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Concentrations of Long-lived Artificial Radionuclides in the Moss-Lichen Cover of Mountain Plant Communities

M. G. Nifontova

Institute of Plant and Animal Ecology, Ural Division, Russian Academy of Sciences, ul. Vos'mogo marta 202, Yekaterinburg, 620144 Russia

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Abstract—Specific features of ^{90}Sr and ^{137}Cs accumulation in individual lichen species and in the moss-lichen cover of plant communities were studied in some mountain ranges of the Polar and Northern Urals. The results showed that the amounts of radionuclides in lichens and mosses of mountain plant communities are at the level characteristic of the moss-lichen cover of flat ecosystems, and their accumulation depends on ^{90}Sr and ^{137}Cs input with the global radioactive fallout. The radionuclide contents in lichens and mosses sampled from different mountain rocks, slopes, and elevations fluctuate around this level. The differences depend both on the structural and functional properties of plants and on the climatic and ecological features of their environment.

Key words: lichens, moss-lichen cover, dynamics of radioactive contamination

Lichens and mosses are successfully used as indicators in long-term radioecological monitoring of the environment. As the Ural region is exposed to a strong anthropogenic pressure, studies on the mechanisms of radionuclide input and migration in its natural biogeocenoses are of great interest. The dynamics of accumulation and fixation of long-lived artificial radionuclides has already been studied in the moss-lichen cover of tundras, forest-tundras, and northern- and middle-taiga forests in relatively flat areas of the Ural region (Nifontova, 1998).

It should be noted, however, that the Urals are a midaltitude mountain system extending meridionally for more than 2000 km and characterized by the prevalence of low-mountain and middle-mountain forms of relief. Radionuclide accumulation by lichens and mosses in mountain regions has been investigated insufficiently. There are only fragmentary and sometimes contradictory data on radionuclide contents in lichens in relation to elevation above sea level (Seaward *et al.*, 1988; Hoffman *et al.*, 1995).

In this article, the results of studies on the accumulation of ^{90}Sr and ^{137}Cs in individual lichen species and the moss-lichen cover of mountain plant communities are presented.

MATERIALS AND METHODS

Studies were performed in the Polar Urals (Mount Slantsevaya, 67°50′ N, 65°50′ E) and Northern Urals (Mount Denezhkin Kamen', 60°50′ N, 59°50′ E; Mount Kos'vinskii Kamen', 59°50′ N, 59°50′ E). Individual lichen species and samples of the moss-lichen cover were collected in plant communities growing on mountain slopes and in the foothills. Plant samples (in two to five replications) were taken from the northern and southern slopes of Mount Slantsevaya (at elevations of 300 and 150 m a.s.l.), the northern slope of Mount Denezhkin Kamen' (1000, 850, 400, and 250 m), and the eastern slope of Mount Kos'vinskii Kamen' (900 m). The lichens *Cladina stellaris* and *Flavocetraria nivalis* were used as indicator species. The moss-lichen cover consisted mainly of species belonging to the genera *Cladina, Cladonia, Cetraria, Pleurozium, Hylocomium*, and *Polytrichum*.

Plant samples were cleaned of extraneous matter, dried to the air-dry state, and incinerated at 450°C. The concentration of ^{90}Sr was determined radiochemically by daughter ^{90}Y with subsequent radiometry of sediments in a universal low-background instrument fitted with an SBT-13 end-window counter; ^{137}Cs was determined using an AI 256-6 gamma spectrometer with a thallium-activated NaI crystal. Statistical error did not exceed 15–20%.

