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# Accumulation of radioisotopes associated with the presence of wood-inhabiting fungi in scots pine (*Pinus sylvestris* L.) wood

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Growth of trees depends on the climatic conditions, environmental pollution and presence of wood-inhabiting fungi. Especial effect is caused by radioactive contamination. Radionuclides not only accumulate in plants, they also distinguish additional irradiation from ionising radiation. Plants lose their biological, environmental protection and material worth due to the action of this factor.

In the present study, specific activities of $^{137}$Cs, $^{40}$K, $^{232}$Th and $^{226}$Ra in the wood of Scots pine (*Pinus sylvestris* L.) and transfer coefficients of those radioisotopes from the contaminated soil to the growing tree were determined. Fluctuations in values of $^{137}$Cs specific activity in the pine wood and transfer coefficients of $^{137}$Cs showed tight correlation with the fluctuations in general (atmospheric) radioactivity caused by nuclear weapons testings and the Chernobyl accident in 1986. A shift in the specific activity of $^{137}$Cs in the wood of the investigated pine tree was recorded as it became infected by a decay-causing fungus *Heterobasidion annosum* (Fr.) Bref. After 1988, a trend of decrease in the specific activity of this radioisotope was recorded.

In a yearly perspective, the specific activity of $^{137}$Cs in the wood of pine showed positive correlation with an intensity of radioactive contamination of atmosphere and soil, as well as with the quality of growing (climatic) conditions and the presence of fungi within a zone of the respective growth ring.

Radioisotope $^{226}$Ra showed a considerable decrease in the specific activity for the years of extremely bad growth (climatic) conditions, however, an impact of the optimal growth conditions or the presence of fungi was non-significant.

The highest specific activity values of $^{40}$K in the pinewood were recorded for the periods of decreased increment (as compared to the mean value of annual radial increment).

**Key words:** accumulation of radioisotopes, decay-causing fungi, pathogens, radioactivity, specific activity, transfer coefficients, Scots pine (*Pinus sylvestris* L.)

## INTRODUCTION

Global radioactive fallout is the result of nuclear tests and the accident in the Chernobyl Nuclear Power Plant. This fallout contaminated forests, their litter and soils. Forests are affected not only by global radioactive fallout but also by the fungal and rot diseases. Scots pine (*Pinus sylvestris* L.) is the most sensitive one to the fungal and rot diseases. Radionuclides accumulate in trees, which receive the internal irradiance of the ionizing rays. Recently, the spread of forests with fungal and rot diseases has been increasing. Therefore, we have come to a hypothesis that tree's resistance against the fungal and rot diseases is the decrease of radionuclides accumulation in them.

Forests protect natural environment and support ecological stability. The affected trees lose the properties of environmental protection. Biological activeness of trees is reliant on climatic conditions, air pollution, and the presence of wood-inhabiting fungi. Defoliation is the main criterion of the appreciation of a tree's state. Defoliation of Lithuania's pines has been gradually increasing in the latter years (Lynikienė et al., 2004; Karpavičius et al., 2004).

Vegetation makes an impact on environmental pollution. Negative environmental influence is transformable through physiological function (Skuodienė et al., 2002). One of the main causes of forests' decline is polluted air. Attenuation of forests, decrease of their productivity and environmental protection functions are global ecological problems. Environmental pollution has influence on both forests' resistance and stability of self-regulation process (Stravinskienė et. al., 2003).

When radioactively contaminated air masses pass by, trees are able to capture quite large amounts of radionuclides on their crowns and trunks. Subsequently, radionuclides are transferred down to the ground by precipitation, fallen parts of the crowns, or are deposited directly from the air. From the soil, radionuclides are absorbed by tree's root systems together with water and nutrients. The main processes of the vertical radionuclides migration in the soil are diffusion, convective transfer, and migration through the root systems (Цыбулька et al., 2004; Щеглов et al., 2004; Butkus et al., 2002; Butkus, 2004; Булгаков et al., 2002). $^{137}$Cs accumulation in wood depends on the growth of the biomass (Butkus et al., 2006).

Fluctuations of radionuclides transfer factor from soil to pinewood may be related not only with the radioactive pollution but with the presence of wood-inhabiting fungi or climatic conditions, too.

Plants receive their internal doses by radionuclides ionizing radiation. The effect of this internal plant's dose to the state of the plant has been investigated insufficiently. While using the pinewood mainly for individual needs, there is a possibility to get additional irradiation because of ionizing radiation.

The main sources of artificial contamination with radionuclides are testings of nuclear weapons (1945–1980) and accidents in the nuclear power plants. The worst accident ever was the explosion of the Chernobyl Nuclear Power Plant reactor No. 4 in 1986 (Arapis et al., 1999; Butkus et al., 2004; Narmontas et al., 2003).

