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COMPARING THE RADIOACTIVE CONTAMINATION OF MARSH LABRADOR TEA (LEDUM PALUSTRE L.) OVER DIFFERENT PERIODS SINCE CHERNOBYL ACCIDENT

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Radioactive contamination of the above-ground phytomass of marsh Labrador tea (Ledum palustre L.) in different periods after the Chernobyl accident was studied. Marsh Labrador tea is widely used in official and folk medicine. The studied species grows in over-moistened pine (less mixed) forests and open oligotrophic and mesotrophic marshes. It was found that in the first four years since the beginning of observations (1991), the magnitude of the specific activity of ^{137}Cs in above-ground vegetative phytomass of marsh Labrador tea, depending on a permanent sample area (PSA), decreased by 1.2–1.4 times. After 10 years, it decreased by 1.6–1.7 times, after 16 years by 1.9–2.1 times, after 21 years by 2.7–3.1 times, and after 27 years by 3.1–6.5 times. An increase in the magnitude of transitions factors was also observed on all PSA over time. Thus, the minimal increase within 1991–2018 was recorded in PSA 11 – by 1.2 times and on PSA 13 – by 1.4 times. The maximum decrease in the magnitude of transition coefficient was observed in PSA 16 – by 2.7 times, in PSA 15 – by 3.0 times, and in PSA 18 – by 2.0 times. It was found that marsh Labrador tea belongs to the group of plants that are characterized by the high content of ^{137}Cs in the above-ground vegetative phytomass. Within the observation period (1991–2018), this content significantly exceeds the admissible levels of radionuclide content in plant medicinal raw materials that are used for manufacturing medical preparations. In the PSA with maximum magnitudes of soil contamination density (400.5 ± 50.73 kBk·m^{-2}) this excess made up 158.4 times in 1991, and 33.7 times (166.9 ± 23.56 kBk·m^{-2}) in 2018. For 27 years of observations, there has been a decrease in the density of radioactive soil contamination by 2.1–2.7 times, which is due to radionuclide decomposition, its vertical migration in the soil, and towards the components of forest ecosystems

Keywords: specific activity of ^{137}Cs, radioactive contamination, migration of radionuclides, phytomass, forest ecosystems

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1. Introduction

Marsh Labrador tea (*Ledum palustre L.*) is a fairly common plant of over-moistened pine (less often mixed) forests, open oligotrophic and mesotrophic sphagnum swamps [1]. The main part of the marsh Labrador tea areal is common in Polissya on the territories that most suffered from radioactive contamination (mainly with ^{137}Cs) as a result of the accident at the Chernobyl nuclear plant.

It is known that as a result of the Chernobyl accident, forests suffered from significant radioactive contamination, which caused a revision of existing ideas and many regulatory documents on the use of forest resources. These resources contain numerous wild medicinal plants, including marsh Labrador tea [2]. However, the radiation situation in the forest arrays of the region changed over time, which is primarily due to the natural decomposition of the radionuclide. Taking into consideration these circumstances, monitoring studies on the dynamics of radioactive contamination of various species of medicinal plants are relevant. They greatly expand our perceptions of ^{137}Cs transition from soil to medicinal plants of forest and marsh ecosystems and make it possible to scientifically substantiate their use in the areas contaminated with radionuclides.

2. Literature review and problem statement

Marsh Labrador tea is an evergreen, branched bush with straight stems 0.5–1.0 m high. Short leaves are 2–6 cm long and 0.2–0.7 cm wide. The inflorescences, consisting of 20–30 white flowers appear on the ends of stems in May [3]. The upper (20–30 cm) leafy part of plant shoots is used for therapeutic purposes [4]. The root system of the plant is branched, surface delves into the soil to the depth of 30–40 cm. Long stems of marsh Labrador tea bend under their own weight and the weight of snow and delve into sphagnum mosses in swamps. The upward growth of sphagnum also contributes to the process. In less moistened areas, shoots are covered by plant debris and easily form additional roots. With the help of root sprouts, bushes grow around the area. The plant grows on peated soils and peatlands with high acidity (pH 3–4) and low aeration of the substrate [5]. In such soils, ^{137}Cs is mainly in water-soluble (15–30 %) and exchange (70–85 %) forms [6] and over the years it is not fixed [7]. In such circumstances, marsh Labrador tea forms permanent symbiotic relationships with mycorrhizae fungi, which supply it with nutrition elements from the organic substrat [8]. 22 species of endophytic fungi for the plant were found in central Polissya of Ukraine [10]. The researchers referred marsh Labrador tea to the clearly manifested mycotrophic plants.

The ecological area of marsh Labrador tea covers mostly damp and wet boreal forests (A_4–A_5) and subors (B_4–B_5). At the same time, the plant is quite often found in lowlands in damp boreal forests and subors [1]. It should be noted that these types of forest plant conditions are quite common in Ukrainian Polissya. Thus, only in Volyn, Rivne, and Zhytomyr regions, where the largest areas of damp and wet boreal forests and subors of Polissya of Ukraine are concentrated, the area of forests in these types of forest plant conditions is 167.1 thousand hectares [11]. Similar results were obtained by other authors [12]. It is in this region that marsh Labrador tea shoots for medicinal purposes are mainly harvested. In damp boreal forests and subors, pure pine plantations of a low class of bonitet or those with the participation of drooping birch are formed. They grow in poor and over-moistened conditions – mainly on peat-glee-podzolic soils with the peat layer of up to 40 cm [13].

