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Current State of Tree Stands in the Zone of Eastern Ural Radioactive Trace Proximal to the Epicenter of Kyshtym Accident

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Abstract—The current state of forest stands has been assessed in the most heavily contaminated part of Eastern Ural Radioactive Trace (EURT) formed as a result of the Kyshtym accident (1957). The main contaminant in the EURT zone is ^{90}Sr, with contamination density varying from 70 to 67 450 kBq/m^2. Herbaceous birch forests dominate in this territory, and more than 85% of them are aged between 70 and 120 years. Pine forests are relatively rare, with tree age reaching 80–110 years in 58% of these stands. The average age of birch forests proved to decrease with an increase in the density of soil contamination with ^{90}Sr, which was explained by the increasing proportion of young birch stands formed in the most heavily contaminated areas during 25–30 years after the accident. No significant dependence of relative stand density and timber volume on the level of soil contamination with ^{90}Sr in different compartments was revealed. A comparison of timber volumes recorded in 2003 and 2020 showed that this parameter was increasing more rapidly in the most heavily contaminated compartments due to active growth of young birch stands in these areas during the corresponding period. Assessing natural forest regeneration in the EURT zone, it was found that tree undergrowth is formed in most compartments, which is potentially capable of ensuring further development of forest ecosystems. The establishment of pine undergrowth was observed for the first time in compartments proximal to the epicenter of the accident, where all pine trees perished during the acute radiation period. These samples contained an increased proportion of plants with morphological abnormalities. No dependence of the rate of tree die-off on the level of soil contamination with ^{90}Sr was revealed. The rates of tree die-off and natural forest regeneration were difficult to estimate accurately because of fires regularly occurring in the EURT zone.

Keywords: Kyshtym accident, Eastern Ural Radioactive Trace, remote consequences, fires, forest stands, *Betula pendula* Roth., *Pinus sylvestris* L., timber volume, relative stand density natural forest regeneration

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The Eastern Ural Radioactive Trace (EURT) was formed as a result of radioactive waste tank explosion at the Mayak radiochemical plant (today, Mayak Production Association) on September 29, 1957, known as the Kyshtym accident. The amount of released radioactive materials was estimated at 7.4×10^{17} Bq (20×10^6 Ci), with about 10% rising to the atmosphere, and the subsequent fallout contaminated an area of about 23 000 km^2. An experimental research station (ERS) was organized at Mayak in 1958 to study the impact of radiation on living objects, radionuclide migration over food webs, and develop approaches to agriculture in contaminated areas. As a result of special measures developed with participation of ERS, the greater part of the EURT area was returned to economic use by 1967. The most heavily contaminated territory was used to establish the East Ural State Nature Reserve [1]. The EURT zone (the head part of the trace) is a unique natural testing ground for analyzing the functioning of natural ecosystems under chronic radiation stress. Studies performed in this zone laid the groundwork for fundamental radioecology and were used to develop practical guidelines for remediating the consequences of radiation accidents [2–4].

The vegetation of the EURT zone consists mainly of birch and, less frequently, pine–birch forests alternating with herbaceous communities. Its detailed geobotanical descriptions were published previously [5–8]. The initial period after the accident was marked by large-scale die-off of pine (*Pinus sylvestris* L.) and, in some cases, birch trees (*Betula pendula* Roth.). The surviving trees suffered damage to needles or leaves and to apical and lateral meristems. The processes of postradiation recovery in the affected forests became dominant 8–10 years later [9]. This stage was generally completed by the early 1990s, when the radiation impact on the biota decreased significantly [5, 10]. Dendrochronological analysis of pine from the EURT zone showed that the impact of radiation on tree-ring growth in 1959–1960 was comparable to that of severe drought, being even stronger in some cases. Eight years later, however, tree-ring growth returned to normal and no longer differed from that in control trees [11].

Extensive radioecological research on forest communities has been carried out in the zones of accidents at Chernobyl [12–15] and Fukushima Daiich NPPs [16, 17], with special attention being paid to the consequences of fires in forests of the Chernobyl zone [13, 18, 19]. Of special significance are comparative studies on the consequences of major nuclear accidents (Kyshtym, Chernobyl, Fukushima) for natural ecosystems, since they help to reveal basic trends in the migration, accumulation, and biological effects of radionuclides and outline the range of factors that modify radiation effects [13, 20].

In this paper we consider the results of some studies on the state of forests in the zone of Kyshtym accident with regard to the remote consequences of acute and chronic radiation exposure. There is no information on the current species and age composition of forests, timber volumes, and prospects for natural forest regeneration in this zone. Based on our own and published data [11, 20–22], we hypothesized that the processes of recovery of forest communities have been completed during the 64-year period after the accident, and the current levels of soil contamination in the EURT zone have no appreciable effect on their development. Variation in recent forest inventory parameters in the contamination gradient depends on the processes of natural development of forest stands, their age-related dynamics and succession. Anthropogenic fires also have a certain effect on the state of forests in the EURT zone [1, 23].