After the Chernobyl accident in 1986, distribution of the radionuclide contamination over Lithuania's territory showed patchy pattern, and the density of $^{137}$Cs spill was recorded not to exceed 18.5 kBq/m$^2$ (Буткус et al., 2001; Nedveckaitė, 2004). The largest patches of soil contamination by $^{137}$Cs after the Chernobyl accident matched the earlier-observed patches of radionuclide spill that had formed because of some previous nuclear explosions (testing of nuclear weapons) (Butkus et al., 2004).

Scots pine is the most abundant species in Lithuania's forests: pine stands make about 37% of all the stands (Lietuvos..., 2003). The most important degraders of pinewood are fungi of the order *Aphyllophorales* s. L. Mycelium of these fungi spreads and acquires nutrients within woody tissues, while fruiting bodies are formed outside, on the surface of the wood. The most common diseases of *Pinus sylvestris* L. include: annosus root rot caused by *Heterobasidion annosum* (Fr.) Bref.; Armillaria root rot caused by *Armillaria* sp.; Scleroderris canker caused by *Gremmeniella abietina* (Lagerb.) Morelet; resin top, lesions and pine blister rust caused by *Cronartium flaccidum* (Alb. & Schw.) Wint.; stem rots caused by *Phellinus pini* (Brot.) Bondartsev & Singer (Fig. 1B); Rhizina root rot caused by postfire ascomycete *Rhizina undulata* Fr.; pine needle cast caused by *Lophodermium seditiosum* Minter, Staley & Millar or *Lophodermella sulcigena* (Link) Tubeuf; snow blight caused by *Phacidium infestans* Karst.; pine needle rust caused by *Coleosporium* sp.; pine twist rust caused by *Melampsora populnea* (Pers.) Karst., and some other diseases (Miškų..., 2000; Ozolinčius, 1999).

Forests are damaged by various abiotic (windthrows, windbreaks) and biotic (diseases, pests, wild game) factors (Lietuvos..., 2003). Tissues and organs of the woody plants serve as a food source and habitation for various micro- and macrofungi. Saprotrophic fungi obtain their nutrients from dead organic matter, as their enzymes are able to degrade lignin and celluloses. Biotrophic (parasitic) fungi that cause various diseases and rots attack living trees. Diseases of woody plants can be either of parasitic or of non-parasitic character. Bacteria, fungi, viruses and mycoplasma cause parasitic diseases. Fungal diseases show the most serious threat to the forest trees. Fungi able to degrade wood are classified into three groups according to the rot pattern they cause: white, brown, or soft rot. Mostly basidiomycetous fungi that are able to degrade all the components of plant cell wall including lignin (Blanchette, 1995) cause white rot. Some of basidiomycetes cause brown rot; in this case, lignin is not being degraded, but only cellulose and hemicellulose (Blanchette, 1995; Rayner et al., 1988). Ascomycetes and bacteria cause soft rot; fungal hyphae and bacteria penetrate less lignified degrading plant tissues, thus, acting on the superficial layers of the wood (Carlile et al., 1994). The data concerning trees' productivity, radionuclides accumulation in them, resistance against fungal pathogens and doses of ionising radiation are missing.

The main aim of the present work was to analyse the accumulation of radionuclides in an ecologically sensitive place, in the regional park of Scots pines and to determine the relationship between the accumulation of radionuclides and the occurrence of fungal pathogens in the wood of Scots pine, as well as to establish the radionuclides accumulation intensity before the manifestation of fungal pathogens and after.

## MATERIALS AND METHODS

The investigated Scots pine was cut in Vilnius district by the village Paaliosė, located near the village Kazokiškės. This place belongs to the Neris Regional Park. (Fig. 1). The Neris Regional Park is an ecologically sensitive place. There are many reserves in this area. Besides, this regional park belongs to the programe *Natura 2000* (Fig. 1).

For the investigation of radionuclides accumulation in the wood, a Scots pine tree (*P. sylvestris* L.) was selected according to the considerable external damage: the top of the crown of this tree was dead, and the rest part was thin (defoliated)

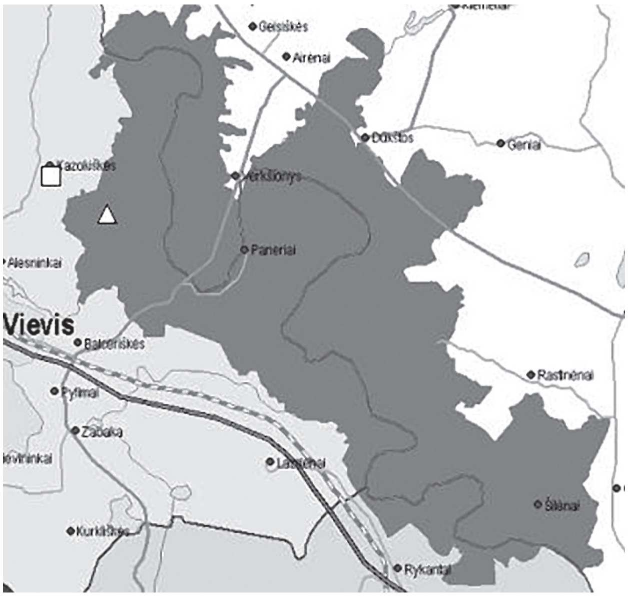

**Fig. 1.** Map of the Neris Regional Park (NRP): ☐ – place of the designed dump, Δ – place of investigation of Scots pine growth, – teritory of NRP (Geoinformacinė..., 2005)