In the first years after the Chernobyl disaster, researchers paid considerable attention to radioactive contamination of medicinal plants in the regions that suffered the greatest radioactive contamination. The sphere of their interests included medicinal raw materials, which are obtained from shoots of marsh Labrador tea. In paper [14], marsh Labrador tea was included in the plants that accumulate ^{137}Cs with a sufficiently high intensity. In publications [15, 16], which covered the main features of radioactive contamination of medicinal raw material by ^{137}Cs, similar conclusions were obtained. However, the obtained results of ^{137}Cs content in medicinal raw materials, unfortunately, were not related to certain magnitudes of the density of radioactive soil contamination and specific environmental conditions. Given this, it is difficult to compare them with each other and draw conclusions on the peculiarities of ^{137}Cs accumulation in marsh Labrador tea and the possibilities of its use at certain levels of radioactive contamination of territories.

In the following period, the researchers studied the ^{137}Cs distribution in marsh ecosystems and the accumulation of radionuclide by different plant species on drained marshes. The studies were conducted in the Western Ukrainian Polissya (Krychil forestry of the state enterprise “Sarnensk forestry” of Rivne oblast). In paper [17], it was shown that forest reclamation makes a significant impact on the intensity of ^{137}Cs accumulation in the phytomass of marsh Labrador tea. On non-reclaimed forest oligotrophic marshes at the density of radioactive soil contamination with radionuclide of 8.5±1.18 kBk·m^{-2}, the specific activity of ^{137}Cs in shoots of marsh Labrador tea was 1,823±193.0 Bk·kg^{-1}. This result exceeded the corresponding hygienic norm more than 3 times. The mean value of the transition coefficient reached 220.34±12.99 m^2·kg^{-1}·10^{-3}. In the area of 15-year-long reclamation of this marsh and at a near density of radioactive contamination of soil with a radionuclide (10.5±1.15 kBk·m^{-2}), the specific activity of ^{137}Cs in medicinal raw material of marsh Labrador tea was 1,409±105.1 Bk·kg^{-1}. The mean value of the transition coefficient decreased to 134.7±4.98 m^2·kg^{-1}·10^{-3}. The resulting data correlate well with those obtained on the territory of the Republic of Belarus. In research [18], it was proposed to use the hydromeliorative method to decrease the radionuclide concentration in valuable plants of forests and marshes.

The studies were carried out on the meso-oligotrophic pine-sphagnum swamp in Rivne nature reserve 20–30 years after the Chernobyl disaster. The findings [19] allowed scientists to attribute marsh Labrador tea to the plants with the medium content of ^{137}Cs. During the research, it was found that the shoots of marsh Labrador tea contained much less radionuclide than other species that grew nearby – mud sedge (*Carex limosa L.*) and marsh scheuhzeria (*Scheuhzeria palustris L.*). Marsh Labrador tea, which under these environmental conditions grew on low hummocks had the mean values of coefficient of ^{137}Cs transition of 98.52 m^2·kg^{-1}·10^{-3}. Other researchers in this region give the mean values of transition coefficient in the link “soil – shoots of marsh Labrador tea” of 61.67 m^2·kg^{-1}·10^{-3}. The research was conducted on mesotrophic swamps [20].

The monograph demonstrated that the shoots of marsh Labrador tea accumulate ^{137}Cs under various forest and plant conditions with different intensity [2]. Thus, on oligotrophic marshes of the Ukrainian Polissya in wet boreal forests, the mean value of the coefficient of radionuclide transition to this medicinal raw material reached 180.9±11.65 m^2·kg^{-1}·10^{-3}, and in damp bors – 235.2±13.67 m^2·kg^{-1}·10^{-3}. On forest mesotrophic marshes, the mean values of this factor were somewhat lower in comparison with oligotrophic marshes: in damp subors – 179.9±10.05 m^2·kg^{-1}·10^{-3}, in wet subors – 200.0±11.76 m^2·kg^{-1}·10^{-3}. The scientists concluded that even a long time after the catastrophe at the Chernobyl nuclear plant, the shoots of marsh Labrador tea remain one of the most contaminated kinds of medicinal raw material. That is why it was recommended to ban industrial harvesting of this medicinal raw material.

In central Sweden, scientists studied the levels of radioactive contamination of the plants of upper sphagnum marshes with Scots pine (*Pinus sylvestris L.)*. They found that in 2004–2007, among vascular plants of the mentioned ecotypes, marsh Labrador tea was marked by the maximum values of the transition coefficient of ^{137}Cs – 158.0±24.34 m^{2}·kg^{-1}·10^{-3} [21].

Researchers explained the high cumulative ability of marsh Labrador tea relative to ^{137}Cs by two main factors. The first is a specific feature of ecotopes where the species grows. These are powerful peatlands with a low degree of decomposition and the existence of insignificant mineral fine earth. These factors cause considerable mobility of the mentioned radionuclide in the soil and vegetation cover of these marshes [22, 23]. The second factor includes biological features of plant species, which grow under quite harsh ecological conditions (poor and moistened). This was reflected in the intensive accumulation of radionuclide as a chemical analog of potassium [24, 25]. In articles [26, 27], it was concluded that upper (oligotrophic) swamps act as phyto-migration radionuclide anomalies. These anomalies are characterized by high mobility of anthropogenic radionuclides in soil and vegetation cover. In publications [9, 28] it was noted that under such conditions, specific trophic relations between higher plants – vascular species and mosses are formed with the help of endophytic fungi. Mosses act as a substrate, in which ^{137}Cs is concentrated, vascular plants (including marsh Labrador tea) – as an acceptor of this radionuclide. Endophytic fungi, which permeate organisms of mosses and vascular plants, combine them. In particular, 22 types of endophytic mucoromycetes were found in the organism of marsh Labrador tea, the factor of species similarity with endophytic fungi in sphagnum mosses equated to 0.32.

