NOVA
SCIENCE PUBLISHERS, INC.

THE CURRENT STATE OF TERRESTRIAL ECOSYSTEMS IN THE EASTERN URAL RADIOACTIVE TRACE

V. N. Pozolotina
I. V. Molchanova
L. N. Mikhaylovskaya
E. V. Antonova
E. N. Karavaeva

400 Oser Avenue, Suite 1600
Hauppauge, N. Y. 11788-3619
Phone (631) 231-7269
Fax (631) 231-8175
E-mail: Main@novapublishers.com
http://www.novapublishers.com

In: "Radionuclides: Sources, Properties and Hazards"
Editor: Javier Guillén Gerada
ISBN: 978-1-61942-748-8 2012

In: Radionuclides: Sources, Properties and Hazards ISBN: 978-1-61942-748-8
Editor: Javier Guillén Gerada

Chapter I

The Current State of Terrestrial Ecosystems in the Eastern Ural Radioactive Trace

V. N. Pozolotina,[*] I. V. Molchanova, L. N. Mikhaylovskaya, E. V. Antonova and E. N. Karavaeva
Institute of Plant and Animal Ecology, Ural Division of Russian Academy of Sciences, Yekaterinburg, Russian Federation

Abstract

A large-scale nuclear accident took place at the Production Association “Mayak” in the Southern Urals in 1957. About 74×10^{15} Bq of radioactive substances were released into the atmosphere, which resulted in the contamination of a vast area, the Eastern-Ural Radioactive Trace (EURT). In this case, the main long-lived radionuclide was ^{90}Sr. In 1967, this area was subjected to a secondary contamination resulting from radioactive sediments transported by wind from the Mayak technological reservoir, Karachay Lake. The ^{137}Cs was predominant in the composition of this contamination. Two contamination range areas were established: impact and buffer zones. Within EURT area the radionuclide contamination density decreases with the distance from the accident location and is fairly described as a power function. The specific activity of radionuclides in the herbaceous plants depend on the density of soil contamination. However, transfers coefficients for plants of impact zone were, as a rule, lower than that for background one. Calculations indicated that inpresent stock of the radionuclides in EURT soils is 570×10^{12} Bq for ^{90}Sr, 66×10^{12} Bq for ^{137}Cs and about 2×10^{12} Bq for ^{239,240}Pu. The stock in the impact zone consist of 75% of ^{90}Sr, 70% of ^{239,240}Pu and only 23% of ^{137}Cs from their total amount within EURT zone. Most of ^{137}Cs stock is located in the buffer area where it was received as a result of the Karachay accident. Doze loads upon some herbaceous plants were evaluated. In the impact zone, they exceed background level on 1–3 orders of magnitudes. The aspects of flora diversity within the EURT were studied. The natural growth in the EURT zone is a complex of synanthropic and semi-natural cenosises on the

[*]E-mail address: pozolotina@ipae.uran.ru.

different stages of degradation and restoration. Species diversity in the impact zone is very high; some communities have up to 65 species, it is associated with a low anthropogenic load. The current state of phytocenosises in the demolished local villages is still largely determined by the degree of man's impact in the pre-accident period and recultivation activities. The natural ecosystems successfully recovered at a faster pace.

Introduction

Modern society faces the need to build its activity within the parameters that determine the stability of the biosphere. Under conditions of an increasingly growing technological burden, one should take into account the formation of a new, globally ecological factor – introduction into the biosphere of artificial radionuclides and the ionizing radiation generated by them. Currently, one of the main ways of radionuclides getting into the environment is through the operation of atomic power plants, which is often accompanied by emergency situations.

Such a complicated radio-ecological situation has developed in the Urals region. Here, during the development of the atomic project in the middle of the last century a powerful production association (PA) "Mayak" was established. At this plant on September 29, 1957 a large radiation accident occurred (so-called Kyshtym accident), during which 74×10^{15} Bq of radioactive substances were discharged into the atmosphere. It resulted in the contamination of large area (23000 km^2), named later as the East-Ural radioactive trace (EURT). ^{90}Sr prevailed among long-lived radionuclides in the emergency emissions. Later, in 1967 this same area was exposed to a secondary contamination caused by wind transfer of radioactive bottom sediments from the shores of the Karachay Lake – the technological reservoir of PA "Mayak". The main contaminant in this case was ^{137}Cs. We have carried out a long-term radio-ecological investigation of the EURT territory in two complementary directions. The first direction includes an assessment of the intensity of radionuclides migration in soils and food chains leading to humans. The second one covers the study of the biological effects on plants under conditions of chronic exposure.

The objectives of this work: 1) ranking of EURT territory in terms of contemporary radionuclide contamination, 2) study of the features of migration of long-lived radionuclides within distinguished zones, 3) evaluation of dose rates, 4) estimation of the state of natural plant communities in the EURT area.

Material and Methods

The territories studied are in the East Ural radioactive trace located within the Trans-Ural forest-steppe, which is characterized by the alternation of steppe meadows, birch, birch and aspen small groves and pine forests [1]. The soil cover is dominated by various subtypes of gray forest soils and chernozem soils of varying thicknesses and degrees of leaching; varieties of brown forest and peaty soils are here as well. Throughout the EURT there are areas with soil cover disturbed by post-emergency rehabilitation measures.

In the course of studies at different distances from the epicenter of the accident, plots were selected covering the main types of ecosystems. Soil profiles were laid on each of them for sampling. As a rule, layers of soil samples were taken with 5–10 cm capacity to a depth of 50 cm. The total content of radionuclides in the 50-cm soil layer, rated to the area, was called the contamination density of radionuclides or the stock. In the vicinity of the profiles, samples of above-ground mass of the dominant plant species, forest and meadow grasses were taken. Background areas, where soil and plant samples were also taken, had been located outside the emergency emission zone in 1957, about 30–40 km from the western border of EURT. All samples were dried to air-dry state, and then incinerated at t=450º C. The content of ^{137}Cs in selected samples was determined by a gamma-ray analyzer with a germanium semiconductor detector "Canberra Packard" (USA) with a detection limit of 0.1 Bq. The content of ^{90}Sr was determined by radiochemical method [2]. The procedures were based on the radinuclide leaching by 6 N HCl-solution from preliminary prepared samples. Precipitating of ^{90}Sr in the oxalate form, separating of ^{90}Sr kept in balance with the daughter product of decay – ^{90}Y. Measurement of the prepared specimen of ^{90}Y was carried out with the use of an alpha-beta radiometer (Russia), detection limit of 0.2 Bq. The plutonium content in samples was also determined by the radiochemical method [3]. This method includes leaching isotopes of plutonium by mixing concentrated acids (HNO_3+HCl) from preliminary prepared samples, precipitating ones on ion-exchange resin, then purifying and stripping them from the ion-exchange column in succession by H_2O and 0.5 N HNO_3 –solution, electrodepositing them on disks made of stainless steel. Measurement of prepared specimens was carried out with the use of an Alpha Analyst type of "Canberra Packard" (USA) spectrometer with semiconductor detectors (PIPS) and GENIE-2000 software. The lower limit of detection was 0.001 Bq. The procedural error of the methods did not exceed 20%. For correct assessment of radionuclides in samples collected in different years, the correction for the radioactive decay was applied.

Geobotanical studies were based upon a scale of abundance of species proposed by O. Drude [4]. It identifies the following gradation: un. (unicum) – species is represented in the community by a single specimen, whose projective cover (PC) is 0.1–1% of the area of test area plot; sol. (solitariae) – species is met sporadically or in very small quantities, with PC 1–5%; sp. (sparsae) – species appears in small amounts or occasional dissemination, with PC 6–10%; cop.$_1$ (copiosae) – species grows quite profusely, with PC 11–25%; cop.$_2$ – species grows abundantly or scattered, with PC 26–50%; cop.$_3$ – species grows very abundantly or scattered, but throughout the community, with PC 51–70%; soc. (sociales) – species is a background in this community, its PC can reach 100%. In addition, classification of K. Raunkier [4] was applied, who identified five types of herbaceous plants according to the location of the renewal buds relative to the soil surface: 1) phanerophytes – buds are located high above the ground; 2) chamephytes – buds are close to the surface, but in the snow layer; 3) hemicryptophytes – renewal buds are on the surface level; 4) cryptophytes – renewal buds are in the soil, and 5) therophytes – annuals with wintering seeds.

