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RESEARCH

Forests in the East Ural Radioactive Trace: structure, spatial distribution, and the ^{90}Sr inventory 63 years after the Kyshtym accident

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Abstract On 29 September 1957, the so-called Kyshtym accident occurred at the USSR's first nuclear weapons plutonium production facility. The East Ural State Reserve (EUSR) was established in the most contaminated part of the radioactive trace, where a substantial part of the forests died in the first years after the accident. The purpose of our study was to evaluate the natural restoration of forests and to verify and update the taxonomic parameters that characterize the current state of forest stands in the EUSR. Data on the forest inventory of 2003 and results of our research of 2020 performed by the same methods on 84 randomly selected sites served as the basis for this work. We developed models to approximate growth dynamics and then updated the 2003 taxation-related forest data for the entire EUSR. According to these models and ArcGIS construction of new data, forest-covered lands make up 55.8% of the whole EUSR territory. The proportion of birch forests in the forest-covered lands is 91.9%; 60.7% of wood resources are located in mature and overmature (81–120-year-old) birch forests. The total timber stock in the EUSR is > 1385 thousand tons. It was revealed that ~ 4.2×10^{14} Bq of ^{90}Sr is situated within the EUSR. The main stock of ^{90}Sr is found in soils. The ^{90}Sr stock in the stands is ~ 1.6–3.0% of the total content in the forests. Only a part of the EUSR forest stands can be used for practical applications.

Keywords Kyshtym accident · Soil contamination density · Aggregated transfer factor · Forest · Species profile · Age profile · Timber stock · ^{90}Sr inventory

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Introduction

The East Ural Radioactive Trace was formed in 1957 by an explosion of a waste container in the Mayak nuclear complex (the Kyshtym accident). Approximately 7.4×10^{17} Bq (20 MCi) of radioactive substances was released into the environment, 10% of which was dispersed by the wind in a northeastern direction, forming a contaminated zone of ~ 23,000 km^2. Roughly 95% of the released radioactivity was represented by radionuclides that have half-lives of 1 year or less; the contribution of $^{90}Sr + ^{90}Y$ was 5.4%, and that of ^{137}Cs 0.036% (Alexakhin et al., 2004; Nikipelov et al., 1990). Since the fifth year after the accident, ecosystems' contamination has been almost exclusively due to ^{90}Sr.

In 1966, the East Ural State Reserve (EUSR) was established in the most contaminated part of the radioactive trace zone (Alexakhin et al., 2004; Sokolov & Krivolutsky, 1993). The purpose of the EUSR creation was to prevent removal of radioactive substances from the contaminated territory, to conduct scientific research on patterns of radionuclides' behavior under natural conditions, and to assess the state of ecosystems affected by the ionizing radiation for a long time. The EUSR was decommissioned at the end of the 1990s, but the area with high levels of contamination is still strictly protected.

By the time of the accident (September 29), birches had shed most of their leaves, and therefore the crowns of birch forests retained less radionuclides than did the crowns of pine trees (Tikhomirov, 1993). Thus, the external exposure of pine trees in the first months after the accident was higher than that of birch trees (Alexakhin et al., 2004). Taking into account the high radiosensitivity of Scots pine, this circumstance explains species-specific differences in the primary effects of radiation between pine and birch forests (Tikhomirov & Karaban, 1993).

In stands of *Betula pendula* with initial density of ^{90}Sr contamination of ~ 92 MBq m^{-2} (area ~ 12 km^2), death of 10% of trees was registered. On the territory with ^{90}Sr contamination density over 140 MBq m^{-2} (approximately 3 km^2), deaths of 50% of birch trees and up to 75% of regrowth were recorded. Complete loss of birch stands was not observed (Alexakhin et al., 2004). In stands of *Pinus sylvestris*, pine had completely died by the autumn of 1959 in an area of ~ 50 km^2 having an initial density of soil ^{90}Sr contamination of 6.3 to 7.4 MBq m^{-2}. Severe crown damage and cessation of pine growth were observed in the area with the density of soil ^{90}Sr contamination of 3.7 to 6.3 MBq m^{-2} (approximately 80 km^2) (Alexakhin et al., 2004).

Two to 3 years after the accident, pine and birch trees demonstrated crown regeneration through the development of lateral shoots. At the same time, a variety of needle and leaf morphoses often formed. After 8–10 years, most of irradiated trees of both species did not differ in appearance from nonirradiated trees (Fesenko et al., 2022; Tikhomirov & Karaban, 1993). Similar effects were noted in the Chernobyl Exclusion Zone (Kozubov & Taskaev, 2002) and in experiments with acute irradiation of forest sites from external sources (Alexakhin et al., 1994; Fesenko et al., 2022). Birch stands are able to regenerate by forming root and stump shoots and by seed reproduction. Pine does not form stump shoots, and its seeds die in the soil at high radiation doses; accordingly, pine forest regeneration began much later (Tikhomirov & Karaban, 1993).

At present, studies on forests in the former EUSR are important and relevant because there are few data on successional processes in forests growing under the conditions of low-dose radiation for more than 6 decades (Pozolotina et al., 2021). In 2013, an inventory of soil contamination density in the former EUSR zone was carried out, and stocks of radionuclides (^{90}Sr, ^{137}Cs, and ^{239,240}Pu) in soils were calculated (Izrael, 2013; Molchanova et al., 2014). These data formed the basis for the inventory of radionuclides in tree stands, which are the second biggest depot that concentrates radionuclides for a long time. Their redistribution proceeds slowly but continuously due to the circulation of substances under the influence of natural (biogenic and abiogenic) factors. Assessment of the state and dynamics of the forest fund and calculation of amounts of radionuclides accumulated in trees are necessary to predict the possibility of practical use of forests (Alexakhin et al., 2004; Matsala et al., 2021; Yoschenko et al., 2018).