and irregular, living needles were yellowish, while the shed ones were of non-uniform colour and had reddish transversal stripes, generally unsatisfactory sanitary condition of the selected pine and some adjacent trees, and the occurrence of fruiting bodies of *H. annosum* and *Trichaptum fuscoviolaceum* (Ehrenb.) Ryvarden on the adjacent stumps pointed to the increased activity of fungal pathogens on the site.

The selected pine was felled and cross-sectioned. A total of sample discs 3–5 cm thick was cut at various positions along the stem. The sample discs were split into smaller pieces along a tangent of the growth rings using 6, 10 and 16 mm-wide mortise chisels. The air-dried samples were burned in a muffle oven at + 480 °C to induce a specific activity of radionuclides in the wood coal. The coal was crushed to powder to make the specimen for a spectrometrical analysis.

Each specimen was placed into 50 $cm^3$ cuvette. A semiconductor Ge(Li) spectrometer was used to measure specific activity of radionuclides within the specimen. The $^{137}Cs$ specific activity was calculated using the following formula (Буткус et al., 2005):

$$A_a = \frac{\frac{S}{t_1} - \frac{S_f}{t_f}}{\eta \cdot \varepsilon \cdot m} \qquad (1)$$

where $A_a$ is $^{137}Cs$ specific activity within the specimen, Bq / kg; $S$ is radionuclide activity spike area calculated from the radionuclide activity measurement data within the specimen, counts.; $S_f$ is radionuclide activity spike area calculated according to the background radionuclide activity, counts.; $t_1$ is time to measure radionuclide activity within the specimen, s; $t_f$ is time to measure background radionuclide activity, s; η is emission probability of $^{137}Cs$ decay energy 662 keV; ε is efficacy of the spectrometer at 662 keV energy; $m$ is the weight of the sample specimen, kg.

Specific activity of radionuclides within the specimen (coal) was translated into the specific activity of radionuclides within unburned samples (natural wood). Natural decay of radionuclides was taken into consideration. The following formula was used to calculate radionuclide specific activity within a year when a particular growth ring was formed:

$$A_r = \frac{m_a \cdot A_a}{m_{š}} \cdot \frac{m_a}{m_{a.v.}} \cdot e^{\lambda \cdot t} \qquad (2)$$

where $A_a$ is radionuclide specific activity within a year when a particular growth ring was formed, Bq / kg; $m_a$ is weight of coal in a cuvette, kg; $A_a$ is radionuclide specific activity within the specimen, Bq / kg; $m_{š}$ is weight of the unburned specimen (natural wood), kg; $m_{a.v.}$ is total weight of the burned specimen (coal), kg; $t$ is time span from the formation of a particular growth ring to the year 2005, s; λ is radioactive decay constant, $s^{-1}$.

We took a sample of soil to calculate the transfer coefficients. The sample of soil was taken considering the dominant direction of the wind at 0–25 cm depth, at 2 cm to 10 cm depth, and at 5 cm to 25 cm depth. Transfer coefficient of the radionuclides from soil to plant was calculated using a relation between the activities of the particular radionuclide in plant and in soil. The following formula was used to show this relationship (Nedveckaitė, 2004):

$$TF = \frac{C_{m.p.}}{C_{m.s.}} \qquad (3)$$

where $TF$ is the transfer coefficient of radionuclide from soil to plant, $m^2 \cdot kg^{-1}$; $C_{m.p.}$ is specific radionuclide activity in plant, $Bq \cdot kg^{-1}$; $C_{m.s.}$ is density of specific radionuclide activity in soil, $Bq \cdot m^{-2}$.

In 1987, the $^{137}Cs$ specific activity in a pine site investigated by us was 3700–4800 Bq / $m^2$ (Буткус et al., 2001). According to the data on $^{137}Cs$ contamination of Lithuania's forest litter – the data collected on the same site in 1991 (Stankevičienė, 1998) – the specific activity of $^{137}Cs$ in the forest litter ranged from 100 Bq / kg to 200 Bq / kg.