RESULTS AND DISCUSSION

In the mountain tundras on the slopes of the Slantsevaya (the Polar Urals), Denezhkin Kamen', and Kos'vinskii Kamen' (the Northern Urals) mountains, the average values of radionuclide contents in the moss-lichen cover were closely similar (t_{exp} = 0.5–2.1 at t_{st} = 2.3). Concentrations of ^{90}Sr in plant samples varied from 90 to 140 Bq/kg dry weight, and those of ^{137}Cs, from 210 to 370 Bq/kg. In the foothills, the amounts of radionuclides accumulated in samples of the moss-lichen cover were significantly lower (t_{exp} = 2.1–3.6 at t_{st} = 2.1) than in samples of the same species composition collected on the slopes. Concentrations of

^{90}Sr and ^{137}Cs in plants did not exceed 60 and 110 Bq/kg, respectively.

These differences were manifested less clearly in the indicator lichen species. As follows from Table 1, ^{90}Sr concentration in *Cladina stellaris* and *Flavocetraria nivalis* thalli collected on mountain slopes varied from 90 to 160 Bq/kg, and ^{137}Cs concentration, from 230 to 450 Bq/kg. In the same lichen species growing in the foothills, concentration ranges were 50–90 Bq/kg for ^{90}Sr and 100–220 Bq/kg for ^{137}Cs. Apparently, individual features of plants (anatomical and morphological structure, thallus age) have an effect on the accumulation of radionuclides by lichens belonging to different taxa.

These differences were studied in more detail using plants collected on mountain slopes at different elevations. On Mount Denezhkin Kamen', the highest radionuclide content was revealed in the moss-lichen cover of mountain tundras at an elevation of 1000 m a.s.l. (Fig. 1). At elevations of 850 and 400 m, ^{90}Sr and ^{137}Cs concentrations in plants decreased by 30–50% (data statistically significant, $t_{exp} = 2.9–7.5$ at $t_{st} = 2.6$); in the foothills, they were equal to only 15–30% of the maximal concentrations.

Mount Slantsevaya is lower, and these differences were less pronounced (Fig. 2). The highest radionuclide content in the moss-lichen cover was revealed in mountain tundras near the summit; in the foothill forest-tundra areas, its radioactivity decreased by 20–50%. The amount of ^{90}Sr and ^{137}Cs accumulated in plants from the northern slope was 1.3–3.5 times greater than that in plants from the southern slope.

Atmospheric fallout is the main source of ^{90}Sr and ^{137}Cs accumulated by lichens and mosses. The amounts of precipitation in mountain ranges, especially on windward slopes, are much greater than in flat areas (Mil'kov and Gvozdetskii, 1958), and this promotes radionuclide accumulation by plants.

Similar data on the increase of ^{137}Cs concentration at greater elevations were obtained for four lichen species of the genus *Umbilicaria* in the mountain regions of Poland (Kwapulinski *et al.*, 1985) and for lichens of highland Romania (Bartok *et al.*, 1998). In addition, vertical zonality in the distribution of artificial radionuclides and a direct correlation between their contents in plants and elevation above sea level were demonstrated (Demkiv, 1967; Mandzhgaladze *et al.*, 1997).

It should be noted that Mount Kos'vinskii Kamen' is characterized by the well-expressed outcrops and placer deposits of two ultrabasic magmatic rocks, pyroxenites and dunites. The former contain a variety of minerals and, upon erosion, form a rough cover with numerous cracks, which accumulate fine earth suitable for plant growth. In the case of dunites, the products of erosion are highly permeable to water, and fine earth in cracks rapidly dries up. Hence, the lichen flora on dunites is relatively poor, whereas that on pyroxenites is rich and diverse (Gorchakovskii, 1975).

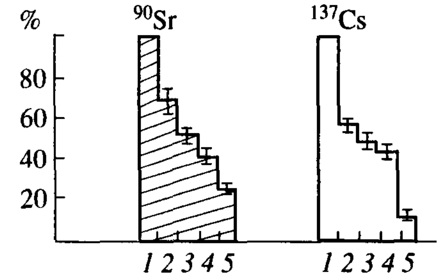

Fig. 1. Distribution of ^{90}Sr and ^{137}Cs in the moss-lichen cover of Mount Denezhkin Kamen' at elevations of (*1*) 1000, (*2*) 850, (*3*) 400, (*4*) 250 m, and (*5*) in the foothills. Radionuclide concentration in plants at an elevation of 1000 m was taken as 100%.