The aims of this study were as follows:

1. to assess the state of forests by updating taxation-related parameters of forest stands in the former EUSR for 2020 on the basis of 2003 taxation data and of newly developed approximation models;
2. to estimate the ^{90}Sr inventory in above-ground parts of trees by means of soil contamination density data and aggregated transfer factors (T_{ag}) of this radionuclide; to assess the possibility of practical use of forests in the former EUSR;
3. to create a series of maps reflecting the radioecological situation and the state of forests in the former EUSR.

Materials and methods

Study area

The former EUSR is located in the forest-steppe zone of the trans-Ural peneplain. Southern and central parts of the zone are dominated by a lacustrine-hilly type of relief. In northern and eastern parts, there is a wide swampy floodplain of the Karabolka River. The climate in the study area is moderately continental, and winters are long and frosty. The coldest month is January with an average temperature of − 12.2 °C. Summers are short and warm, and the warmest month is July with an average temperature of + 19.3 °C. The average annual precipitation is ~ 530 mm, droughts occur often, automorphic landscape types predominate, and elevation of localities is 130–250 m a.s.l. (Kukarskih et al., 2021; Martyushov et al., 2000). Western and southwestern winds prevailing in this region determined the shape of the radioactive trace (Teterin, 2011). Various subtypes of forest gray soils predominate within the EUSR; brown soils and chernozems are less common (Pozolotina et al., 2012). Vegetation in the EUSR is represented mainly by birch (*Betula pendula* Erch.) forests, sometimes with an admixture of aspen (*Populus tremula* L.) and Scots pine (*Pinus sylvestris* L.), interspersed with herbaceous communities. Homogeneous pine forests are rare. Detailed geobotanical descriptions of vegetation in the EUSR have been published earlier (Martyushov et al., 2000; Pozolotina et al., 2012; Smirnov, 1993).

Verification and updating of taxonomic characteristics of EUSR forest stands from 2003 to the present

The assessment of forests on the territory of the former EUSR was based on the verification and updating of forest inventory materials and was carried out by the methods of visual and measuring valuation utilized in 2003 by employees of the Nizhny Novgorod Forest Survey Expedition (*Taxation description of the forest enterprise of Eastern Ural State Reserve*, *PA Mayak*, 2003). According to these materials, the territory of the former EUSR was divided into forest taxation sites; the configuration and size of the sites were determined by means of aerial photographs and topographic maps according to vegetation parameters. The taxonomic description was carried out according to the 1st accuracy grade, i.e., with maximum detail, which ensured the best quality of the results of the forest survey.

During summer seasons of 2019–2020, we performed a selective forest inventory of 84 sites in different parts of the former EUSR by the same methods (*Taxation description of the forest enterprise of Eastern Ural State Reserve*, *PA Mayak*, 2003) officially recommended by the Forest Management Manual (*Forest Management Manual*, 2018). The configuration and size of the forest taxation stands were determined using a 2003 map, and locations of the sites were georeferenced with the help of the Global Positioning System (GPS), with reference to noticeable landmarks. A detailed description of this work is presented in ref. Pozolotina et al. (2021).

Based on a comparison of the results obtained in 2020 with the data from 2003, models were developed to approximate the growth dynamics of stands by means of the main parameters. Coefficients in these models were selected by the nonlinear least squares approach and the "nls" function of the R software. The models made it possible to update the forest inventory materials of 2003 for the whole territory of the former EUSR for the year 2020.

For forest lands, the following characteristics were given in 2003 for each compartment: (1) area, (2) boundaries, (3) stand composition, (4) age profiles of species in the stand, (5) relative fullness of the stand, and (6) height profiles of species in the stand. The type of landscape, area, boundaries of sites, and composition of the forest stand did not change during the 2003–2020 period. To estimate the average age of stands in 2020, it is permissible to add 17 years to their age in 2003.

Based on data from a forest plan of Chelyabinsk Oblast (*A forest plan of the Chelyabinsk Region*, 2017) and our own expedition research, it was assumed that in the period from 2003 to 2020 in the forests of the former EUSR, there were no large-scale catastrophic events considerably disturbing natural succession processes. Fires did occur on the territory of the EUSR; the forest assessment of 2012 recorded 218 sites with signs of ground fires in different years and one crown fire (*A forest plan of the Chelyabinsk Region*, 2017). In the case of prolonged burning, forest mortality was noted, but the proportion of such sites in the EUSR is small (Rovny et al., 2010; Tarasov et al., 2010). In addition, the regrowth was not included in the timber stock computations.

To estimate the height of birch stands, a model is proposed here that relates tree growth in height during the 2003–2020 period to their age (Supplement 1, Fig. 1). The relation of the parameters can be described by the equation

$$H_{2003-2020} = 23.0320 - 4.9824 \times lnA_{2003} \quad (1)$$

where $H_{2003–2020}$ is the tree height increment (m) in the 2003–2020 period, and $ln\ A_{2003}$ is the natural logarithm of stand age (years) in 2003. All the coefficients of the equation are statistically significant at $p<0.05$. The coefficient of determination of the model (R^2) is 0.79. To determine the height of stands in 2020, the increments $H_{2003–2020}$ calculated by the model were added to the height of trees in 2003.

A model linking relative forest density in 2020 to their density and age in 2003 is described by the following formula:

$$D_{2020} = 0.9725 + \left(0.5602 \times lnD_{2003}\right) - \left(0.0020 \times A_{2003}\right) \quad (2)$$

where D_{2020} is relative forest density in 2020, $ln\ D_{2003}$ is the natural logarithm of forest density in 2003, and A_{2003} is stand age in 2003. All coefficients of the equation are statistically significant at $p<0.05$. The coefficient of determination for the model is 0.55.