Radioactive contamination of different plant species in forest ecosystems was studied mainly in the first 10–15 years after the Chernobyl disaster. They were concentrated to a different extent in Ukraine, Belarus, Sweden, Finland, Poland, Italy, Austria, and Germany. During the research, the values of the specific activity of ^{137}Cs in parts and organs of certain plant species, as well as radionuclide transition coefficients, were established. Comparison of the determined indicators in different plant species allowed scientists to divide them into groups by intensity of accumulation of this radionuclide. However, quite often these studies were conducted without a detailed study of radioactive contamination of territories and a detailed description of ecological conditions.

There were much fewer publications that analyzed the results of similar studies conducted on different types of marshes. More often these were fragmentary observations conducted over several years. While studying the ^{137}Cs distribution in the components of oligotrophic and mesotrophic sphagnum marshes after the Chernobyl accident, scientists determined the levels of radioactive contamination of the most common plant species. The researchers recognized that the above-ground part of marsh Labrador tea contained significant activity of radionuclide. Despite the wide scope of the research, it should be noted that they were often carried out within one or several years. In addition, there is a small number of publications, which are written based on many years of observations, which, however, do not provide a qualitative characteristic of radioactive contamination of aboveground phytomass of marsh Labrador tea. Given the noted facts, longitudinal monitoring studies, which are aimed at establishing the patterns of ^{137}Cs migration to the most common in certain ecological conditions and economically valuable plant species are quite important. These plants include marsh Labrador tea.

3. The aim and objectives of the study

The aim of this study is to detect the levels of radioactive contamination of marsh Labrador tea in different periods after the Chernobyl accident and to establish the patterns of dynamics of the specific activity of ^{137}Cs in the above-ground part of this species. This information is important to understand the patterns of migration of this radionuclide in damp subors, to predict radioactive contamination of plants that grow under these ecological conditions. In addition, the findings are of practical importance in view of the resuming harvesting of valuable medicinal plants.

To achieve the aim, the following tasks were set:

– to explore the changes in the density of radioactive contamination of forest soils within the observation period;

– to detect the patterns in dynamics of the specific activity of ^{137}Cs in the above-ground part of marsh Labrador tea since the Chernobyl accident;

– to establish the coefficients of the transition of ^{137}Cs to the above-ground vegetative phytomass of marsh Labrador tea.

4. Materials and methods for studying the levels of radioactive contamination of marsh Labrador tea

The studies were conducted within 1991–2018. in Zhytomyr Polissya on the territory of the state enterprise "Luhynsk forestry" (Ukraine) in 5 permanent sample areas (PSA). Forest plantations on the PSA had quite close forestry characteristics (Table 1).

Table 1

Location of PSA and forestry characteristic of forest plantations

Number of PSA	Forestry	Quarter/area	Composition of tree state	Age, years*	Density	Type of forest and plant conditions
11	Lypnytsk	3/1	10P	55	0,55	B_{3-4}
13	Lypnytsk	3/13	9P1B	55	0,60	B_{3-4}
15	Povchansk	50/16	10P	50	0,75	B_{3-4}
16	Luhynsk	79/1	10P+B	60	0,60	B_{3-4}
18	Povchansk	50/12	10P+B	65	0,50	B_{3-4}

*Note: * the age of the tree state is indicated as of the beginning of research (1991)*

The sections of the PSA location are of the same type and are located among pine forests of blueberry-green-moss (the type of forest conditions – damp subors), in non-deep (depth up to 0.5–0.7 m), flat, closed, no-drain hollows with the area of 0.02–0.04 ha. The type of forest plant conditions is the transition from damp to wet subors – B_{3-4}. Under these conditions, the level of groundwater was at the depth of 20–30 cm. This led to marsh formation of the mentioned sections and formation of surface peated turfy-medium-podzol-glee soils on sandy loam fluvioglacial deposits The capacity of the peat layer was 30–40 cm.

The tree state is of medium density (0.50–0.60), represented by ordinary pine with insignificant inclusion of drooping birch (*Betula pendula Roth*). Young growth is single, from both the above-mentioned breeds. The undergrowth is not dense, closed up to 0.1, with grove location. It included black alder (*Frangula alnus Mill.*), mountain ash (*Sorbus aucuparia L.*), grey willow (*Salix cinerea L.*), and sharp-leaved willow (*Salix aurita L.*). The grass and bush tier is of medium density with a projective cover of 60–75 %, the species distribution in it is determined by the conditions of microrelief. In wetter places, marsh Labrador tea makes up 30–40 %, bog bilberry (*Vaccinium uliginosum L.*) – 5–15 %, black sedge (*Carex nigra* (*L.*) *Reichard*) – 1–3 % are common. Cotton grass (*Eriophorum vaginatum L.*) and ordinary loosestrife (*Lysimachia vulgaris L.*) are found as inclusion in this tier, bilberry (*Vaccinium myrtillus L.*) – 10–15 % and cowberry (*Vaccinium vitis-idaea L.*) – 3–5 % are found on low hummocks. The moss tier is characterized by projective cover of 80–98 %, the species distribution in it is also determined by topographic conditions. Specifically, deceptive sphagnum (*Sphagnum fallax* (*H .Klinggr.*) *H. Klinggr.*) – 40–45 % prevails in wetter places. Capillary sphagnum (*Sphagnum capillifolium* (*Ehrh.*) *Hedw.*) – 10–15 % and marsh aulacomnium (*Aulacomnium palustre* (*Hedw.*) *Schwaegr.*) takes a smaller part in the formation of the moss tier. Schreber pleurozium (*Pleurozium schreberi* (*Willd. ex Brid.*) *Mitt.*) – 5–15 % and dicrane (*Dicranum polysetum* Sw.) – 5–10 % are found on hummocks. The cenoses of a marsh- sphagnum pine forest was formed on the areas.

