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Impact of distance from the glacier on the content of ^{137}Cs and ^{90}Sr in the lichen *Cetrariella delisei*

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HIGHLIGHTS

- ^{90}Sr and ^{137}Cs were investigated in soil and *Cetrariella delisei* from the Arctic.
- Activity in Cetrariella delisei were dependent of distance from the glacier.
- ^{137}Cs and ^{90}Sr activity in surface soil did not present clear pattern.
- Environmental variability may impact accumulation of ^{137}Cs and ^{90}Sr by lichens.

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ABSTRACT

The Arctic region is substantially a pristine area, but this unique part of the globe has also been contaminated by anthropogenic radioactive nuclides, and now there is still measurable activity of anthropogenic isotopes, even though more than 50 years have passed since the main source. Radionuclides in the Arctic, especially ^{90}Sr have seldom been studied despite their considerable environmental importance. This manuscript covers the results of ^{90}Sr and ^{137}Cs measurements in soil and lichen *Cetrariella delisei* collected from the Svalbard in 2012. In both lichen thalli and surface soils high activities of ^{90}Sr and ^{137}Cs were recorded and ranged between 3.69 and 28.1 Bq kg^{-1} ^{90}Sr and 5.38–280.1 Bq kg^{-1} ^{137}Cs in thalli and between 4.53 and 12.78 Bq kg^{-1}dw ^{90}Sr and 60.6–426.1 Bq kg^{-1}dw ^{137}Cs in surface soil layer. The activity of ^{90}Sr and ^{137}Cs in lichen thalli was influenced by distance from the glacier. This showed that during radionuclide biomonitoring of particular area with the use of lichens, it is important to take into account influence of environmental variability on radionuclides contents.

1. Introduction

The contamination of the Svalbard area by ^{90}Sr and ^{137}Cs is relatively low compared to areas of lower latitudes; however, this region has also been affected by the fallout of radioactive isotopes of anthropogenic origin (UNSCEAR, 2000). Nuclear weapons tests as well as the Chernobyl disaster (1986) and accident in Fukushima (2011) are the main causes of radioactive contamination of terrestrial ecosystems (Gwynn et al., 2005; WOMARS, 2005).

The main source of ^{90}Sr in Arctic was testing of nuclear weapons in the atmosphere in the 1950s and 1960s and air mass movement in the upper atmosphere and stratosphere (Gwynn et al., 2005). Integrated deposition density of ^{90}Sr in northern hemisphere was about 0.7 kBq m^{-2} in latitudes 70°–80° N and about 0.24 kBq m^{-2} in latitudes 80°–90° N (WOMARS, 2005). According to data published in the 1980s, total deposition of ^{137}Cs in the Svalbard region could range from 1.51 kBq m^{-2} to 2.2 kBq m^{-2} (Hallstadius et al., 1982). Later research determined the deposition of ^{137}Cs from atmospheric weapon testing at a lower level between 0.39 and 1.09 kBq m^{-2} (UNSCEAR, 2000). Another study, based on ^{137}Cs content of glacial ice cores, estimated deposition caused by nuclear weapons tests even at lower level of 0.2–0.54 kBq m^{-2} (Pinglot et al., 1994). At the same time, detailed scrutiny has shown that the fallout of ^{137}Cs due to the Chernobyl disaster was rather negligible and amounted roughly 0.02 kBq m^{-2} (Pinglot et al., 1994).

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After Chernobyl accident, total ^{90}Sr release constitutes around 11–12% of ^{137}Cs total release but more than 90% of ^{89,90}Sr activities were released in fuel particles and fell over land near reactor so input to the Arctic was marginally low (CEC, 1998; Aarkrog, 2003). It is estimated that the ^{90}Sr deposition in Norway constituted only 1–3% of ^{137}Cs (Skuterud et al., 2005). After Fukushima nuclear power plant accident, the atmospheric release of ^{137}Cs was in the range of 13–15 PBq, but the total deposition on the archipelago remains indeterminate (Povinec et al., 2013). The maximum ^{137}Cs activity concentration in air at Ny-Ålesund, Iceland and Northern Europe were at a similar level of 0.7 mBq m^{-3} (Paatero et al., 2012; Thakur et al., 2013). Therefore, it can be assumed that after the Fukushima nuclear power plant accident the deposition in Svalbard it could be similar to Central Europe 0.87 Bq m^{-2} (Saniewski and Zalewska, 2016).

Vegetation of Arctic regions is dominated by cryptogamic organisms, such as lichens and bryophytes. These organisms are widely used as bioindicators of different pollutants, including heavy metals, persistent organic pollution, polycyclic aromatic hydrocarbons, and radionuclides (Nimis et al., 2002; Guidotti et al., 2003; Augusto et al., 2013). In the case of the Svalbard archipelago occurrence of cryptogams, especially lichens, is limited due to reindeer grazing (van der Wal et al., 2001). Because of that we decided to choose *Cetrariella delisei* lichen to estimate radionuclide contamination as it is a species reluctantly grazed by herbivores, commonly occurred in the Arctic area, and easy to identify in the field (Węgrzyn et al., 2016).