Thirty-three splinters (samples) were taken for the isolation of fungi, weighed and air-dried for one month in room temperature. Mycological investigation of the 33 wood samples was carried out at the Laboratory of Phytopathogenic Microorganisms, Institute of Botany, Lithuania. In the laboratory, each sample was dissected with a sterile knife into three pieces to make three replications and washed with distilled water, while the surface was sterilized in a sterile hood (Sieber et al., 1991). The sterilized woody pieces were placed on malt extract media in Petri dishes, which were incubated at + 25 °C in the dark for two to three (or more, if necessary) weeks until the isolation of pure cultures was possible. Samples for microscopical observation were prepared from dried cultures using 3% KOH solution. For better differentiation and identification of fungal spores, the samples were submerged in the solution of methylen blue to test their cyanophyllic reaction and to highlight spore surface ornamentation. Sulfovanillin was used to highlight gloeocystides. Amyloid and dextrinoid reactions of the spores were tested using iodine-based Melzer's Reagent and Lugol's solution. Fungi were identified by morphological properties and biochemical reactions of the cultures and spores using a magnifying glass, stereo- and light microscopes, as well as the literature available.

## RESULTS AND DISCUSSION

Of the 33 wood samples (in three replicates) subjected for fungal isolation, 27 produced fungal growth (Table 1).

Wood sample No. 6PAp 59–60 has produced growth of fungal mycelia that closely resembled that of *H. annosum,* otherwise none of the samples showed any presence of this pathogen (Table). If the investigated tree had been really infected by annosus root rot, our sampling effort might have been insufficient, or the pathogen has not yet progressed well into the stem from the infected roots. No other isolated fungi can be attributed to the typical mycobiota of the pinewood. Most of the identified taxa do not cause serious plant diseases or wood decay (Table). Some of the fungi could also be regarded as contaminants.

In the present study, we calculated specific activities of $^{137}Cs$, $^{40}K$, $^{232}Th$ and $^{226}Ra$ in the pinewood. Figure 2 shows variation in the specific activity of $^{137}Cs$ in the pinewood during the period from 1937 to 2004 (Fig. 2).

Some of the peaks in the fluctuation of $^{137}Cs$ specific activity in the pine wood (Fig. 2) could be associated with the following events/periods: intensive testing of nuclear weapons (1945–1966); secondary contamination of wood by absorbtion and migration of $^{137}Cs$ from roots to the stem (1969–1979); possible secondary radioactive contamination of wood by later testing of

Table. **Fungi, isolated from 33 wood samples, taken from the declining Scots pine tree**

| Number of the wood sample | Fungal taxa |
|---|---|
| 6PAp 43–44 | *Stemphylium botryosum* Sacc., *Penicillium* sp., *Aspergillus* sp. |
| 6PAp 45–46, 6PAp 47–48 | – |
| 6PAp 49–50 | *Torula* sp. |
| 6PAp 51–52 | *Nigrospora* sp |
| 6PAp 53–54 | *Humicola fuscoatra* Traaen, *Penicillium* sp. |
| 6PAp 55–56 | *Melanospora fallax* Zukal |
| 6PAp 57–58 | *Humicola fuscoatra* Traaen, |
| 6PAp 59–60 | *Talaromyces* sp, *Mycelia sterilia* (? *Heterobasidion annosum* (Fr.) Bref.) |
| 6PAp 61–62 | *Penicillium* sp. |
| 6PAp 63–64, 6PAp 65-66 | – |
| 6PAp 65–66, 6PAp 67–68 | *Humicola grisea* Traaen |
| 6PAp 69–70 | *Humicola fuscoatra* Traaen |
| 6PAp 71–72 | *Thielaviopsis basicola* (Berk. & Broome) Ferraris, *Penicilium* sp., *Humicola grisea* Traaen |
| 6PAp 73–74 | *Humicola grisea* Traaen, *Penicillium* sp. |
| 6PAp 75–76 | *Talaromyces* sp. |
| 6PAp 77–78 | - |
| 6PAp 79–80 | *Exosporium* sp. |
| 6PAp 81–82 | *Penicillium* sp. |
| 6PAp 83–84 | *Aspergillus* sp., *Penicillium* sp., *Talaromyces* sp. |
| 6PAp 85–86, 6PAp 87–88 | *Penicillium* sp. |
| 6PAp 89–90 | Talaromyces sp. |
| 6PAp 91–92 | *Penicillium* sp., *Talaromyces* sp. |
| 6PAp 93–94 | *Botrytis cinerea* Pers., *Chaetomium* sp. |
| 6PAp 95–96 | *Taeniolella stilbospora* (Corda) Hughes |
| 6PAp 97–98 | *Humicola fuscoatra* Traaen |
| 6PAp 99–00 | *Penicillium* sp. |
| 6PAp 01–02 | *Talaromyces* sp. |
| 6PAp 03–04 | *Stemphylium botryosum* Sacc., *Humicola fuscoatra* Traaen |
| 6PAp heartwood + 6 bark | *Penicillium* sp., *Cylindrocarpon destructans* (Zinssm.) Scholten |

Comment: P – Scots pine (*Pinus sylvestris* L.); Ap – part of the trunk 1 m from the stump; 43–44 – tree rings of the years 1943 and 1944.

nuclear weapons (1980–1985); and the Chernobyl accident in 1986. From 1988, specific activity of $^{137}$Cs decreases, but in an irregular pattern: some increase was recorded in the period from 1993 to 1996. We investigated the same period that reflected the $^{137}$Cs contamination in the tree. However, the limits of this period cannot be determined exactly because of $^{137}$Cs migration among the tree rings.