Relative density of forest stands was determined taking into account all trees growing in the stands. The model allows to correctly calculate the current density in pure birch forests (~92% of such forests) and in areas with a small admixture of aspen (~2% of such forests) because growth dynamics of these species are similar (Kozlovskiy & Pavlov, 1967).

The situation is different in stands with a high proportion of Scots pine (~6% of such forests). Growth dynamics of these trees are different from those of birch trees. Nonetheless, it is necessary to take into account specific features of the comparison period. In 2003, pine trees in most stands were 30–60 years old, while trees older than 85 years were rare. As a rule, conifers and deciduous trees are characterized by general growth tendencies at this age (Nagimov et al., 2002). Discrepancies between coniferous and deciduous trees will increase over time. For the current moment, we introduced an assumption: the use

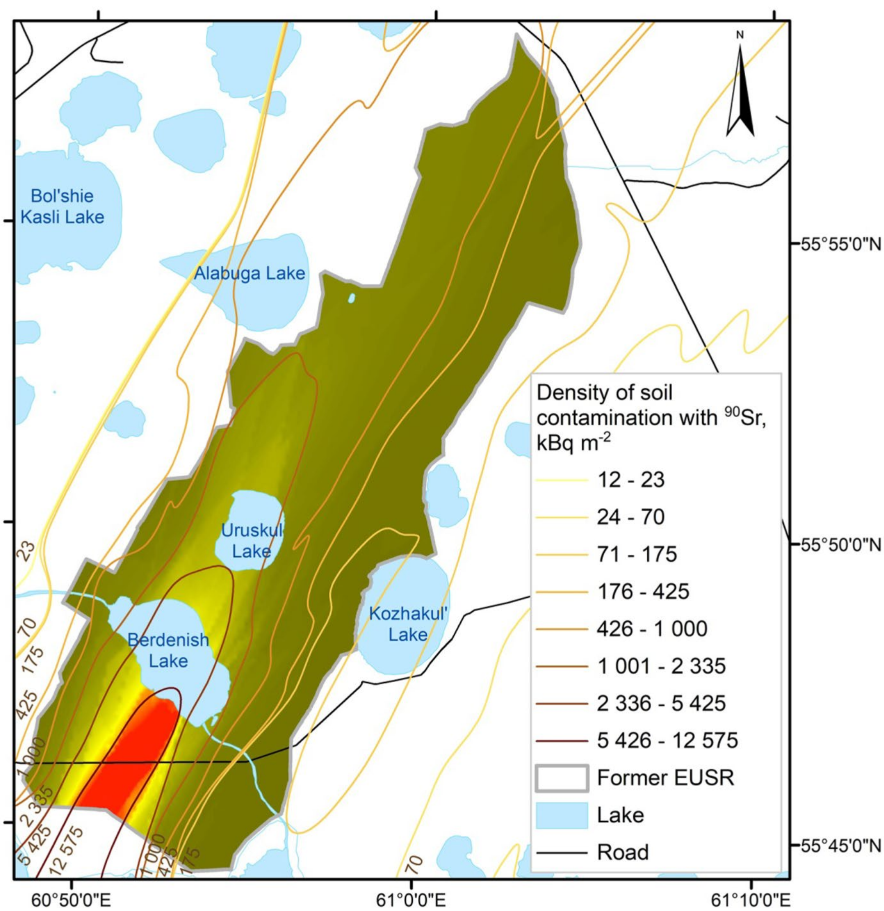

Fig. 1 Density of soil contamination with ^{90}Sr on the territory of the former East Ural State Reserve (EUSR)

of the models proposed for birch is acceptable for medium-aged pine and mixed pine-birch forests.

The timber stock (m^3 ha^{-1}) was determined from regional data tables linking the height of birch and pine stands, their relative density, and the timber stock for the forest-steppe inventory district of Chelyabinsk Oblast. Standard timber stocks of birch and pine in forests with a maximal density of 1.0 are given in Supplement 1, Table 1 (Nagimov et al., 2002).

Given that for further calculations of the ^{90}Sr content of trunks, knowing the mass of wood (M, kg) at each site is required, additional calculations were included in the model:

$$M = k \times P \times A \times D \times S \tag{3}$$

where M (mass) is the mass of trunk wood per site, P (percent) is the proportion of species in the stand, A (area) is the area of the site, D (density) is relative density of the stand in 2020, S (stock) is the timber stock in the stand at a maximal density of 1.0 (Supplement 1), and k is the coefficient that links the volume of fresh trunk wood (m^3) with its air-dry weight (kg).

To calculate k, we employed results of measurements of model trees growing at a small distance from the EUSR. The average density of fresh birch wood was 827 kg m^{-3}, and that of pine wood 744 kg m^{-3}, while the percentage of air-dry matter in the birch trunk was 60%, and that in the pine trunk 51% (Usoltsev et al., 2012). The average density of aspen wood was 713 kg m^{-3}, and the dry matter percentage in the trunk was 58% (Usoltsev, 1985). Computation results are given in Supplement 2. To assess the ratio of dry mass of above-ground tree parts (wood, bark, branches, and leaves/needles), we used results of measurements of 60 model birch trees and 187 pine trees, calculated by us according to data from ref. Usoltsev et al. (2018) (Supplements 3 and 4) and (Supplement 1, Table 2). Because some regional parameters characterizing aspen were absent, an assumption was made that the parameters determined for birch can be utilized instead.