The purposes of this study were as follows: (1) to estimate the main forest inventory parameters of stands in the zone proximal to the epicenter of Kyshtym accident (2) to assess the state of tree stands depending on the level of soil contamination with ^{90}Sr; (3) to evaluate the dynamics of forest development in the EURT zone by comparing recent data with forest inventory parameters recorded in 2003; and (4) to analyze specific features of natural forest regeneration in the contaminated territory. The hypotheses to be tested were that (a) the rate of timber volume accumulation does not differ along the gradient of radioactive contamination; (b) an increase in the level of soil contamination leads to a higher tree die-off in mature and overmature stands; and (c) natural forest regeneration on account of undergrowth does not depend on contamination density.

MATERIAL AND METHODS

Study region

The EURT lies within the Transural Peneplain in the forest–steppe zone of the Southern Transural province [24}. Its territory is a low-relief plain (elevations 130–250 m a.s.l.) with lakes and depressions. The largest lakes are Berdenish and Uruskul’. The central part of the territory is slightly elevated, and its northeastern part is occupied by the marshy floodplain of the Karabolka River [6]. The climate of the forest-steppe zone is moderately continental with, with long cold winters (average January temperature −17°C) and warm, often droughty summers (average July temperature 18°C). Annual average precipitation is 400–500 mm. The soil cover is composed mainly of different subtypes of gray forest soils and, in places, leached chernozems [6, 7]. Forest communities are represented mainly by birch forests, sometimes with an admixture o aspen. Mixed pine–birch forests are less frequent [5, 6, 8].

The EURT territory is a narrow sector extending northeastward for more than 100 km [25, 26]. Short-lived radionuclides prevailed in the fallout; among long-lived ones, ^{90}Sr (half-decay period 28.8 years) contributed most to radioactive contamination of the EURT zone. Its total contents in the EURT soils are currently estimated at about 570 × 10^{12} Bq [27]. Being an analog of calcium, this radionuclide is actively accumulated by living organisms, thereby creating a long-term hazard to ecosystems [28]. The EURT territory was repeatedly contaminated in 1967 as a result of silt and sand transfer from the shores of shallowed Lake Karachay, which was used as an open reservoir for radioactive waste storage. The main contaminant in this case was ^{137}Cs, but its amount was only about 2.2 × 10^{13} Bq, i.e., significantly lower than that of ^{90}Sr [29]. Detailed characteristics of radioactive contamination in the EURT territory are given in previous studies [1, 4, 7, 25, 27].

The level of radiation impact in different areas was estimated from the density of soil contamination with ^{90}Sr. The central EURT axis is contaminated most heavily, with soil contamination density decreasing from 67 450 kBq/m^2 at 5 km from the epicenter of the accident to 70 kBq/m^2 at 36 km. The decrease in this parameter both along the central axis and from the axis to the periphery of the trace has an exponential character [7, 27, 30]. The background level of soil contamination with ^{90}Sr in the Ural region is 1–3 kBq/m^2 [31].

Studies were performed in 2019 to 2021 in the EURT part proximal to the epicenter of the accident, at 6–16 km from the industrial site (Fig. 1). On the whole, 84 compartments were studied within 23 quarters along the central axis and at the periphery of the trace, compared to two compartments in neighboring territories (18.5 km south and 25.7 km southwest of the epicenter) with soil contamination at the back-