1.1. The Spatial Distribution of Long-Lived Radionuclides in Soil-Vegetation Covers at EURT

The experience gained in the radio-ecological survey of contaminated areas indicates the need for their ranking according to the content of radionuclides. It facilitates the interpretation of the received data and helps provide a strategy for further study of features of migration and redistribution of radionuclides in soil and vegetation cover. Ranking results are also used to arrange non-uniformly scaled monitoring, determine body burden on living organisms, and justify social protection and rehabilitation measures. The ranking is based on the principle of separation of impact and buffer and background zones. The impact zone is located in the area of the maximum content of radionuclides; the buffer zone is adjacent to the impact zone and includes territory with a gradient of radionuclide contamination falling to background level [5, 6].

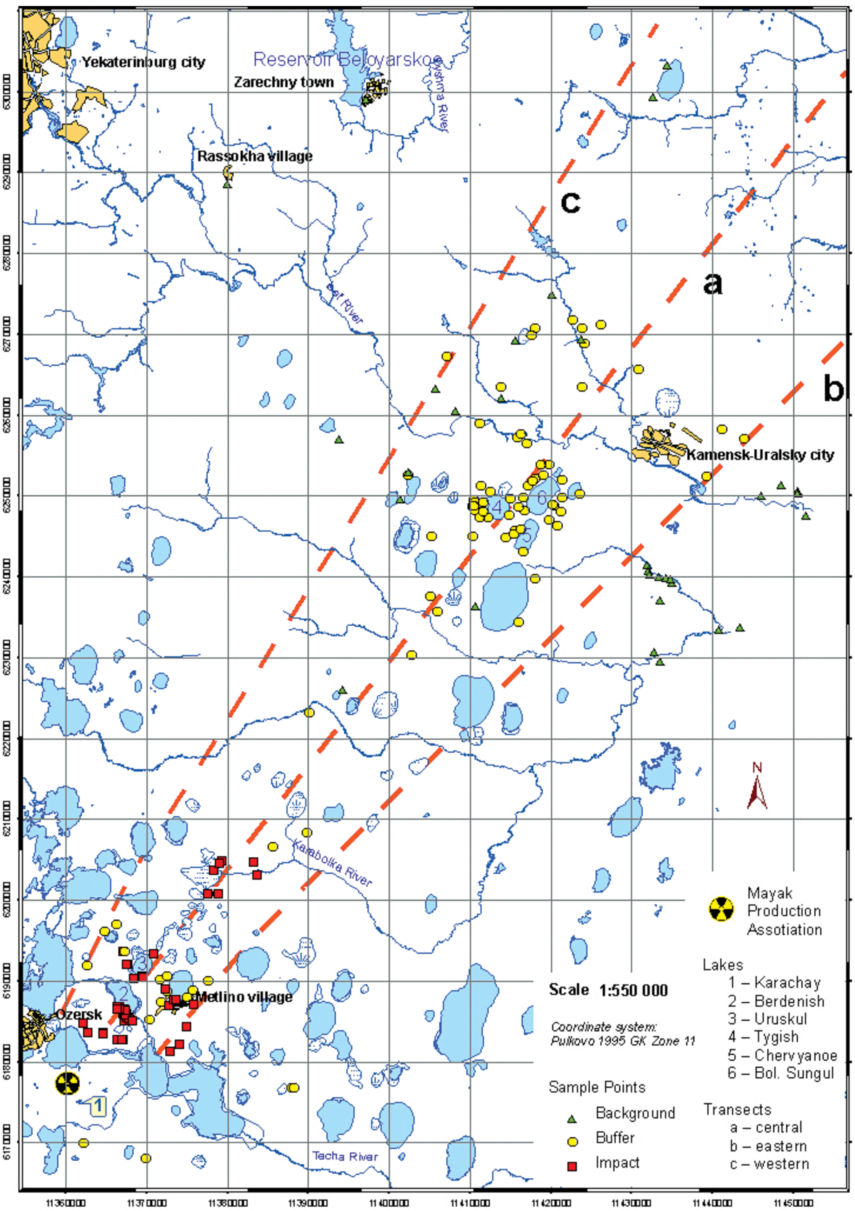

Figure 1. The sketch-map of the investigation region.

Figure 2. The albino-type chlorophyll mutation in *Cirsium setosum* population.

EURT territory was ranked according to the above outlined principles. Considering the significant trace length, the gradient of contamination, and the wide variety of soils and ecosystems, we have established three transects on the surveyed territory. Figure 1 shows the central transect (a) coincided with the axis of EURT, eastern (b) and western (c) ones covered the periphery parts of the trace. We agreed that the impact zone was part of EURT area, located near the epicenter of the accident, where the contamination level of ^{90}Sr exceeded 1×10^6 Bq/m^2. The buffer zone was the territory with the gradient of pollution from 1×10^6 Bq/m^2 to the background values, which in selected background plots were 1.6±0.8 kBq/m^2, 5.0±2.0 kBq/m^2 and 0.1±0.05 kBq/m^2 for ^{90}Sr, ^{137}Cs and $^{239,240}Pu$, respectively.

The spatial distribution of radionuclides in the EURT area is shown on Figure 2. It is clear that within the central transect the changes of contamination density of studied radionuclides with increasing distance from the epicenter of the accident are satisfactorily approximated by a power function (R^2 varied within 0.58 − 0.65). In this case, the radionuclides located according to the level of contamination in a row $^{90}Sr > {}^{137}Cs > {}^{239,240}Pu$. On the eastern periphery of the trace the distribution of ^{90}Sr, ^{137}Cs and $^{239,240}Pu$ is subject to the same dependence. However, here the value of ^{90}Sr and ^{137}Cs stocks are almost identical, and with increasing distance come down from 100 kBq/m^2 to 10 kBq/m^2. On the western periphery of the trace the content of ^{137}Cs in soil, regardless of the distance, is kept at a level (5–10) kBq/m^2. Therefore the soil-vegetation cover of areas adjacent to the eastern border of the impact zone is contaminated with ^{137}Cs to a greater extent than that of the western zone. Additional quantities of this nuclide could enter the soil cover of the eastern section from the other sources of pollution. The stocks of $^{239,240}Pu$ are much lower and change from 5 kBq/m^2 to 0.2 kBq/m^2 as the distance from the pollution source grows. We should note the high variability in stocks of radionuclides in the soils of the surveyed sites. This variation can be contributed by the unevenness of the primary precipitation, landscape-geochemical characteristics of radionuclides migration, their additional inflow with regular emissions of

PA "Mayak", as well as activities for the rehabilitation of contaminated sites, and the type of ecosystems.

To assess the landscape-geochemical features of migration of radionuclides the geochemical interfaces, characterized by the greatest diversity of types of plant communities, were studied. As an example, the results of one of these studies are listed below. A flow adjacent site was chosen in the impact zone near the Berdenish Lake, 13 km from the epicenter Kyshtym accident. Its territory has a variety of plant communities with native and disturbed during the reclamation operations soil cover. As evident from these data (Table 1), the lowest content of ^{90}Sr, ^{137}Cs and ^{239,240}Pu was found in the frequently flooded banks of the lake. In transit to the watershed area their stock in the soils of selected ecosystems increases. The watershed area includes the reclamated territory of the former village, an undisturbed meadow and small woodland. The area under the forest with its man-made disturbance lead to a decrease in stocks of ^{90}Sr and to some extent stocks of ^{239,240}Pu in the soil.

