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Initiation of radioecological monitoring of forest soils and plants at the Lithuanian border region before the start of the Belarusian nuclear power plant operation

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Abstract Knowledge of the background activity concentrations of anthropogenic radionuclides before the start of operation of the new nuclear power plant in Belarus, BelNPP, is an issue of great importance for neighbouring countries. In this study, we provide the pilot characterisation of the Lithuanian part of the 30-km zone of the BelNPP, emphasising the forest plants, terrestrial mosses, forest organic and mineral topsoil to describe the preoperational radioecological state of the pine forest ecosystem. Key anthropogenic radionuclides (^{14}C, ^{3}H, ^{137}Cs and ^{239,240}Pu) were analysed. The ^{14}C specific activity varied from 97.80 ± 1.30 to 102.40 ± 0.79 pMC. The ^{3}H specific activity in the tissue-free water tritium form varied from 13.2 ± 2.2 TU to 20.8 ± 2.3 TU, which corresponded to the ^{3}H level of precipitation in this region. The activity concentrations of ^{239,240}Pu in soil and moss samples did not exceed 1 Bq/kg and were mainly due to global fallout after nuclear tests. The ^{137}Cs inventory in the pine forest soils of the Lithuanian part of the BelNPP 30-km zone varied from 930 ± 70 to 1650 ± 430 Bq/m^2. High variation of the inventory and uneven distribution in the soil profile conditioned a wide range of ^{137}Cs activity in terrestrial plants from 1.0 ± 0.5 to 40.5 ± 1.8 Bq/kg dry weight. The abundance of microorganisms in different seasons and soil depths do not exceed the natural levels. According to PCA loads, the number of microorganisms and variability of ^{137}Cs specific activity is determined by soil abiotic parameters.

Keywords Anthropogenic radionuclides · Natural radionuclides · Terrestrial · Microorganisms · Arenosol properties

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Introduction

The expansion of the number of operating nuclear power reactors in the east Baltic region is of great importance for Lithuania, where active discussions on this issue have been taking place, both within the general public and on a political level. The need for new research and the implementation of monitoring programmes is crucial to keep these discussions scientifically sound in the future, when the Belarusian nuclear power plant (BelNPP) will be under operation. The BelNPP construction site is located close to the Lithuanian border (20 km) and the capital of the country, Vilnius (50 km). A part of the BelNPP 30-km zone is located on Lithuanian territory (Fig. 1). Information about the activity of anthropogenic radionuclides originating from the BelNPP operation is of great concern in neighbouring countries.

Lithuania has experience in operating the NPP at the Ignalina site, which is rather close (114 km) to the location of the NPP in Belarus. After the national referendum in 2004, Lithuania agreed to close the Ignalina Nuclear Power Plant (INPP) as part of accession agreement to European Union. Reactor Unit 1 was shut down on December 31, 2009. The INPP now is in the decommissioning process.

As was shown in many studies (Mikhailov et al. 1999; Mažeika 2002; Nedveckaitė et al. 2007; Jasiulionis and Rozkov 2007; Gudelis et al. 2010; Mazeika et al. 2016; Jefanova et al. 2018), terrestrial ecosystems near the INPP contained traces of ^{14}C, ^{3}H, ^{60}Co and ^{137}Cs originating from the INPP. The same radionuclides can probably form traces in the environment of the BelNPP during the normal operation period; therefore, we initiated a basic study of these radionuclides in the Lithuanian part of the 30-km zone of the new NPP.

Because of the biological importance of carbon (^{12}C, ^{13}C and ^{14}C) and the biological incorporation of radioactive ^{14}C through photosynthesis, it is of great importance to run ^{14}C measurements in the environment surrounding nuclear facilities.

Processes of ^{3}H production in nuclear reactors are reported in detail by the International Atomic Energy Agency (IAEA 1981). ^{3}H is produced in the fuel, core components and coolant and is distributed wherever gas or fluid streams take place in the NPP. ^{3}H in gaseous effluentions of the INPP with an annual release rate of ~ 10^{10}–10^{11} Bq/year have been reported (Report on results 2011), and ^{3}H contribution from the INPP was traced in vegetation material, including annual tree rings, stems of mudwort and leaves of grey alder (*Alnus incana* L.), in the forms of tissue-free water tritium

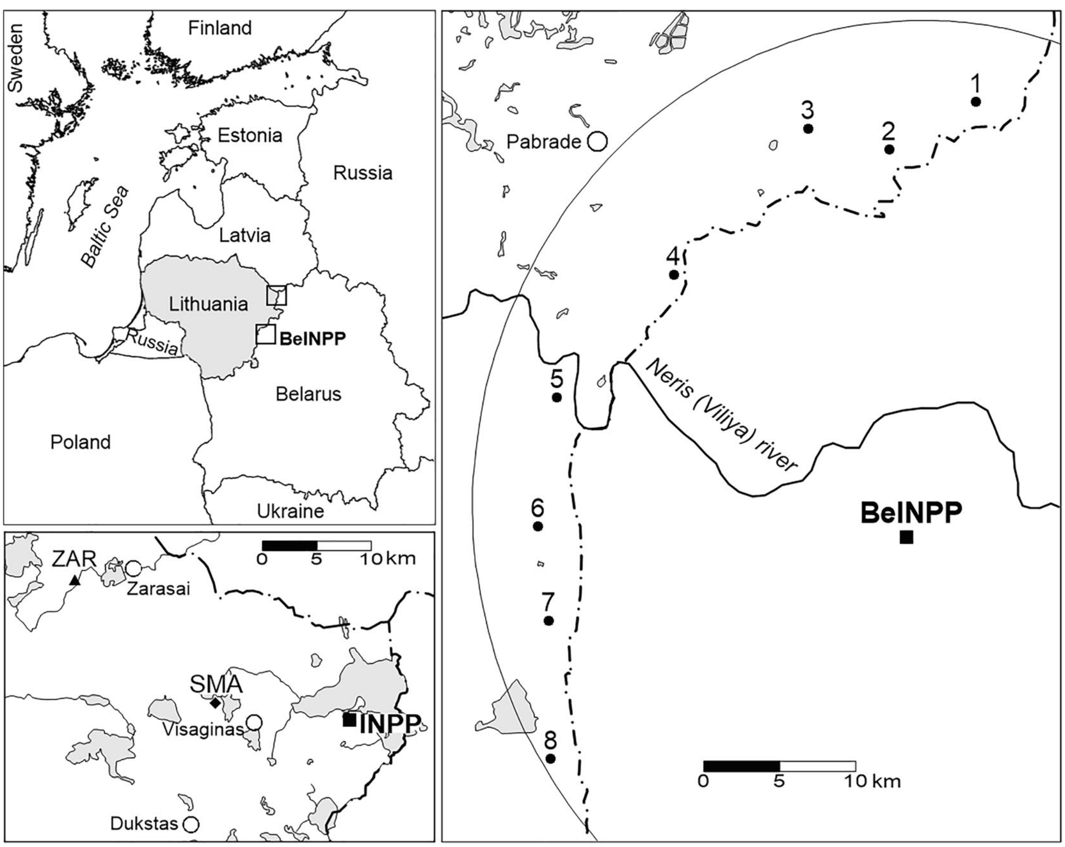

Fig. 1 Location of Smalvos background sampling site (SMA) and the new monitoring sites in the 30-km zone of the BelNPP (1–8)

(TFWT) and organically bound tritium (OBT) with maximum values in the range of 8–10 Bq/l in the prevailing wind direction from the INPP (Mažeika et al. 2008).

Along with other radionuclides, ^{137}Cs entered the environment from global fallout following the nuclear weapons tests in the atmosphere in the period between 1945 and 1980 and after the accidents of the Chernobyl NPP in April 1986 and the Fukushima Daiichi NPP in March 2011 (Trapeznikov et al. 2007; Hirose 2012; Nazarbayev et al. 2017; Suchara 2017). After the Chernobyl accident, more than 200,000 km^2 of Europe received levels of ^{137}Cs above 37 kBq/m^2, with over 70% of this area being in the three most affected countries: Belarus, Russia and Ukraine. The deposition of ^{137}Cs was extremely diverse, as it intensified in areas where it rained when the contaminated air masses passed. Based on analysis of 582 soil samples, the average ^{137}Cs inventory for the whole Lithuanian territory was estimated to be approximately 1000 Bq/m^2 (median 700 Bq/m^2), with several more heavily contaminated (up to 10,000 Bq/m^2) areas in southeastern and western parts of the country (Mažeika 2002; Butkus et al. 2014). Airborne gamma surveys in small spots revealed maximum contamination by radioactive caesium, with levels of up to 30,000 Bq/m^2 in 1988 (Butkus et al. 2014). According to the caesium isotopes activity ratio (^{134}Cs/^{137}Cs), the input of ^{137}Cs originating from the Chernobyl accident was approximately 20% in the least contaminated territory and 50–55% in the most contaminated territory (Mažeika 2002). In the many years following the Chernobyl accident, ^{137}Cs fallout remained distributed in the upper soil (0–20 cm) layer (Dubchak 2017; Kudzin et al. 2017). The ageing effect of ^{137}Cs was found to be responsible for the irreversible adsorption of ^{137}Cs to organic particles in the soil and decreasing ^{137}Cs's bioavailability (Tagami 2017). In the pine forest of the Chernobyl NPP exclusion zone, the percentage of ^{137}Cs's activity is the most substantial in the OH sub-horizon (24–45%), and this value is the highest for heath pine forest ecosystems (Kudzin et al. 2017). ^{137}Cs uptake and removal by plants depending on different abiotic, biotic and physiological factors, including the role of microorganisms and biologically active additives, have been studied by Guillen et al. (2017), Shin and Adams (2017), Dubchak (2017) and Shchur et al. (2017).