Figures 3 and 4 show variation in the specific activity of natural radionuclides $^{226}$Ra, $^{232}$Th, and $^{40}$K in the pinewood during the period from 1937 to 2004. The fluctuations in the $^{226}$Ra specific activity in the growth rings ranged from (0.4 ± 0.1) Bq/kg to (29.0 ± 6.8) Bq / kg (Fig. 3). The peak activity values were estimated for the periods 1959–1969, 1970–1974, 1973–1979, and 1980–1984. From the year 1980, the $^{226}$Ra specific activity decreased (Fig. 3).

The fluctuations in the $^{232}$Th specific activity ranged from (1.0 ± 0.4) Bq / kg to (62 ± 21) Bq / kg (Fig. 3). The peak activity values were estimated for the periods 1960–1968, 1971–1988,

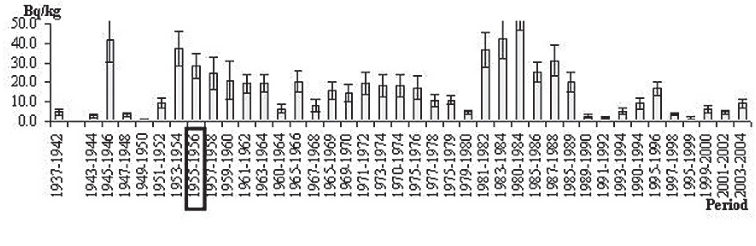

**Fig. 2.** Variation in the specific activity of artificial radionuclide $^{137}$Cs in Scots pine wood during the period from 1937 to 2004. Solid rectangle shows dating of the growth ring from which *H. annosum* has been isolated

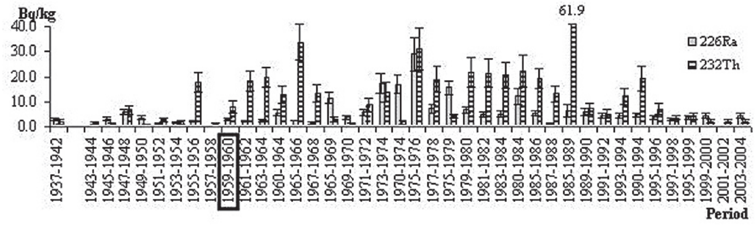

**Fig. 3.** Variation in the specific activity of $^{226}$Ra and $^{232}$Th in Scots pine wood during the period from 1937 to 2004. Solid rectangle shows dating of the growth ring from which *H. annosum* has been isolated

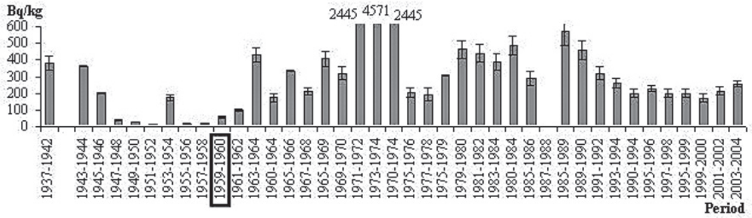

**Fig. 4.** Variation in the specific activity of $^{40}$K in Scots pine wood during the period from 1937 to 2004. Solid rectangle shows dating of the growth ring from which *H. annosum* has been isolated

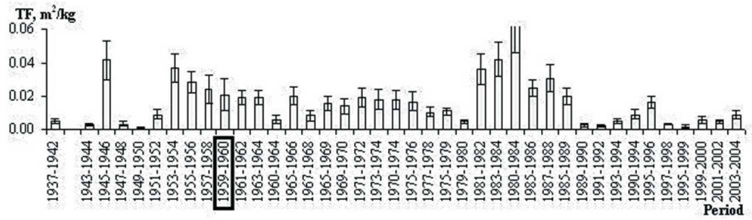

**Fig. 5.** Variation in the coefficients of $^{137}$Cs transfer from 0–25 cm soil layer to the investigated Scots pine tree during the period from 1937 to 2004. Solid rectangle shows dating of the growth ring from which *H. annosum* has been isolated

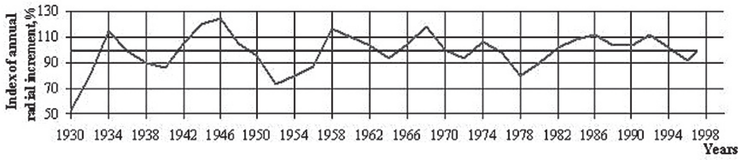

**Fig. 6.** Variation in the indices of annual radial increment of *P. sylvestris* in *Pinetum myrtillo-sphagnosum* during the period 1930–1997 20)

and 1993–1994. From the year 1986, the $^{232}$Th specific activity decreased (Fig. 3).