The purpose of this study was to determine the current concentration levels of ^{90}Sr, ^{137}Cs in lichen *Cetrariella delisei* and soil in the Svalbard region. Due to the relatively long half-life, accumulation, these are two most important anthropogenic radionuclides typical for beta (^{90}Sr) and gamma emitters (^{137}Cs). It was aimed to recognize main factors affecting levels of isotopes concentration in lichen in the context of (i) relationship between accumulation efficiency in the thalli and concentrations in corresponding soil substrate and (ii) the glacier as a potential, secondary source of isotopes accumulated by the lichen.

2. Material and methods

2.1. Study area and sampling

Sampling of lichen and soil materials was conducted during the summer season 2012 in the Kaffiøyra Plain (the northern part of Oscar II Land, NW Spitsbergen; Fig. 1). Kaffiøyra is a coastal lowland situated on the eastern coast of the Forlandsundet strait and bordered by several glaciers: Aavatsmarkbreen from the north, Dahlbreen from the south, and Waldemarbreen, Irenebreen, Elisebreen, Agnorbreen, Eivindbreen, Andreasbreen, Oliverbreen from the east. The samples were collected at 12 locations designated along the transect leading from the glacier foreland of Waldemarbreen towards the seashore (Fig. 1). Soil samples were taken at same locations directly under the thalli to a depth of 4 cm. All lichen and soil samples were carefully cleaned of plant debris in the field and subsequently air-dried.

2.2. Laboratory analysis

The lichen and soil samples were ashed at a temperature of 450°C in a muffle furnace. After homogenization the ^{137}Cs activity were measured using a gamma spectrometry system. Extended Range Coaxial Ge Detectors (XtRa) model GX4018 (Canberra) with a relative efficiency of 40% and a resolution of 1.8 keV for the 1332 keV peak of ^{60}Co were applied. The detector was coupled to an 8192-channel computer analyser and GENIE 2000 software. The measurements for each sample lasted 80,000 s. The ^{90}Sr activity was determined after γ-ray measurements. Firstly, the sample residue was digested with concentrated nitric acid. After digestion, the residue was collected on hard filter paper and discarded. The filtrate was diluted with distilled water to 150 ml. The reagents 100 ml of 8% oxalic acid, 20 mg of natural strontium, and ammonium (to raise pH to 4–4.5) were added to the diluted filtrate. The solution was heated to 80°C in order to completely precipitate the strontium oxalate. The precipitate was collected on hard filter paper and allowed to dry in ambient conditions. The oxalate was then converted to carbonate at 650°C in a muffle furnace. Subsequently, the strontium carbonate was separated from calcium carbonate with 65% HNO_3. Radium removal was done by precipitation with $BaCrO_4$ in the presence of a buffering agent (pH = 5.5). 20 mg of stable yttrium was added, and the samples were allowed to stand for 21 days to reach complete equilibrium between ^{90}Y and ^{90}Sr (Volchock et al., 1957). The yttrium was then precipitated as a hydroxide, converted to oxalate and collected on a pre-weighed filter. Beta activity of the samples was measured using Low-Level Beta Counter FHT 7700T (ESM Eberline) with the background count rate of 0.01 counts s^{-1} and the lowest detectable activity of 3 mBq per sample. The time measure for each sample was 21,600 s. Obtained date of ^{90}Sr and ^{137}Cs were recalculated for decay corrected back to the time of sampling.

Loss on ignition (LOI) method was used to estimate total organic matter in soil based on gravimetric weight change with high temperature oxidation of organic matter. After drying at 105°C, the samples were ignited in a muffle furnace for 5 h at 550°C.

The reliability and accuracy of measurements performed in our laboratory were verified in 2018 during the intercalibrations organized within the National Atomic Energy Agency in Poland (PAA) and analysis organized yearly by IAEA-MEL Monaco (Table 1).

2.3. Statistical data analysis

Levene's test and the Kolmogorov-Smirnov test were used to assess the equality of variance and normality of the distribution for the dataset. Since the assumptions were not achieved, even after Box-Cox-transformation of the data, the correlation between all analyzed variables (the distance from the glacier forehead, ^{137}Cs and ^{90}Sr in the thalli of *C. delisei*, ^{137}Cs and ^{90}Sr in soil, normalized content of ^{137}Cs and ^{90}Sr in soil, content of LOI in soil) were tested with Spearman's rank correlation coefficients and graphically presented in the scatter plots, while the differences between the content of radionuclides in lichen thallus and soil were tested with nonparametric Mann–Whitney *U* test.