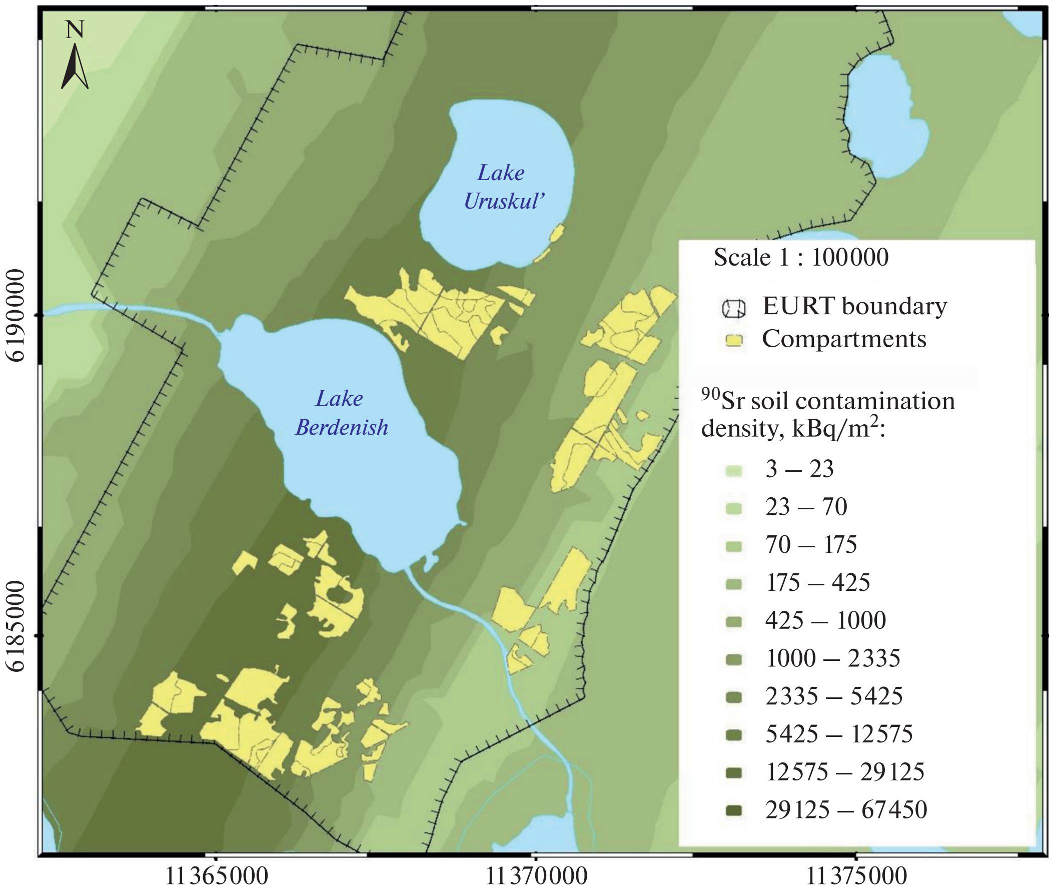

Fig. 1. Schematic map of the location of compartments studied in the EURT head part, with ^{90}Sr soil contamination density mapped according to [27], with modifications. Here and in Fig. 5, the coordinate system Pulkovo 1995 GK Zone 11 is used.

ground level and similar landscape–geochemical conditions.

In our previous study, the recorded levels of soil contamination density with 90Sr were interpolated to unsampled areas by ordinary kriging, and the Monte Carlo method was used to quantify uncertainty in the estimated total contents of this radionuclide in the EURT soils [27]. These data were normalized as of 2021 with regard to ^{90}Sr half-decay period and georeferenced to the study compartments using the ArcGIS 10.8.1 system [32] (Fig. 1). Since the contamination gradient decreased exponentially with increase in distance from the accident epicenter, the data on soil contamination density were natural log transformed (Table 1).

Methods for Evaluating Forest Inventory Parameters

Selective visual forest inventory in the EURT zone and neighboring background areas was performed with regard to the density of soil contamination with ^{90}Sr [33]. Basic parameters of tree stands were described in circular relascopic plots within the study compartments. The number of plots per compartment varied from two to five depending on its area and tree stand uniformity and relative density. In each plot, relative stand density was determined using an angle gauge [34], and the breast-high diameter and height of five to ten model trees of each forest-forming species were measured with a tree caliper and a Nikon Forestry Pro laser hypsometer. Descriptions were made of stand composition, the presence of undergrowth, traces of fires, and dead tree trunks.

The average age of forest stands was determined from tree height using regional tables of the time course of tree growth [35]. Timber volumes were estimated with reference to standard tables for normal pine, birch, and aspen (*Populus tremula* L.) stands in the forest–steppe zone o Chelyabinsk oblast [36]. The following age groups of pine stands were distinguished: young stands, up to 20 years; polewood stands, 21–40 years; maturing stands, 61–100 years; mature stands, 101–140 years; overmature stands, older than 141 years. The age groups of birch stands were as follows: young, up to 20 years; middle-aged, 21–70 years; maturing, 71–80 years; mature, 81–90 years; overmature, older than 91 years. For non-mixed uneven-aged stands, the weighted average age

Table 1. Inventory parameters of tree stands and morphological characteristics of trees in the EURT zone and neighboring background areas

Contamination density intervals, ln	Stand composition (number of compartments with a given composition)	Birch			Pine			Relative density	Stand volume, m^3/ha
		age, years	diameter, cm	height, m	age, years	diameter, cm	height, m		
0–1.1 (background)	8P2B (2)	60	23	20	85	27	22	0.7	235.0
4.6–4.78	10B, 10B + B (8)	101	30	25				0.7	219.9
	7B3B (1)	105	28	24				0.8	246.0
	8B2B (1)	80	34	24				0.4	123.0
5.02–5.97	10B, 10B + B, 10B + B + A, 10B + A (12)	108	29	25				0.7	204.3
	7B3B (1)	85	31	24				0.5	154.0
6.07–6.97	10B, 10B + B, 10B + A (8)	86	26	24				0.8	239.8
	10P – C (1)	–	–	–	65	25	22	0.6	165.0
	7B3B+B (1)	110	28	24				0.4	117.0
7.28–7.95	10B, 10B + B, 10B + A (5)	80	24	24				0.7	218.2
	10B + P (1)	110	26	16				0.4	73.0
	4B2A2P2B (1)	30	16	16	40	12	12	0.6	86.0
	5B3P2A (1)	80	29	23	100	39	25	0.6	182.0
	7B3A + P (1)	100	30	22				1.0	276.0
	7P3B (1)	70	18	24	85	28	25	0.7	230.0
	8P2B (1)	30	16	12	30	16	12	0.6	70.0
	9B1P (1)	70	24	23				0.5	154.0
8.19–8.99	10B, 10B + B, 10B + A, 10B + B + A (16)	89	26	24				0.8	223.4
	10B + A + P (1)	80	24	24				0.9	277.0
	7P3B (1)	100	28	24	85	36	25	0.8	262.0
	7P3B + A (1)	30	16	12	30	16	12	0.6	70.0
	8P2B (1)	100	28	24	85	34	24	0.7	214.0
	9B1A (1)	80	28	24				0.9	260.0
9.25–9.86	10B, 10B + B, 10B + A (13)	70	23	22				0.6	168.5
	10B + P (1)	40	20	18	30	15	10	0.3	73.0
	5B5B (1)	85	28	24				0.7	216.0
	5P5B (1)	85	32	24	85	32	24	0.8	245.0
	7B3B (1)	90	27	24				0.9	277.0
	8B2A (1)	80	24	23				0.8	234.0
	9B1A + B (1)	85	24	20				0.9	201.0

Tree species: (B) birch, (P) pine, (A) aspen, (C) cultures.

was determined based on the proportions of certain groups of trees in the stand [37].