In addition to global origin, ^{137}Cs entered the environment locally in sites of nuclear facilities with radioactive effluents under normal operating conditions. An annual rate of ^{137}Cs emissions of in airborne and liquid releases of the INPP are reported ~ 10^7–10^8 and ~ 10^7–10^9 Bq/year, respectively (Report on results 2011). Due to several global origin sources, such low ^{137}Cs contribution from local sources could hardly be traced in animate and inanimate constituents of terrestrial ecosystems (Jefanova et al. 2014).

Sources of plutonium isotopes in the environment are well known and these are nuclear weapon tests in the atmosphere (global fallout) and various nuclear accidents, such as the Chernobyl and Fukushima, nuclear accident in Thule (NW Greenland) in 1968 and satellite accidents. The SNAP 9A satellite accident caused a several-fold increase in the ^{238}Pu/^{239,240}Pu ratio in 1964 (UNSCEAR 1982; Vintró et al. 2000; Zheng et al. 2012). The Pu in the environment of Lithuania originated mainly as a result of global fallout. The Chernobyl accident added Pu traces in some locations as well. After the Chernobyl accident, aerosol samples at sampling station in Vilnius showed a high activity of actinides up to 10,000 mBq/m^3 for Pu (with ^{240}Pu/^{239}Pu atom ratio varying from 0.41 to 0.42), which was associated with the presence of "hot" particles of different composition (Lujaniene et al. 2006). Activity concentration of Pu measured in the ground-level air of Lithuania in 1995–1999 showed a clear downward trend (Lujanienė et al. 2012). The ^{240}Pu/^{239}Pu atom ratio of aerosols in Preila (Lithuanian maritime region) in 1995–1999 varied from 0.135 to 0.247 (mean value of 0.202) being in 1997–1998 closer to the global fallout value. The ^{240}Pu/^{239}Pu atom ratio in Vilnius was close to the Chernobyl value in 1995 and later on it decreased to the global fallout level. Atmospheric depositions of aerosol particles on the Earth surface resulted in the soil contamination by Pu. After the Chernobyl accident, ^{239240}Pu concentrations in Lithuanian soil varied from 0.05 ± 0.01 to 1.30 ± 0.09 Bq/kg day week with ^{238}Pu/^{239,240}Pu activity ratio ranging from 0.3 to 0.45 (Druteikiene 1999). Activity concentration of ^{239,240}Pu in surface (0–5 cm) soil samples (n = 48) collected at four locations in 2010–2012 varied from 0.05 ± 0.01 to 0.70 ± 0.05 Bq/kg, dry weight, and the ^{238}Pu/^{239,240}Pu activity ratio ranged from ~ 0.03 to 0.07 (Lujanienė 2013). Meadow and forest soil samples (n = 48) collected in autumn of 2011 showed ^{239,240}Pu activity concentration of 0.07–0.53 Bq/kg for meadow soil, whereas higher activity concentrations were found in forest soils (0.74–1.80 Bq/kg). ^{238}Pu/^{239,240}Pu activity ratio and ^{240}Pu/^{239}Pu atom ratio were 0.02–0.18 and 0.18–0.24, respectively (Ezerinskis et al. 2016).

Athmospheric pollution control in forest monitoring sites were developed across the world and have operated for a long period of time. The monitoring stations are devoted to systematic observations of parameters related to a specific problem and produce time series measurements of physical/chemical/biological variables in order to answer questions about environmental change (Ferretti 2013).

When conducting radioecological assessments of terrestrial ecosystems, much attention is paid to soil-inhabiting organisms. Soils are habitat to a huge variety of microorganisms, insects, annelids and other invertebrates, as well as plants and algae (Aislabie and Deslippe 2013). Microorganisms play major roles in ecosystems and contribute to numerous important biological and chemical processes (Tedersoo et al. 2014; Beirn et al. 2017). In forest ecosystems, soil-inhabiting microorganisms are highly sensitive to environmental changes and are able to effectively respond to changing environmental conditions (Siles et al. 2018). Fungi are considered the main decomposers, while bacteria represent another important and integral part of the microbial community in forest soils (Lladó et al. 2017). Human activities, including land management, climate change and other disturbances, have a great impact on soil-inhabiting microorganisms. Microbial community structures can be influenced by biotic and abiotic factors: depth of organic horizon, soil organic matter properties, pH, main nutrient elements, microelements content. Therefore, microorganisms can be used as bioindicators of soil changes, including changes due to the soil's exposure level to pollutants in the ecosystem (Yurkov et al. 2012; Tedersoo et al. 2014; Escobar et al. 2015). Soil yeasts respond to changes in abiotic factors, including soil organic matter content, pH, conductivity, temperature, availability of water and macronutrients, such as N, P, K, Na and Mg (Yurkov 2017). The optimal pH range for growth of yeasts and fungi is between the values of 3 and 8 and between 5.5 and 9.0 for that of bacteria (Krulwich et al. 2011; Péter et al. 2017).

By monitoring the abundance of microorganisms in contaminated soils, it is possible to clarify the restoring process of the natural equilibrium. Changes in soil-inhabiting microorganisms' composition and species diversity and resistant populations can be observed when pollution concentrations increase. Investigation of microorganisms' distribution and determination of microorganisms' metabolism and activity are important in the monitoring of the biological degradation of environmental pollutants. Bacteria can interact with radionuclides via multiple mechanisms, including bioreduction, biomineralization, bioaccumulation or biosorption. On the other hand, radionuclides may exert radio- and chemotoxic effects on bacteria, thus influencing the structure and activity of microbial communities. Fungi can accumulate ^{137}Cs, and it has been proposed that they can be used as ecofacts (bioindicators) of contaminated sites containing radionuclides (Theodorakopoulos et al. 2017). Effective microorganisms' products are usable for soil remediation or for reducing the uptake of anthropogenic radionuclides from soil to plant (Shchur et al. 2017).

This study deals with the initial characterisation of the Lithuanian part of the 30-km zone of the BelNPP, emphasising the forest plants, terrestrial mosses, organic and mineral topsoil for monitoring purposes with the task to optimise sampling procedures. The aim is to describe the preoperational radioecological state of pine forest soil located in the potential impact zone of the BelNPP.

Environmental settings, sampling sites and methods

Studies of the health and environmental consequences of the Chernobyl accident have evidenced that the uptake and retention of ^{137}Cs have generally been much higher in semi-natural ecosystems than in agricultural ecosystems, and the clearance rate from forest ecosystems remained extremely slow (Balonov 2013). The monitoring sites were established in the Lithuanian part of the 30-km zone of the BelNPP, in forest ecosystems. The eight sampling sites were selected in the Lithuanian part of the 30-km zone of the BelNPP near the Belarus-Lithuania border in a ~ 60-km long semi-regular arc. The Smalvos (SMA) site was used as a temprorary and spatial background. Smalvos sampling point is situated about 115 km away from BelNPP and about 14 km from INPP (Fig. 1). Smalvos site represents mature forest ecosystem on *Podzol* soils in restricted territory of Gražutės Region Park and has been monitored for radionuclides since 1997.

Forest ecosystems on *Arenosols* with a low groundwater table dominate in the Lithuanian part of 30-km zone territory of the BelNPP. Blueberry pine forest more than 50 years old with rowan and other shrubs dominates. The sampling sites are represented by natural pine forest ecosystems with low human impact. According to historical maps compiled before World War I, half of the sites (referred to as sampling sites 2, 3, 7 and 8) were, at that time, forested territories (Samas 1997). Consequently, the territories have been forested for at least the past 100 years and represent old forest. All the investigated forest ecosystems hosting the sites are developed on sands of different origins and geomorphological features: continental sand dunes, undulating moulds of kames, fluvial terraces. The relief is flat or undulating. The altitudes are in the range of 126–225 m above the sea level (Table 1). *Podzol* soils exactly match to the Smalvos background site were not discovered in the investigated BelNPP 30-km zone in Lithuania territory. However, widespread here *Arenosols* (Table 1) are related by origin to *Podzols* (Retallack 2005).