The samples of aboveground phytomass of marsh Labrador tea (20 cm long) on each PSA were selected in late June – early July three times. At the same time, the sample consisted of both the growth of the current year and that of last year, the sample volume was 1,000 cm^3. In the places of the selection of samples of above-ground vegetative phytomass of marsh Labrador tea, the soil samples were taken three times. This sample consisted of soil, which was taken from around the studied bushes of marsh Labrador tea by a cylindrical drill at the depth of 10 cm at 5 points (by the envelope method).

The samples of the soil and phytomass were dried to air-dry state at the temperature of +80 °C for 72 hours. Homogenization of samples was carried out on sample preparing devices ПРП–01 and ПРГ–01Т. The samples were placed in Marinelli vessels of the volume of 1000 cm^3 and weighed on scales ВВ–1037. The specific activity of ^{137}Cs in the samples was measured on multi-channel gamma-spectrum-analyzers in 1991–2000 – Nokia LP–4900B "AFORA" with the semiconductor detector DGDK 100–B3 and the scintillation detector BDEG–63; in 2001–2018 – SEG–001 "AKP–S"–150 by the scintillation detector BDEG–150 (NaI(Tl)) 150×100 mm. The relative error of measurement of the mentioned indicator did not exceed 8 %. The transition coefficient (TC) acted as an indicator of the intensity of ^{137}Cs accumulation in the "soil-plant" system.

5. The density of radioactive soil contamination and specific activity of ^{137}Cs in the above-ground part of marsh Labrador tea

5. 1. Dynamics of the density of radioactive soil contamination

After the arrival of radioactive elements at forest ecosystems, they were consolidated on the woody tier, and subsequently, radionuclides migrated to those tiers of vegetation, which are located below, and to the soil cover. Over time, after the migration of a major amount of ^{137}Cs to the soil surface, its redistribution in the latter and migration to forest plants through the root systems began. Given these circumstances, the studies that give an idea of the density of radioactive soil contamination at certain intervals after the accident are important in radioecology. This information is the basis for subsequent analysis of the dynamics of ^{137}Cs content in different types of plants.

Table 2

Dynamics of the density of radioactive contamination of soil with ^{137}Cs in permanent sampling areas during the observation years

No. of PSA	The density of radioactive contamination of soil with ^{137}Cs in different years, kBk·m^{-2}					
	1991	1995	2001	2007	2012	2018
13	53.0±6.71	49.1±8.95	43.1±6.12	36.5±4.51	29.7±4.15	24.4±2.97
11	72.7±7.12	64.0±8.66	52.9±6.77	45.6±6.27	36.1±4.07	26.5±2.39
16	250.7±29.82	216.9±24.94	190.1±6.86	172.5±21.03	141.3±16.76	119.9±13.57
15	339.8±49.05	289.7±48.52	251.4±31.46	219.7±26.53	197.5±22.23	159.5±24.60
18	400.5±50.73	340.9±43.25	305.0±31.94	284.2±42.28	247.0±28.07	166.9±23.56

Constant sampling areas in the planting year have different density of radioactive contamination of soil (Table 2): from 53.0±6.71 (PSA 13) to 400.5±50.73 kBk·m^{-2} (PSA 18). Naturally, this indicator decreased in all the areas over time. Thus, on PSA 13 within the period from 1991 to 2018 it decreased by 2.2 times, in PSA 11 by 2.7 times, on PSA 16 by 2.1 times, in PSA 15 by 2.1 times, and in PSA 18 by 2.4 times. A decrease in the magnitude of the density of radioactive contamination of soil in all PSA is explained, first of all, by the natural decomposition of the radionuclide.

In addition, a certain part of ^{137}Cs for a long period (32 years after the Chernobyl accident) migrated from soil to numerous components of forest ecosystems. It also affected an increase in its content in soil. The part of radionuclide, which came to forest plants, entrenched in them – woods of woody breeds and shrubs, and a part returned to the soil with annual falling (leaves, needles, shoots, and the phytomass of herbaceous plants). At certain intervals, ^{137}Cs that was contained in branches and shoots of trees, shrubs, and bushes also returned to the soil after certain periods of time. The described process in some way could affect the existing mosaic character of radioactive contamination of soil on specific forest areas. This could manifest itself in the heterogeneity of the process of decreasing the density of radioactive soil contamination in the studied permanent sampling areas during the observation period. The same conclusion can be drawn after analyzing a decrease in this indicator on all PSAs during shorter periods of observation. Thus, the density of radioactive soil contamination on the PSA decreased by 1.2–1.4 times for the first years of observation (1991–2001), and by 1.4–1.6 times within 16 years.