3. Results

Arithmetic mean activity of ^{137}Cs in *C. delisei* thalli was 77.4 Bq kg^{-1}dw and ranged from 5.38 Bq kg^{-1} dw to 280 Bq kg^{-1} dw (Table 2, Fig. 2). In the case of ^{90}Sr, arithmetic mean activity in lichen thalli was 11.1 Bq kg^{-1} and changed in the range from 3.7 Bq kg^{-1}dw to 28.1 Bq kg^{-1}dw (Table 2, Fig. 2). Arithmetic mean activity of radionuclides in surface soil layer was 211 Bq kg^{-1}dw for ^{137}Cs (ranged from 60.6 Bq kg^{-1}dw to 426 Bq kg^{-1}dw) and 7.5 Bq kg^{-1}dw for ^{90}Sr (ranged from 4.5 Bq kg^{-1}dw to 12.8 Bq kg^{-1}dw).

In the case of loss on ignition in soil, it ranged from 10.3% to 49.6% and the highest organic matter concentration occurred near the shoreline (Table 2). The ^{137}Cs value normalized by LOI ranged from 2.8 to 15 and in case of ^{90}Sr the dispersion was smaller and within range from 0.15 to 0.57. The higher values were found nearby glacier forehead in both cases.

The content of ^{137}Cs significantly differed between *C. delisei* and soil samples (z-score = −3.147; p = 0.0009; Fig. 2A); on the other

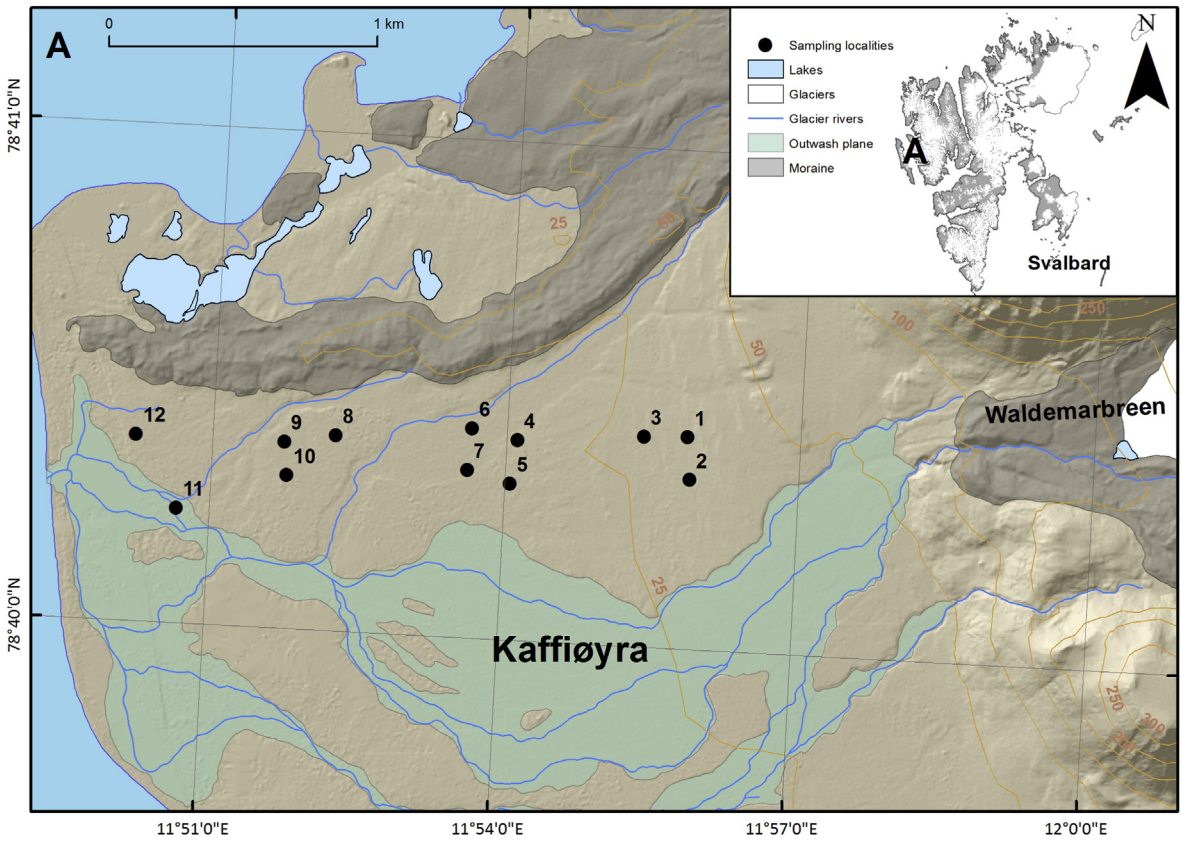

Fig. 1. Kaffiøyra Plain with its location on Svalbard archipelago.