In the case of undulated relief, sampling sites were situated in the middle of the slope and on the flattest side of the mould or dune. Sampling points of moss and soil were selected randomly. The main two sampling criteria were the imperceptible trampling of the surface and the continuous cover of the predominating terrestrial mosses (*bryophytes*). Terrestrial mosses can effectively accumulate a variety of substances from direct atmospheric deposition (Jiang et al. 2018).

A quadrat frame with 20 × 20-cm sides and 20 cm in height was used to collect organic and mineral soil samples for radionuclide analysis. The frame was planted vertically until reaching 20 cm in depth from the moss surface. The sampling point distance from the stems of trees was > 3 m. Series of living moss and soil horizons were collected, registering the actual depths of soil horizons. The depth values were used for sampled soil volume and soil bulk density determination.

The undisturbed and fully developed organic soil horizon was sampled. It is composed of the sequence of organic topsoil horizons, OL (organic litter), OF (organic fragmented horizon) and OH (organic humus horizon), distinguishable according to the decomposition degree of organic matter. OH horizon contains > 70% of humic component and OL horizon is low decomposed and contains < 30% in (Zanella et al. 2018). Mineral topsoil horizon A underlies by the organic horizons and contains < 20% of organic material (IUSS 2015). Thin transitional horizon (A) was combined with 0–5 cm during the sampling of mineral topsoil for the gamma assay. The organic soil depth was measured during sampling for soil-inhabiting microorganisms analysis using cylinder, 8 cm in diameter and 10 cm in height. The sampling was performed in 1997, 2003 and 2018 at the SMA site, as well as in autumn of 2017, spring, summer and autumn of 2018 and spring of 2019 in sites 1–8 in the BelNPP 30-km zone. The scheme of soil horizons and sampling for soil-inhabiting microorganisms is shown in Fig. 2.

Soil samples were dried to constant mass at laboratory conditions (18–20 °C), weighed for water content determination and crushed to pieces < 2 mm in diameter. Soil pH values were measured in soil:liquid suspensions (1:10) after incubation for 12 h. Soil was air-dried and liquids were of two kinds: weak salt solution (0.1 M $CaCl_2$) and water.

Terrestrial plant samples included mosses and vascular plants: blueberry shrubs (*Vaccinium myrtillus* L.), rowan leaves (*Sorbus aucuparia* L.), mugwort stems (*Artemisia* sp.) and birch leaves (*Betula* sp.). The living mosses were separated with scissors, which were used to cut away the green parts. *Pleurozium schreberi* prevailed in sampling sites 1 and 3–7, and *Hylocomium splendens* prevailed in sampling sites 2 and 8. Other moss types occurred in small amounts. In most cases, samples were mixes of different moss taxes (Table 1).

The sampling seasons of 2017, 2018 and 2019 were different according to air temperature and precipitation amount. There were rain showers in eastern Lithuania during sampling in the last ten days of July 2017, and it was colder than the climatic norm. During August 2017, the precipitation amount was close to the climatic norm. The precipitation amount from September to October of 2017 was higher than the climatic norm (1.5–2 times) and was close to the climatic norm in November 2017. The highest temperature of November 2017 was 2–2.5 °C higher than the climatic norm. Temperature and precipitation during all seasons of 2018 were close to the climatic norm. The beginning of spring of 2019 was dry (0.2–0.6 of the climatic norm), and the air temperature was 1.2–2.9 °C higher than the climatic norm. At the end of May 2019, the precipitation and temperature were close to the climatic norm (LHS 2019). All samplings were performed at the end of seasons: the end of August, May and November.

The specific activity of ^{14}C in plant samples was measured using the liquid scintillation counting (LSC) method (Gupta and Polach 1985; Arslanov 1985). A conventional procedure for benzene synthesis was applied (Kovaliukh and Skripkin 1994). ^{14}C activity counting in benzene was performed with a TriCarb 3170 TR/SL.

Table 1 Main features and properties of sampling sites and soils

Site	Location	Depth of organic horizons (mean ± SD, cm) OL+OF+OH*	pH of soil horizons OH/A** in 0.01 M $CaCl_2$ / in H_2O	Mineral soil profile / Soil group name***	Relief and soil parent rocks	Absolute elevation a.s.l. (m)
SMA control	N 55° 36′ 53.6″ E 26° 22′ 1.05″	9.0 ± 1.0	2.6/2.6 / No data	*Ah–E–Bh–Bs–C* / *Podzol*	Plain glaciolacustrine	144
1	N 55° 00′ 20.4″ E 26° 09′ 44.8″	5.8 ± 2.0	2.4/2.9 / 3.3/3.8	*Ap–B–C* / *Eutric Arenosol*	Plain fluvioglacial	170
2	N 54° 58′ 33.3″ E 26° 04′ 16.0″	4.8 ± 1.9	2.4/2.7 / 3.5/3.9	*A–C* / *Protic Arenosol*	Parabolic dunes, Aeolian	160
3	N 54° 58′ 26.7″ E 25° 59′ 15.3″	5.1 ± 1.7	3.1/3.3 / 3.9/4.1	*AE–Bs–C* / *Brunic Arenosol*	Plain glaciolacustrine	150
4	N 54° 54′ 33.1″ E 25° 50′ 46.7″	5.8 ± 2.2	2.4/3.0 / 3.5/4.1	*A–E–Bs–C* / *Albic Arenosol*	Plain, glaciolacustrine	146
5	N 54° 50′ 24.9″ E 25° 43′ 22.3″	1.3 ± 1.0	4.5/4.2 / 5.1/5.2	*Ap–AB–C* / *Fluvic eutric Arenosol*	Terrace, fluvioglacial	126
6	N 54° 45′ 42.9″ E 25° 43′ 40.6″	2.2 ± 0.7	2.5/3.0 / 3.3/4.0	*Ah–Bs–C* / *Eutric brunic Arenosol*	Plain peripheral fluvioglacial	225
7	N 54° 42′ 53.0″ E 25° 43′ 21.9″	4.6 ± 1.1	2.8/2.7 / 3.5/3.7	*A–B–C* / *Eutric Arenosol*	Kame slope, peripheral fluvioglacial	213
8	N 54° 38′ 08.7″ E 25° 43′ 03.2″	4.9 ± 3.8	3.0/3.2 / 3.8/4.3	*Ah–Bs–C* / *Eutric brunic Arenosol*	Plain fluvioglacial	171

*As defined by Zanella et al. 2018. *OL*, loose plant remains, litter; *OF*, fragmented horizon; and *OH*, humus horizon

**pH uncertainty ±0.10

***By IUSS Working Group WRB (2015). Description of horizons: *Ah*, mature topsoil, high diffusion of soluble organic compounds; *Ap*, former plowed topsoil; *Bhs*, illuviation of complex compounds of sesquioxides and organic matter; *C*, parent rock, sand with low intensity of soil-forming processes

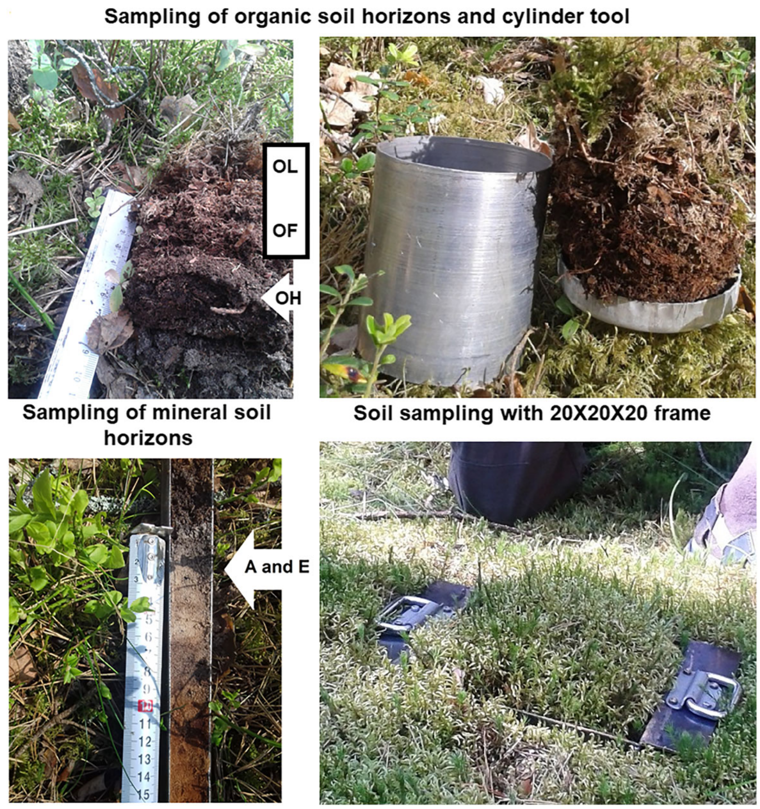

Fig. 2 Soil sampling tools and sampled soil horizons location in profiles

The specific activity of ^{3}H in monthly samples of atmospheric precipitation and TFWT form of plant samples was measured using the low-background LSC method according to the procedure (ISO 9698 2019). The water fraction for ^{3}H determination was extracted from plant samples using the vacuum distillation method. The precipitation water samples underwent primary distillation, electrolytic enrichment, neutralization and final distillation. Eight milliliters of tissue-free water or water after electrolytic enrichment were mixed with the scintillation cocktail, and ^{3}H activity was measured with a Quantulus 1220.