Such decrease may be determined, on the one hand, by prolonged deposition of pollutants in the perennial organs of woody plants, and on the other hand, by the removal of the upper and most contaminated soil layer during land remediation [7]. Analysis of values of ratio ^{90}Sr/^{137}Cs and ^{90}Sr/^{239,240}Pu in soils show that territories of the bank zone and watershed area are different according to the intensity of radionuclide migration. In the subaqueous ecosystem the lower values of radionuclide ratio reflect the relatively high migration ability of ^{90}Sr, which leads to its self-decontamination [8]. Besides that, decontamination of the bank zone of the lake is facilitated by weak expression of surface drain processes. They are interfered with the high density of vegetation cover, which is formed in the absence of anthropogenic load. According to the degree of contamination, ecosystems of the watershed area may be arranged in the following row: steppe fescue meadow> secondary brome post-forest meadow > border birch forest > birch forest> ruderal meadow. Contribution of contemporary gas-aerosol emissions by PA “Mayak” in contamination of the studied territory was evaluated according to the level of radionuclide content in forest litter. Within the soil profile the forest litter was marked as the indicating layer, which summarizes content of radionuclide pollutants of vegetation cover, introduced via root and aerial ways. Investigations were carried out in forest areas of western and eastern transects, identical in composition of plant communities and soil and ecological conditions. They were located almost at the same distance from PA “Mayak”. Since current gas-aerosol emissions of PA “Mayak” mainly include ^{137}Cs among long-lived radionuclides, while ^{239,240}Pu is practically absent [9], below is the represented data on ^{90}Sr and ^{137}Cs (Table 2).

The average content of ^{90}Sr at forest litter of the western transect makes 500 Bq/m^2, and the eastern transect is 2.5 times more. The same refers to difference in levels of soil contamination with ^{90}Sr on these areas. Content of ^{137}Cs in forest litter of the eastern transect is 25 times greater than that of the western one, while the level of soil contamination differs only 9 times. Relative enrichment of forest litter with ^{137}Cs is also indicated by the change in ratio ^{90}Sr/^{137}Cs. Increasing content of ^{137}Cs in forest litter of the eastern transect, not proportional to the increase in soil contamination level, might have been be caused by the additional inflow consisting of gaseous and aerosol emissions from PA “Mayak”. As noted above, EURT territory was exposed to additional contamination. In 1967, a winter with little snow was followed by an extremely dry summer. Karachay Lake, which was used by PA “Mayak” as an open repository of radioactive waste, became very shallow. Bottom sediments contaminated mostly with ^{137}Cs, had been rising with the wind and carried the long distances.

Table 1. The radionuclide stocks in the soil of the different ecosystem types, kBq/m^2

Type of geochemical interfaces	^{90}Sr	^{137}Cs	$^{239,240}Pu$	^{90}Sr / ^{137}Cs	^{90}Sr / $^{239,240}Pu$
Coastal area of the lake					
water edge, reeds	270±50	60±10	1.3±0.2	4.6	207
beach zone, reed-sedge brakes	2 300±630	210±50	7.3±0.9	11.3	315
Watershed area					
birch forest	8 150±200	310±90	25.0±6.0	26.2	326
border of the birch forest	10 600±350	410±100	26.4±6.4	25.7	401
steppe fescue meadow	16 700±3 540	700±200	62.2±15	23.8	268
secondary brome post-forest meadow (native)	13 900±2 900	400±100	33.2±9.5	34.7	418
ruderal meadow (anthropogenic disturbed)	6 700±270	200±60	15.9±1.6	35.9	421

Table 2. The radionuclides content in the forest litter and soil

Samples	Transects	^{90}Sr, Bq/m^2	^{137}Cs, Bq/m^2	$^{90}Sr/^{137}Cs$
Litter	Western	500±370	20±5	25.0±10.9
	Eastern	1 200±300	500±100	2.4±0.8
Soil, 0-15 cm	Western	18 600±4 500	8 900±3 400	2.1±0.4
	Eastern	58 300±13 300	81 700±21 800	0.7±0.2

Table 3. The radioactive inventories in soils of EURT (in brackets confidence intervals are given), n×10^{12} Bq

Locality	^{90}Sr	^{137}Cs	$^{239,240}Pu$
Impact	428.2 (286.4–643.4)	15.1 (10.2–22.4)	1.175 (0.623–2.242)
Buffer	143.0 (70.0–357.0)	51.0 (26.0–56.0)	0.5 (0.4–0.6)
Total	571.2	66.1	1.675

We made a quantitative evaluation of the contributions of these two events as to contamination of soil and vegetation cover of EURT on the impact and its adjacent areas of the buffer zone of the trace. Calculations were made with the use of values of radionuclide ratios that characterize precipitations of various origins, and stocks of radionuclides at reference sites. We also took into consideration the level of global background and contribution of gaseous and aerosol emissions from PA “Mayak”. Previously it was found that in the accident fallout in 1957 the ratio value of $^{90}Sr/^{137}Cs$ was 71.0, while it was 0.3 in the contaminated bottoms sediments of Karachay Lake shores. Solving the system of equations using the above ratios, we calculated the contribution of the two accidents into contamination with ^{90}Sr and ^{137}Cs of soil cover at each transect:

$$x+y=a, \tag{1}$$

$$v+p=b, \tag{2}$$

$$-71x+v=0, \tag{3}$$

$$-0.3y+p=0, \tag{4}$$

where

x − ^{137}Cs, v − ^{90}Sr, received during the accident in 1957 (kBq/m^2);
y − ^{137}Cs, p − ^{90}Sr, brought with the lake bottom sediments of Karachay Lake (kBq/m^2);
a − total content of ^{137}Cs, b − ^{90}Sr in the sampling areas (kBq/m^2).

More detailed calculations of the contribution of various sources into radioactive contamination of soils are given [10]. As one would expect, the main contribution (97%) in the contamination of the central transect was made by the Kyshtym accident, on the western one it constituted 67% and on the eastern one − 31%, based on the total content of radionuclides in soils. Wind transfer of sediments of Karachay Lake added to this contamination 3%, 26% and 63% respectively. The contribution of global fallout and emissions of PA "Mayak" into pollution of the central transect is very small if compared with emergency inflow (<0.1%) and in adjacent territories it does not exceed 7%. Data characterizing the levels of contamination of soil and vegetation cover and patterns of spatial distribution of radionuclides allowed us to assess their integral stock on the study area (Table 3). It is clear that the soil of the impact zone have a concentration of the principal amount of ^{90}Sr (75%) and plutonium isotopes (70%). At the same time most of the ^{137}Cs (77%) is located in the buffer area. This imbalance in the distribution of radionuclides is conditioned by the fact that contamination of the buffer area was mostly contributed by the Karachay accident in 1967.

1.2. Features of Uptake of Long-Lived Radionuclides by Plants

It is known that the uptake of radionuclides by plants depends on their specific features, as well as the complex of soil and climate and environmental factors. During study of the accumulation ability of plants on EURT territory we took into account the wide diversity of plant communities, significant trace length and change of density of soil contamination with the distance. Therefore, samples of herbs and certain species of herbaceous plants, commonly grown at EURT, have been selected on a limited area in accordance with their ranking within the impact and buffer zones.

In the first stages of research we assessed the intrapopulation variation of the accumulation ability of plants as to ^{90}Sr, ^{137}Cs and ^{239,240}Pu. In addition we made special sampling of some species (5 replications for each species) in a limited area of EURT with an average density of soil contamination with ^{90}Sr is 13200 kBq/m^2, ^{137}Cs − 500 kBq/m^2 and ^{239,240}Pu − 50 kBq/m^2. The level of soil contamination with radionuclides is reflected in their content in the aboveground plant mass (Table 4).