Table 1
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	0.23 ± 0.01	0.26 ± 0.003	Pass	Pass	Accepted	IAEA
^{90}Sr	0.45 ± 0.04	0.53 ± 0.005	Pass	Pass	Accepted	
^{137}Cs	18.52 ± 0.52	18.78 ± 0.56	Pass	Pass	Accepted	PAA
^{90}Sr	4.47 ± 0.44	4.09 ± 0.21	Pass	Pass	Accepted	

hand, no difference was recorded in case of the ^{90}Sr content (z-score = 0.952; p = 0.347; Fig. 2B). The contents of both ^{137}Cs and ^{90}Sr in the *C. delisei* thalli strongly depend on the distance from the glacier forehead (Table 3; Fig. 3A); however, the opposite patterns for these radionuclides were revealed: the ^{137}Cs content decreased significantly with the distance, while the ^{90}Sr content increased. The content of LOI in soil samples was negatively associated with the distance from the glacier forehead (Table 3; Fig. 3A). The content of ^{90}Sr in soil was negatively related with the content of ^{90}Sr in *C. delisei* and positively with the content of ^{137}Cs in soil (Table 3; Fig. 3B). Considering other variables, their changes with the distance from the glacier forehead did not appear to be significant (Table 3; Fig. 3A). Both, ^{90}Sr and ^{137}Cs normalized activity calculated as isotope activity in soil divided by the share of organic matter in soil presented a similar trend and increased with distance from the glacier forehead (Table 3; Fig. 3A).

4. Discussion

The presented results show that levels of ^{137}Cs activity in the lichen *C. delisei* in 2012 (5.4–280 Bq kg^{-1}) was slightly higher than previously reported for Svalbard (Gwynn et al., 2004). The analyses of lichen samples collected from around Kongsfjorden located 20 km away from Kaffiøyra in 2001 and 2002 showed that ^{137}Cs activity concentrations ranged from 30 Bq kg^{-1} to 140 Bq kg^{-1} (Gwynn et al., 2004). Similar range of activity were found in bryophytes: *Ptilidium ciliare* and *Racomitrium lanuginosum* collected in 2012 in Kaffiøyra and reached 82.7 and 208.1 Bq kg^{-1}, respectively (Saniewski et al., 2020). Activity of ^{137}Cs in arctic plants *Salix polaris* and *Cassiope tetragona* collected in 2014 near Longyearbyen were lower and reached 5.5 Bq kg^{-1} and 1.4 Bq kg^{-1}, respectively (Kłos et al., 2017). This can be caused by the physiology of plants and lichen. 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 (Nimis et al., 2002). At the same time the activities of ^{137}Cs in lichen presented in this study were definitely lower than activity in lichen from a highly contaminated area, that is in Vaga and Østre Namdal districts, areas which received significant Chernobyl fallout, with deposition densities of about 80 kBq m^{-2} and 40 kBq m^{-2}, respectively. ^{137}Cs in living part of *Cladonia arbuscula* thalli collected in 2000–2003 in those areas range from 1115 Bq kg^{-1} to 3510 Bq kg^{-1} (Skuterud

Table 2
Total and normalized contents of radionuclides (^{137}Cs and ^{90}Sr; Bq kg^{-1}dw) in the lichen *Cetrariella delisei* and corresponding soil samples, and LOI in soil (%) determined at particular localities.

n	Distance from the glacier forehead (m)	*Cetrariella delisei* [Bq kg^{-1} dw]		Soil [Bq kg^{-1} dw]			Normalized (soil)	
		^{137}Cs	^{90}Sr	^{137}Cs	^{90}Sr	LOI	^{137}Cs	^{90}Sr
1	1550	280 ± 4	3.7 ± 0.3	191 ± 4	8.1 ± 0.9	28	6.8	0.3
2	1630	87 ± 2	7.2 ± 0.5	251 ± 6	12.8 ± 0.9	49.6	5.1	0.3
3	1790	120 ± 3	7.4 ± 0.7	238 ± 5	8.3 ± 0.8	30.4	7.7	0.3
4	2190	32.9 ± 2	12.8 ± 0.8	212 ± 5	5.2 ± 0.9	33.7	6.3	0.2
5	2270	168 ± 3	6.6 ± 0.5	200 ± 4	6.7 ± 0.9	18.9	10.6	0.4
6	2350	6.9 ± 1.4	4.2 ± 0.6	247 ± 5	10.3 ± 0.8	22.2	11.2	0.5
7	2470	58.3 ± 2	4.7 ± 0.5	132 ± 3	8 ± 0.9	17.7	7.4	0.5
8	2940	17.8 ± 1.2	17.9 ± 0.7	426 ± 8	6.1 ± 0.6	32.4	10.5	0.2
9	3080	74.9 ± 2.1	15.3 ± 0.6	60.6 ± 2.1	5 ± 0.6	21.9	2.8	0.2
10	3160	5.4 ± 1.2	10.3 ± 0.7	178 ± 5	6.1 ± 0.7	28	6.2	0.2
11	3570	29.9 ± 2.3	14.4 ± 1	288 ± 5	9.2 ± 0.8	18.7	14.9	0.6
12	3620	48.1 ± 2.7	28.1 ± 1.3	102 ± 2	4.5 ± 0.6	10.3	9.9	0.4
Mean	2552	77.4	11.1	211	7.5	26	8.3	0.3
SD	718	80	7.14	94.5	2.4	10.2	3.3	0.1