When describing the undergrowth, special attention was paid to regeneration of pine and birch, the main forest-forming species. Morphological alterations in the undergrowth were recorded. The occurrence of relatively recent ground fires (over the past decade) was estimated from the presence of burns at tree bases. The level of tree die-off was determined visually from the number of dead trunks lying within the line-of-sight range from the observation point.

Timber volume per hectare, a convenient parameter that not only integrates physical characteristics of tree trunks but also has direct practical significance. This parameter was used as the main criterion for assessing the state of forests in the EURT zone, where it showed a statistically significant correlation with relative stand density ($R^2 = 0.783$; $p = 0.00001$).

The basic parameters recorded in this study were compared with the results of 2003 forest inventory performed in the compartments by the Nizhny Novgorod expedition under contract with Mayak [38]. A comparative analysis of data on the age and density of stands and timber volumes made it possible to evaluate changes that occurred in the EURT forests over the past 16–18 years. The radiation situation in this one has stabilized during this period, with the ambient gamma dose rates decreasing more than 3000-fold, compared to those in the initial period after the accident [26, 39].

Statistical hypotheses were tested using correlation and regression analyzes in in the STATISTICA v. 10 package [40].

RESULTS

Herbaceous birch forests (of herb–grass, stone bramble, shrub, and fern types) dominate in the EURT head part, accounting for about 9% of all forest in the area. The proportion of mixed pine–birch forests of stone bramble, shrub, and fern types is small, and single sites are occupied by pure pine stands planted after the accident.

Tree Stand Age

Birch forests were studied in 84 compartments. Stands younger than 20 years were absent, the proportions of middle-aged and maturing stands were about 21 and 12%, respectively, while overmature stands were dominant (over 46%). The current age of birch trees in the dominant group (91–130 years) is concordant to that recorded during the 2003 forest inventory, when it was estimated at 81–90 years [38]. Among both pure and mixed pine stands (10 compartments), maturing and polewood stands were prevalent (60 and 40% respectively). Thus, forest stands that survived the 1957 Kyshtym accident proved to dominate in the EURT compartments. Pine trees aged 85 years were also found in background areas.

The average age of birch trees proved to decrease along the contamination gradient (R^2 = 0.202; p = 0.00002) (Fig. 2). This agrees with the results of 2003 forest inventory and may be explained by a higher die-off rate of old trees and intense young tree growth in the most contaminated areas. This assumption is supported by data on higher variation in the age of birch trees within heavily contaminated compartments where its range was 30–110 years, compared to 80–120 years in slightly contaminated compartments. No such trend was observed for pine trees within forests stands: their age did not change along the contamination gradient (R^2 = 0.094; p = 0.33). Detailed characteristics of forest stands along the EURT contamination gradient are given in Table 1.

Timber Volume

Timber volumes of forest-forming species showed no dependence on the density of soil contamination with ^{90}Sr (R^2 = 0.012; p = 0.31). Likewise, ground fires that left their marks in some compartments caused no reduction in timber volume (R^2 = 0.020; p = 0.58). Comparing timber volumes recorded in the same compartments of the contamination gradient in 2020 and 2003, it was found that the difference between the respective values increased significantly with increase in soil contamination density (R^2 = 0.103; p = 0.0028) (Fig. 3).

Similar comparisons for different age groups of birch showed that the growth of timber volume between 2003 and 2020 reached a peak in the youngest age group, slowed down in groups aged up to 70–75 years, and became negative in the group older than 50–85 years (Fig. 4). In general, this dependence was adequately described by a linear regression equation ($y = 145.69–1.89x$; R^2 = 0.49; p = 0.00001). The data on relative stand density showed similar trends, with the only difference that negative values of its growth were revealed earlier, beginning from the age of 55–65 years. An increase in the average tree height in young and middle-age stands and a decrease in the relative density of mature and overmature stands occurred during the period from 2003 to 2020 (Table 1).

Tree Die-off

No linear dependence of die-off rate on the density of soil contamination with ^{90}Sr was revealed (R = 0.216; p = 0.68). Ground fires that left visible traces on tree trunks proved to have an effect on tree die-off. We used a pooled sample of tree stands (regardless of tree age and soil contamination density in the compartments) to compare the frequencies of compartments with birch die-off and compartments with traces of ground fires and revealed a correlation between these events (χ^2 = 8.25; p = 0.004). Tree die-off occurred independently of fires, but compartments without dead trees proved to be more numerous among those affected by fires. A probable explanation is that fallen trees burned to ashes during ground fires.

The frequencies of compartments with traces of fires and tree die-off were normalized relative to the numbers of compartments surveyed within areas with particular densities of soil contamination with ^{90}Sr (%). Analysis of the results showed that the linear relationship between these events in the contamination gradient lacks statistical significance (R^2 = 0.002; p = 0.93). There were some compartments where no fire occurred but tree die-off was considerable. They were usually located distantly from the boundaries of the EURT zone. As a rule, fires spread to this zone from human-populated areas.