Table 4. The specific activity of radionuclides in the aboveground mass of plants growing on limited EURT area, Bq/kg of the air-dry matter

Species	^{90}Sr		^{137}Cs		^{239,240}Pu	
	$\bar{x} \pm m_{\bar{x}}$ (min-max)	CV, %	$\bar{x} \pm m_{\bar{x}}$ (min-max)	CV, %	$\bar{x} \pm m_{\bar{x}}$ (min-max)	CV, %
Trifolium medium L.	419 260±78 025 (228 000-591 600)	37.2	304.8±72.3 (193-530)	47.4	3.23±0.79 (0.56-5.76)	58.8
Lathyrus pratensis L.	37 888±17 595 (3 504-85 496)	92.9	133.8±78.8 (23.0-390.5)	117.8	0.13±0.06 (0.06-0.13)	77.7
Urtica dioica L.	71 876±18 387 (21 360-107 044)	51.2	22.2±6.9 (6.9-39.1)	62.2	0.78±0.37 (0.14-1.78)	82.4
Leonurus quinquelobatus Gilib.	23 060±4 730 (9 038-31 080)	41.0	10.0±2.4 (5.8-17.2)	48.0	0.32±0.14 (0.02-0.69)	76.9
Arctium tomentosum Mill.	8 114±3 741 (3 907-21 341)	92.2	14.0±4.2 (8.4-28.2)	60.0	0.52±0.22 (0.13-1.16)	67.0
Rumex confertus Willd.	7 028±2 966 (1 056-14 877)	84.4	6.4±1.2 (3.9-9.3)	37.5	0.30±0.09 (0.01-0.64)	36.6
Bromopsis inermis (Leys). Holub	5 528±1 339 (1 596-7 838)	48.4	5.7±1.0 (3.1-7.7)	35.1	0.58±0.19 (0.27-1.2)	62.5

Thus maximum specific activity in the aboveground mass of the species studied was noted for ^{90}Sr. Content of ^{137}Cs varies within 5−304 Bq/kg, and ^{239,240}Pu within 0.13–3.23 Bq/kg. A wide range of specific activity of each of the radionuclides in the aboveground mass of plants grown under identical conditions is conditioned by the species specificity. Attention should be paid to the high content of ^{90}Sr in *Trifolium medium* and *Urtica dioica*, and the lowest in *Bromopsis inermis*. The highest specific activity of ^{137}Cs (130 and 305 Bq/kg) was found in the representatives of the *Liguminosae* family, and ^{239,240}Pu in *Trifolium medium*. High volatility in accumulation ability within a population of one plant species is marked for ^{90}Sr and ^{239,240}Pu. So the specific activity of these radionuclides in the aboveground mass of one plant species may vary within the order of magnitude, and coefficients of variation (*CV*) may reach 82–93%.

High intrapopulation diversity of one species of plants according to accumulation of ^{90}Sr was also observed in the work [11]. Intrapopulation differences between specimens in their ability to accumulate ^{137}Cs appeared to a lesser extent. Its specific activity varies, usually 2–3 times under the coefficient of variation 35–62%. An exception is *Lathyrus pratensis*, with a quantity of 117.8%.

A wide range of pollution levels allowed us to estimate regularities of inflow of the main pollutants (^{90}Sr and ^{137}Cs) into the plants, depending on their stocks in the soils. By the examples of common species *Urtica dioica* L. we showed that the content of radionuclides in it does not vary in direct proportion to the level of soil contamination, but is reliably described by power function with a coefficient of determination R^2 = 0.96 for ^{90}Sr, 0.51 for ^{137}Cs and 0.84 for Pu respectively (Figure 3). Similar dependency was observed for other species and, in general, for herbs.

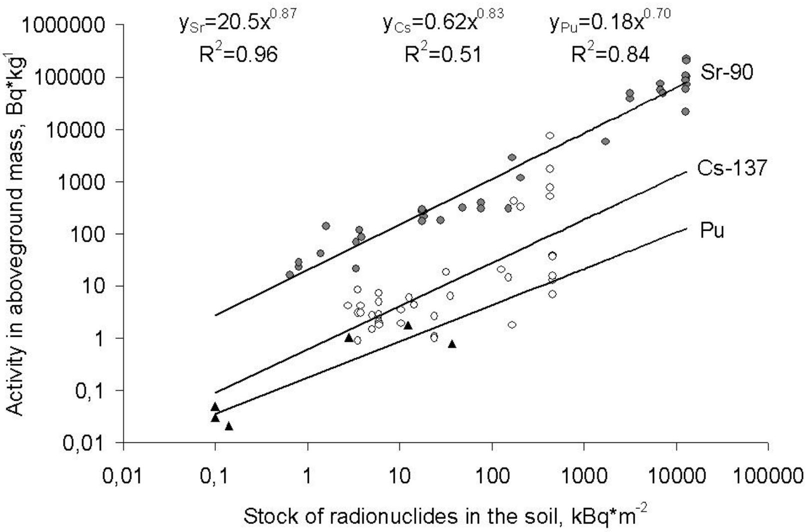

Figure 3. The specific activity in the *Urtica dioica* L. aboveground mass depending on stock of radionuclides in the soils.

Table 5. The transition coefficients ($m^2\ кг^{-1}\times10^{-3}$) of radionuclides to plants

Species	^{90}Sr			^{137}Cs		
	Impact	Buffer	Background	Impact	Buffer	Background
Melandrium album (Mill.)	8.8±2.0	10.1	55.2	0.12±0.04	1.42±0.13	1.11
Stellaria media (L.) Cyr.	4.0	25.6	60.0±32.6	0.05	0.47	0.72±0.07
Urtica dioica L.	8.7±1.6	13.0±1.8	29.7±2.9	0.45±0.25	0.60±0.17	0.60±0.15
Rumex confertus Willd.	1.9±0.6	8.7±2.4	9.4±2.9	0.03±0.01	0.79±0.27	0.60±0.20
Arctium tomentosum Mill.	1.2±0.5	3.9±0.4	15.8±4.6	0.17±0.11	0.09±0.04	0.37±0.12
Cirsium setosum (Willd.) Bess.	7.7±1.7	–	31.5±12.4	0.30±0.13	–	–
Achillea millefolium L.	5.1±3.5	3.0±0.5	14.9±6.9	0.95±0.31	0.16±0.02	2.19±1.20
Tanacetum vulgare L.	7.6	9.6	37.0±13.0	0.31	0.17	0.15±0.03
Artemisia vulgaris L.	5.0 ±1.1	3.0±2.7	6.8±3.8	0.06±0.01	0.16±0.06	0.14±0.02
Leonurus quinquelobatus Gilib.	1.2±0.2	3.7±1.8	18.6±2.7	0.016±0.004	0.10±0.00	0.09±0.01
Pulmonaria mollissima M. Pop.	25.2±1.8	–	38.0	0.91±0.06	–	1.9±0.2
Plantago major L.	10.4±3.1	6.7	55.6±60.5	2.2±1.3	0.6	5.9±1.2
Mean±S.D.	7.2±2.4	8.7±2.5	33.5±6.1	0.46±0.24	0.46±0.13	1.35±0.58

Conditioned by a wide range of soil contamination it is reasonable to characterize the accumulation ability of plants according to the most informative indicator – transition coefficient ($m^2/kg\cdot10^{-3}$). In the surveyed areas all examined species were characterized with a high variability of these coefficients, depending on the specific features and conditions for plant growth (Table 5). However, general rules that determine the uptake of radionuclides to plants showed up clearly. Mathematical analysis has shown that plants growing in the impact zone usually accumulate radionuclides to a lesser extent than in the background territory. Comparison of these samples by Student's test showed highly reliable differences (for ^{90}Sr t_{exp} = 44.2; for ^{137}Cs t_{exp} = 8.6 at t_{tabl} = 2.83 and P = 0.05). It can be assumed that contributingto this decrease of accumulating ability of plants is the specific physical-chemical state of radionuclides in soils, as well as barrier-regulating mechanisms, which are formed in the process of plant adaptation to conditions of chronic pollution of the environment. In all cases, the accumulating ability of plants as to ^{90}Sr is 1–2 degrees greater than that for ^{137}Cs.