Radionuclide $^{40}$K is a nutrient that is vitally important for a plant. The fluctuation of its specific activity reflects the biological activity of a tree. It has been noted that assimilation of this radionuclide by a tree is uneven. In the present study, the greatest activity of $^{40}$K was recorded for the periods 1937–1946, 1963–1974, 1979–1986, and 1989–1990; while the lowest one, for the periods 1947–1962 and 1975–1978. From the year 1991, the $^{40}$K specific activity decreased (Fig. 4).

As the specific activitys of radionuclides (artificial $^{137}$Cs and natural $^{226}$Ra, $^{232}$Th, $^{40}$K) in soil and in wood of the investigated pinewood were estimated, the coefficients of the radionuclides transfer from the soil layer (0–25 cm) to the pine tree were calculated using formula (3). Figure 5 shows the $^{137}$Cs variation of transfer coefficients from soil to pinewood (Fig. 5).

Until the year 1951 (except for the period 1945–1946), the coefficients of $^{137}$Cs transfer from 0–25 cm soil layer to the investigated pine tree averaged only 0.010 ± 0.003 m$^2$/ kg (Fig. 5). From 1953 up to 1979, those coefficients averaged 0.018 ± 0.005 m$^2$/kg, and their values showed only slight fluctuations from year to year. Significant increase in the transfer coefficients values was recorded for the period 1981–1988 (Fig. 5). This phenomenon could be associated with the intensive testings of nuclear weapons during that period. The Chernobyl accident could influence an increase in the transfer coefficients values for the period 1986–1988. From 1989 to 2004, there is a decrease in those values, and especially for the period 1989–1993, when $^{137}$Cs transfer coefficients averaged only 0.005 ± 0.001 m$^2$/ kg (Fig. 5). A slight increase in the coefficient values in 1993–1996 could be associated with the secondary contamination by $^{137}$Cs via pine roots. However, $^{137}$Cs migrates among the tree rings, therefore, we cannot appreciate the retrospective pollution of $^{137}$Cs by TF variations of the period limits.

The $^{226}$Ra and $^{232}$Th transfer coefficients variation during the period from 1937 to 2004 are uneven. The periods of the increased coefficient values for $^{226}$Ra are in 1945–1950, 1969–1979**,** and, for $^{232}$Th, in 1955–1968 and in 1973–1989. From 1990 to 2004 (except for the period 1993–1995), there is a decrease in the $^{232}$Th transfer coefficients values.

In $^{40}$K transfer coefficients variation during the period from 1937 to 2004, some periods of increased coefficients values can be distinguished: 1937–1946, 1963–1974, 1979–1986, and 1989–1990. From the year 1991, those values decrease.

A shift (increase) in the $^{137}$Cs specific activity in pinewood and in the values of this radionuclide transfer coefficients (from soil to tree) was recorded as the pine became infected by the decay-causing fungus *H. annosum* in 1959–1960. The values of $^{137}$Cs transfer coefficients during the period 1959–1978 were more or less even and averaged 0.016 ± 0.005 m$^2$/ kg. This value is similar to an average value calculated for the whole period investigated (1937–2004). An opposite trend could be observed with the values of specific activity and transfer coefficients of natural radionuclides $^{226}$Ra, $^{232}$Th and $^{40}$K: those values decrease in 1959–1960 and start to increase somehow later.

If we evaluate the climatic conditions, biological state of pine, presence of wood-inhabiting fungi and radioactive pollution, it is possible to state that $^{137}$Cs transfer from soil to pinewood are most determined by the radioactive pollution from air to needles, to bark, to branch and later from soil to root system.

Almost in all the tree ring samples, where $^{137}$Cs specific activity was increased, we determined the presence of wood-inhabiting fungi, however, those atypical to mycobiota.

Trees accumulate environmental information in tree rings through all the period of growth (Karpavičius, 2004). The dendrochronological monitoring is used for indication of natural state (ecological, climatic, forest type, place of growth etc.) taking into consideration the information of the tree rings.

Variation in the specific activities of radionuclides in pinewood and the values of the radionuclide transfer coefficients (from soil to tree) could be associated not only with artificial radioactive contamination or presence of the fungal pathogens, but also with variation in growth (climatic) conditions. Figure 6 shows variation in the indices of annual radial increment (IARI) of *P. sylvestris* in *Pinetum myrtillo-sphagnosum* during the period 1930–1997 (Stravinskienė, 2002) (Fig. 6).

The highest values of IARI show the years of the best pine growth (e. g. 1934, 1946, 1958, 1968, 1974, 1986, 1992, Fig. 6). Analysis of growth (climatic) conditions of the investigated pine, its damage by fungal pathogens and artificial radioactive contamination showed that transfer of $^{137}$Cs from soil to wood had been determined by atmospheric contamination via foliage, twigs and bark, and, later, through roots.

