 5.0	41.4 ± 2.6	–	698.6 ± 10.5
Bellsund	1988	55.0 ± 2.5	317.2 ± 7.7	114.6 ± 3.3	297.7 ± 6.8	395.3 ± 7.6 382.0 ± 7.1	156.3 ± 3.9	682.4 ± 9.7
N-W Sørkapp Land	2008	17.4 ± 2.1	190.1 ± 3.4	53.9 ± 4.3	112.2 ± 2.2	16.6 ± 1.4	99.3 ± 2.9	26.7 ± 13
Kaffiøyra	2012	–	90.5 ± 2.1	–	–	–	82.7 ± 2.3	208.1 ± 3.8
Bellsund	2016	–	51.1 ± 31	–	–	–	–	–
E Sørkapp Land	2016	6.8 ± 1.0	–	–	–	–	–	–
Ny-Ålesund	2017	–	22.7 ± 1.0	–	–	–	–	51.2 ± 1.4
Petuniabukta	2017	33.9 ± 1.0	8.8 ± 0.6	–	–	–	–	–
Adventdalen	2017	–	–	–	–	–	–	54.1 ± 1.4

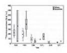

Fig. 2. Average activity of ^{137}Cs in cryptogams from Svalbard archipelago, box represent standard deviation and whiskers represent min-max.

was mainly connected with the radioactive decay and with the dilution being a result of growth of new parts of plants. Taking into account radioactive decay formula (1) and data from both years at Sørkapp Land station the effective half-lives were equal to 7.4 years in *F. nivalis,* 22 years in *C. delisei,* 18 years in *C. islandica,* 22.3 years in *S. globosus,* 17.4 years in *S. uncinata* and 4.9 years in *R. lanuginosum* (Fig. 3).

$$N_{(t)} = N_0 \left(\frac{1}{2}\right)^{\frac{t}{t_{\frac{1}{2}}}} \tag{1}$$

Calculated biological half-life was higher than effective half-time and most of the values reported in the literature for the biological half-life of ^{137}Cs in different lichen species (Papastefanou et al., 1988; Heinrich et al., 1999). This situation can be explained by an unaccounted continuous radionuclide influx or high variability of ^{137}Cs activity in biological samples even in short transect from the glacier forehead (unpublished data).

In 2012, one year after Fukushima accident, the activity of ^{137}Cs in lichen species was equal to 90.5 Bq kg^{-1} and only in the case of bryophyte representative – *R. lanuginosum,* the activity was eight times higher than in 2008, but samples were collected in other location (Kaffiøyra), in the distance of ca. 265 km where differences in precipitation can be over two times higher, that that may influence deposition (Førland et al., 2011) (Table 3). Therefore, the impact of the Fukushima fallout on radioactive caesium isotope levels in the tested organisms can not be clearly indicated. The main jet stream of the plume from Fukushima mostly travelled close to the North Pole (over the Greenland) and Scandinavia to the Central Europe and first signal was detected in Europe on 19th of March (station in Reykjavik) (Povinec et al., 2013). The radioactive cloud reached Spitsbergen on 23rd of March and the highest ^{131}I activity was recorded on 26th of March (Thakur et al., 2013). In the Longyearbyen, in the period from 24th of March to 11th of April the activity of ^{137}Cs in aerosols ranged from 0.003 mBq m^{-3} to 0.37 mBq m^{-3} and the maximum ^{137}Cs activity concentration at Ny-Ålesund was 0.675 mBq m^{-3} (Paatero et al., 2012; Thakur et al., 2013). Although ^{134}Cs/^{137}Cs ratio in aerosol at Ny-Ålesund was almost 1, ^{134}Cs in samples of bryophytes and lichens was at levels below limit of determination. The main reason for this was the analysis of samples 6 years after collection. In beard lichen (*Bryoria* sp. and *Alectoria* sp.) collected throughout the Northern Finland during the 2011–2013 period ^{134}Cs activity ranged from 0.24 Bq kg$^{-1}_{\mathrm{fw}}$ to 1.3 Bq kg$^{-1}_{\mathrm{fw}}$, but effective half-life of ^{134}Cs was only 0.91 year (Koivurova et al., 2015). Also ^{134}Cs in lichens and mosses from coastal zones of the Canadian Arctic and Alaska in 2012 and 2013 was detected only in a few samples (Cwanek et al., 2020).