Gamma-ray spectrometry were sampled: 19 soil samples from Smalvos background site, 46 soil and 39 plant samples from the BelNPP 30-km zone edge. The number of samples measured by gamma-ray spectrometry method is 19 for the INPP and 46 for the BelNPP regions in investigation of soil profile as well as 39 for the BelNPP regions in plants samples. Air-dried plants and samples from organic soil sub-horizons OL, OF and OH were combusted in a muffle furnace at 450 °C for 5 h. Deeper soil layers were measured in the dry condition. Two geometries, 60 and 3 ml, were applied. The weight of soil samples in 60-ml containers varied from 20 to 83 g. The weight of plants ash samples in 60- and 3-ml containers varied from 3 to 10 g and from 0.4 to 2.6 g, respectively. Weight for soil samples in 60-ml containers varied from 20 to 83 g; for plants ash from 3 to 10 g per sample. Weight for plants ash in 3-ml containers varied from 0.4 to 2.6 g per sample. Gamma-ray–emitting radionuclides in soil and plant ash samples were measured using an ORTEC gamma-ray spectrometer with an HPGe GWL-120-15-LB-AWT detector (resolution 2.25 keV at 1.33 MeV) at the Nature Research Centre (Vilnius), as described in Gudelis et al. (2000). ^{137}Cs was assessed according to the gamma line of ^{137m}Ba at 661.66 keV (a daughter product of ^{137}Cs) and ^{40}K according to the gamma line at 1462 keV. The counting time of samples varied from 80,000 to 450,000 s. Activity concentration of gamma-ray–emitting radionuclides was calculated for dry weight in all cases.

In order to determine the specific activity of plutonium isotopes, the ash samples of plants and soil were dissolved in strong acids (HNO_3, HCl, HF and $HClO_4$). TOPO/cyclohexane extraction and radiochemical purification using TEVA resins (100–150 μm) were used to separate Pu isotopes. ^{242}Pu (AEA Technology UK, Isotrak, QSA Amersham international, ATP10020) was applied as yield tracers in the separation procedure. The overall recovery of Pu isotopes was about 80%. For more information, see Lujanienė (2013). The accuracy and precision of analysis were verified using reference materials (IAEA-135, NIST SRM No 4350B and 4357) and in inter-comparison exercises. The precision of Pu measurements was better than 7% (at a 2-s level). After purification, Pu isotopes were electroplated onto stainless steel disks and measured using an alpha-spectrometry system with passivated implanted planar silicon (PIPS) detectors with an active area of 450 mm^2 (AMETEK, Oak Ridge, Tenn, USA).

Isolation of soil-inhabiting microorganisms from the forest soil was fulfilled by serial dilution and plating on selective media, as described in Domsch et al. (2007) and Crous et al. (2019). Dilutions ranging from 10^{-2} to 10^{-5} were plated in duplicate onto solid 2% (w/v) malt extract agar (MEA, Liofilchem, Italy) supplemented with 100 ppm chloramphenicol (Carl Roth GmbH, Germany) for cultivable filamentous fungi. For isolation of the yeasts, glucose-ammonia media (GA glucose, 20 g; yeast extract, 2 g; $(NH_4)_2SO_4$, 5 g; K_2HPO_4, 0.15 g; $MgSO_4$, 0.5 g; NaCl, 0.1 g; $CaCl_2$, 0.1 g; agar, 20 g; H_2O, 1000 ml) supplemented with 100 ppm chloramphenicol was employed. Organotrophic bacteria were isolated on nutrient agar (NA, Liofilchem, Italy), *Actinobacteria* and mineral nitrogen–assimilating bacteria on starch–ammonia agar (SAA) (Kharel et al. 2010). Plates with MEA were incubated at 24 ± 1 °C for 7 days, GA and SAA at 27 ± 1 °C for 3 days and NA at 30 ± 1 °C for 2 days.

Microorganism abundance was calculated as CFU (colony-forming units) per gram of dry soil. The colonies of microorganisms in the dishes were counted and calculated as follows (Carter and Gregorich 1993):

$$n = \frac{\mathrm{abc}}{d}$$

where n is colony forming units per gram of dry soil (CFU/g), a is number of colonies in the Petri dish, b is dilution number, c is the volume of suspension (ml), d is weight of dry soil (g).

Statistical analysis was performed using XLSTAT and PAST3 software. Principal component analysis (PCA) was applied for soil characteristics (organic soil depth, bulk density, pH and free water content) of OH and A soil horizons. The evaluation of the characteristics was done by numerical methods after data autoscaling (van den Berg et al. 2006):

$$X\mathrm{ij} = \frac{Xi - X\mathrm{mean}}{\mathrm{SD}}$$

where X_{ij} is standard chracteristic, Xi is raw data, X_{mean} is the mean of the characteristics and SD is standard deviation in the data set.

Results and discussion

The data on ^{14}C in terrestrial plants in the Lithuanian part of the BelNPP 30-km zone for the recent period of observations (2017–2018) are presented in detail in Table 2.

We compared the ^{14}C data attributed to the BelNPP 30-km zone edge with similar data attributed to the INPP 30-km zone for the period of its decommissioning and with global background values. For the ^{14}C background assessment, several data sets have been used: Northern Hemisphere data for the period of 1983–1997 (Hua and Barbetti 2004), local tree rings data (Mazeika et al. 2008; Ežerinskis et al. 2018) and data on annual vegetation from the Lithuanian national parks. All these data sets were in good correlation (Ežerinskis et al. 2018) and showed the continuous decline of ^{14}C originated from the thermonuclear weapon tests (from 124 pMC in 1983 to 102 pMC in 2015). Nowadays, the ^{14}C background for biota directly related to atmospheric CO_2 is approaching the ^{14}C level close to cosmogenic origin, equal to 100 pMC.

^{14}C specific activity in terrestrial plants (mosses, leaves of blueberries, rowan and birch) from all sites studied in the BelNPP 30-km zone varied insignificantly (Table 2). In all the terrestrial plants, ^{14}C specific activity varied from 97.80 ± 1.30 to 102.40 ± 0.79 pMC and the average value within standard deviation (SD) was 99.33 ± 1.30 pMC, which is slightly lower than the contemporary ^{14}C level in the atmosphere. This weak ^{14}C depletion can be related to differences in plant metabolism or plant surface contamination resulting in some fraction of "old" carbon in the sample. All samples of mugwort with ^{14}C values within a narrow range from 100.14 ± 0.75 to 102.40 ± 0.79 pMC evidenced a very good relation of this species with atmospheric CO_2.

The data on ^3H activity concentration in terrestrial plants and atmospheric precipitation within the 30-km

Table 2 ^{14}C specific activity in plants in 2017–2018

Sites	Plants	^{14}C (pMC ± σ)	^{14}C (Bq/kg ± σ), dry weight*
1	Moss	98.50 ± 0.50	129.9 ± 0.7
	Blueberry	98.80 ± 0.60	128.8 ± 0.8
	Rowan	97.90 ± 0.60	123.3 ± 0.8
	Mugwort	100.14 ± 0.75	129.2 ± 1.0
2	Moss	99.00 ± 0.50	132.2 ± 0.7
	Blueberry	98.80 ± 0.60	128.1 ± 0.8
	Birch	99.60 ± 1.10	128.5 ± 1.4
	Mugwort	101.24 ± 0.80	130.6 ± 1.0
3	Moss	98.30 ± 1.30	128.5 ± 1.7
	Blueberry	99.30 ± 0.60	130.5 ± 0.8
	Rowan	97.80 ± 0.60	122.3 ± 0.8
	Mugwort	102.40 ± 0.79	132.1 ± 1.0
4	Blueberry	99.10 ± 0.50	129.9 ± 0.7
	Rowan	98.40 ± 0.50	123.4 ± 0.6
	Mugwort	100.20 ± 0.77	129.3 ± 1.0
5	Blueberry	100.00 ± 0.45	130.8 ± 0.6
	Rowan	97.80 ± 1.30	121.3 ± 1.6
	Mugwort	101.59 ± 0.87	131.1 ± 1.1
6	Blueberry	98.40 ± 0.50	128.7 ± 0.7
	Rowan	98.90 ± 0.50	127.5 ± 0.6
	Mugwort	101.16 ± 0.81	130.5 ± 1.0
7	Blueberry	98.40 ± 0.45	127.9 ± 0.6
	Rowan	98.30 ± 1.30	125.5 ± 1.7
	Mugwort	101.03 ± 0.80	130.7 ± 1.0
8	Blueberry	98.20 ± 0.60	127.2 ± 0.8
	Rowan	98.00 ± 1.10	122.9 ± 1.4
	Mugwort	100.61 ± 0.80	129.8 ± 1.0

*Calculated basing on C_{org} fraction in sample material

zone of the BelNPP for the period of observations (2017–2019) are presented in Table 3 and Fig. 3.