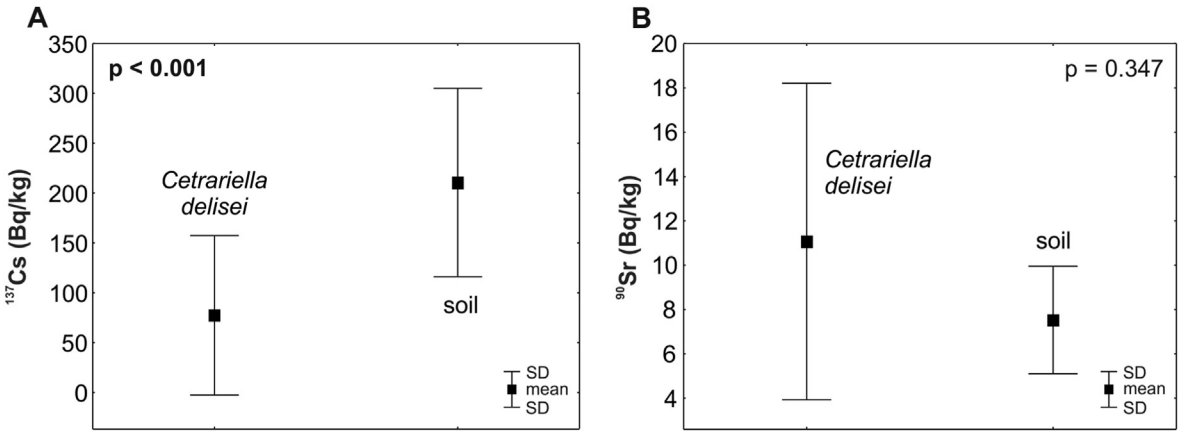

Fig. 2. Comparison between the content of ^{137}Cs (A) and ^{90}Sr (B) in the lichen *Cetrariella delisei* and corresponding soil samples. Black square represents arithmetic mean, whiskers marks one standard deviation (SD), while p values is presented according to the Mann-Whitney *U* test.

Table 3
Spearman's rank correlation coefficients between the studied variables; significant correlations are marked in bold (* - p < 0.05).

Variable	Distance from the glacier forehead	^{137}Cs *C. delisei*	^{90}Sr *C. delisei*	^{137}Cs soil	^{90}Sr soil	Normalized ^{137}Cs soil
^{137}Cs *C. delisei*	**−0.622***					
^{90}Sr *C delisei*	**0.685***	−0.371				
^{137}Cs soil	−0.245	−0.231	−0.028			
^{90}Sr soil	−0.482	0.126	**−0.650***	**0.587***		
LOI soil	**−0.594***	−0.028	−0.063	0.510	0.224	
Normalized ^{137}Cs soil	0.252	−0.217	−0.028	0.475	0.252	
Normalized ^{90}Sr soil	0.182	0.084	−0.357	−0.035	0.448	**0.608***

et al., 2005). Higher activities of ^{137}Cs were measured in lichen individuals of the genus *Cladonia* collected at the "Kraton-3" underground nuclear explosion site in 2002. Activity concentration of ^{137}Cs ranged from 92 Bq kg^{-1} to even 89,000 Bq kg^{-1} and the deposition of ^{137}Cs was also few magnitudes higher: 0.36–700 kBq m^{-2} (Ramzaev et al., 2007). For the area "Kraton-3", where deposition of ^{90}Sr ranged from 0.13 kBq m^{-2} to 770 kBq m^{-2}, the activity in lichens ranged from 24 Bq kg^{-1} to 88,000 Bq kg^{-1} (Ramzaev et al., 2007). Similar activities of ^{90}Sr presented in the our study (3.7 Bq kg-1 to 28.1 Bq kg-1) were measured in Norway in Vaga and Østre Namdal districts, wherein total ^{90}Sr deposition density was much higher than on Svalbard and was 5 kBq m^{-2} in 1987 wherein activity in *Cladonia arbuscula* ranged from 5.5 Bq kg^{-1} to 22 Bq kg^{-1} (Skuterud et al., 2005).