The inventory of ^{90}Sr in forest stands in the former EUSR

^{90}Sr is a long-lived β emitter with a half-life of 28.8 years. Previously, we have determined ^{90}Sr soil contamination densities in the EUSR (Molchanova et al., 2014; Pozolotina et al., 2012). The ordinal kriging method was used to interpolate ^{90}Sr soil contamination density values for the whole EUSR territory, and the Monte Carlo method was employed to quantify uncertainties of integral stocks (Molchanova et al., 2014). All data on soil contamination densities were normalized to 2020 with consideration of the ^{90}Sr half-life.

Estimation of ^{90}Sr stocks in stands of the EUSR was conducted on the basis of data about timber stocks of various species in forest compartments. It is known that concentrations of this radionuclide vary among different parts of trees (leaves/pine needles, branches, bark, and wood). The highest concentrations are usually observed in bark and leaves/needles, and minimal levels in wood. The differences can reach an order of magnitude in the studied tree species (Mikhailovskaya et al., 2022; Shcheglov et al., 2001). Therefore, ^{90}Sr stocks were computed separately for the different parts of trees.

Table 1 Age profiles of the stands in the EUSR in 2020

Parameter	Birch						
Age, years	21–40	41–60	61–80	81–100	101–120	121–140	Total
Area, km^2	3.9	19.9	16.0	31.7	13.9	0.1	85.6
Timber stock (fresh mass), tons	35,700	208,332	259,432	549,005	230,163	882	1,283,515
	Scots pine						
Age, years	21–40	41–60	61–80	81–100	101–120	121–140	Total
Area, km^2	0.5	3.0	0.5	1.1	0.6	-	5.7
Timber stock (fresh mass), tons	4124	45,331	8395	21,400	14,718	-	93,967
	Aspen						
Age, years	21–40	41–60	61–80	81–100	101–120	121–140	Total
Area, km^2	-	0.1	0.2	0.3	-	-	0.6
Timber stock (fresh mass), tons	-	1076	2736	5247	-	-	8514

Table 2 Stocks (tons) of tree parts (air-dry matter) at sites having different densities of soil contamination with ^{90}Sr

Species	Tree parts	Densities of soil contamination with ^{90}Sr, kBq m^{-2}			
		23–1000	1001–5424	5425–12,754	12,755–29,125
Birch	Trunk	306,886	354,745	64,320	34,905
	Bark	41,602	48,040	8555	4709
	Branches	45,186	52,201	9367	5125
	Leaves	12,499	14,424	2540	1410
	Σ	**406,173**	**469,410**	**84,781**	**46,149**
Scots pine	Trunk	25,950	16,161	3967	24
	Bark	1696	1090	276	2
	Branches	2313	1453	360	2
	Needles	944	625	163	1
	Σ	**30,904**	**19,330**	**4766**	**29**
Aspen	Trunk	7588	7702	704	310
	Bark	1004	953	93	41
	Branches	1102	1128	102	45
	Leaves	297	309	27	12
	Σ	**9991**	**10,174**	**926**	**407**
Total timber stock of wood, bark, branches, leaves/needles, tons		447,068	498,913	90,473	46,585
Area of forest lands with specified density of soil contamination with ^{90}Sr, km^2		38.2	42.4	7.3	4

It was also found that aggregated factors of transfer (T_{ag}) of ^{90}Sr from soil to trees' above-ground parts depend on soil contamination density according to power function $y = a \cdot x^b$. The equations were taken from refs. Mikhailovskaya et al. (2021) and Mikhailovskaya et al. (2022), and are shown in Supplement 5.

We made several assumptions to calculate total ^{90}Sr stocks in the stands. Firstly, we did not consider the dependence of T_{ag} on various soil types' characteristics. Previously, T_{ag} has been determined for forests growing on dominant automorphic soils (Mikhailovskaya et al., 2021, 2022), but there is a small proportion of forests growing on hydromorphic soils, whose T_{ag} values may be different. Secondly, parameters of ^{90}Sr accumulation are similar between birch and aspen (Otreshko et al., 2015; Shcheglov et al., 2001); therefore, the stocks of ^{90}Sr in mixed stands were calculated using T_{ag} obtained for birch.

Mapping of the former EUSR territory

A consolidated database for 2003 and 2020 was created for storage and analysis of attributive information, describing 2572 sites within the EUSR. Taxation-related characteristics as well as sites' area and geometric mean of densities of soil contamination with ^{90}Sr (both parameters were calculated with the help of geographic information system ArcGIS 10.8.1 (ESRI, 2019) were included in the database for each forest stand.

The EUSR map scheme was digitized, with compartment boundaries corresponding to the 2003 taxation and other landscape elements (lakes, swamps, and roads). Maps of the density of soil contamination with ^{90}Sr, the current vegetation distribution, species profiles, ages of forest stands, and timber stocks within each stand were constructed in ArcGIS 10.8.1 (ESRI, 2019). The compartments' rasters were overlaid on the SRTM-1 digital relief model (www.nesdis.noaa.gov), which has a precision of 1″ (approximately 30 m).

Results

The current state of forest stands in the EUSR

The data characterizing densities of soil contamination with ^{90}Sr and the state of vegetation in the former EUSR are presented in the map-schemes. In Fig. 1, sectors with different levels of the soil contamination are bounded by isolines. Maximal levels of the soil contamination are near the central axis, close to the accident's epicenter; the ^{90}Sr content decreases toward the periphery of the radioactive trace. The area of forested and nonforested lands on the EUSR territory (total area is 164.5 km^2 according to an ArcGIS estimate) for different densities of soil contamination with ^{90}Sr is shown in Supplement 1, Table 3.

Figure 2 depicts the location of different categories of land in the EUSR zone. Areas covered by forests account for 55.8%. On nonforested lands (44.2%), swamps occupy 8.9%, and lakes 7.7%; the share of meadows, roads, and glades is 27.6%.