The TFWT values in rowan leaves selected from the 30-km zone of the BelNPP on 09-08-2018 varied from 13.2 ± 2.2 to 17.1 ± 2.3 TU, with an average value of 15.0 ± 2.5 TU. A similar but slightly higher ^{3}H level was characteristic of blueberry shrubs from the same territory, which had an average value of 18.8 ± 2.5 TU and ranged from 17.3 ± 2.2 to 20.8 ± 2.3 TU. TFWT values for plants were close to the ^{3}H level in precipitation (Fig. 3): for 2018 (plants sampling year), the values of average, minimal and maximal ^{3}H activity concentrations were as follows: 10.3, 5.7 and 18.3 TU, respectively.

Despite its low radiation significance, ^{3}H is a very important specific mobile radionuclide, due to its complex global inventory from thermonuclear weapons testing and from cosmogenic production, as well as because of its local excess often being traced as originating from NPP sites. ^{3}H in atmospheric precipitation has been measured in Lithuania for the past 20 years, which allows the ^{3}H time series of monthly precipitation since 1999 to act as a basis for interpretation for the ^{3}H distribution in terrestrial ecosystems, both for background areas and NPP sites (Jefanova et al. 2018). ^{3}H monthly data for precipitation are characterised by seasonal variations, with maximum values in the spring–summer months (May–August) and with minimum values in autumn–winter months (October–February), but with the evident decline of ^{3}H from thermonuclear weapons testing to almost the ^{3}H level in precipitation corresponding to cosmogenic production. The annual averaged ^{3}H activity concentration in precipitation in eastern Lithuania for the last several years is approaching 10 TU, with the lowest values in winter (5–8 TU) and the highest values in summer (11–18 TU). The seasonal variations of ^{3}H activity concentration in precipitation, with some smoothing and averaging effects dependant on the water turnover rate, form the ^{3}H background level in animate and inanimate constituents of terrestrial ecosystems (Fig. 3).

The data on ^{137}Cs specific activity in terrestrial plants and soils in the Lithuanian part of the 30-km zone of the BelNPP for the recent period of observations (2017–2018) are presented in Table 4.

Terrestrial plants accumulate radionuclides through two ways: by direct deposition from the atmosphere and by root uptake from the soil. Being the main route of ^{137}Cs's entry into biological migration in terrestrial ecosystems, the uptake of ^{137}Cs by plants is higher in soil characterised by a higher content of organic matter (Suchara 2017). The coniferous forests, with their herbal-shrubby storey, and the large surface area of the forest canopy act as significant interceptors of dry and wet atmospheric deposition. Rowan leaves, stems and leaves of blueberries, as well as mosses were selected for analysis of ^{137}Cs uptake by plants. ^{137}Cs specific activity in rowan, blueberries and mosses selected from the BelNPP 30-km zone varied significantly, from 1.1 ± 0.5 to 18.9 ± 1.5 Bq/kg, the average value within SD 7.3 ± 4.5 Bq/kg, from 0.8 ± 0.2 to 40.5 ± 1.8 Bq/kg, the average value within SD 14.0 ± 12.1 Bq/kg, and from 5.4 ± 1.1 to 25.9 ± 1.3 Bq/kg, the average value within SD 13.3 ± 6.6 Bq/kg, respectively. Rowan leaves evidenced the lowest variability and lowest level of ^{137}Cs,

Table 3 ^{3}H specific activity in tissue-free water from plants sampled in 09-08-2018

Sites	Rowan leaves			Blueberry shrubs		
	^{3}H (± 1σ), TU	^{3}H (± 1σ), Bq/l, water	^{3}H (± 1σ) Bq/kg, fresh weight*	^{3}H (± 1σ), TU	^{3}H (± 1σ), Bq/l, water	^{3}H (± 1σ) Bq/kg, fresh weight*
1	15.3 ± 2.2	1.8 ± 0.3	0.99 ± 0.14	17.3 ± 2.2	2.0 ± 0.3	0.97 ± 0.12
2	14.5 ± 2.2	1.7 ± 0.3	0.96 ± 0.15	19.2 ± 2.3	2.3 ± 0.3	1.23 ± 0.15
3	14.6 ± 2.2	1.7 ± 0.3	0.96 ± 0.14	17.5 ± 2.2	2.1 ± 0.3	0.95 ± 0.12
4	17.0 ± 2.3	2.0 ± 0.3	1.03 ± 0.14	18.1 ± 2.3	2.1 ± 0.3	1.05 ± 0.13
5	13.2 ± 2.2	1.6 ± 0.3	0.85 ± 0.14	19.1 ± 2.4	2.3 ± 0.3	1.24 ± 0.15
6	17.1 ± 2.3	2.0 ± 0.3	1.19 ± 0.16	19.2 ± 2.3	2.3 ± 0.3	1.10 ± 0.13
7	13.7 ± 2.2	1.6 ± 0.3	0.92 ± 0.15	18.9 ± 2.3	2.2 ± 0.3	0.96 ± 0.12
8	14.9 ± 2.2	1.8 ± 0.3	0.91 ± 0.13	20.8 ± 2.3	2.5 ± 0.3	1.23 ± 0.14
Average ± SD	15.0 ± 1.4	1.8 ± 0.17	0.97 ± 0.10	18.8 ± 1.1	2.2 ± 0.13	1.09 ± 0.13

*Calculated basing on free water content in sample material

while the mean uptake of ^{137}Cs by blueberry and moss was similar (14.0 and 13.3 Bq/kg); however, ^{137}Cs variability in moss was twice as low as that in blueberry. In addition, significantly higher specific activities of natural fallout radionuclides (^{7}Be and ^{210}Pb) were found in moss compared to rowan leaves and blueberry. Based on all measurements the average values of ^{210}Pb activity concentration (± SD) for the mentioned plant species were 218 ± 36, 62 ± 6, and 23 ± 6 Bq/kg, respectively. The data on short-lived ^{7}Be in plants were more uncertain; however, they showed the same tendency as ^{210}Pb. The prevailing ^{7}Be activity level was in moss 500 Bq/kg, in rowan leaves and in blueberry 200 Bq/kg. This evidences that rowan leaves effectively intercept atmospheric deposition during one vegetation season and uptake by roots is negligible. The blueberry, as a perennial plant with roots penetrating to 10 cm depth, uptake ^{137}Cs mainly from the soil for several seasons. The permanent development of moss cover in coniferous forests gives them the ability to retain ^{137}Cs from direct atmospheric deposition for several seasons.

Apart from the blueberries, the highest specific activity of ^{137}Cs is characteristic of organic soil horizons, OF and OH, the average values within SD 36.4 ± 17.8 Bq/kg and SD 30.4 ± 16.9 Bq/kg, respectively (Table 4).

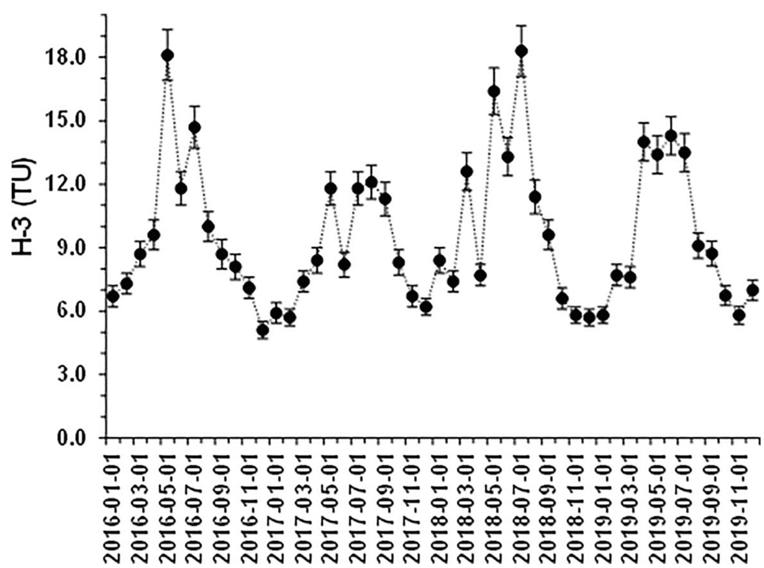

Fig. 3 ^{3}H activity concentration in atmospheric precipitation sampled near Zarasai (ZAR) and INPP