Although global fallout from atmospheric nuclear weapons testing is considered as one of the main sources of radioactive contamination in the Arctic region, relatively high radionuclide activity in biological samples can be caused by an additional input from a melting glacier. Pinglot et al. (1994) indicated that in Svalbard's glaciers the radioactive layers formed after nuclear tests and Chernobyl accident have been well preserved. The analyses of ice core profiles also indicated the nuclear tests and the disaster at Chernobyl as the perpetrators of radioactive deposition (Pinglot et al., 1999). The ice of Svalbard glaciers reaches an activity of even 40 mBq kg^{-1} (Pinglot et al., 1999). The Waldemarbreen glacier decreased by 31.4% until 2015 compared to its maximum extent

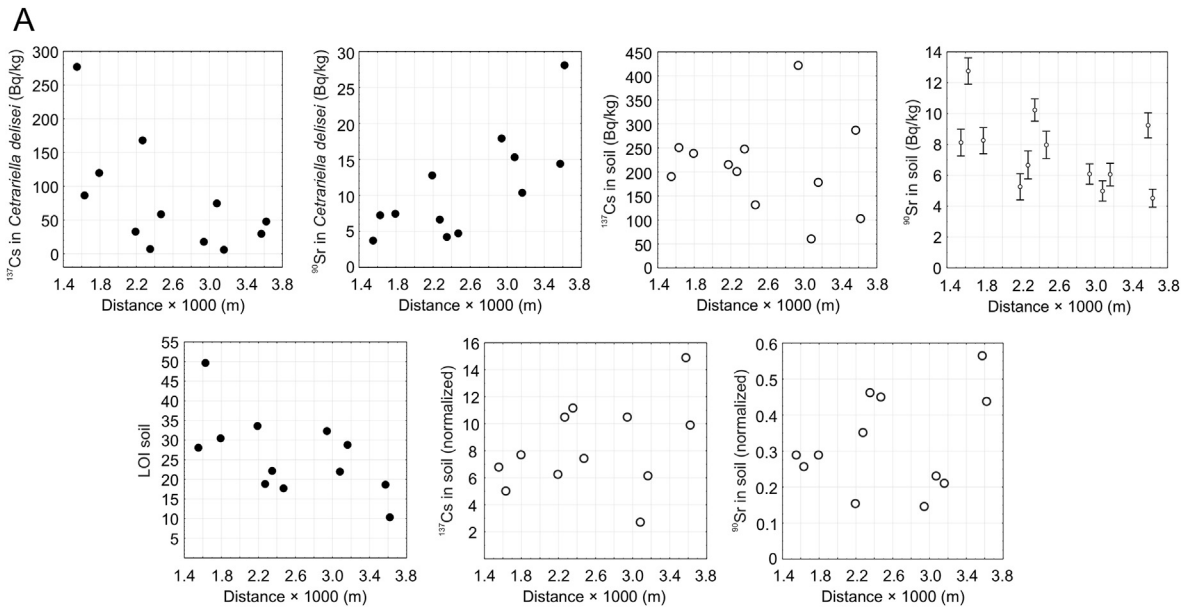

Fig. 3. Scatter plots illustrating relationships of studied parameters (^{137}Cs and ^{90}Sr in *Cetrariella delisei*, ^{137}Cs and ^{90}Sr in soil, content of LOI in soil, and normalized content of ^{137}Cs and ^{90}Sr in soil) with the distance from the glacier forehead (A) as well as relationships between all studied parameters (B). Whiskers indicate measurement errors (^{90}Sr in soil vs. Distance); for the remaining parameters, dots contain measurement errors (for the values, see Table 2). Significant correlations between the parameters (plots with fill dots) were revealed according to Spearman's rank correlation test (see Table 3).

during the Little Ice Age (Sobota et al., 2016). The studied activity of radionuclides was not observed to decrease. The fact that ^{90}Sr, ^{137}Cs concentrations in 2012 were similar or slightly higher than a decade ago may indicate an additional inflow of these isotopes from the glacier. The aggregated transfer factor (Tag) is defined as the ratio of radionuclide activity concentration in plants (Bq kg^{-1}) and the total deposition density in the soil (Bq m^{-2}) (IAEA, 2009). The aggregated transfer factors (Tag) for soil to lichen ranged mostly from 0.12 to 0.99 and the median and mean were 0.37 and 0.40, respectively (Dohi et al., 2015). The biological half-times (Tbio) of the airborne radioactive elements in the epigeic (ground growing) lichens have been estimated to vary from about 1 to 17 years, depending on species, contamination source, environmental and ecological conditions as well as radionuclides washoff with water and with the growth of lichens (biomass increase) (Synnott et al., 2000). Assuming deposits at the levels of 0.2–1.5 kBq m^{-2} after nuclear weapons tests in the 1960s, and 0.020 kBq m^{-2} and 0.84 Bq m^{-2} after accidents in the Chernobyl and Fukushima nuclear power plants, the activity of ^{137}Cs in lichens may range from 2 Bq kg^{-1} to 79 Bq kg^{-1} depending on Tag reporting by Dohi et al. (2015) and considering 12-years biological half-times of the element in thalli (Tbio). The values obtained in this way, lower than the results of our measurements, may be another argument supporting the concept about additional sources of isotopes in the Svalbard region. Additionally, activities of ^{137}Cs in soil is visibly higher than that recorded about decade ago from a nearby Brøggerhalvøya (Brogger peninsula, Kongsfjorden) region (Dowdall et al., 2005). The average activity in soil samples collected in 2002 was 151 Bq kg^{-1} and stayed between 65 Bq kg^{-1} and 250 Bq kg^{-1}. At the same time, the share of organic matter averaged 31.6% with the range from 14.3% to 46.5% was similar to that observed in our study (Table 2). The activity concentrations of ^{137}Cs in soil samples near Longyearbyen collected in 2014 were also lower and range from 12.7 Bq kg^{-1} to 57 Bq kg^{-1} (average 27.9 Bq kg^{-1}) (Kłos et al., 2017). Such a high ^{137}Cs activity in the soil suggests a notorious source of the isotope, which may constitute the nearest melting glacier.