On the forest lands, birch forests occupy 91.9%, and pine forests 5.8%. The proportion of forests with aspen is 2.2%, and that of forests with other species (*Larix sibirica* Ledeb. and *Populus alba* L.) is 0.1%. From the comparison of our findings with the 2003 taxation data, it is possible to conclude that changes on lands not covered by forests in the period in question were small. The area of forest lands did not change.

Herbaceous birch forests predominate at the most contaminated sites, and there are also sparse birch forests with a small admixture of pine and aspen. Aspen also grows in small groves in depressions of relief. Pine forests and mixed pine-birch forests are mainly located on the periphery of the contaminated zone and occur as separate islets in central and northern parts of the EUSR at sites having the density of soil contamination with ^{90}Sr of 175 to 5425 kBq m^{-2}.

Age profiles of both birch and pine stands vary widely (see Fig. 2), and quantitative data are given in Table 1. It turned out that the largest areas are occupied by birch forests aged 81 to 120 years, i.e., mature and overmature stands; 60.9% of timber stocks are represented by them. Pine forests of 41–60 years of age are dominant in the EUSR; their proportion in timber stocks of this species is 48.2%; 81–100-year-old trees predominate in the few aspen stands. The total timber stock (fresh mass) on the EUSR territory is more than 1385 thousand tons.

Figure 3 shows the distribution of timber stocks (without separation by species) at sites having different densities of soil contamination with ^{90}Sr. Comparing Figs. 2 and 3, we can establish which species determine the main timber stocks in various parts of the EUSR.

A more detailed analysis of stocks of different tree parts along with levels of soil contamination in compartments is presented in Table 2.

As expected, trunk wood makes the main contribution to the stocks (it constitutes 75.6–75.9% in

Table 3 Stocks of ^{90}Sr in 2020 in different components of forest stands, Bq

Species	Part	Densities of soil contamination with ^{90}Sr, kBq m^{-2}				
		23–1000	1001–5424	5425–12,754	12,755–29,125	**Total**
Birch	Wood	1.8E+11	8.8E+11	5.1E+11	5.2E+11	**2.1E+12**
	Bark	1.3E+11	6.2E+11	3.4E+11	3.4E+11	**1.4E+12**
	Branches	8.4E+10	3.8E+11	2.0E+11	2.0E+11	**8.6E+11**
	Leaves	3.5E+10	1.5E+11	8.0E+10	7.8E+10	**3.4E+11**
	Summary	4.3E+11	2.0E+12	1.1E+12	1.1E+12	**4.7E+12**
Scots pine	Wood & bark	6.9E+09	1.7E+10	1.0E+10	1.1E+08	**3.4E+10**
	Branches	7.0E+08	1.9E+09	1.3E+09	1.3E+07	**3.9E+09**
	Needles	3.6E+08	9.8E+08	6.6E+08	6.0E+06	**2.0E+09**
	Summary	8.0E+09	2.0E+10	1.2E+10	1.3E+08	**4.0E+10**
Aspen	Wood	4.5E+09	1.9E+10	6.0E+09	4.6E+09	**3.4E+10**
	Bark	3.3E+09	1.3E+10	3.9E+09	3.0E+09	**2.3E+10**
	Branches	2.1E+09	8.0E+09	2.3E+09	1.7E+09	**1.4E+10**
	Leaves	8.4E+08	3.2E+09	9.2E+08	6.8E+08	**5.7E+09**
	Summary	1.1E+10	4.3E+10	1.3E+10	1.0E+10	**7.7E+10**
Stock of ^{90}Sr in stands, Bq		4,5E+11	2.1E+12	1.2E+12	1.1E+12	**4.8E+12**
Stock of ^{90}Sr in soils of forest area, Bq		1.5E+13	8.8E+13	5.5E+13	7.0E+13	**2.3E+14**
Stock of ^{90}Sr in soils of EUSR (without lakes)		2.8E+13	1.4E+14	7.4E+13	9.1E+13	**3.4E+14**
Stock of ^{90}Sr on whole territory of EUSR		2.8E+13	1.7E+14	1.2E+14	9.8E+13	**4.2E+14**