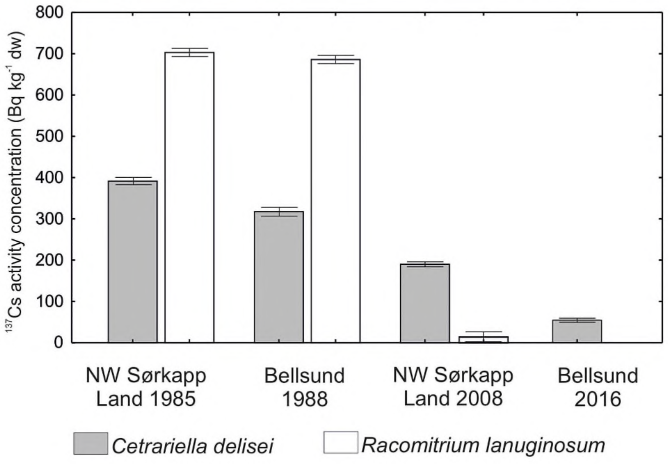

Fig. 3. Activity of ^{137}Cs in *R. lanuginosum* and *C. delisei* in period 1985–2016.

In 2016 activity concentrations of ^{137}Cs in *F. nivalis* collected in E Sørkapp Land was 6.8 Bq kg^{-1} dw and it was almost two and half times lower than in 2008. Also, in the case of *C. delisei* decrease is observed and in 2016 activity at the Bellsund station was 51.1 Bq kg^{-1} dw (Fig. 3; Fig. 4). Based on samples taken in years 1988 and 2016 in Bellsund the effective half-life in *C. delisei* was 11.4 years and was twice two times lower than in the same species but based on data from 1985 to 2008 from N-W Sørkapp Land. This could have been caused by the specifics of the sampling area and various environmental conditions, such as substrate pH, soil texture, snow cover, presence of glaciers, which can disturb ^{137}Cs activity in lichen and mosses.

In 2017, in the case of both bryophytes and lichens, the average activity concentrations of ^{137}Cs decreased to 52.6 Bq kg^{-1} dw and 21.8 Bq kg^{-1} dw, respectively. In the case of *F. nivalis* ^{137}Cs activity was five times higher than in the previous year, but samples were collected in the distance of ca. 200 km (Table 3). The ^{137}Cs activities found in *R. lanuginosum* samples collected at two different station (Ny-Ålesund and Adventdalen) were at similar level of 50 Bq kg^{-1} dw.

Beside the chronological pattern, the differences between activity of ^{137}Cs in the lichens and bryophytes could have been connected to different sampling locations and could have arisen from different morphology and physiology and thus different bioaccumulation efficiencies and retention pattern specific to the species. Eckl et al. (1986) and Nimis et al. (2002) indicated a strong correlation between the content of radionuclides in thalli and the substratum on which they grow. It was shown that different processes, such as erosion, accumulation of organic material, gleying, and decarbonation, which occur in

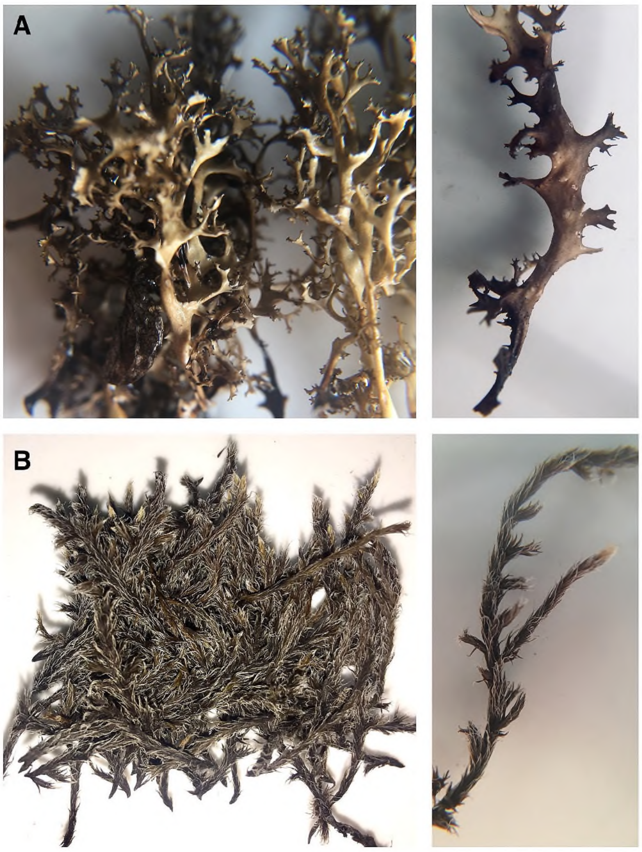

Fig. 4. Fragments of proposed radionuclide indicators: *C. delisei* (A) and *R. lanuginosum* (B).

glacier forehead can significantly affect the ability of lichen and mosses to accumulate metals. Mobility of ^{137}Cs increases with decreasing pH, because the ^{137}Cs-ions bounded by clay minerals can be exchanged by hydrogen ions. Low values of pH in the snow cover of lower part of the glacier may have contributed to acidification of the soil near the glacier and to increase in bioavailability of ^{137}Cs (Fig. 2; Nawrot et al., 2016).