The distance from the glacier forehead seemed to be the essential factor determining the isotopes activity in *C. delisei*. In the case of ^{137}Cs in lichen and share of organic matter in soil decrease with increasing distance from the glacier forehead (Table 2). Lichens are extremely efficient accumulator of chemical elements which are taken up from deposited aerosols, substrate solutions and rain (Nimis et al., 2002). Therefore, cesium ions, which are chemically similar to potassium (nutrient metal) ions, are easily incorporated into the biological structure of lichens (Nimis et al., 2002). Like other heavy metals, mobility of ^{137}Cs increases with decreasing pH, because the ^{137}Cs-ions bound by clay minerals can be exchanged for hydrogen-ions. With increasing pH there is less exchange, ^{137}Cs remains bound and is therefore not available. Low values of pH (3–4.5) 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, which is more strongly sorbed than ^{90}Sr in the top layer of soil (Nawrot et al., 2016).

For ^{90}Sr an increase of activity in lichen was recorded with increasing distance from the glacier forehead. As recorded by Węgrzyn et al., (2016), soil pH measured in the same samples along the Kaffiøyra Plain increased with the distance from the glacier forehead. Comparing pH values with obtained radionuclides content in the lichen thalli, a positive relationship may be assumed between ^{90}Sr activity in lichen and soil pH. The trend was opposite to ^{137}Cs, which may suggest that the pH has no influence on the retention of this radionuclide, or the influence of the pH is masked by the action of the other variables affecting ^{90}Sr mobility in the soil. The mobility of ^{90}Sr is around an order of magnitude greater than that ^{137}Cs, the last is strongly absorbed by organic matter (Cross et al., 2002; Dowdall et al., 2005). Normalized activity of ^{90}Sr and ^{137}Cs in soil significantly correlates ($r = 0.7$, $p < 0.05$) which suggests that the content of organic matter has a great impact on the variability of activity in soil (Table 3; Fig. 3). In general, Sr^{2+} adsorbs to a wide range of aluminosilicates, Fe oxides and other soil minerals via weakly bound outer-sphere surface complexes at the solid water interface (O'Day et al., 2000; Sahai et al., 2000; Chorover

et al., 2008). Similar to ^{137}Cs, ^{90}Sr at low pH is more mobile and more bioavailable, in the experiments about 30% of ^{90}Sr was sorbed to the sediment at pH equal 4 and about 10% was sorbed at pH equal 2 (Wallace et al., 2012). But it is also important the point of zero charge (PZC) described as the pH at which the net charge of total particle surface is equal to zero. The pH of the Sr-sorption edge for a particular soil/sediment is, therefore, highly dependent on the PZC of the adsorbing minerals present. The sorption edge for Sr onto the sediment for chlorite (PZCChlorite = 4.7, Alvarez-Silva et al., 2010) had higher PZC then illite (minor clay fraction) (PZCIllite = 2.5, Hussain et al., 1996; Zhuang and Yu, 2002), which may also explain why some sorption of ^{90}Sr was seen at low pH. Wallace et al. (2012) observed almost complete sorption of ^{90}Sr to the sediments in pH ranged from 6 to 8 while the amount of Sr^{2+} sorbed decreased in pH greater than 8. Migration speed and contamination distribution are a local phenomenon depending on physico-chemical characteristics of the soil, such as pH, organic matter content, and grain size (Baeza et al., 1995; Gaca et al., 2006). In the relatively short transect of 2000 m from the glacier forehead to the seashore, different processes, such as erosion, accumulation of organic material, gleying, and decarbonation, can prevail and significantly affect the ability of lichen to accumulate metals.