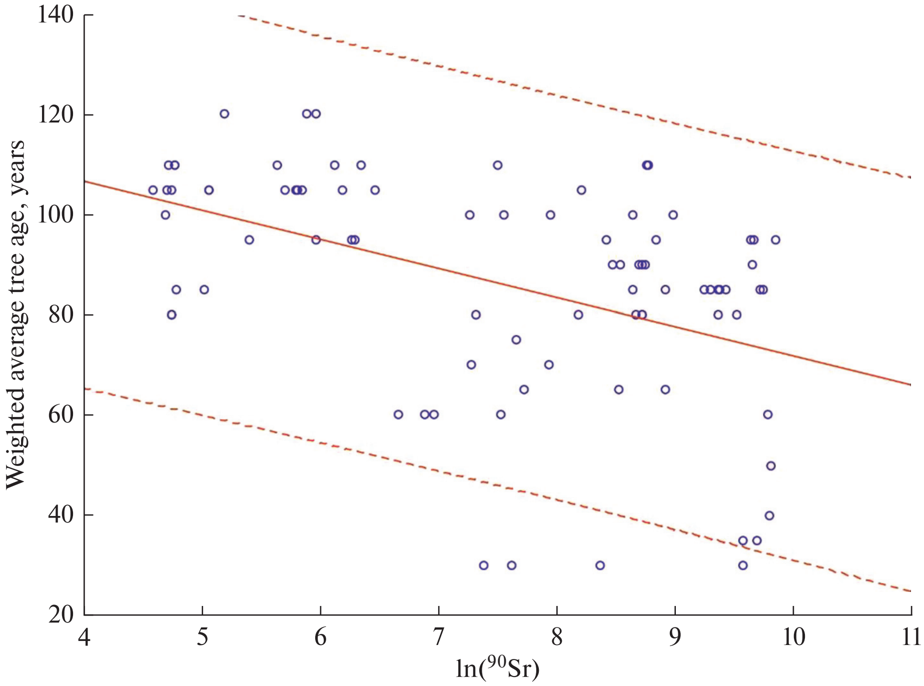

Fig. 2. Relationship between birch tree age in forest stands and ^{90}Sr soil contamination density. Here and in Figs. 3 and 4, dashed lines show 95% confidence intervals.

The State of Undergrowth

To predict the development of tree stands in the near future, regeneration of forest-forming species was evaluated in compartments with different levels of soil contamination with ^{90}Sr. The results showed that soil contamination level had no effect on the occurrence of pine undergrowth ($R2$ = 0002; p = 0.96) or birch undergrowth (R^2 = 0.043, p = 0.22). Pine undergrowth of one or two ages prevailed in the majority of plots. Pine undergrowth was found in 23 out of a total of 84 compartments surveyed in the EURT head part, with pine as a component of tree stand being found in only 8 compartments. On the whole, pine as a basic or accessory component of forest (with a frequency of more than 10% or less than 5%, respectively) occurred in 13 out of 84 compartments.

The question of pine expansion to the most heavily polluted zone proximal to the accident epicenter is of special interest, since all pine trees in this area perished during the first years after the accident. The schematic map in Fig. 5 shows the area where no pine undergrowth occurred in 2003 whereas in 2020 some birch stands in this part of EURT were found to contain abundant pine undergrowth aged about 5 and 20 years. In 2003, pine trees aged 20–35 years were already found in some compartments at the EURT periphery (Fig. 5); therefore, these trees appeared in the contaminated zone 10–25 years after the accident.

In 2020, young pine trees in the most heavily contaminated plot included a considerable proportion of specimens with disturbances of growth and development (Fig. 6). The frequency of defoliation and dechromation reached 40%, and shoot die-off, multiple apices, crooked stems and morphoses of needles were observed in no less than 30% of trees from the corresponding sample.

DISCUSSION

Detailed geobotanical descriptions of forest and herbaceous communities in the EURT territory contaminated after the Kyshtym accident are available from previous publications [5–8]. They provide evidence for dominance of birch forests (91.7%), with pine and pine–birch stands covering about 8% of the total forested area. Forest phytocenoses damaged after the accident subsequently recovered in the same habitats, while abandoned plowed fields and areas of demolished villages were occupied by secondary herbaceous communities [5, 7]. As shown by analyzing the taxonomic diversity of these communities, plant species richness in the study area depends not so much on the level of soil radioactive contamination as on the diversity of community types in the test compartments and the type and intensity of economic activities in the period before the accident [8, 41].