In connection with this, it was interesting to compare radionuclide contents in the same representatives of different lichen taxa collected from the eluvium formed on the surface of dunites and pyroxenites. In 1975, the average ^{90}Sr and ^{137}Cs concentrations in plants were estimated at 170 and 660 Bq/kg, respectively (Table 2). On pyroxenites, these concentrations in the same lichen species were usually higher: 260 for ^{90}Sr and 1080 Bq/kg for ^{137}Cs.

These findings were confirmed in 1990 (Table 2). In lichens growing on dunites, the average concentration of ^{90}Sr was 100 Bq/kg, and that of ^{137}Cs, 270 Bq/kg; in the same species collected from pyroxenites, the respective concentrations were 160 and 450 Bq/kg. In both cases, radionuclide concentrations were significantly lower in plants collected from dunites than in plants from pyroxenites ($t_{exp} = 2.2–4.2$ at $t_{st} = 2.1$).

Experiments demonstrated the possibility of a sufficiently intensive radionuclide migration from solutions and soils to the lichens through the basal parts of their podetia (Troitskaya *et al.*, 1971; Nifontova, 1982). Moreover, there are data that the content of ^{137}Cs in the thalli of *Cladina subtenuis* from granite outcrops is four times higher than in the same lichen from clay soils and is comparable with its content in plants accumulating this radionuclide from sterile sandy soils

Table 1. Radionuclide concentrations in indicator lichen species, Bq/kg (above the line, in the Polar Urals; below the line, in the Northern Urals)

Species	Mountain slopes		Foothills	
	^{90}Sr	^{137}Cs	^{90}Sr	^{137}Cs
Cladina stellaris	150 ± 30 / 100 ± 20	450 ± 70 / 310 ± 50	90 ± 10 / 50 ± 10	190 ± 40 / 120 ± 30
Flavocetraria nivalis	160 ± 30 / 90 ± 10	430 ± 90 / 230 ± 30	50 ± 10 / 70 ± 10	100 ± 40 / 220 ± 20

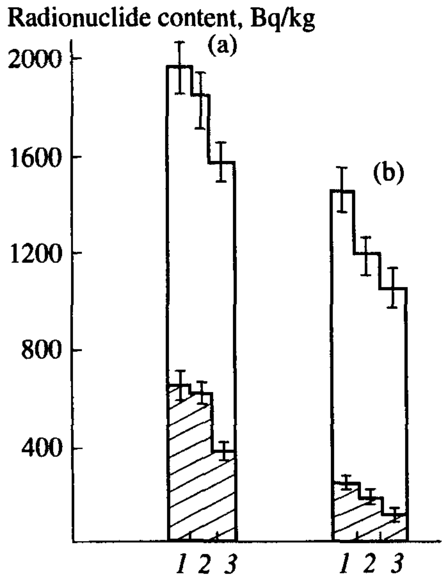

Fig. 2. Contents of ^{90}Sr (hatched area) and ^{137}Cs in the moss-lichen cover on the (a) northern and (b) southern slopes of Mount Slantsevaya at elevations of (*1*) 300 m, (*2*) 150 m, and (*3*) in the foothills.

(Garher and Jenkins, 1991). Apparently, the texture, structural features, and specific physicochemical properties of parent rocks have an effect on the process of radionuclide transfer to plants from the soils formed on the basis of these rocks.

It was noted previously (Nifontova, 1995) that radionuclide contents in lichens of different taxa vary within a wide range. As shown in Table 2, the highest and the lowest concentrations of ^{90}Sr and ^{137}Cs in different lichen species growing on both dunites and pyroxenites can differ by a factor of 1.5–2.5.