1.3. Changes of the Radiation Dose from the Time of the Accident to the Present

Since the Kyshtym accident in 1957 the radioecological situation in the area of the East-Ural Radioactive Trace has undergone significant changes. Scattered at the explosion radioactive waste contained mainly short-lived radionuclides, the most significant contribution was made by ^{144}Ce +^{144}Pr and ^{95}Zr+^{95}Nb. The main danger in the long term was long-lived ^{90}Sr, kept in balance with the daughter product of decay – ^{90}Y: their content in the isotopic mixture was about 5.4%. Laid-down mixture was characterized by the presence of gamma-radiation with a total energy at the time of trace formation 7.63 MeV per decay of ^{90}Sr, accepted as "the frame" radionuclide, as well as beta-radiation with a total activity approximately 3 times greater than the gamma-rays component. Living objects in EURT territory received the main part of the radiation dose during the first four years after the accident. Over the years, the energy of gamma radiation decreased from 7.6 to 0.004 MeV per decay of ^{90}Sr, which resulted in the ninetieth years in reduction of the exposure dose of gamma-radiation at 1 m height in 2800 times [12].

In our study the contribution of the external γ-radiation from natural and artificial radionuclides was calculated based on measurements made with a dosimeter-radiometer MKS-AT 1117MBDPB-01 and dosimeter DRG-01T. At the background territory the exposure dose rate (gamma-rays) was 9−11 μR/h, at the buffer zone − 15−20 μR/h, and at the impact zone it ranged within 20−157 μR/h. During evaluation of the doses accumulated by plants due to ^{90}Sr and ^{137}Cs, we used several approaches. First, on the basis of concentrations of radionuclides in topsoil we calculated absorbed doses to the organs of plants, located in 0−5 cm soil layer. This approach was especially important for cryptophytes and hemicryptophytes plants that have renewal gemmae located on the soil surface or buried into the topsoil. The absorbed dose rate (R) from incorporated radionuclides was calculated according to the model [13]: $R=q_1L_{(\mathrm{Sr+Y})}+q_2L_{(\mathrm{Cs})}$, where q_1 and q_2 – measured specific activity of ^{90}Sr and ^{137}Cs in the soil or vegetative mass; L – absorbed dose rate (cGy/s) created by this radionuclide inside a uniformly contaminated volume at q_0 = 3.7×10^4 Bq/g. This simple model allows us to estimate, at the first approximation, the absorbed doses of different species of plants and compare cenopopulations from different EURT zones according to this parameter. As an example, Table 6 shows the results of calculation of accumulated doses for cryptophytes growing in the impact, buffer and background zones.

It is clear that the absorbed doses calculated for plants in the buffer areas, are usually greater by one order of magnitude than the background areas, and in impact coenopopulations differences with background plantings make 3-4 orders of magnitude. If one takes into account that the lifetime of many herbaceous plants can reach 20 years, plagiotropic parts of cryptophytes can accumulate doses of about 7–9 Gy during the entire period of ontogeny.

Table 6. The specific activity of radionuclides in 5 cm soil layer and caused by them radiation doses for renewal gemmaes of cryptophytes

Zone	Community type	Specific activity, Bq/kg		Exposure dose rate, C/kg×h	Absorbed dose rate, mGy/year
		^{90}Sr	^{137}Cs		
Impact	Dry secondary forbs-grass meadow	113 135–122 750	5 141–5 160	$9.8–11\times10^{-7}$	334.0–362.2
	Border of the birch forest	141 550	7 040	1.2×10^{-6}	419.7
Buffer	Birch outlier	646	314	8.2×10^{-9}	2.8
Background	Old-ploughed field	15	31	4.1×10^{-10}	0.14

Table 7. The absorbed dose changes depending on the distance from the soil surface

Investigated plot	Distance from the surface soil, cm	Absorbed dose rate from ^{90}Sr+^{90}Y, mGy/month
Forest border, N 55º46.47 E 60º53.11	0	3.9
	10	2.5
	20	2.3
	30	2.1
	40	2.0
	50	1.8
	60	1.7
	70	1.6
	80	1.5
	90	1.4
	100	1.3

Obviously these doses refer to small doses for vegetable objects. In order to estimate the radiation dose on the leaves and stems of plants we used coefficients characterizing attenuation of the radiant flux depending on the distance from the soil surface (Table 7). We also took into account irradiation of plants by radionuclides accumulated in the stems and leaves. Thereto, we measured the power flux in the grass, then the aboveground mass of plants at the site was cut and measurements were repeated. The results of calculations of the absorbed dose with a glance to radionuclides accumulated in the vegetative mass of plants showed that in areas with dominating *Poaceae* family (*Bromopsis inermis*), the contribution of incorporated radionuclides is small (from 1.6 to 4.6%). The main source of irradiation is the soil that accumulated a maximum of radionuclides. On sites with dominating *Urtica dioica* – accumulator of ^{90}Sr, the situation is different, and contribution of radionuclides incorporated in vegetative organs varies from 2.8% in the ground surface (1–10 cm) to 28.5% at the height of 80–100 cm.

1.4. Brief Analysis of the State of Flora and Vegetation in the EURT Area

The situation in the impact zone of EURT ruled out the possibility of human habitation, therefore this territory became a unique testing area for scientific research to assess the state of vegetation for the long-term influence of ionizing radiation. First open publications on the assessment of the Kyshtym accident showed that substantial changes in composition and structure of phytocoenoses in the EURT head area appeared within 2 years after the accident. Coniferous trees that first died received doses over 30–40 Gy during the autumn-winter period. Lethal doses, which caused the death of birch stands, were about 5 times greater. The greatest damage was observed in the lower and middle part of the crown. The top level was blown by the wind and washed by rain so it was damaged to a lesser extent. In some cases, changes in community composition were caused not by the direct effect of radiation, but indirect factors. So, 2 years after the accident the defoliation of trees, and partial drying and destruction of trunks occurred in strongly damaged forests. The increase in brightness, temperature and precipitation contributed to a better development of light-demanding herbaceous plants [14]. At plots where the pines perished and birch trees were damaged, the phytomass of grasses increased by 3–5 times, mainly due to reproduction of *Carex*, *Trifolium*, *Calamagrostis*, *Poa* and others. Multiple morphoses were observed in the newly emerging leaves and shoots, though abnormalities were temporary; 3-4 years later the most irradiated of the trees did not differ from the control specimens. Phenological observations showed that foliage expansion and further blossoming of the trees on the contaminated areas was delayed.

From the structure of herbaceous communities, cryptophytes and hemicryptophytes, that have renewal buds located in soil or on the surface, have fallen out completely or reduced their projective cover during the first years. Therophytes reproduced only by seeds have fallen out completely [15].

Similar results were obtained in the course of studies performed in the U.S. at old fields near nuclear weapons testing sites [16]. Additionally, large-scale experiments with irradiation of natural communities by powerful γ-sources, held in the tropical forests of Puerto Rico, broad-leaved forests in Wisconsin, Mediterranean-type forests in France, and coniferous-deciduous forests in the state of Georgia and in Central Russia [17-20] showed that plant communities can survive a fairly intense irradiation. Significant rearrangements in them are observed at cumulative doses over 25 Gy.

Since the date of the Kyshtym accident the radiation doses significantly decreased, and succession processes in phytocoenoses largely regained their former species composition. It is of interest to assess vegetation at EURT territory 50 years after the accident.

Our investigations show that the EURT vegetation presently comprises a wide variety of ecosystem types [7] and high species diversity. A detailed description of the major types from the most contaminated (impact) zone is listed below. Currently, the vegetation here is typical for the steppe zone and is characteristic for the region. Birch forests, grassy steppe communities, as well as small groves of birch and aspen, located in the relief lowering, and rarely pine forests, are represented here. Prior to the accident this area included a small village, arable land and meadows. After 1957, the fields were abandoned, forming temporary plant communities, which represent stages in the process of restoring natural vegetation [15]. On the place of evicted villages recultivation works were carried out: buildings were demolished, the soil plowed to a depth of 70 cm or the upper and most polluted layer was removed. Such areas became overgrown with the nitrophilous vegetation usual for this area. It is still growing because the clay soil firmly retains nitrogen. 50 years after the accident, most of the fallows passed the successional stage, which precedes either the formation of a young forest, or steppe, depending on soil type, i.e. stage of initial phytocoenoses.