5. 2. Change of the specific activity of ^{137}Cs in the above-ground part of marsh Labrador tea

A gradual change in the specific activity of ^{137}Cs in the above-ground part of marsh Labrador tea was observed in all PSAs (Table 3). Within the first 4 years since the beginning of observations, it decreased, depending on PSA, by 1.2–1.4 times; after 10 years – by 1.6–1.7 times, after 16 years – by 1.9–2.1, after 21 years – by 2.7–3.1 times and after 27 years – by 3.1–6.5 times. Within the observation period (1991–2018), a specific dynamic of a decrease in indicator that is characteristic of the given sampling area was observed in each PSA. Thus, in PSA 16, the magnitude of the specific activity of ^{137}Cs decreased from 54,020±7,358.8 to 10,193±1,452.6 Bk·kg^{-1} (by 5.3 times), and in PSA 18 from 79,200±9,558.0 to 16,841±2,223.4 Bk·kg^{-1} (by 4.7 times). PSA 11 was characterized by a decrease in the magnitude of the specific activity of radionuclide by 3.3 times (from 7,400±689.8 to 2,245±369.5 Bk·kg^{-1}). In addition, the maximum decrease of ^{137}Cs content was found in PSA 15 from 70,150±9,004.1 to 10,823 ±903.9 Bk·kg^{-1} (by 6.5 times), and minimal – in PSA 13 from 7,050±885.6 to 2,316±286.0 Bk·kg^{-1} (by 3.1 times). This may be explained by the specificity of the soil conditions on each of them, and due to this, by the processes that occur in them and on which the migration of ^{137}Cs to the above-ground vegetative part of marsh Labrador tea depends. In addition, the mentioned patterns, to some extent, may depend on the age and state of bushes of marsh Labrador tea themselves. Thus, researchers who studied the specific activity of radionuclide in blueberry bushes, which in some types of forest plant conditions increases along with marsh Labrador tea, found that there was a decrease in this indicator with the age of bushes [29]. The author of the paper explained the findings by the fact that young plants are characterized by the greater activity of exchange processes, and therefore, by more intensive absorption of nutritive elements and water from soil. It is likely that similar processes can also occur in marsh Labrador tea.

It was found that the mean values of the specific activity of ^{137}Cs in the above-ground vegetative phytomass of marsh Labrador tea in the PSA depends on the density of radioactive soil contamination and variation of the latter within each permanent sampling area. Statistics of the distribution series in two PSAs (with maximum and minimum magnitudes of the density of radioactive soil contamination) were analyzed in the first and last years of observation (Table 4). It was established that there were significant differences between the minimum and maximum values of the studied indicators. Thus, in PSA 13 in 1991 the minimal value of density of radioactive contamination of soil was 39.7 kBk·m^{-2}, which is by 1.5 times lower than the maximum value (61.2 kBk·m^{-2}). In 2018 the maximum value of the analyzed indicator in this sampling area was 1.6 times higher than the minimum value (22.1 kBk·m^{-2}). In PSA 18 in 1991, the maximum value of the levels of soil contamination with ^{137}Cs was 1.5 times higher than the minimum value that was (299.3 kBk·m^{-2}). In 2018, the maximum value of the density of radioactive contamination of soil exceeded the minimal value by 1.6 times (135.4 and 213.0 kBk·m^{-2}). Similar patterns are observed at the minimum and maximum values of the specific activity of ^{137}Cs in the above-ground vegetative phytomass of marsh Labrador tea. The results also show that both indicators had medium variability on both permanent sampling areas within the observation period. They also showed that there was no significant change in the variation in indicators at their general tendency to decrease. Thus, in PSA 13 (the lowest density of radioactive soil contamination), the magnitude of the coefficient of variation of this indicator in 1991 was 12.7 % and in 2018 – 12.2 %; in PSA 18 (the highest magnitude of the indicator) – 12.7 and 14.1 % (respectively). A similar trend is observed for the coefficient of variation of average ^{137}Cs activity in the above-ground vegetative phytomass of marsh Labrador tea: in PSA 13 in 1991 it was 21.8 %, and in 2018 – 12.4 % and in PSA 18 – 20.9 % and 22.9 % (respectively). The resulting materials show that in these types of forest plant conditions, variability, and the magnitude of the specific activity of ^{137}Cs in the above-ground vegetative phytomass of marsh Labrador tea is determined mainly by the density of radioactive soil contamination. The impact of other possible factors is small.

Table 3

Dynamics of the specific activity of ^{137}Cs in the above-ground part of marsh Labrador tea in permanent sampling areas in different years

No. of PSA	The specific activity of ^{137}Cs in the above-ground part of the phytomass in different years, Bk·kg^{-1}					
	1991	1995	2001	2007	2012	2018
13	7,050±885.6	5,460±647.6	4,241±243.8	3,728±470.3	2,576±330.4	2,316±286.0
11	7,400±689.8	6,353±790.2	5,294±821.1	4,081±494.3	2,767±462.3	2,245±369.5
16	54,020±7358.8	38,598±8622.8	33,762±4085.0	27,975±3302.9	19,293±2335.8	10,193±1452.6
15	70,150±9004.1	54,896±7430.8	43,361±6444.5	33,160±4652.7	22,954±2836.4	10,823±903.9
18	79,200±9558.0	57,317±9486.5	48,095±5490.6	38,286±6463.3	29,429±4084.6	16,841±2223.4

Table 4

Statistics of the series of distribution of values of the average density of radioactive soil contamination (kBk·m^{-2}) and specific activity of ^{137}Cs (Bk·kg^{-1}) in the above-ground vegetative phytomass of marsh Labrador teas on PSAs 13 and 18 in 1991 and 2018

No. of PSA	Indicators	Year	Statistics of distribution series						
			M	*m*	*std*	*V*, %	*P*, %	min	max
13	As	1991	53.0	± 6.71	11.6	21.9	12.7	39.7	61.2
		2018	24.4	± 2.97	5.1	21.1	12.2	22.1	34.5
	Am	1991	7,050	± 885.6	1,533.9	21.8	12.6	5281	8010
		2018	2,316	± 286.0	495.3	21.4	12.4	1791	2775
18	As	1991	400.5	± 50.73	87.9	21.9	12.7	299.3	457.2
		2018	166.9	± 23.56	40.8	24.5	14.1	135.4	213.0
	Am	1991	79,200	± 9,558.0	16,554.9	20.9	12.1	69,198	98,309
		2018	16,841	± 2,223.4	3,851.1	22.9	13.2	13,558	21,080