Considering the differences between lichen and bryophytes, the latter keep their leaves over winter, so accumulated contaminants are not lost through leaf fall (Dowdall et al., 2005). They are tissue organisms, with the epidermal layer that constitutes a protective barrier. In regard to the lichens, they are formed by thallus and do not possess epidermal tissue like bryophytes or cuticule like vascular plants. They can take up radionuclides with the substrate solution as well as from deposited aerosols, water vapor and rain (Eckl et al., 1986). However, lichens have the ability to convert sparingly soluble radionuclides into easily movable form and to increase their migration ability which allow to actively transport the elements into the lower parts of the thallus and gradually get rid of them by decomposing those fragments of the thallus (Malikova et al., 2019). Furthermore, it is important that content of the longer-lived radionuclides, like ^{137}Cs, in lichen thalli are associated with deposition during at least a few years (depending on the biological residence time) prior to collection of samples (Ellis and Smith, 1987). Study conducted by Hanson and Eberhardt (1971) showed that lichens are unable to take up potassium from the soil, therefore accumulation of ^{137}Cs as potassium analogy could be performed by lichens to satisfy their potassium needs (Eckl et al., 1986). On the other hand, Mietelski et al. (2000) suggested that caesium is partially leached out of lichen thallus in contradictory to bryophytes which keep caesium in original ration. Nevertheless, Sawidis et al. (1997) proved that rain and snow caused leaching effect of ^{137}Cs also in case of bryophytes after about two years. Previous studies showed that bryophytes accumulate higher amount of ^{137}Cs (Dowdall et al., 2005), however it was proven that shortly after the radioactive accident bryophytes presented higher activity of ^{137}Cs than lichen but, after several years, due to differences in biological half-life, the proportion between the activities of ^{137}Cs in lichens and mosses changes (Topcuoğlu et al., 1995; Iurian et al., 2011). The degree of radionuclide accumulation in bryophytes and lichen is largely determined by their species and age as well as ecological conditions of their habitat, but not by growth form (Nimis et al., 2002; Nifontova, 2006). Within seven studied species of lichens and bryophytes, *C. delisei* (lichens) and *R. lanuginosum* (bryophyte) presented the highest bioaccumulation ability as well as widest occurrence in Arctic (Fig. 4; Table 2). In the period from 1985 to 1988 the activity concentrations of ^{137}Cs in both species stayed almost unchanged indicating negligible impact of Chernobyl fallout in the region.

Accumulation of ^{137}Cs in lichens and bryophytes may affects also other components of ecosystems, especially the herbivores. The Svalbard reindeer subspecies *Rangifer tarandus platyrhynchus* is the only ruminant that grazes the tundra all year round. Its diet is divided into a summer diet, dominated by the green parts and flowers of vascular plants and graminoids, and a winter diet, consisting of mosses, lichens, graminoids and woody parts of dwarf-shrubs (Bjørkvoll et al., 2009; Węgrzyn et al., 2018). The long-living vegetation exposed to radionuclide accumulation through many years and then consumed by reindeer, contributes to the accumulation of elements in their organisms (Sancho et al., 2007; Węgrzyn et al., 2018). The transfer of ^{137}Cs through the food chain from lichens and plants to reindeer was previously reported by Nevstrueva et al. (1967) and Skuterud et al. (2005). However still little is known about ^{137}Cs accumulation patterns in particular species that form the reindeer forage. The activities of ^{137}Cs in Svalbard reindeer in 1980 range from 0.3 to 2.7 Bq kg^{-1} ww and was similar to activity in 2003 which ranged from 0.08 ± 0.03 to 1.16 ± 0.18 Bq kg^{-1} ww and they were much lower from mainland Northern Norway (Finmark) and ranged from 56 to 177 Bq kg^{-1} ww in 2004 (Gwynn et al., 2005). Simoões and Zagorodnov (2001), suggestes that the Svalbard is one of the most affected Arctic areas by anthropogenic pollution due to atmospheric circulation. Because of that it is important to study the temporal changes of radioactive contamination of this region in all ecosystem components as well as understand the transfer pattern of elements within trophic chain, that in Svalbard includes also the transport over the lichen/-bryophyte–reindeer–human food chain.

4. Conclusions

Presented paper found relatively high activity concentrations of ^{137}Cs in lichens (129.7 Bq kg^{-1} dw - 391.3 Bq kg^{-1} dw) and in bryophytes (41.4 Bq kg^{-1} dw - 698.6 Bq kg^{-1} dw). Within studied species, *C. delisei* (lichens) and *R. lanuginosum* (bryophyte) presented the highest ^{137}Cs bioaccumulation efficiency. Widespread and relatively high efficiency of bioaccumulation specific to *R. lanuginosum* and *C. delisei* indicate that these species can serve as a good fallout originated radionuclide indicators for the Arctic region.

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