Table 2. Radionuclide concentrations (Bq/kg) in lichens collected from substrates formed on different parent rocks (years of observation: above the line, 1975; below the line, 1990)

Lichen species	Dunites		Pyroxenites	
	^{90}Sr	^{137}Cs	^{90}Sr	^{137}Cs
Cladina arbuscula	110 ± 10 / 90 ± 10	690 ± 60 / 280 ± 30	200 ± 30 / 150 ± 10	1260 ± 150 / 500 ± 40
Cladina rangiferina	180 ± 20 / 110 ± 10	870 ± 110 / 330 ± 30	260 ± 120 / 170 ± 10	1070 ± 90 / 480 ± 30
Cladina stellaris	170 ± 20 / 120 ± 10	890 ± 80 / 390 ± 40	280 ± 20 / 180 ± 20	1650 ± 100 / 600 ± 60
Cladonia amaurocraea	280 ± 40 / 90 ± 10	840 ± 70 / 200 ± 20	210 ± 20 / 160 ± 10	1180 ± 100 / 450 ± 50
Flavocetraria cucullata	130 ± 20 / 90 ± 10	430 ± 40 / 240 ± 20	250 ± 20 / 140 ± 20	850 ± 80 / 330 ± 30
Cetraria laevigata	190 ± 20 / 80 ± 10	470 ± 20 / 220 ± 30	330 ± 30 / 190 ± 20	910 ± 120 / 460 ± 50
Alectoria ochroleuca	140 ± 20 / 90 ± 10	460 ± 60 / 200 ± 20	300 ± 30 / 140 ± 20	650 ± 70 / 360 ± 40

The available data are sufficient for tracing the dynamics of the radionuclide content in the moss-lichen cover of mountain tundras. During 15 years, the amounts of ^{90}Sr and ^{137}Cs accumulated by lichens from Mount Kos'vinskii Kamen' decreased by 40–60%, on an average (Table 2). Similar results were obtained in studies on radionuclide contents in the moss-lichen cover of Mount Slantsevaya. In the mid-1970s, the average concentrations of ^{90}Sr and ^{137}Cs in the moss-lichen cover of mountain tundras were 390 ± 30 and 1320 ± 130 Bq/kg; in the foothill forest-tundra areas, they were 260 ± 30 and 930 ± 90 Bq/kg, respectively. After ten years, radioactive contamination decreased by 50–60% in the mountain tundras and by 50–70% in the forest-tundra. In the next decade, radionuclide contents in plants further decreased by 10% on the mountain slopes and by 10–20% in the foothills.

Changes in the proportions of radionuclides in plants confirm the trend described above. In the mid-1970s, the ratio of their specific activities ($^{137}Cs/^{90}Sr$) was 3.3–4.3; today, it ranges from 1.8 to 2.8. This is consistent with data on the dynamics of radionuclide content in the moss-lichen cover of flat areas of the arctic, northern, and southern tundras, the forest-tundra zone, and the northern taiga subzone of the Polar and Northern Urals (Nifontova, 1998).

At northern latitudes, the peak of radionuclide contents in lichens was recorded in the late 1950s and the early 1960s. The subsequent gradual decrease of radioactive contamination is explained by physical decomposition and biological removal of radionuclides from the thalli, on the one hand, and by the decrease of global radioactive fallout, followed by its stabilization at a lower level, on the other (Boltneva *et al.*, 1977; Chelyukanov and Savel'ev, 1991).

The data described above show that the amounts of radionuclides accumulated by lichens and mosses in the mountain plant communities of the Polar and Northern Urals are within the limits previously determined for the moss-lichen cover of flatland ecosystems and depend on ^{90}Sr and ^{137}Cs input with the global atmospheric fallout. However, differences in radionuclide content are observed between the plants growing on different mountain rocks and slopes and at different elevations. These differences depend both on the structural and functional characteristics of plants and on specific climatic and ecological conditions at the site of their growth.

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