Note: As is the density of radioactive contamination of soil, Am is the specific activity of ^{137}Cs in above-ground vegetative phytomass of marsh Labrador tea

We established the dependence between the density of radioactive soil contamination and specific activity of ^{137}Cs in the above-ground vegetative phytomass of marsh Labrador tea for each PSA in different years of observation. The relation between these indicators has its own characteristics in different periods from the time of radionuclide arrival to forest ecosystems (Fig. 1). It is described by linear equations and calculations prove its considerable closeness:

– in 1991 – y=219,32x–5417,4; R^2=0,99;
– in 1995 – y=186,38x–3695,7; R^2=0,98;
– in 2001 – y=176,99x–2872,3; R^2=0,99;
– in 2007 – y=139,02x–254,43; R^2=0,96;
– in 2012 – y=125,31x–924,79; R^2=0,99;
– in 2018 – y=84,83x–47,04; R^2=0,91.

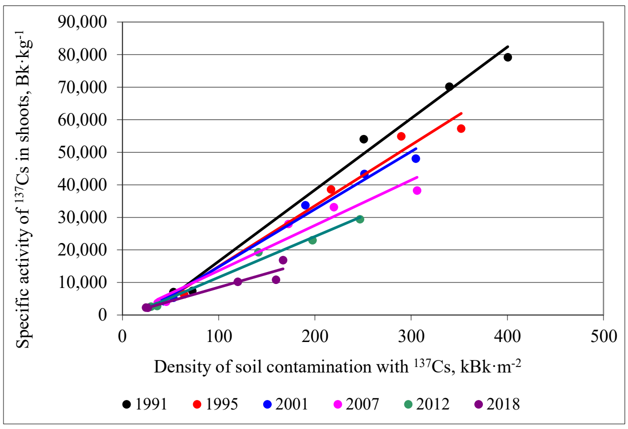

Fig. 1. Dependence of specific activity of ^{137}Cs in shoots of marsh Labrador tea on the density of soil contamination with ^{137}Cs in different years after the accident at Chernobyl nuclear plant

The resulting materials of regression analysis have theoretical significance. Based on a quantitative assessment of the process that occurs with the migration of ^{137}Cs in this type of forest ecosystem at considerable intervals of time after its radioactive contamination. In addition, they characterize the intensity of absorption of the radionuclide by marsh Labrador tea. The presented dependences and graphs can be used in the practice of harvesting medicinal raw materials from this type of plant in different periods after the time of ^{137}Cs arrival.

A decrease in the specific activity of ^{137}Cs in the shoots of marsh Labrador tea in permanent sampling areas over the years was observed. The trend of dynamics of this indicator in permanent sampling areas is described accordingly by exponential equations (Fig. 2):

– in PSA 13: y=3E+39e$^{-0,0411x}$, R^2=0,98;
– in PSA 11: y=1E+43e$^{-0,0454x}$, R^2=0,98;
– in PSA 16: y=3E+52e$^{-0,0552x}$, R^2=0,93;
– in PSA 15: y=1E+60e$^{-0,0638x}$, R^2=0,95;
– in PSA 18: y=5E+49e$^{-0,0518x}$, R^2=0,93.

The resulting materials enable taking into account potential magnitudes of the specific activity of ^{137}Cs in the shoots of marsh Labrador tea at certain magnitudes of soil contamination density after a certain period of time. Thus, in 2030 specific activity of ^{137}Cs in the shoots of marsh Labrador tea in PSA 13 will make up 1,345 Bk·kg^{-1}, in PSA 11 – 1,320 Bk·kg^{-1}, in PSA 16 – 6,435 Bk·kg^{-1}, in PSA 15 – 6,344 Bk·kg^{-1}, in PSA 18 – 10,413 Bk·kg^{-1}.

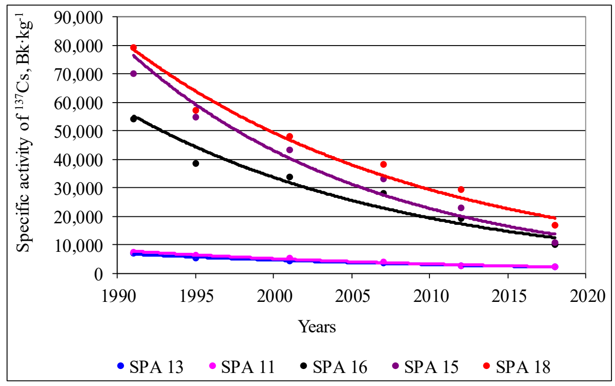

Fig. 2. Dynamics of the specific activity of ^{137}Cs in the shoots of marsh Labrador tea in different years after the Chernobyl accident

When comparing the obtained estimated data to the hygienic standard of the specific activity of ^{137}Cs in herbal medicinal raw materials used to manufacture medicines, it can be stated that in 2030 the radionuclide content will still exceed the permissible levels (500 Bk·kg^{-1}).