Almost every wood sample representing growth ring of increased $^{137}$Cs specific activity produced fungal growth. However, none of the identified taxa could be attributed to the typical mycobiota of pine.

Analysis of the variation of IARI during the period 1937–1997 showed that the average values of the IARI (about 99%) were recorded for the periods when the $^{137}$Cs specific activity in pinewood was increased. During the periods 1956–1960 and 1985–1986, the values of the IARI were average or above the average (i. e. tree growth conditions were satisfactory), however, specific activity of this radionuclide did not show any dependence and was close to the average value calculated for the whole period investigated (1937–1997). The $^{137}$Cs specific activity jumped over its average calculated value during the period 1951–1956, but, at the same time, IARI values dropped much lower compared to their average value.

During the period 1963–1966, the fluctuation of $^{226}$Ra specific activity values was insignificant. This could be determined by the average IARI values of the period and the absence of wood-inhabiting fungi in the respective growth rings. A decrease in the $^{226}$Ra specific activity could be observed in 1977–1978, when IARI values were extremely low (Fig. 8). Fungi were not isolated from the respective growth rings. The specific activity of this radionuclide did not show any increase during the period of the highest values of IARI (i. e. when tree growth conditions were the best), however, it showed decrease as the IARI decreased. It is possible that the presence of mycobiota atypical of pine in the investigated wood, as well as very good tree growing conditions have little influence on the assimilation of $^{226}$Ra. On the other hand, the periods of the decreased $^{226}$Ra specific activity could be associated with the periods of extremely poor growing conditions. However, very good growing conditions during 1959–1960 did not influence the activity that could possibly be determined by pathogen-induced obstruction of assimilation of the natural radionuclide $^{226}$Ra.

Mycobiota atypical of pine was commonly isolated from the wood samples taken from growth rings that represented increased $^{232}$Th specific activity (except for the periods 1947–1948 and 1963–1966). The $^{232}$Th specific activity had increased values during the periods of superb pine growth (1943–1948, 1959–1960, 1967–1968, 1985–1986, and 1993–1994), however, those values were not maximal, but just as high as the average activity calculated for the whole investigated period. The peak values were recorded for the periods of average or below-average values of the IARI, e. g. 1955–1956 and 1976–1981 for $^{232}$Th. It is possible that the presence of atypical mycobiota of pine could have more impact on the assimilation of $^{232}$Th than the quality of the growing (climatic) conditions.

Analysis of the impact of the best growing conditions on the assimilation of natural radionuclides by the pinewood showed dependence of this impact upon the maturity of the tree.

Analysis of variation of the specific activities of $^{40}$K and $^{137}$Cs in the pinewood showed that the ability to assimilate potassium was negatively affected by the amount of caesium uptaken. This relationship was supported by the specific activities values of these two radionucleides calculated at different stages of tree development. It is obvious that assimilation of $^{40}$K by pine is closely related to the uptake of $^{137}$Cs and biological activity of the tree depending on its age.

The following general conclusion can be drawn from the present discussion of the results: ability of a tree to assimilate radionuclides is determined by several important factors such as radioactive contamination (this is important only for the uptake of artificial radionuclides), growing (climatic) conditions of the tree, and its biological damage by fungal diseases. It is very likely that the impact of all these factors is complex, thus, it is difficult to analyse their impact separately.

## CONCLUSIONS

1. Wood sample of 59–60 years annual ring was found to be affected by the produced growth of fungal mycelia that closely resembled that of *H. annosum*. If the investigated tree had been really infected by annosus root rot, our sampling effort might have been insufficient, or the pathogen has not yet progressed well into the stem from the infected roots. None of other fungi found could be attributed to the typical mycobiota of pinewood. Most of the identified taxa are not known to cause serious plant diseases or wood decay.

2. The highest values of indices of annual radial increment (IARI) correlate with the years of the best pine growth (e.g. 1942–1948, 1958–1976, 1982–1994).

3. In the variation of artificial $^{137}$Cs activity in the pinewood during the period from 1937 to 2004, the peaks in the fluctuation could be associated with the following: intensive testing of nuclear weapons (1945–1966); secondary contamination of the wood by absorbtion and migration of $^{137}$Cs from roots to the stem (1969–1979); potential secondary radioactive contamination of wood by later testing of nuclear weapons (1980–1985); the Chernobyl accident in 1986; and from 1990, $^{137}$Cs activity decreases because of the absence of radioactive pollution. However, $^{137}$Cs migrates among the tree rings, thus, we cannot evaluate the retrospective pollution of $^{137}$Cs by the activity variations taking into consideration the period limits.

4. Almost each wood sample of increased $^{137}$Cs specific activity produced fungal growth. However, none of the identified taxa could be attributed to the typical mycobiota of pine. Analysis of the variation of IARI during the period 1937–1997 showed that the mean values of IARI (about 99%) were recorded for the periods when the $^{37}$Cs specific activity in the pinewood was high.