5. Conclusions

Similar or higher activities of ^{90}Sr and ^{137}Cs both in lichen *C. delisei* and soil compared to the results from ten years ago suggest that the glacier can be a potential, secondary source of isotopes. Accumulation efficiency of radionuclides in the lichen thalli seems to be influenced by distance from the glacier forehead, which has a statistically significant effect on ^{137}Cs and ^{90}Sr activity in *C. delisei* and LOI in soil. However, when implementing biomonitoring of radionuclide contaminations with lichens, it is important to take into account influence of environmental variability especially in terms of influence of organic material, pH, river erosion that may affect the ability of lichen to accumulate metals or other contaminations.

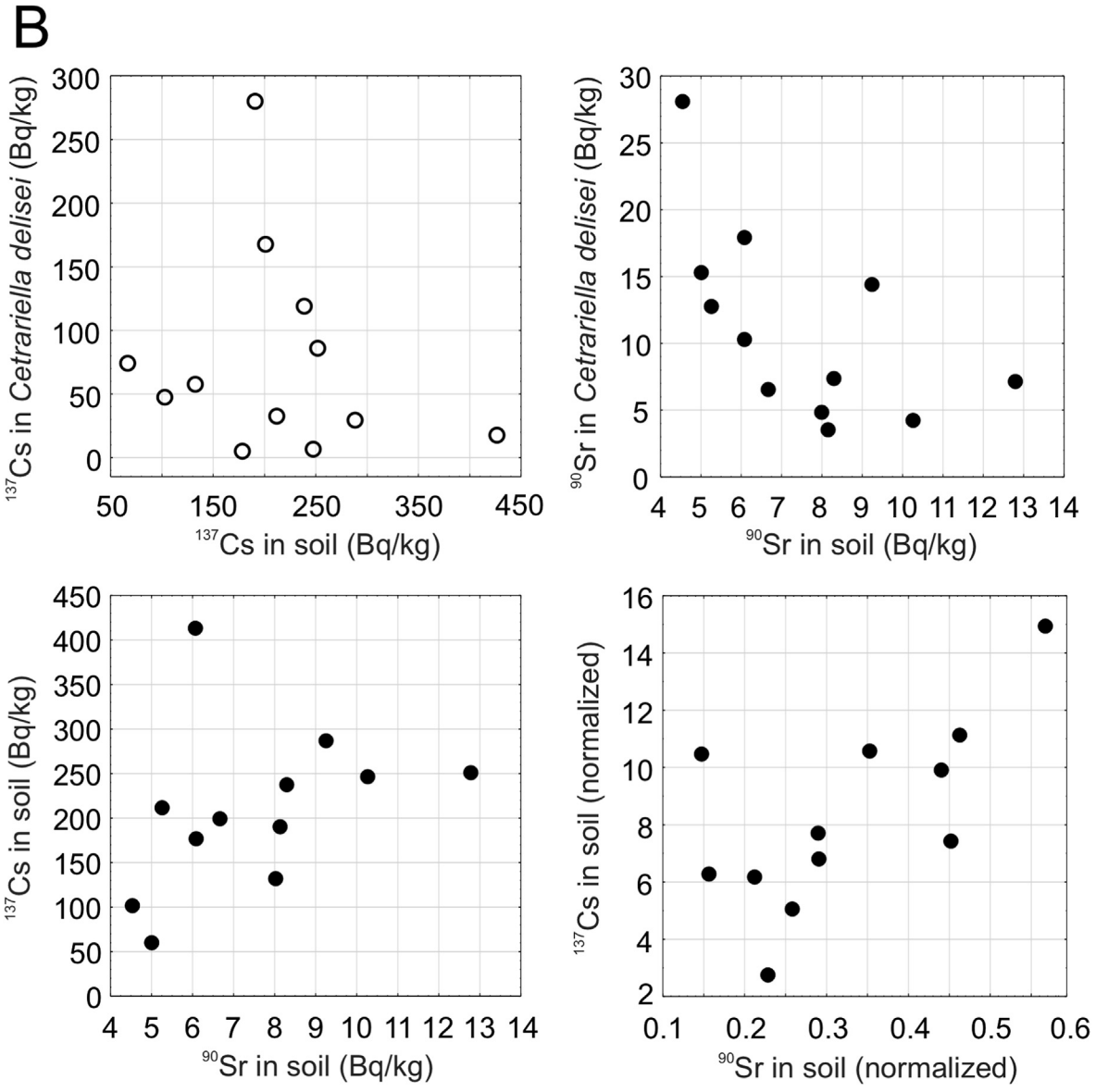

Fig. 3. (*continued*).

CRediT authorship contribution statement

M. Saniewski: Conceptualization, Methodology, Resources, Writing - original draft, Funding acquisition. **P. Wietrzyk-Pełka:** Formal analysis, Data curation, Writing - review & editing, Funding acquisition. **T. Zalewska:** Validation, Supervision. **P. Osyczka:** Formal analysis, Writing - review & editing. **M.H. Węgrzyn:** Conceptualization, Investigation, Resources.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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