Radiation impact on the biota in the initial period after the accident was estimated in terms of absorbed doses, because the rapid decay of short-lived radionuclides generated powerful radiation. The length of the acute radiation period after accident in the Urals was

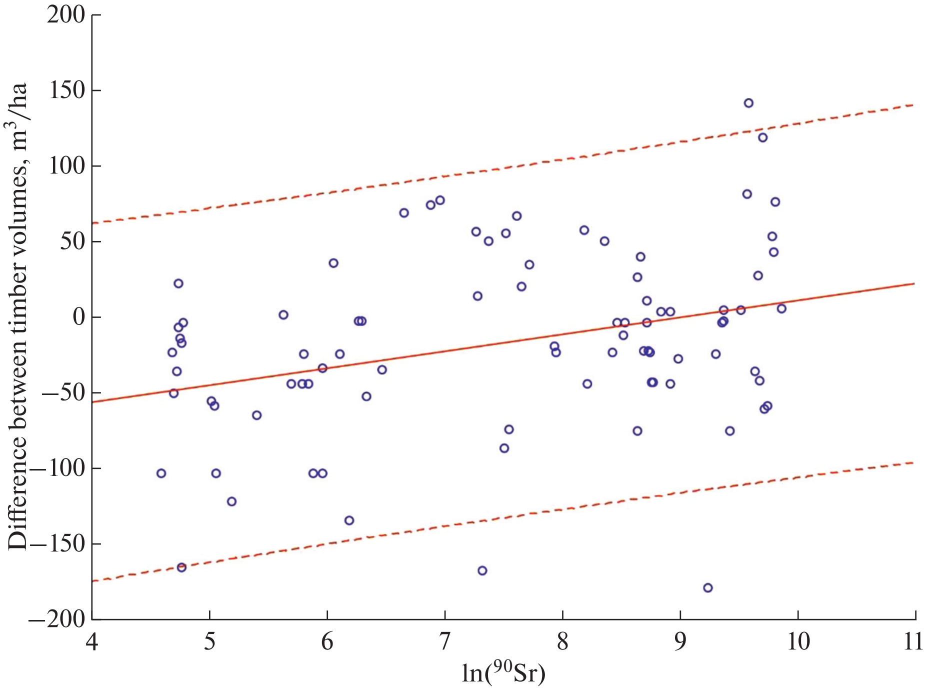

Fig. 3. The difference between timber volumes recorded in 2020 and 2003 as dependent on ^{90}Sr soil contamination density.

different from that in Chernobyl [28], where the accident occurred in spring and the acute period lasted for about a month [42, 43]. The accident in the Urals occurred in autumn, in the period of physiological dormancy, when all metabolic activities of plants, including the processes of recovery, were reduced. Therefore, effective radiation doses were those accumulated over the entire acute period, from autumn to the next spring [28]. The maximum radiation doses absorbed during the acute period near the site of the accident were in the range of 100–800 Gy for pine buds and 20–200 Gy for birch buds [28]. Such radiation burden resulted in the death of all pine trees (LD_{50} for this species is 10–13 Gy) and a considerable proportion of birch trees (LD_{50} = 30–40 Gy) [28, 44, 45]. The absorbed doses decreased with increase in the distance from the accident site along the central axis and from the central axis to the periphery of the trace, which allowed the survival of many trees [28].

The acute stage was followed by a long period of chronic irradiation, with radiation doses decreasing abruptly but still having a strong damaging effect. Tree crowns gradually became cleaned of radionuclides, with the greater part of radioactivity entering the forest litter and then the soil, and absorption by roots became the main way of radionuclide intake by plants. This period lasted for 5–6 years [20] and, as shown in Scots pine, was characterized by the minimum tree ring growth with gradual recovery of tree metabolic activity [11]. The followed the period of chronic quasi-equilibrium, which has continued to date.

A major proportion of birch forests in the EURT zone have already approached the biological life span limit. There is no significant dependence of relative stand density and timber volume on the level of soil pollution with ^{90}Sr. This confirms our hypothesis that timber volume will no longer change after 64 years since the accident. The results of early studies in the Kyshtym and Chernobyl zones [9, 43, 46, 47] show that radiation damage to the cambium reduces the growth of tree trunks and makes them more fragile. The suppressing effect of radiation in affected trees may be enhanced due to invasion by pest insects, parasites, and wood-decomposing fungi [46–49]. However, the majority of damaging factors lose their effect with time: physiological processes in trees growing in the EURT zone were recovered within 7–8 years after the accident [9, 11].

Comparing timber volumes recorded in 2003 and 2020, it was found that this parameter during the corresponding period increased at a higher rate in the most heavily contaminated plots, which was probably due to the greater proportion of young stands formed in these plots 25–30 years after the accident. Comparisons of differences between timber volumes recorded in 2020 and 2003 for different age groups showed that that the growth of this parameter reached a peak in the young age group (30–36 years) and decreased to zero by the age of 70–75 years, with subsequent reduction of timber volume in the stand. This is in agreement with the standard pattern of birch development with age [50].