Forest communities occupy up to 45% of the head of EURT. In most cases, the age of the trees is about 60–70 years. They are represented by herbaceous birch forests (forb birch forest, forb-reedgrass pure birchwood and forb-reedgrass birch forest with a single pine and aspen, willow-herb-reedgrass birch forest, sedge-grass-brome-reedgrass birch forest, stone bramble-sedge grass birch forest, steppe-meadow-seseli birch forest).

Total projective cover (PC) of these forests is usually up to 70%, sometimes 90%. Forests stand is represented with the *Betula pendula*, with some *Pinus silvestris* and *Populus tremula*. In the second sublayer one can find several species of *Salix* and *Padus*, *Sorbus aucuparia* and *Acer negundo.* Undergrowth is formed by the same forest-forming species. PC of undergrowth is rather small, only 5–10%. The density of the canopy is usually 40–60%, rarely 70%. The composition of shrub layer includes *Chamaecytisus ruthenicus*, *Genista tinctoria, Cerasus fruticosa*, etc.

Dominants of the herbaceous plants of forests are usually *Calamagrostis arundinacea, Rubus saxatilis.* In a steppe version of a birch forest the dominant species include *Festuca rubra, Seseli libanotis, Carex praecox*. Accompanying species with high degree of constancy are grasses, sedges, as well as *Cirsium setosum*, *Galium boreale, Fragaria vesca*, etc. Certain species growing here (*Galium verum, Seseli libanotis, Trifolium montanum*, etc.) indicate that the reedgrass birch forests bear signs of steppe as well. Besides that, ruderal and meadow-ruderal plants can be found in the forests quite often. The height of the grass stand varies from 50 to 100 cm. Species diversity ranges from 29 to 65 species. Moss cover is almost unexpressed.

Special attention should be given to the most transformed forest community in the area of the central axis in 6 km from the epicenter of the accident – ruderal lungwort-thistle community, developed on the place of forb-reedgrass birch forest. Total PC is 100%. There are mature birch trees; the undergrowth is formed by small numbers of aspen and pine trees. The bushes are represented only by *Rosa majalis*. The height of the grass stand reaches 100–120 cm. The dominants here are *Cirsium setosum* and *Pulmonaria mollissima*, codominants are presented by *Lathyrus pratensis*. Besides that, forest, meadow and forest-meadow and ruderal species grow here (33 species registered in total).

Old-growth brome- willow-herb aspen forest grows on the western periphery of trace. Density of the forest stand is 40–50%. Undergrowth is formed by a large number of *Populus tremula* with rare *Prunus padus* and *Betula pubescens*). Shrub synfolium is made up mainly of the *Rosa canina*. The composition of herbaceous synfolium consists of more than 35 meadow-forest species with 90% of PC; height of the grass stand is 100–120 cm. Dominating species are *Epilobium angustifolium* and *Bromopsis inermis.*

The Karabolka River flows along the central axis of the impact zone (see Figure 1). Tall bushes of *Salix* and *Carex* grow along its banks in a narrow strip. Total PC reaches 70%. Undergrowth is formed by single young birch trees. Shrub synfolium is formed mainly by *Salix pentandra* and *S. caprea* with rare *Ribes nigrum*. The height of the grass stand varies between 70 and –90 cm. About 30 species grow in the community. Dominants in this phytocenosis are *Carex rostrata* and *Filipendula ulmaria*. Associated species, as well as the dominants, are typical for moistened habitats; *Equisetum fluviatile, Scirpus sylvaticus, Lycopus europaeus* were found here.

Herbaceous communities occupy about 40% of the impact zone. Grassland coenoses mostly represent post-forest meadows (secondary cow-parsnip-brome meadow with raspberries, secondary forb-brome meadow, secondary forb-grass meadow with stone bramble, secondary forb-thistle-brome meadow with birch). High PC – up to 100% - is typical for such plant communities.

By the end of vegetation period grass stand reaches 80-120 cm. There are single species of young trees (*Betula pendula*) and bushes (*Spiraea crenata*, *Rosa majalis*, *Ribes nigrum*). Meadow-ruderal, meadow and meadow-forest species, such as *Bromopsis inermis*, *Calamagrostis epigeios*, *Poa pratensis,* come to the fore recently. In most cases they are associated with usual meadow species – *Dactylis glomerata*, *Achillea millefolium*, *Knautia arvensis*, different species of *Vicia, Trifolium*, *Lathyrus, Veronica*, as well as forest species – *Fragaria vesca*, *Chamaenerion angustifolium*, *Geranium sylvaticum*. Some ruderal species were found in the studied communities – *Cirsium setosum, Sonchus arvensis, Urtica dioica, Lithospermum officinale*, though they are not abundant.

In phytocoenoses of steppe areas and meadows on the shores of the Berdenish and Uruskul Lakes (see Figure 1) vegetation has largely retained its original appearance. Such is the steppe fescue meadow adjacent to the low, relatively gentle southern slopes of the limestone outcrops near Berdenish Lake. Total PC reaches 100%. Species diversity reached 65 species. There are single young birch trees, shrub layer is more expressed and is formed mainly by *Spiraea crenata*. Grasses and sedges (*Festuca pseudovina*, *Stipa capillata, Carex praecox*) dominate in the grass layer. Typical steppe meadow species such as *Galium verum*, *Artemisia commutata, Silene baschkirorum* are frequently met. However, ruderal species as *Cirsium setosum, Berteroa incana, Leonurus quinquelobatus* also penetrate into these communities.

The *Phragmites communis* brakes with *Salis* are adjacent to the shores of lakes and the edges of marshes in the northern part of the impact zone. The total PC in these phytocoenoses reaches 50%. Shrub layer forms *Salix pentandra* with a fairly high abundance – up to 15%. The birch grows occasionally. The height of the grass stand is very high and reaches 90-150 cm. The high degree of moisture probably has a restricting influence, and therefore species diversity here is extremely poor - only 9 species. The *Phragmites* dominate in this cenosis, the other species are met in single specimens (*Cirsium setosum*, *Lysimachia vulgaris*, *Solanum dulcamara*).

A summary of the above-listed data leads us to the conclusion that natural ecosystems practically went off the recovery stages. Its status, diversity and species resources have a very high estimation. Those anthropogenically transformed in the EURT zone localities deserve special attention. Our investigations show that recovery successions go very slowly. The relationship between radiation and successions is not detected. The land anthropogenic use is a defining factor of the disturbance level of these communities.

Anthropogenically transformed communities (ruderal thistle-brome community, meadow-ruderal thistle-bluegrass-brome community, ruderal beakchervil-thistle-nettle community) occupy areas on the southern shore of Berdenish Lake (see Figure 1). Prior to the accident these areas sheltered a village, subsequently subjected to recultivation. Total PC is 80-90%. The height of the grass stand varies from 50 to 150 cm. Species diversity is relatively low (12 – 32 species). These communities are characterized by a high proportion of ruderal plants with such species as *Bromopsis inermis*, *Cirsium setosum* and *Urtica dioica* dominating in the community, forming extensive brakes and suppressing other species. Besides that, they form a rough, recalcitrant ground litter, which also prevents germination of less aggressive species, and, as a result, a further regenerative succession of communities. *Anthriscus sylvestris, Elytrigia repens, Melandryum album* are found quite often.