5. 3. Coefficient of ^{137}Cs transition to above-ground phytomass of marsh Labrador tea

In order to estimate the intensity of ^{137}Cs accumulation in the above-ground vegetative phytomass of marsh Labrador tea in different periods since the Chernobyl accident, the magnitude of the transition coefficients for each PSA was determined (Table 5). Rather high values of TC were obtained throughout all the years of observation and in all permanent sampling areas. A significant variation of this indicator was observed in permanent sampling areas throughout all observation years:

– in 1991 its minimal value was 103±11.1 m^2 kg^{-1}·10^{-3}, and maximal value 226±47.5 m^2 kg^{-1}·10^{-3} (the latter exceeded the former by 2.2 times);

– in 1995 – 105±22.6 and 194±20,1 m^2 kg^{-1}·10^{-3} (the latter exceeded the former by 1.9 times);

– in 2001 – 99±3.2 and 177±1.7 m^2 kg^{-1}·10^{-3} (the latter exceeded the former by 1,8 times);

– in 2007 – 91±6.9 and 164±15.7 m^2 kg^{-1}·10^{-3} (the latter exceeded the former by 1.8 times);

– in 2012 – 77±8.6 and 137±2.0 m^2 kg^{-1}·10^{-3} (the latter exceeded the former by 1.8 times);

– in 2018 – 70±5.8 and 101±1.6 m^2 kg^{-1}·10^{-3} (the latter exceeded the former by 1.5 times)

It should also be noted that the maximum and minimum values of TC in certain years are not typical for a particular PSA. This can be explained by a combination of edaphic factors, the degree of development, and the condition of bushes of marsh Labrador tea, as well as weather conditions of a particular year. However, in all PSAs, there was a decrease in the magnitude of the TC over the years. Thus, in PSA 13 this decrease for the period of 1991–2018 was by 1.4 times, in PSA 11 – 1.2 times, in PSA 16 – 2.7 times, in PSA 15 – 3.0 times, in PSA 18 – 2.0 times. The different intensity of a decrease in TC in different PSA may also indicate the existence of certain features in the development of bushes of marsh Labrador and in the soil conditions.

Additionally, the value of the transition coefficient (TC) for each observation period of all PSAs (Table 6) was calculated. This indicator more objectively characterizes the intensity of ^{137}Cs arrival at the above-ground vegetative phytomass of marsh Labrador tea and reflects the leveling of those environmental factors that can affect the above-mentioned process.

Table 5

Dynamics of coefficients of ^{137}Cs transition to above-ground phytomass of marsh Labrador tea on permanent sampling areas in different years

No. of PSA	Coefficient of ^{137}Cs transition in different years, $m^2 \cdot kg^{-1} \cdot 10^{-3}$					
	1991	1995	2001	2007	2012	2018
13	133±1.3	114±7.3	101±8.0	102±7.7	90±17.2	95.2±6.76
11	103±11.1	105±22.6	99±3.2	91±6.9	77±8.6	88±20.3
16	226±47.5	175±29.3	177±1.7	164±15.7	137±2.0	85±5.8
15	208±11.7	194±20.1	173±17.1	150±3.9	116±1.6	70±5.8
18	201±22.4	167±11.8	157±2.1	135±8.7	119±3.1	101±1.6

Table 6

Mean coefficients of ^{137}Cs transition to above-ground phytomass of marsh Labrador tea on permanent sampling areas within the years of observation

Statistics	Mean coefficients of ^{137}Cs transition for different years, $m^2 \cdot kg^{-1} \cdot 10^{-3}$					
	1991	1995	2001	2007	2012	2018
M	174.2	150.9	141.4	128.5	107.5	87.7
m	15.74	12.01	9.78	8.27	6.61	4.83
Std	60.96	46.51	37.86	32.03	25.61	18.71
V, %	35.0	30.8	26.8	24.9	23.8	21.3
P, %	9.0	8.0	6.9	6.4	6.2	5.5
min	91.0	60.2	85.8	77.7	59.5	56.4
max	297.7	230.7	204.0	183.9	136.2	125.7

The analyzed materials indicate that there was a decrease in mean values of the TC on certain PSAs over the years: from 174±15.7 in 1991 to 88±4.8 $m^2\ kg^{-1} \cdot 10^{-3}$ in 2018 (it decreased by 2.0 times). The found patterns can be explained by a decrease in the ^{137}Cs content in the soil layer occupied by root systems of marsh Labrador tea due to its migration to woody breeds, shrubs, and bushes. In addition, there was a migration of radionuclides outside the upper layer of soil, which was sampled to determine the density of radioactive contamination of soil.

6. Discussion of the features of contamination with ^{137}Cs of aboveground phytomass of marsh Labrador tea after the Chernobyl accident

This article generalized the results of the studies, which were conducted at certain intervals (4–6 years) in permanent sampling areas for quite a long period. Based on the obtained data, we generalized the quantitative assessment of lengthy (for 27 years) processes that characterize the radiation situation in forest ecosystems. Due to the results given in this study, it is possible to predict the levels of radioactive contamination of marsh Labrador tea, which is the basis for its further use. This is the merit of this study.

The results of the research into the peculiarities of contamination with ^{137}Cs of aboveground phytomass of marsh Labrador tea after the Chernobyl accident were received by solving a number of problems. Thus, these results were obtained when studying a change in the density of radioactive contamination of forest soils during the observation period. A decrease in the levels of radioactive contamination of soil was observed in all permanent sampling areas (Table 2). This situation can be explained primarily by the natural decomposition of radionuclide and ^{137}Cs migration from soil to numerous components of forest ecosystems. The findings are the basis for subsequent research into the dynamics of radionuclide content in the above-ground phytomass of the studied species.