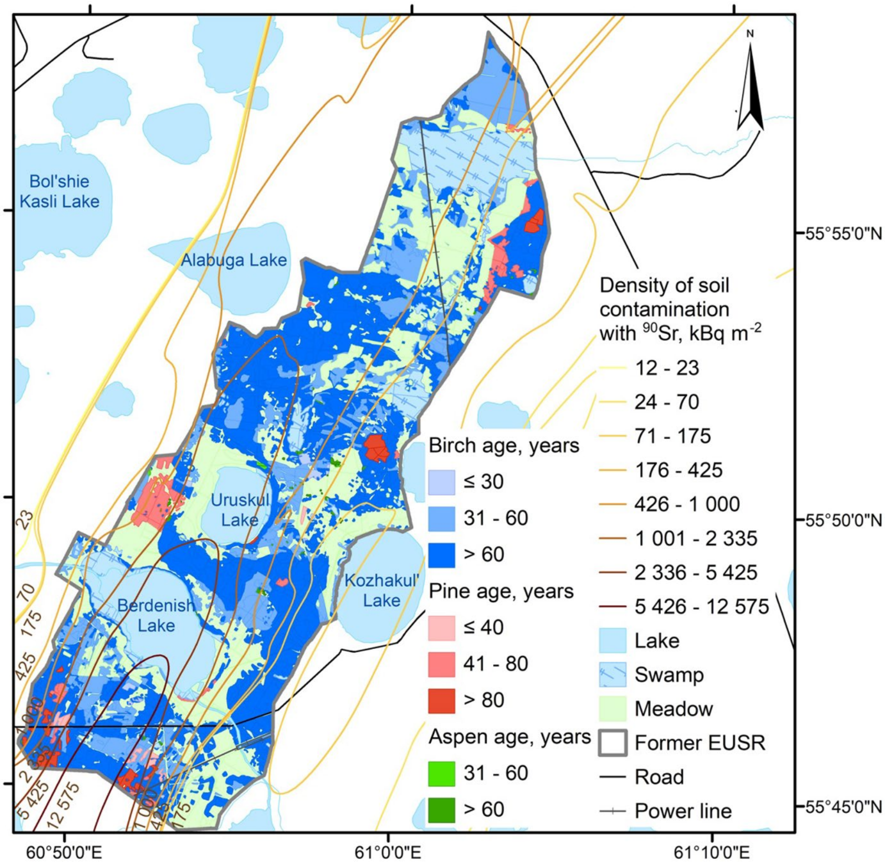

Fig. 2 The current species profile and age profile of forest stands in the former EUSR

deciduous species and 83.8% in pine), bark and branch proportions are an order of magnitude smaller, and the proportion of leaves and needles is 3 to 3.7%.

The inventory of ^{90}Sr in various parts of birch, pine, and aspen trees

^{90}Sr concentrations in different tree parts (trunk wood, bark, branches, and leaves/needles) in the EUSR were calculated using equations linking radionuclide aggregated transfer factors (T_{ag}) with the soil contamination densities (Mikhailovskaya et al., 2021, 2022). These equations are given in Supplement 5. The ^{90}Sr inventory in different tree parts is summarized in Table 3.

The data indicated that soils are the main depot of this radionuclide in ecosystems. Based on our data, soils contain 97.9% of ^{90}Sr released into forests. On average, the stock of this radionuclide in forest stands is 2.1% of total. It is important to note the increasing tendency of the ^{90}Sr proportion in forest stands with a decrease in its concentration in the soil. For the range of densities of soil contamination with ^{90}Sr 23–1000 kBq m^{-2}, its stock in trees is 3.0%; at soil contamination density 1001–5424 kBq m^{-2}, the stock in trees is 2.4%; at soil contamination density 5425–12,754 kBq m^{-2}, the stock in trees is 2.1%; and at soil contamination density 12,755–29,125 kBq m^{-2}, the stock in trees is 1.6%. This phenomenon is explained by the nonlinear dependence of ^{90}Sr aggregate transfer factors (T_{ag}) on soil contamination density (Mikhailovskaya et al., 2021, 2022).

The data on the distribution of ^{90}Sr in the tree parts allow us to assess the possibility of their practical use. We compared ^{90}Sr concentrations in wood, bark, branches, and needles of trees with permissible levels of contamination according to Sanitary Rules 2.6.1.759–99 (*Ionizing radiation, radiation safety. Permissible levels of* ^{137}*Cs and* ^{90}*Sr in forest products. SR 2.6.1.759–99. 2.6.1*, 1999) and calculated forest areas and dry matter stocks of various tree parts suitable for commercial applications (Table 4).

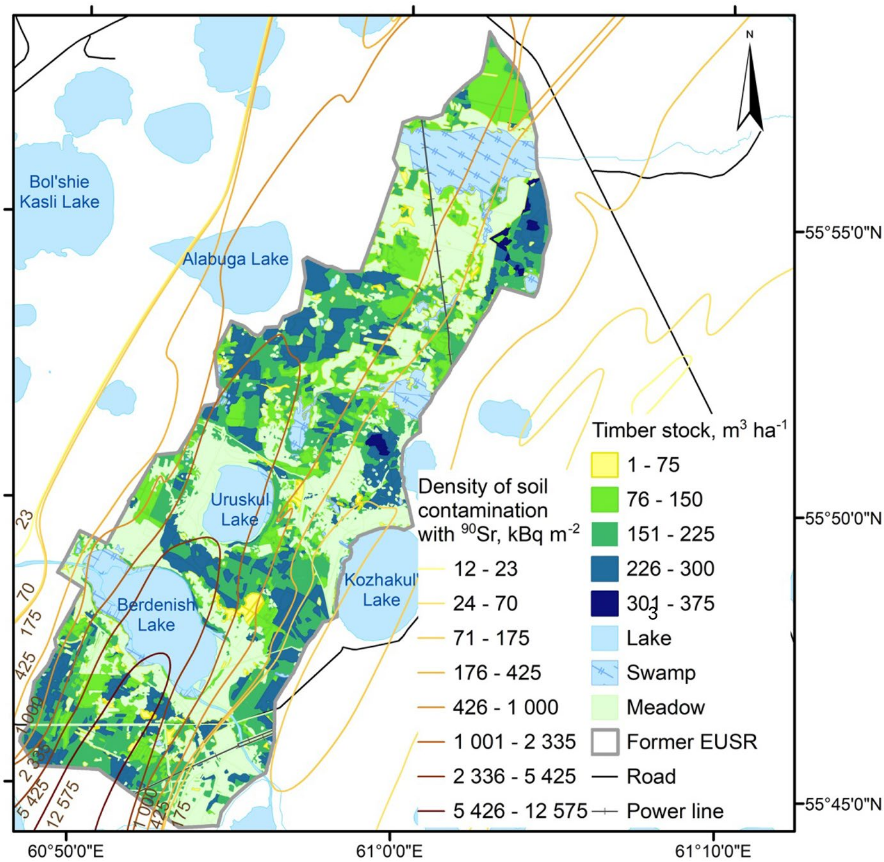

Fig. 3 Timber stocks in the forest stands on the EUSR territory

One can see that only a part of the EUSR forest stands can be used for economic purposes; for example, only 15.9% of the birch trunks can be utilized for firewood, without bark and branches at that. Birch bark cannot be used for furniture and handicrafts, and young pine shoots cannot be employed for animal feed additives.