5. The fluctuations in the $^{226}$Ra specific activity in the annual rings ranged from (0.4 ± 0.1) Bq/kg to (29.0 ± 6.8) Bq / kg. The peak activity values were estimated for the periods 1947–1948, 1959–1969, 1970–1979, and 1980–1984. The atypical mycobiota in the pinewood did not have influence on $^{226}$Ra specific activity

values, as well as the climatic situation when IARI was above the mean values of IARI. In cases when the IARI are the mean values of IARI, the $^{226}$Ra specific activity decreases.

6. The fluctuations in the $^{232}$Th specific activity ranged from (1 ± 0.4) Bq/kg to (61.9 ± 21) Bq / kg. The peak values were estimated for the periods 1960–1968, 1971–1986, and 1993–1994. The peaks were determined in periods, when IARI were close to or higher than the mean values of IARI. The mycrobiota in the pinewood has influence on $^{232}$Th specific activity values.

7. Assimilation of $^{40}$K by a tree is uneven. In the present study, the highest activity of $^{40}$K was recorded for the periods 1937–1946, 1963–1974, 1979–1986, and 1989–1990, while the lowest one, for the periods 1947–1962 and 1975–1978. From 1991, the $^{40}$K specific activity decreased. The $^{40}$K specific activity increased during the periods of superb pine growth (1943–1948, 1959–1960, 1967–1968, 1985–1986, and 1993–1994), however, those values were not maximal. The peak values were recorded for the periods of mean or below-mean values of the IARI, e.g. 1937–1942, 1953–1954, and 1979–1981 for $^{40}$K. It is obvious that assimilation of $^{40}$K by pine is closely related to the uptake of $^{137}$Cs.

8. Initially, fungal mycelia that closely resembled that of *H. annosum* in the pinewood do not have influence on either artificial ($^{137}$Cs) or natural ($^{226}$Ra, $^{232}$Th) radionuclides. However, after about 50 years of pine growth, assimilation of radionuclides significantly decreases in correlation with the mean of all the growth period.

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## RADIONUKLIDŲ KAUPIMOSI PUVINIŲ PAŽEISTOS PAPRASTOSIOS PUŠIES (*PINUS SILVESTRIS* L.) MEDIENOJE TYRIMAS

*Santrauka*

Sumedėjusių augalų biologiniam vystymuisi daug įtakos turi klimato sąlygos, aplinkos tarša, pažeistumas ligomis. Ypatingu poveikiu pasižymi radioaktyvioji užtarša. Patekę į augalą radionuklidai ne tik kaupiasi juose, bet ir sukelia augalams papildomą apšvitą dėl radionuklidų skleidžiamos jonizuojančiosios spinduliuotės. Šių veiksnių pažeisti augalai praranda biologinę, aplinkosauginę, materialiąją vertę.

Nustatyti $^{137}$Cs, $^{40}$ K, $^{232}$Th ir $^{226}$Ra savitieji aktyvumai medienoje bei pernašos iš dirvožemio į pušį koeficientai (*Pinus sylvestris* L.). $^{137}$Cs savitojo aktyvumo medienoje bei pernašos koeficientų kaita atitinka branduolinių bandymų ir Černobylio atominės elektrinės avarijos užtaršų kaitą. Nuo tų metų, kai medienoje nustatytas puvinio sukėlėjas (*Heterobasidion annosum*), stebimas radionuklidų savitųjų aktyvumų pokytis, tačiau nuo 1988 m., praėjus 53 pušies augimo metams, radionuklidų savitieji aktyvumai medienoje pradeda mažėti. $^{137}$Cs ir $^{40}$K pernašos į grybinių ligų ir puvinių pažeistos pušies (*Pinus sylvestris* L.) spyglius ir žievę koeficientai nustatyti mažesni nei radionuklidų pernašos į nepažeistos pušies žievę ir spyglius koeficientai.

$^{137}$Cs savitojo aktyvumo pušies medienoje padidėjimas sutampa su oro ir dirvožemio radioaktyviosios užtaršos padidėjimu, geriausiomis augimo klimato sąlygomis ir grybų buvimu rievių mėginiuose.

$^{226}$Ra savitojo aktyvumo pušies medienoje sumažėjimą lemia ypač blogos medžio augimo sąlygos, bet nenustatyta mikrobiotos ir itin gerų augimo sąlygų ryškios įtakos.

$^{40}$K didžiausios savitojo aktyvumo vertės pušies medienoje nustatytos laikotarpiais, kai metinės rievės prieaugio indeksas (MRPI) yra mažesnis nei vidutinis arba artimas jam.

**Raktažodžiai:** radionuklidų kaupimasis, savitasis aktyvumas, pernašos faktorius, pušis (*Pinus sylvestris* L.)