Analyzing the patterns of changes in the specific activity of ^{137}Cs in the above-ground part of the marsh Labrador tea since the Chernobyl accident, a gradual decrease in the studied indicator during the observation time was recorded (Table 3). Thus, for the first 4 years, the ^{137}Cs content in the above-ground marsh Labrador tea decreased by 1.2–1.4 times according to the PSA, and after 10 years, it decreased by 1.6–1.7 times. The maximum decrease in the studied indicator was observed 27 years after the accident and ranged from 3.1 to 6.5 times (according to the PSA). It was established that the magnitude of the specific activity of ^{137}Cs in the above-ground vegetative phytomass of marsh Labrador tea depends on the density of radioactive soil contamination (Fig. 1). Thus, the obtained results show that the higher the levels of radioactive contamination of soil, the higher the magnitudes of radionuclide content in the above-ground phytomass of marsh Labrador tea. In addition, potential magnitudes of the specific activity of ^{137}Cs were calculated in the shoots of marsh Labrador tea at the assigned magnitudes of the density of radioactive soil contamination (Fig. 2). The established dependences can be used in the practice of harvesting this type as medicinal raw materials. However, the obtained results suggest that marsh Labrador tea remains an intense accumulator of radionuclides, so its use for medicinal purposes even after 10 years is inappropriate.

In order to estimate the intensity of accumulation of radionuclide in the above-ground vegetative phytomass of marsh Labrador tea, the transition coefficient was calculated (Table 5). In the process of solving this issue, it was established that high values of the coefficient were obtained in all PSAs. Thus, in 1991, the highest values of the studied indicator were recorded in PSA 16, and the lowest in PSA 11. However, in 2018, the transition coefficient on these PSAs did not exceed 90 $m^2 \cdot kg^{-1} \cdot 10^{-3}$. The research results show that different intensity of decreasing the transition coefficient was observed in all PSAs, which can be associated with the environmental conditions of the growth of the studied representative. Analysis of the data on the intensity of accumulation of ^{137}Cs in the leafy shoots of marsh Labrador tea for many years makes it possible to recommend the use of the mean value of TC for many years to compare the intensity of radionuclide absorption by different species. The resulting information, combined with the data on the changes in the specific activity of ^{137}Cs in the shoots of marsh Labrador tea, makes it possible to develop recommendations for its use in specific years after the arrival of radionuclide in forest ecosystems.

The results indicate that significant levels of radioactive contamination of marsh Labrador tea are observed even after such a lengthy period (1986–2018) since the ^{137}Cs arrival in forest ecosystems. This requires the continuation of the research, as well as similar studies in different types of forest and plant conditions.

7. Conclusions

1. During the observation period (1991–2018), a decrease in the density of radioactive contamination of soil by 2.1–2.7 times was noted, which is explained by the decomposition of radionuclide and its migration to the components of forest ecosystems.

2. It was found that marsh Labrador tea belongs to the group of plants, which are characterized by a high content of ^{137}Cs in the above-ground vegetative phytomass. During the observation period (1991–2018) this content significantly exceeded the permissible levels of radionuclide content in the plant medicinal raw materials used to manufacture medicines. In permanent sampling areas with maximum magnitudes of the density of radioactive contamination of soil (400.5±50.73 kBk·m^{-2}), it was exceeded by 158.4 times in 1991, by 33.7 times in 2018 (166.9±23.56 kBk·m^{-2})

3. A decrease in the specific activity of ^{137}Cs in the above-ground vegetative phytomass of marsh Labrador tea since the Chernobyl accident was observed. During the observation period (1991–2018), it decreased by 3.1–6.5 times and is described by a straight-line equation of the $y=aX+b$ type.

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MEMBRANE FILTRATION SIMULATION STUDY WITH VARIATION IN THE NUMBER OF FILTERS ON PEAT WATER MEDIA

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The rapid population growth has an impact on the increasing need for drinking water. In swamp areas, the need for drinking water cannot be met immediately because it still contains organic compounds that make the water unfit for consumption. Peat water contains dissolved organic compounds that cause the water to turn brown and have an acidic character, so it needs special processing before it is ready for consumption. For peat water to be used by the community for drinking water, it is necessary to find an easy and cheap way to treat peat water. The use of a filtration device is one of the solutions that must be done in peat water treatment. The purpose of this study was to determine the effect of flow patterns, speed, and pressure on the filtration process with variations in the type of membrane and filtration arrangement. This research method was carried out by simulation using ANSYS 14.5 series. The simulation process begins with designing a filtration device with the following types: two-filter, three-filter, and four-filter. Then the simulation was performed by entering the value of the peat water properties into the regulatory equation.

The results of this study indicate that the collaboration of two membranes with different holes in type-2 and 3 filters produces a good filtration rate. However, in type-4 filters, the use of a similar membrane is highly recommended. This filtration rate is influenced by the presence of a cross-flow reversal (CFR) region that appears, when using different filtration membranes at low pressure it doesn't matter. However, in other cases of systems operating at high pressure, CFR that appears tends to decrease the filtration rate, this is because CFR inhibits the flow rate in the filtration process

Keywords: swamp areas, peat water, type of membrane, filtration arrangement, ANSYS 14.5

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1. Introduction

The rapid population growth has an impact on the increasing need for drinking water. In swamp areas, the need for drinking water cannot be met immediately because it still contains organic compounds that make the water unfit for consumption. In the South Kalimantan area, we still encounter a lot of peat water, which is inundated peatlands or lowlands. Peat water contains dissolved organic compounds that cause the water to turn brown and have an acidic character, so it needs special processing before it is ready for consumption. For peat water to be used by the community for drinking water, it is necessary to find an easy and cheap way to treat peat water. The use of a filtration device is one of the solutions that must be done in peat water treatment.

Filtration with a membrane system is very suitable for application in peat water purification. In this purification process, several layers of membranes are needed to remove dissolved organic substances, so that the purified water is suitable for consumption. To determine the processes that