Table 4 Activity of ^{137}Cs in plants (in 2017/2018) and in soil horizons (in summer 2017) and total inventory of ^{137}Cs in soil

Sites	Activity of ^{137}Cs (Bq/kg ± 2σ)								Inventory of ^{137}Cs in soil (Bq/m^2 ± 2σ)
	Plants in 2017 and 2018			Topsoil organic horizons in summer 2017			Mineral topsoil depth (cm)		
	Rowan leaves	Blueberry shrubs	Moss	OL	OF	OH	0–5	5–10	
SMA background	n/s*	n/s	11.8 ± 1.0	7.5 ± 1.0	31.3 ± 1.5	67.1 ± 2.7	17.8 ± 2.4	3.0 ± 1.4	1410 ± 230
1	7.5 ± 1.2	1.3 ± 0.1	7.2 ± 0.5	10.4 ± 0.8	8.5 ± 1.3	7.2 ± 1.4	4.1 ± 1.1	9.8 ± 1.8	1010 ± 210
	7.5 ± 1.0	15.3 ± 1.0	10.8 ± 0.9						
2	n/s	38.8 ± 1.5	12.2 ± 0.6	14.7 ± 1.1	51.3 ± 2.3	17.1 ± 1.4	5.5 ± 1.2	<mda**	930 ± 70
	12.0 ± 1.4	21.4 ± 1.2	14.6 ± 1.3						
3	8.9 ± 0.8	5.3 ± 0.3	9.8 ± 0.7	53.3 ± 2.6		46.7 ± 2.7	12.2 ± 1.8	3.5 ± 1.7	1650 ± 430
	6.9 ± 1.0	6.2 ± 0.8	10.5 ± 1.0						
4	4.8 ± 0.8	5.8 ± 0.5	6.1 ± 0.6	5.5 ± 0.9	29.1 ± 1.7	43.5 ± 2.4	14.4 ± 1.9	8.8 ± 1.8	1600 ± 280
	3.5 ± 0.8	4.3 ± 0.3	5.5 ± 1.0						
5	2.8 ± 1.1	0.8 ± 0.2	7.1 ± 1.0	12.4 ± 1.3		11.4 ± 2.7	10.4 ± 2.6	4.9 ± 1.2	1230 ± 300
	1.1 ± 0.5	3.1 ± 0.7	5.4 ± 1.1						
6	7.5 ± 1.1	14.4 ± 1.4	17.8 ± 0.7	11.0 ± 1.1	50.1 ± 2.4	27.3 ± 2.4	8.3 ± 1.9	3.0 ± 1.1	1110 ± 270
	5.3 ± 1.1	11.5 ± 0.8	17.5 ± 1.3						
7	2.8 ± 0.5	40.5 ± 1.8	22.5 ± 1.0	49.3 ± 3.1		50.2 ± 2.5	11.9 ± 2.3	3.9 ± 1.4	1470 ± 310
	10.1 ± 1.5	16.7 ± 1.3	25.6 ± 1.3						
8	18.9 ± 1.5	19.9 ± 0.9	21.7 ± 1.0	19.2 ± 0.9	48.1 ± 2.4	39.5 ± 2.2	11.6 ± 1.7	3.2 ± 1.5	1410 ± 360
	10.3 ± 1.1	18.9 ± 1.3	18.6 ± 1.9						

**n/s*, not sampled

**< *mda*, below detectable acivity, mda = 1.5 Bq/kg

The ^{137}Cs data attributed to particular sites evidenced certain variability: the ^{137}Cs level was relatively high both in blueberries and soil horizon OH from sites 2, 7 and 8; relatively high in soil but relatively low in blueberries from sites 4 and 6; and relatively high in moss from sites 6, 7 and 8. The lowest ^{137}Cs level in soil and terrestrial plants with ^{137}Cs inventory prevailing in mineral soils (Fig. 5) was from sites 1 and 5, located in close proximity to settlements and river valleys.

According to the BelNPP 30-km zone soil profiles data (Table 4), the ^{137}Cs inventory changes in 2017 in the north–south direction were as follows: 1000 ± 200 Bq/m^2 in sampling sites 1 and 2, 1600 ± 400 Bq/m^2 in sampling sites 3 and 4, 1100 ± 200 Bq/m^2 in sampling sites 5 and 6 and 1500 ± 300 Bq/m^2 in sampling sites 7 and 8. For the comparison and ^{137}Cs background assessments, we used a soil profile near the Smalvos locality (Fig. 1), where ^{137}Cs was measured several times after the Chernobyl accident (Fig. 4). The total inventory of ^{137}Cs originated from nuclear tests, and the Chernobyl accident in eastern Lithuania near the border with Belarus had undergone an increasing trend from north to south, which was evaluated a few years after the Chernobyl accident (Mažeika 2002; Butkus et al. 2014).

The ^{137}Cs inventory in the Smalvos background site was slightly reduced in time as follows: 1630 ± 280 Bq/m^2 in 1999, 1440 ± 240 Bq/m^2 in 2003 and 1410 ± 230 Bq/m^2 in 2018. The ^{137}Cs inventory in organic horizons was also reducing: 800 ± 90 Bq/m^2 in 1999, 580 ± 60 Bq/m^2 in 2003 and 480 ± 50 Bq/m^2 in 2018. This corresponds to the percentages of the total ^{137}Cs inventory: 49%, 40% and 34%, respectively. Despite ^{137}Cs inventory reducing in organic horizons, its inventory in mineral soil was growing as follows: 835 ± 140 Bq/m^2 in 1999, 865 ± 120 Bq/m^2 in 2003 and 930 ± 140 Bq/m^2 in 2018. ^{137}Cs is retained in a 20-cm thick soil layer composed of 10 cm of organic horizons and 10 cm of mineral horizons. Based on the landscape (pine forest ecosystems on a sandy plain) similarities and ^{137}Cs deposition way, it is assumed that the same distribution will also be in the 30-km zone of the BelNPP.

The ^{137}Cs distribution between upper (organic topsoil) and lower (mineral topsoil) sections of soil profiles from the Lithuanian part of the 30-km zone of the BelNPP in 2017 is presented in Fig. 5.

The contribution of ^{137}Cs contained in organic horizons to the total ^{137}Cs inventory varied from 7 to 63%, with lowest values (7% and 11%) in sites 1 and 5 and the highest values (63% and 43%) in sites 2 and 3. The lowest percentage of ^{137}Cs in organic horizons compared to total inventory may be a consequence of the higher water percolation due to mechanical disturbances in particular sites. The highest percentage value of ^{137}Cs in organic horizons compared to the total inventory is potentially related to the low water permeability of aeolian sands (site 2) or nearby arable land being the potential source of dust containing ^{137}Cs (site 3).

A few preliminary measurements of plutonium isotopes in soil samples indicated specific activities of about 1 Bq/kg (site 2, OF horizon 0.85 ± 0.04 Bq/kg; site 3, OH horizon 1.01 ± 0.10 Bq/kg; site

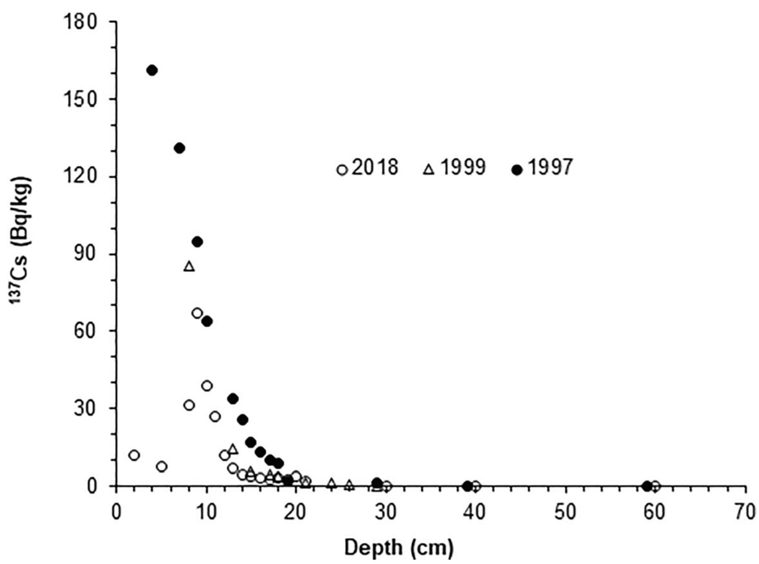

Fig. 4 ^{137}Cs activity concentration distribution in the forest soil profile near Smalvos (SMA). The soil layer down to 10 cm in depth represents organic soil horizons, including moss (M), organic litter (OL), organic fermentative (OF) and organic humus (OH). Below 10 cm depth, mineral horizons (fine sand) occur. The sampling in 1997 was in the local depression near the peat bog and evidenced higher deposited ^{137}Cs activity compared to later sampled profiles