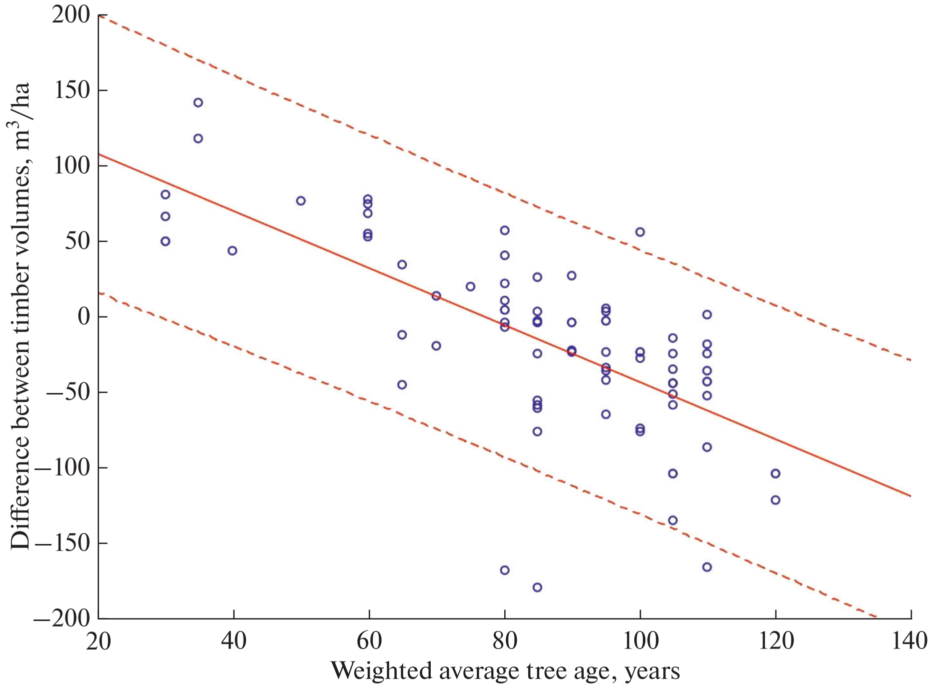

Fig. 4. Comparison of differences between timber volumes recorded in 2020 and 2003 in different age groups of trees in birch stands.

The rate of tree die-off showed no dependence on the level of soil contamination with ^{90}Sr. It should be noted that the die-off processes are affected by fires regularly occurring in the EURT zone mostly in April to May [23]. The greatest ground fire in this zone occurred in 2008; it spread over a vast area with ^{90}Sr soil contamination density ranging from 19 to 37000 kBq/m^2 [23]. In general, fires affected relatively small areas downwind from the burning zone. Nevertheless, a two- to eightfold increase in parameters of radiation situation was observed on these days at control points located at a distance of up to 10–15 km from the fire site, but all these parameters returned to the initial level within a few days after the fire. Forest fires in the Chernobyl zone, including crown fires in 2015, also have not caused any significant redistribution of radioactivity even on the local scale [18, 51].

The assessment of natural forest regeneration in the EURT zone showed that most of compartments contain birch and pine undergrowth, which is potentially capable of ensuring further development of forest ecosystems. However, no definite relationship between the presence of undergrowth and the level of soil radioactive contamination was revealed (the amount of undergrowth was not estimated in this study). It is noteworthy that pine undergrowth of one or two different ages prevailed in most of the plots. This agrees with the data on "pyrogenic" nature of periodic regeneration of conifer species after ground fires [52]. The impact of fires on forest regeneration manifests itself in different ways: on the one hand, fires destroy the undergrowth of tree species; on the other hand, they also destroy the herbaceous layer and forest litter, thereby providing for successful large-scale rooting of a new generation of trees [52].

The expansion of pine to birch stands in compartments proximal to the epicenter of the accident, where all pine treed died in 1958, was observed for the first time in 2020. No pine undergrowth was recorded in these compartments during the 2003 forest inventory. In 2020, the corresponding samples contained an increased proportion of plants with signs of suppression (defoliation and needle dechromation) and increased frequency of morphoses (no less than 30%), including multiple apices, crooked stems, shortened internodes, and alterations of needle shape. The relief of apical dominance because of apical bud damage in young pine trees occurs in all forest stands, but the frequency of trees with multiple apices in the control usually does not exceed 5% [53].

Multiple and diverse morphological disturbances in young pine trees were described in the Chernobyl zone during the initial period after the accident [43]. Forests in the zone affected by the Fukushima accident also contained increased proportions of young Japanese red pine [54] and Japanese fir trees [16] with multiple apices, while no morphoses were observes in mature trees. The authors consider that these disturbances are a temporary phenomenon that manifests itself only during the initial period after the accident. However, Igonina et al. [55] found that not only pine trees irradiated in the Chernobyl zone but also their