Our findings enable geo-botanical forecasting in this area. Figure 4 shows forest locations of different age groups that require special attention. Extensive sites with 100–140-year-old birch stands are marked; they occupy a substantial area (30.9 km^2). Forest management measures in the form of stand regeneration cuttings should be implemented at these sites.

It is necessary to investigate forests in the most contaminated part of the EUSR, where in the first years after the accident, pine trees died off completely. In 2003, pine regrowth was not detectable in these areas, it appeared later. In 2020, we recorded regrowth of 5- or 15-year-old trees having a high proportion of damage, and the causes of morphogenesis require additional research (Pozolotina et al., 2021).

Discussion

According to our estimates, the inventory of ^{90}Sr in the EUSR area is 4.2×10^{14} Bq. It is known that ~ 7.4×10^{16} Bq of isotopes was dispersed in the environment by the accident (Nikipelov et al., 1990). The proportion of ^{90}Sr in the isotope mixture was 2.7%, i.e., approximately 2.0×10^{15} Bq. The amount of ^{90}Sr remaining in natural ecosystems after radioactive decay from 1957 to 2020 should be approximately 4.4×10^{14} Bq.

Aarkrog with colleagues (1997) demonstrated that the ^{90}Sr inventory calculated in 1996 for a territory of 30–300 km within a 15° sector along the central axis of the EUSR was 2×10^{14} Bq. The uncertainty of the integral was $(1–5) \times 10^{14}$ Bq. According to their

Table 4 Estimated forest area and stocks of trees' various parts (in the former EUSR) suitable for practical use as of 2020

Material	PL* of ^{90}Sr, kBq kg^{-1}	Tree part	Birch		Tree part	Scots pine	
			Area, km^2	Dry matter stock, tons		Area, km^2	Dry matter stock, tons
Wood for technological raw materials (timber, boards)	2.3	Wood	58.0 (35.2%)	508,644 (61.8%)	Wood and bark	4.8 (2.9%)	46,524 (5.0%)
Bark for industrial use	2.3	Bark	15.4 (9.3%)	20,497 (19.0%)			
Wood for building of houses	5.2	Wood	73.2 (44.5%)	654,712 (79.5%)	Wood and bark	5.1 (3.1%)	49,167 (5.3%)
Wood, branches, and bark for making furniture and other purposes	0.52	Wood	18.5 (11.2%)	182,206 (22.1%)	Wood and bark	2.1 (1.3%)	25,442 (2.7%)
		Bark	0.0	0.0			
		Branches	0.0	0.0	Branches	2.0 (1.2%)	2040 (1.7%)
Young pine shoots for animal feed additives	0.1	-	-	-	Branches	0.0	0.0
		-	-	-	Needles	0.0	0.0
Firewood	0.37	Wood	12.7 (7.7%)	131,077 (15.9%)	Wood and bark	2.0 (1.2%)	24,108 (2.6%)
		Bark	0.0	0.0			
		Branches	0.0	0.0	Branches	1.8 (1.1%)	1899 (1.6%)

**PL* permissible levels of ^{90}Sr in forest products (kBq kg^{-1}) according to sanitary rules 2.6.1.759–99 (*ionizing radiation*, *radiation safety. Permissible levels of* ^{137}*Cs and* ^{90}*Sr in forest products. SR 2.6.1.759–99. 2.6.1*, 1999)

model, in the range from kilometer 0 to kilometer 30, the inventory was ~ 1.8×10^{14} Bq. Those authors regard this value as doubtful because they had no samples from this sector.

According to the model from ref. Molchanova et al. (2014), the stock of ^{90}Sr in soils in the central part of the trace at a distance of 6–36 km from the accident epicenter in 2013 was 2.5×10^{14} Bq, with an uncertainty interval of $(1.1–5.8) \times 10^{14}$ Bq. Taking into account radioactive decay by the year 2020, this value should be 2.1×10^{14} Bq, with an uncertainty interval of $(1.0–4.9) \times 10^{14}$ Bq. The large uncertainty intervals are due to the fact that there were few sampling points in some areas. Besides, contamination in this zone is heterogeneous; often, sites close to each other under similar topological and ecological conditions differed in soil contamination density by up to an order of magnitude (Mikhailovskaya et al., 2019). In total, the ^{90}Sr inventory we obtained in the ecosystems of the former EUSR is comparable to the estimates published earlier.

The largest stock of ^{90}Sr is concentrated in soils; forest stands retain 1.6 to 3% of this radionuclide. Similar data have been reported for the ^{90}Sr distribution in forests from global radioactive fallout (Aleksakhin & Naryshkin, 1977; Mikhailovskaya et al., 2012). On the territory of the Belarusian Polessje contaminated by the Chernobyl fallout, at 20 years after the accident, the ^{90}Sr stock in birch trees varies from 3 to 19% and in pine trees from 2 to 11% of the total stock of this radionuclide in ecosystems (Perevolotsky et al., 2005, 2007). The discrepancies in estimates are probably due to dissimilarities of soils and climatic conditions between the Ural region and Belarus.