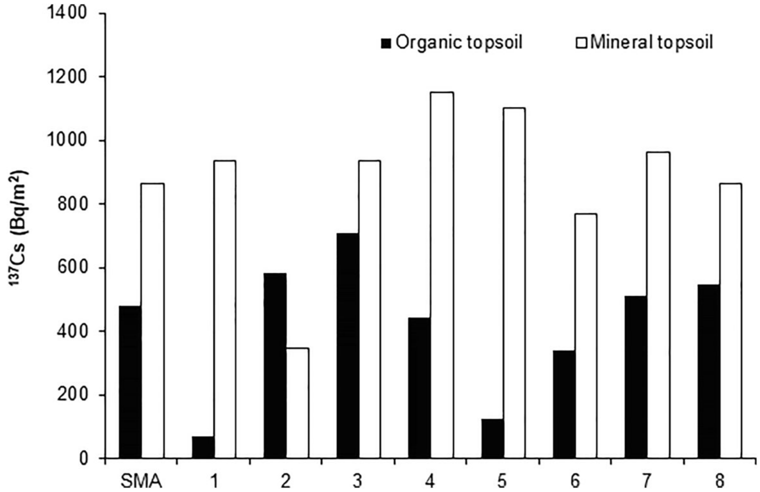

Fig. 5 ^{137}Cs inventory in soil profiles. SMA presents data from the Smalvos site as background

7, OH horizon 0.95 ± 0.05 Bq/kg) and an activity ratio of ^{238}Pu/^{239,240}Pu, a ratio typical of global fallout. Contrarily, lower activity concentration (by twice) containing traces of the Chernobyl-derived plutonium was found in a moss sample (site 7, M layer 0.40 ± 0.04 Bq/kg). Additional sampling are required to assess the impact of the Chernobyl-derived plutonium on the studied area.

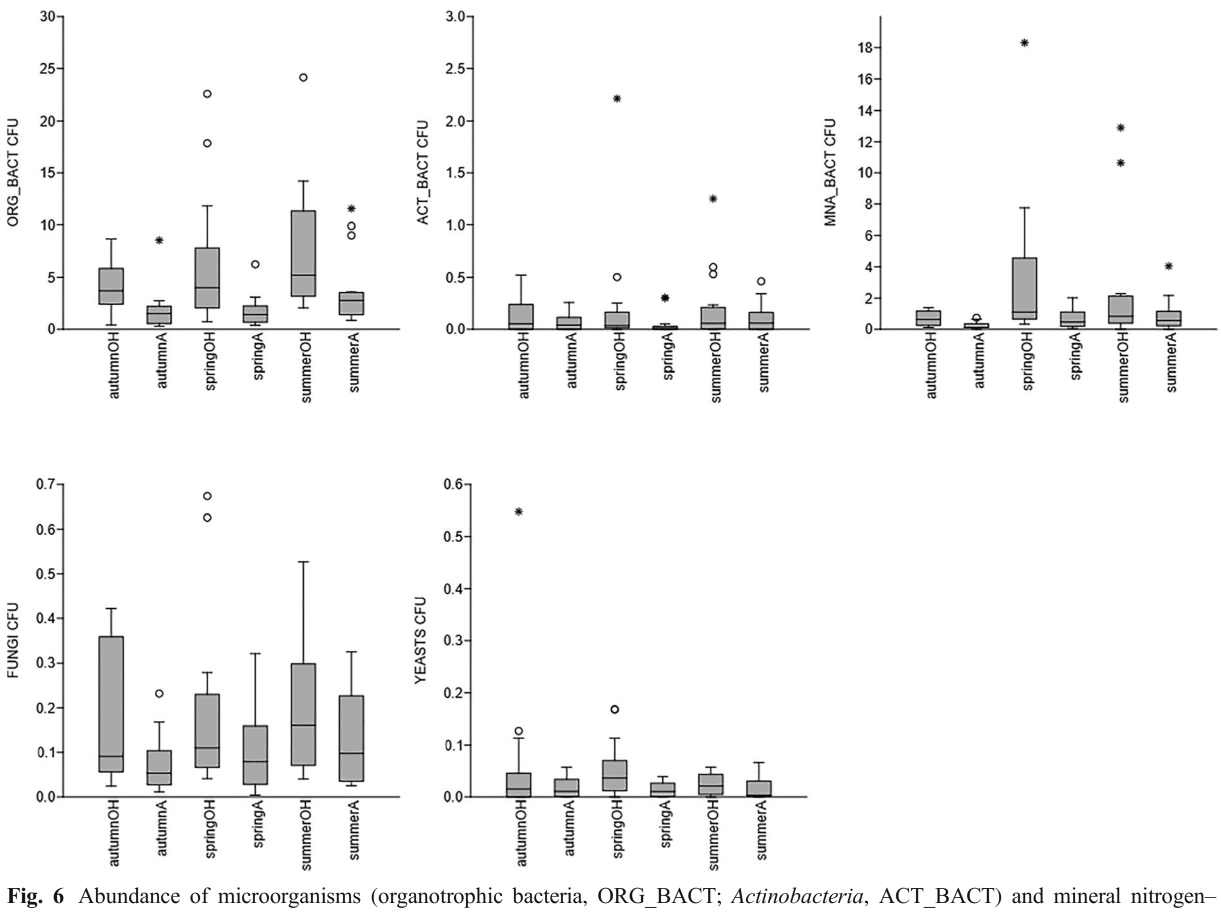

Fig. 6 Abundance of microorganisms (organotrophic bacteria, ORG_BACT; *Actinobacteria*, ACT_BACT) and mineral nitrogen–assimilating bacteria, MNA_BACT; filamentous fungi, FUNGI and YEASTS) by seasons in OH an A soil horizons

Many environmental factors, including microorganisms, can influence the bioavailability and transport of radionuclides in ecosystems. Variability of microorganisms depends greatly on climate conditions, such as precipitation and temperature (He et al. 2017).

The main microorganism groups' abundance was assessed for the evaluation of the microbiological state in the BelNPP 30-km zone. The evident differences in microorganism variability by seasons were detected. The detailed microorganism abundance analysis by seasons demonstrates that the highest abundance of the most microorganism groups is reached in summer and spring (Fig. 6). All groups of microorganisms were more abundant in the OH horizon in comparison with the A horizon. The number of organotrophic bacteria (ORG_BACT) in OH ranged from 4.2×10^5 to 2.4×10^7, and the concentration of fungi ranged from 2.4×10^4 to 6.7×10^5 CFU per gram of dry soil. Yeasts and *Actinobacteria* (ACT_BACT) were not isolated from all soil samples, but in some sites, their number reached up to 5.4×10^5 (in autumn of 2018) and 2.2×10^6 CFU per gram of dry soil (in spring of 2019), respectively.

The obtained results of counts and detection frequency of microorganisms in examined sites corresponded with those usually found in forest soil (Vieira and Nahas 2005; Popelářová et al. 2008; Ghorbani-Nasrabadi et al. 2013; Aleinikovienė et al. 2017). Mineral nitrogen–assimilating bacteria (MNA_BACT) are most common in soil with low acidity (Baldrian 2017). The largest numbers of organotrophic bacteria, *Actinobacteria*, and mineral nitrogen–assimilating bacteria were found in less acidic soils (sites 3, 5 and 8). With increasing soil acidity, the bacterial content in most of the studied sites decreased. The largest number of fungi in the OH horizon was found in site 7 and in the A horizon in sites 3 and 7. Compared to other sites, site 5 was the most specific in terms of fungal abundance (Fig. 7). Such differences could be largely determined by the chemical composition and soil type, as well as soil moisture parameters (Ritz and Young 2004).