In work [21] E. Smirnov gave a detailed analysis of flora in the head part of EURT taking into account life forms, distinguished by anatomical and morphological and ecological features. The influence of life forms of plants and their ability to accumulate radionuclides reveals itself only when it is peculiarly adapted to the specific conditions of growth (high humidity or salinity) or has a distinctive root system structure. Radio-sensitivity of the species largely depends on the life forms of plants, in particular, on location of the renewal buds with reference to the source of ionizing radiation. E.G. Smirnov identified several species that have increased in number on the fourth year after the accident, when short-lived radionuclides decayed and the radiation dose was decreased by two orders of magnitude. Among them – *Cirsium setosum, Taraxacum officinale, Chamaenerion angustifolium, Sonchus arvensis, Potentilla anserine, Poa pratensis.* It was assumed that these species would occupy a dominant position on the EURT territory.

Our research showed that the forecast proved to be correct as to *Cirsium setosum*. This species takes a special place in the community of EURT, it is found in most of the described communities. It is significant to note that at the most contaminated site located 6 km from the epicenter of the accident, the *Cirsium setosum* population has over 70% of plants with albino-type chlorophyll mutation (Figure 4). Growing plants in experimental conditions from seeds collected in this cenopopulation confirmed that this mutation is inherited by next generations.

It can be assumed that due to weakening competition from more radiosensitive plants, aggressive *Cirsium setosum*, which is a vegetative mobile with numerous seeds, has a distinct advantage and scattered throughout EURT territory, appearing not only in synanthropic phytocoenoses, but also in quasinatural communities.

We also discovered that annual and biennial plants, reproducing solely by seeds, are rarely found at the studied EURT sites – mostly in phytocoenoses of the little-used forest roads. Perhaps they are regularly carried here with a transport.

A comparison of impact zone geobotanical descriptions with their adjacent buffer territory (group of Tygish, Chervyanoe, Sungul Lakes, and see Figure 1) showed that the species composition of plant communities is similar to that of the coastal edges of the Berdenish and Uruskul Lakes. However, most of the buffer zone is a residential area. Many villages are located in this territory. Therefore, it is rather hard to maintain the direct comparison of buffer and impact zones. In most cases aligned watersheds and gentle slopes are used for tillage and pasture. Grazing lands are generally occupied with natural meadow vegetation with interplanting grain crops and legumes. A significant part of the investigated area of the buffer zone is covered with mixed birch and pine forests and forest outliers. Shrub synfolium of such forests have *Rubus idaeus*, *Rosa majalis*, *Ribes nigrum*. Herb synfolium is represented by *Rubus saxatilis*, *Fragaria vesca, Glechoma hederacea, Trifolium pratense*, abundant *Geum rivale*, *G. aleppicum*.

Summarizing the foregoing material, we can say that the vegetation of EURT now presents a complex of synanthropic and semi-natural plant communities at different stages of restoration successions. The steppe nature of the studied forest communities can be attributed to increase of brightness and heating of the soil due to dilution of the forest canopy that has arisen under the influence of radiation.

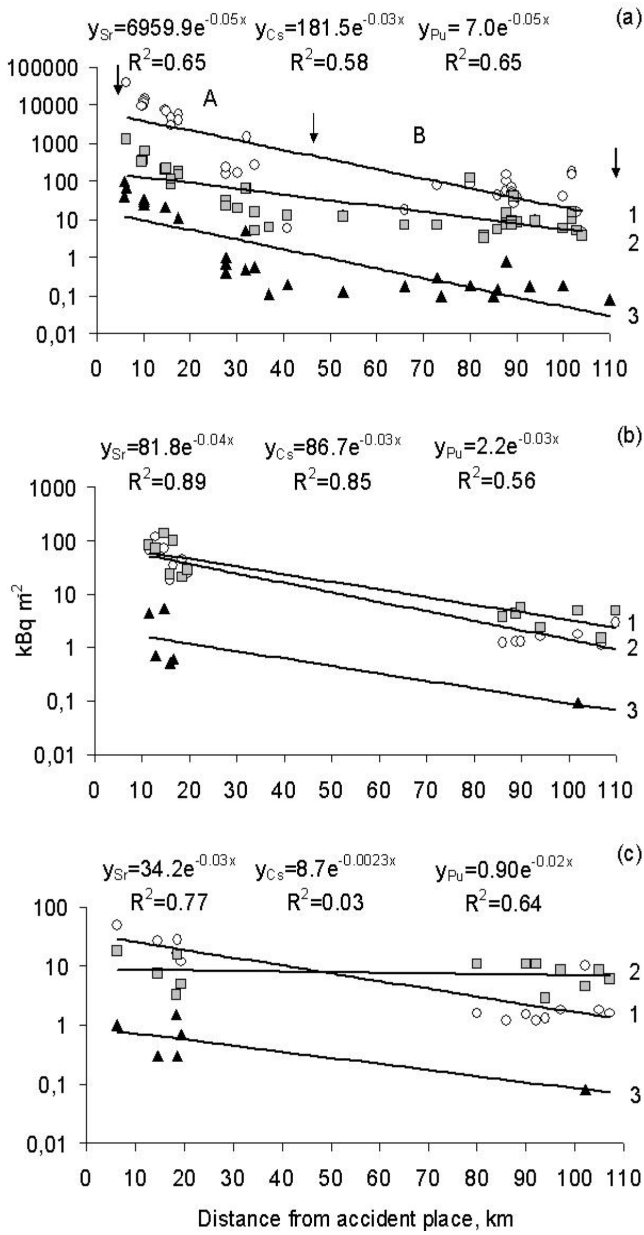

Figure 4. Stock of rdionuclides in soils of the impact (A) and buffer (B) zones of the.EURT. The transects: *a* – central, *b* – eastern, *c* – western. 1 – ^{90}Sr, 2 – ^{137}Cs, 3 – $^{239, 240}$Pu.

In this case we may state a development of the secondary effects of irradiation. The involvement of ruderal species in meadows and forest coenoses of the impact zone is reduced, while plants typical to the communities play a significant role. Species diversity is very high, which is associated with low anthropogenic load.

It is significant to note that the current state of phytocoenoses in place at the demolished local villages is still largely determined by the degree of man's impact in the pre-accident period and recultivation activities.

In recent studies by other authors [22], species diversity and the state of plant communities at the head of EURT is evaluated very high. This area preserves 16 species of plants listed in the “Red Book”. Despite the high levels of radioactive contamination, this zone is regarded as the core of ecological frame of the forest-steppe zone, which plays an important role in preserving biodiversity and maintaining ecological stability in the region.

Having agreed with such high assessment of the diversity of ecosystems in this zone and their species richness, we believe that the quality of the gene pool of flora can be detected only in the course of special ecological and genetic research. The presence of genetic damage in plants of the EURT area is indicated by a high frequency of chromosomal aberrations and rare alleles of certain enzymes [23-28], increased variability in vital capacity and radioresistance of contemporary brood, and a large number of different morphoses detected at the early stages of ontogenesis [5,29]. This theme is very wide and requires an independent review.

Conclusion

The Kyshtym accident in 1957 at the nuclear facility of “Mayak” (Southern Urals) has led to the formation of the East-Ural radioactive trace. Taking into account the length of the investigated area, it was ranked by the level of radionuclide contamination with selection of the impact and buffer zones. The study of the spatial distribution of radionuclides in the trace showed that within the trace axis and its eastern periphery the changes in their stocks were satisfactorily approximated by a power function with increasing distance from the epicenter of the accident. At the same time, radionuclides are arranged in a row $^{90}Sr \geq {}^{137}Cs > {}^{239,240}Pu$ according to the level of ground contamination. Content of ^{137}Cs in soil on the western periphery of the trace does not depend on the distance. Study of geochemical integrations, including the coastal zones of aquatic ecosystems, water-logged grounds and watershed areas revealed contribution of ecosystem types, landscape diversity and recultivation activities in the intensity and direction of migration flows of radionuclides. We noted that decontamination processes dominate at the depressed elements of the landscape.