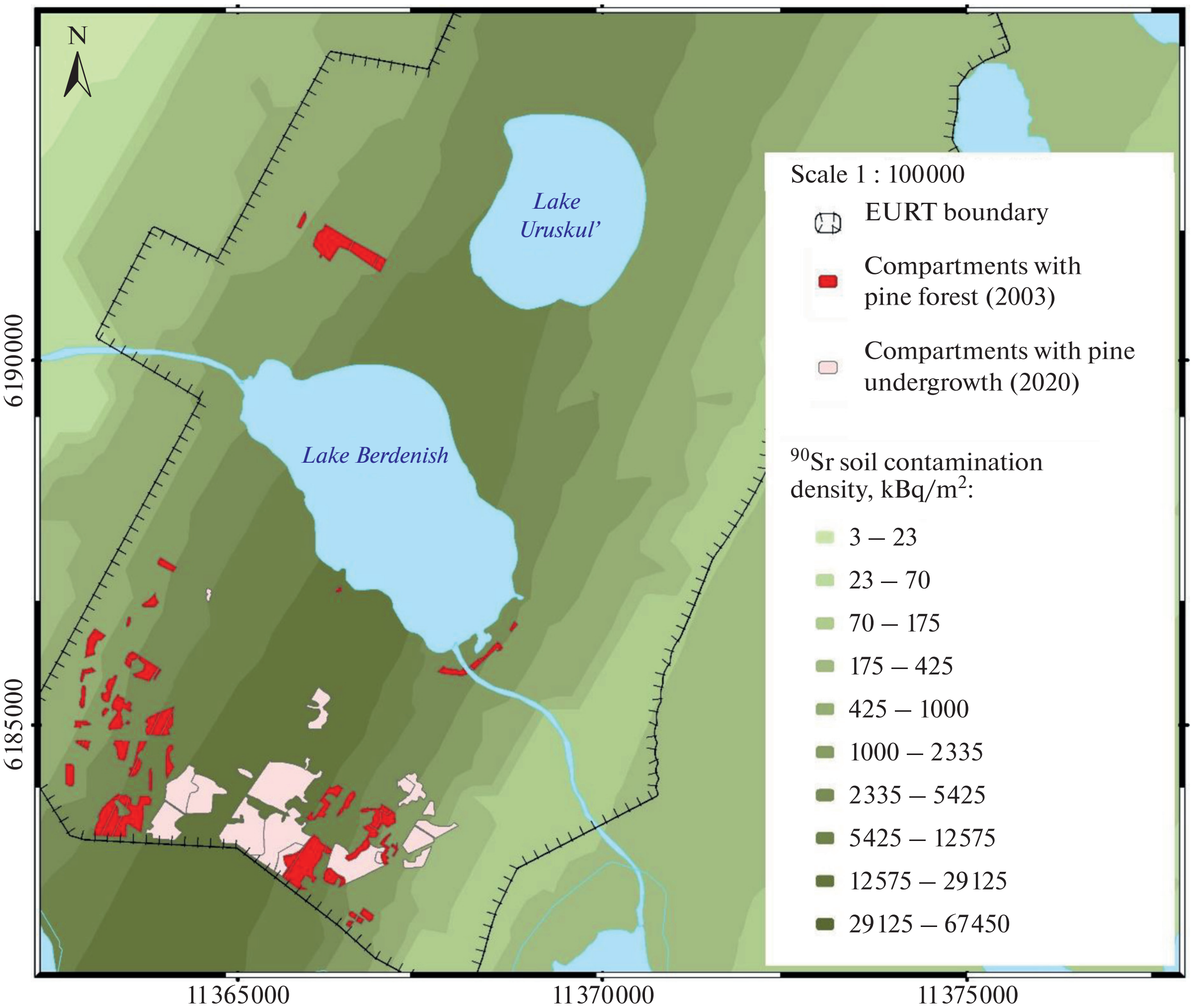

Fig. 5. Occurrence of pine forests and pine undergrowth in the EURT head part in 2003 and 2020.

irradiated F_2 progeny grown under clean conditions included a significantly increased proportion of plants with various morphoses, compared to the control. Additional studied are necessary for elucidating mechanisms responsible for morphological anomalies in young pine trees from the EURT area.

According to our data, the development of forest stands in the EURT zone follows the standard trends that are characteristic of the study region and depend on the composition of main forest-forming species and the period of their life cycle [36, 50, 56]. Subsequent successional processes in these forests ay follow different scenarios, either without replacement of forest-forming species or with partial replacement of deciduous species by pine. On the one hand, pine seedlings in herbaceous forests are poorly competitive with herbs, with birch and aspen being capable of occupying vacant areas much more rapidly [57]. On the other hand, large-scale age-dependent tree die-off in mature and overmature stands, which prevail in the EURT zone, contributes to the natural thinning of stands, which may provide for more successful survival of pine undergrowth [58].

CONCLUSIONS

Birch forests dominate in the most heavily contaminated part of the EURT, where our study was performed, and more than 85% of them are aged between 70 and 120 years. Pine forests are relatively rare, with tree age reaching 80–110 years in 58% of these stands. The average age of birch forests proved to decrease with an increase in the density of soil contamination with ^{90}Sr, which was explained by the increasing proportion of young birch stands formed in the most heavily contaminated areas during 25–30 years after the accident.

No significant dependence of timber volume on the level of soil contamination with ^{90}Sr was revealed. A comparison of timber volumes recorded in the same compartments in 2003 and 2020 showed that this parameter was increasing more rapidly in the most

Fig. 6. Anomalies in the development of Scots pine from the RURT zone: (a) stem crookedness, (b) stem die-off; (c) stem die-off and formation of multiple apices (photos by N.S. Shimalina, Institute of Plant and Animal Ecology, Ural Branch, Russian Academy of Sciences).

heavily contaminated compartments due to active growth of young birch stands. Comparisons of differences between timber volumes recorded in 2020 and 2003 for different age groups showed that the growth of this parameter reached a peak in the young age group (30–36 years) and decreased to zero by the age of 70–75 years, with subsequent reduction of timber volume in the stand.

No definite dependence was revealed between the rate of tree die-off and the level of soil contamination with ^{90}Sr. Forest fires regularly occurring in the EURT zone have influence on the die-off process.

Assessing natural forest regeneration in the EURT zone, it was found that most compartments contain the undergrowth of main forest-forming species, which are potentially capable of ensuring further development of forest stands. The establishment of pine undergrowth in birch stands growing in the compartments proximal to the epicenter of the accident, where all pine trees perished in 1958, was observed for the first time in 2020. Pine samples from these compartments contained an increased proportion of young trees with signs of suppression and morphological abnormalities.

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CONFLICT OF INTERESTS

The authors declare that they have no conflict of interest.

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