The importance of the loads of separate environmental characteristics can be revealed by PCA analysis. The arrow length in PCA diagrams indicates the importance of the environmental variables, and its orientation

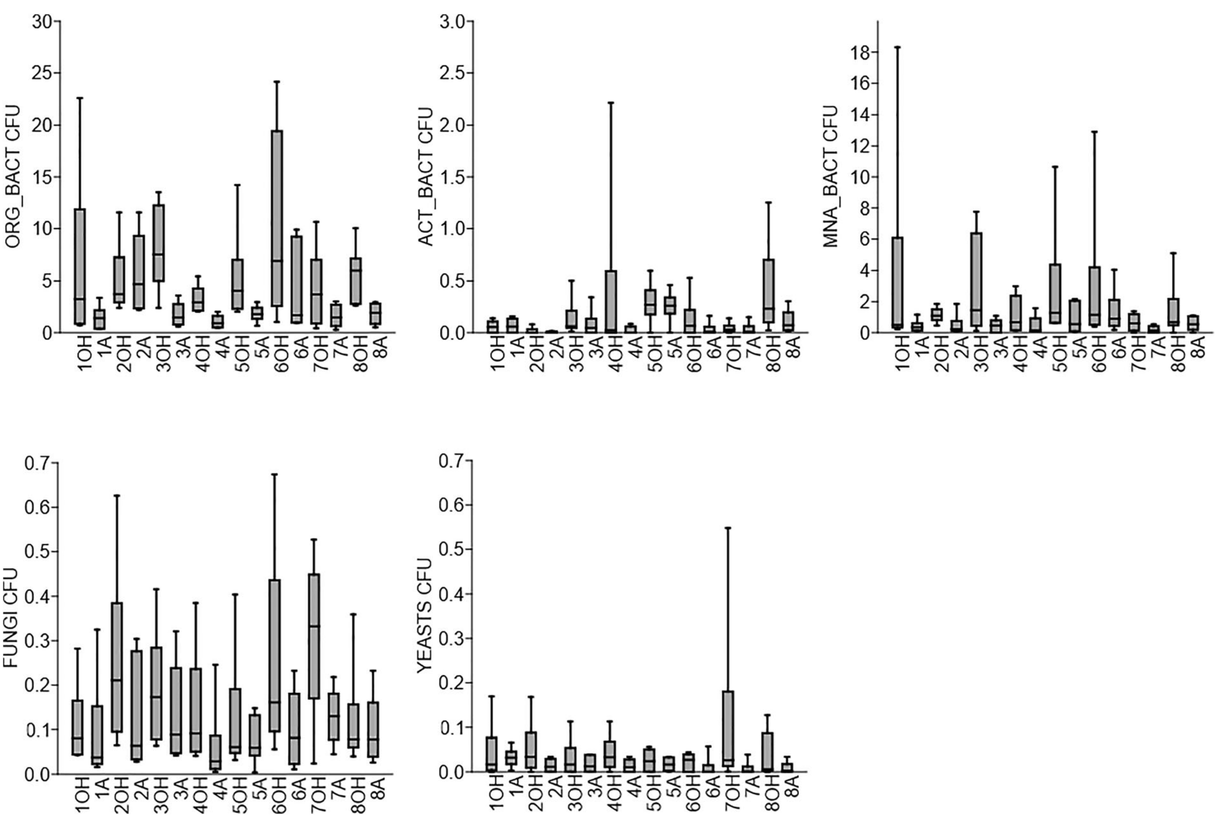

Fig. 7 Abundance of microorganisms (organotrophic bacteria, ORG_BACT; *Actinobacteria*, ACT_BACT; mineral nitrogen–assimilating bacteria, MNA_BACT; filamentous fungi, FUNGI and YEASTS) by sampling sites

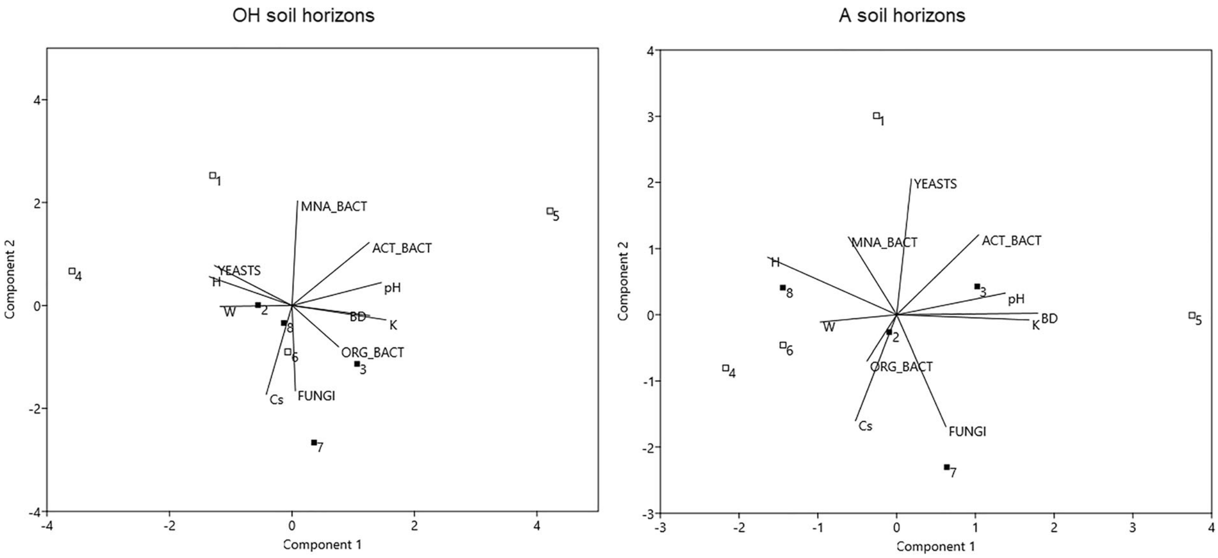

Fig. 8 PCA diagrams for environmental properties and microorganism's abundance in the OH and A horizons. Environmental variables are specific activities of ^{137}Cs (Cs, Bq/kg) and ^{40}K (K, Bq/kg); depth of soil organic horizon (*H*, cm); water content in soil organic horizon (*W*, %); bulk density (BD, g/cm^3); acidity (pH) and abundance of microorganisms in CFU, million colonies per gram of dry soil (ORG_BACT, organotrophic bacteria; ACT_BACT, *Actinobacteria*; MNA_BACT, mineral nitrogen–assimilating bacteria; FUNGI, filamentous fungi and YEASTS). Empty and filled squares point out soils of different ages, < 100 and > 100 years, respectively

reflects the correlation with the axes. The first axis in the OH horizon PCA diagram is relatively strongly and positively related to bulk density (BD) and pH value. The same axis in a negative way overlaps with water content (*W*). These results reflect natural relations between organic matter decomposition rate and water content or pH value. Acidic soil organic horizon is looser, as the decomposition of organic matter is slower in comparison with less acidic substrates. Acidic and low-decomposed material can absorb comparably more water and be unpalatable for fauna (Zanella et al. 2018). As a result, acidic soil organic horizon is usually thicker, that is reflected in the PCA diagram. The abundance of filamentous fungi in the OH horizon grows in the acidic environment, and simultaneously, it is positively correlated with the specific activity of ^{137}Cs. Interrelations between fungi and radionuclides were emphasised by Shukla et al. 2017. Organotrophic bacteria demonstrate the lowest loads with soil properties in comparison with other investigated microorganisms. It is known mineral nitrogen–assimilating bacteria are most abundant in soils with neutral pH (Baldrian 2017). Meanwhile, *Actinobacteria* have a closest correlation with pH, and this was regularity repeated with a lower load for soil horizon A in the PCA. High potassium content (K) is positively correlated with pH and negatively associated with organic soil depth. The interrelations are similar for the soil A horizon, but they are weaker. The PCA diagram for A soil horizon demonstrates weaker coherence between soil properties and microorganism abundance in comparison with the OH soil horizon. Selected environmental properties determine 39% and 43% of variability for the A horizon and for the OH horizon, respectively. Additionally, it was revealed that the increasing age of the forest ecosystem reduces variability of soil physical, chemical and biological properties (Fig. 8).

Conclusions

Our study evidenced that the main radioecological parameters of terrestrial ecosystems located in the Lithuanian part of the 30-km zone of the BelNPP do vary in temporal and areal dimensions and should continually be observed and assessed when BelNPP is under operation.

The ^{14}C and ^{3}H levels in terrestrial plants within the 30-km zone of the BelNPP are approaching the level determined by cosmogenic origin. The ^{14}C specific activity varied from 97.80 ± 1.30 to 102.40 ± 0.79 pMC. The ^{3}H specific activity in the TFWT form varied from 13.2 ± 2.2 to 20.8 ± 2.3 TU, which corresponded to the ^{3}H level in precipitation for this region. ^{14}C and ^{3}H are mobile radionuclides, and their level in the environment can perhaps be traceable during the BelNPP operation, as was similarly evidenced by the operational experience of the INPP and other NPPs.

The ^{137}Cs inventory in the pine forest soils of the Lithuanian part of the BelNPP 30-km zone varied from 930 ± 70 to 1650 ± 430 Bq/m^2. This determined the level of ^{137}Cs activity in terrestrial plants ranging from 1.0 ± 0.5 to 40.5 ± 1.8 Bq/kg dry weight The activity concentrations of $^{239,240}Pu$ in soil and moss samples did not exceed 1 Bq/kg and were mainly due to global fallout after nuclear tests.

PCA analysis supports that microorganism abundance and basic soil properties are the factors related with ^{137}Cs transfer in terrestrial ecosystems.

Sampling of forest soils and plants for ^{137}Cs and microbiota analysis is most effective in summer. The main informative soil horizon revealing with the highest ^{137}Cs specific activity in long-term assessments is OH, but in the case of operative year-to-year assessments, forest plants and upper organic topsoil horizons must be sampled too.

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