The complex nature of soil contamination in the investigated area is conditioned by contribution of another accident – the wind transfer of contaminated bottom sediments from the shores of Karachay Lake being an open storage of liquid radioactive waste by PA “Mayak”. ^{137}Cs was the main contaminant. Certain influence is exerted by contemporary atmospheric emissions by PA “Mayak”. Currently, the impact zone is mostly (95.7%) contaminated with ^{90}Sr after emergency emissions in 1957. The western periphery is distinguished by a relative decrease of stocks of ^{90}Sr and growth of ^{137}Cs ones after the Karachay accident. Contamination of the eastern part of the trace is formed mostly (63%) by the same source.

With a wide range of radionuclide contamination of soils, specific activity of ^{90}Sr, ^{137}Cs and $^{239,240}Pu$ in certain species of plants in general vary in accordance with a power function. The values of transition coefficients that characterize accumulative ability of the plants vary within wide limits. There is a clearly expressed reduction of accumulative ability of the plants growing in the impact zone, and a high intrapopulation diversity of plants according to their ability to accumulate the radionuclides.

Living objects in EURT territory received the main part of the radiation dose during first four years after the accident. Over the years, the energy of gamma-radiation decreased from 7.6 to 0.004 MeV per decay of ^{90}Sr. Our study showed that the absorbed doses calculated for plants in the buffer areas are usually greater by one order of magnitude than in the background areas, and in impact coenopopulations differences with background plantings are 3–4 orders of magnitude. If one takes into account that the lifetime of many herbaceous plants can reach 20 years, plagiotropic parts of cryptophytes can accumulate doses of about 7–9 Gy during the entire period of ontogeny. Obviously these doses refer to small doses for plants.

Vegetation of EURT now presents a complex of synanthropic and semi-natural plant communities at different stages of restoration successions. Forest communities have signs of steppe nature that can be attributed to increased brightness and heating of the soil due to the open forest canopy that has arisen in the first years under the influence of radiation. These changes indicate secondary effects of irradiation in ecosystems. The involvement of ruderal species in all coenoses of the impact zone is reduced, while plants typical to forests and meadows play a significant role. Species diversity in the impact zone is very high; some communities have up to 65 species, which is associated with a low anthropogenic load. It is significant to note that the current state of phytocoenoses on the land of the demolished local villages is still largely determined by the degree of man's impact in the pre-accident period and recultivation activities. The natural ecosystems successfully recovered at a faster pace.

Acknowledgments

This study was completed with support by the Russian Foundation for Basic Research (project no. 11-04-01260), the Interdisciplinary Projects of the Ural Division of the Russian Academy of Sciences (no. 09-M-24-2001) and the Program for Directional and Fundamental Investigations of the Ural Division of the Russian Academy of Sciences (DFI-1, №11-4-01-NC).

References

[1] P.L. Gorchakovsky, “The vegetationMoscow (1968) pp111-262. (in Russian).

[2] F.I. Pavlotskaya, G.A. Fedoseev, E.V. Babicheva, L.N. Zatsepina and E.B. Tiuriukanova, *Pochvovedenie*, N2 (1964). (in Russian).

[3] Q. Chen, A. Aarkrog, S.P. Nielsen, H. Dahlgaard, H. Nies, Y. Yu and K. Mandrup, *J. of Radioanalytical and Nuclear Chemistry*, 172, N2 (1993).

[4] Field geobotany, Moscow, Leningrad (1964) (in Russian).

[5] V.N. Pozolotina, I.V. Molchanova, E.N. Karavaeva, L.N. Mikhaylovskaya, and E.V. Antonova, “The current state of terrestrial ecosystems in the Eastern Ural Radioactive trace: contamination levels and biological effects”, Yekaterinburg (2008). (in Russian).

[6] I.V. Molchanova, E.N. Karavaeva, and L.N. Mikhaylovskaya, “Radioecological investigation of soil-plant cover”, Yekaterinburg (2006). (in Russian).
[7] V.P. Firsova, I.V. Molchanova, P.V. Meshcheryakov, T.S. Pavlova, E.N. Karavaeva, E.V. Prokopovich and V.V. Toshchev, “Soil and ecological conditions of accumulation and redistribution of radionuclides in the zone EURT”, Yekaterinburg (1996). (in Russian).
[8] E.N. Karavaeva and I.V. Molchanova, *The Soviet J. of Ecology*, N10 (1979).
[9] A.S. Bakurov, G.P. Shejn, G.M. Aksenov and S.I. Rovny, Proceedings of the conference on the 50th anniversary of the Mayak accident, 25-26 Sep. 2007 (Chelyabinsk, Russia) pp8-25. (in Russian).
[10] A. Aarkrog, H. Dahlgaard, S.P. Nielsen, A.V. Trapeznikov, I.V. Molchanova, V.N. Pozolotina, E.N. Karavaeva, P.I. Yushkov and G.G. Polikarpov, *Sci. of the Total Environ.*, 201 (1997).
[11] A.V. Zheleznov, N.B. Zheleznova, N.I. Smetanin and V.S. Sukhanovskaya, *Russian J. of Genetics*, 38, N5 (2002).
[12] B.V. Nikipelov, A.S. Nikiforov, O.L. Kedrovsky, M.V. Strakhov and E.K. Drozhko, “Practical rehabilitation of territories contaminated as a result of implementation of Nuclear Material Production Defense Programs”. Oak Ridge National Laboratory, USA (1990).
[13] G.V. Gorshkov, “Penetrating radiations from radioactive sources,” Leningrad (1967). (in Russian).
[14] F.A. Tikhomirov and R.T. Karaban, “Ecological after-effects of the radioactive contamination at South Ural”, Moscow (1993) pp85-95. (in Russian).
[15] E.G. Smirnov, “Ecological after-effects of the radioactive contamination at South Ural”, Moscow, pp79-84 (1993). (in Russian).
[16] G.M. Woodwell, *Science*, 156, 774 (1967).
[17] R.B. Platt, “Radioecology”. Reinhold: N.Y. (1963).
[18] G.M. Woodwell and L.N. Miller, *Science*, 139, 3551 (1963).
[19] F.A. Tikhomirov, “The ionizing radiation influence on ecological systems”, Moscow (1972). (in Russian).
[20] N. Poinsot-Balaguer, R. Castet and E. Tabone *J. Environ. Radioactivity*, 14, (1991).
[21] E.G. Smirnov, “Ecological after-effects of the radioactive contamination at South Ural”, Moscow, pp103-108 (1993). (in Russian).
[22] A.V. Lagunov, and A.I. Smagin, *Voprosy radiatsionnoi besopasnosti*. Special issue (2007). (in Russian).
[23] L.V. Cherezhanova, R.M. Aleksakhin and E.G. Smirnov, *Russian J. of Genetics*, 7, N4 (1971).
[24] V.A. Shevchenko, V.I. Abramov and V.L. Pechkurenkov, “Ecological after-effects of the radioactive contamination at South Ural”, Moscow (1993). (in Russian).
[25] V.A. Shevchenko, V.A. Kal'chenko, V.I. Abramov, A.V. Rubanovich, V.V. Shevchenko, L.I. Grinikh, *Radiatsionnaia biologiia. Radioecologiia*, 39, N1 (1999). (in Russian).
[26] E.A. Lysenko, V.I. Abramov and V.A. Shevchenko, *Russian J. of Genetics*, 36, N9 (2000).

[27] V.A. Kal'chenko, V.I. Abramov, A.V. Rubanovich, L.N. Kostina, I.S. Fedotov, E.V. Igonina, G.I. Kuznetsova, and V.A. Shevchenko, *Radiatsionnaia biologiia. Radioecologiia*, 42, N6 (2002). (in Russian).
[28] V.N. Pozolotina, I.V. Molchanova, L.N. Mikhailovskaya and E.V. Ul'yanova, *Russian J. of Ecology*, 36, N5 (2005).
[29] V.N. Pozolotina, E.V. Antonova and E.M. Karimullina, *Russian J. of Ecology*, 41, N6 (2010).