At present, the quality of EUSR stands at most sites has high ratings on potential productivity and tree growth rate. A similar conclusion was made in 2003 too (*Taxation description of the forest enterprise of Eastern Ural State Reserve, PA Mayak*, 2003) and in more recent assessments of Chelyabinsk Oblast forests (*A forest plan of the Chelyabinsk Region,* 2017). It is of interest to compare the territory of the EUSR with a network of specially protected natural areas in the forest-steppe zone of Chelyabinsk Oblast (Lagunov & Smagin, 2007). Experts use different methods: examining similarities of organisms' groups and communities, the presence of species from the regional endangered species list (Red Book), and the number of endemics

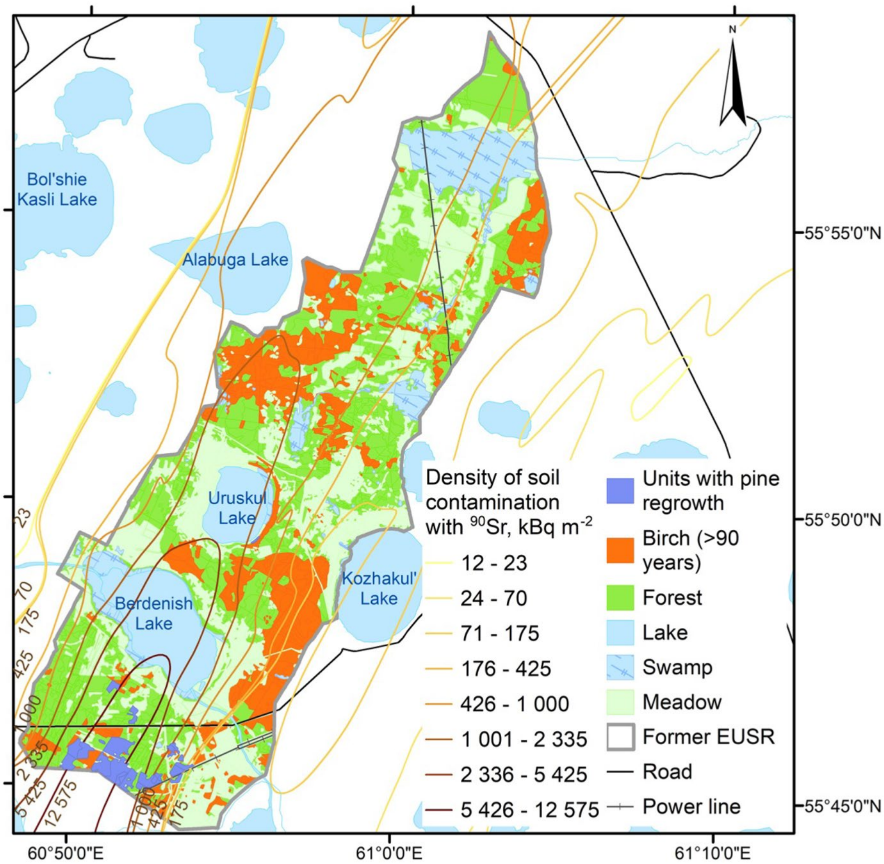

Fig. 4 Areas requiring silvicultural measures (birch stands 100–140 years old) and special study (regrowth of pine trees in the most contaminated part of the EUSR)

and relics. It is reported that the zone of the former EUSR is similar to Karagay, Troitsky, and Sanarsky sanctuaries. These territories play a key role in the maintenance of the ecological balance and in the preservation of biological and landscape diversity in the region, where the degree of economic land use is high (Lagunov & Smagin, 2007; Martyushov et al., 2000).

Conclusions

Currently, on forest lands of the former EUSR, birch forests occupy 92%, and pine forests 5.8%. The largest areas belong to birch forests aged 81 to 120 years, i.e., mature and overmature stands; 60.9% of timber stocks are represented by them. Young pine forests of 41–60 years of age are dominant in the EUSR. The total timber stock on the EUSR territory is more than 1385 thousand tons. Trunk wood makes the main contribution to the stocks (it constitutes 75.6–75.9% in deciduous species and 83.8% in pine).

The ^{90}Sr inventory that we determined in the ecosystems of the former EUSR (4.2×10^{14} Bq) is comparable to estimates published earlier. The stock of ^{90}Sr in soils of the forest area is 2.4×10^{14} Bq, and in forest stands, it is 4.8×10^{12} Bq. This means that soils contain on average 97.9% of the ^{90}Sr released into forests. An increasing tendency of the ^{90}Sr proportion in trees with a decrease in its concentration in the soil was noted. This phenomenon is explained by a nonlinear dependence of ^{90}Sr T_{ag} on soil contamination density.

Comparing ^{90}Sr concentrations in wood, bark, branches, and needles of trees with permissible levels of contamination according to Sanitary Rules (Russia), we can conclude that only a small part of the EUSR forest stands can be used for economic purposes. It is worth mentioning the importance of the EUSR for basic and applied research into the decreasing impact of radiation on the biota. This zone is characterized by high diversity of landscapes, soil types, and ecosystems and by a wide range of radioactive-contamination levels. The human impact in this area has been minimized. These circumstances have created an opportunity to study the radionuclide redistribution among ecosystem components and consequences of exposure to low doses for living organisms.

Author contribution Vera N. Pozolotina: conceptualization, writing, and editing of the paper. Julia V. Shalaumova: database creation and processing, calculations, and maps' visualization using ArcGIS. Vladimir A. Lebedev: field research, database creation and processing, and draft preparation. Andrey A. Grigor'ev: field research, database creation and processing, and draft preparation. Ludmila N. Mikhaylovskaya: determination of the ^{90}Sr content in samples of soil and tree parts and editing of the paper. Makar Modorov: field research, creation of approximation models, database processing, and calculations. Oleg V. Tarasov: database design and paper preparation.

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Data availability All data generated and analyzed during this study are included in this published article and its supplementary information files.

Declarations

Ethics approval All authors have read, understood, and have complied as applicable with the statement on "Ethical responsibilities of Authors" as found in the Instructions for Authors and are aware that with minor exceptions, no changes can be made to authorship once the paper is submitted.

Conflict of interest The authors declare no competing interests.

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