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Seasonal variations of radon concentration in soil air in different geological conditions on the example of Estonia

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Radon risk in Estonia is among the highest in Europe, influencing human health in many areas. The measured radon level in soil air differs considerably between spring–summer and autumn–winter periods at the same measuring point. Such variations are an obvious obstacle in interpreting reliably the radon risk level in the soil. To tackle with this problem, a monitoring system was established. Radon (^{222}Rn) concentrations in soil air were investigated in four geologically different sites at three depths during three years every 26–40 days. The results showed that at every site the concentration of radon in soil air depended on the eU (^{238}U) concentration in Quaternary deposits and underlying bedrock, on rock types, as well as on aeration circumstances during measuring, such as temperature, topsoil aeration, precipitation and air pressure. The measured radon level concentration starts to increase in autumn when the topsoil turns wet, air humidity increases and ground begins to freeze. It reached the maximum in late winter, when the ground is most frozen. The radon concentration is at its lowest during the warm and dry summer period when topsoil aeration and radon permeability are at their maximum.

Key words: radon, soil air, seasonality, monitoring, soil types

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INTRODUCTION

Random studies by the Estonian Radiation Protection Centre in collaboration with the Swedish Radiation Protection Institute in 1996–1999 have shown that the average concentration of radon (^{222}Rn) is almost 120 Bq m^{-3} (UNSCEAR, 2000) in indoor air of single-storey dwellings in Estonia. The radon concentration exceeds the permissible limit (200 Bq m^{-3}) in indoor air in 33% of the dwellings and may reach 2,000 Bq m^{-3}, in a few cases even 10,000 Bq m^{-3} (Pahapill et al., 2003). It was found that Estonia is among the top four EU countries with high indoor radon risk.

The Geological Survey of Estonia (EGK) started solving this issue in 2001. The first map of radon risk in Estonia was compiled in 2005, basing on the methodology developed in the Swedish Radiation Protection Centre (Åkerblom, 1994; Clavensjö, Åkerblom, 1994). It was found (Petersell et al., 2005) that almost one third of mainland Estonia has a high (>50 kBq m^{-3}) or very high (>250 kBq m^{-3}) radon risk level (Estonian Centre for Standardisation, 2009). These are regions with

high eU concentration (>3.5–5 mg/kg) in soil or bedrock.

The major radon sources in North Estonia are Lower Ordovician uranium-rich graptolite argillite (Dictyonema shale) and Obolus sandstone (phosphorite). They are exposed along the North Estonian Klint and in the slopes of the buried valleys. Both rock types occur as sub-parallel beds in the lower portion of the Ordovician sequence and dip southwards some 3 m per kilometre. The graptolite argillite bed increases in its thickness from the east to the west, 0.2 m up to 6 m. Its uranium concentration varies, being mainly between 30 and 210 mg/kg (Petersell, 1997). In the Obolus sandstone bed lying under the graptolite argillite, the uranium concentration depends directly on phosphorus concentration in the rock, and varies mainly between 4 and 40 mg/kg (Loog, Petersell, 1990).

Interlayers or lenses of clay and siltstone with higher uranium concentration are found in the Devonian sandstones in southern Estonia. They have the thickness from some centimetres to 3 m. Devonian sandstones are locally enriched with zircon (up to 3 kg/m^3) and monazite. For instance, zircon is the main source of radioactivity in Czech Republic (Mikšova, Barnet, 2002).

Among the crystalline basement rocks, present as fragments and fines in the Quaternary cover, the most important are *rapakivi* and pegmatite granites. These rocks crop out in southern Finland and were transported to Estonia by glaciers. Uranium concentration in *rapakivi* granite varies within 3–10 mg/kg (Koljonen, 1992). Granitoidal material occurs in various concentrations in tills and other Quaternary deposits.

Mapping showed that the radon level in the soil air of Estonia is highly varying. It was found that a noticeable positive correlation existed between the radon concentration in soil air and in indoor air of dwellings. Predictable impact of soil radon concentration on its concentration in indoor air and the Estonian standard (Estonian Centre for Standardisation, 2009) were used for classifying the radon risk areas in the Radon Risk Map of Estonia (Petersell et al. 2005). These classes are the following: low (<10 kBq m^{-3}), normal (10–50 kBq m^{-3}), high (50–250 kBq m^{-3}) and very high (>250 kBq m^{-3}).

It was discovered that reiterate measurements at the same site may give highly different results. Reasons for extensive seasonal variation of radon in soil air have been investigated in Nordic countries by different authors (Åkerblom, 1994; Clavensjö, Åkerblom, 1994; Åkerblom, Mellander, 1997; Winkel et al., 2001; Sundal et al., 2004; Sakoda et al., 2011). These have been comparatively short-term measurements (lasting <1–2 years) and conducted in the areas of low or background level of radon risk. The reasons for variation in the Estonian geological conditions have remained unclear. The need of enlightening the issue emerged when the assessment of radon risk level in soil under buildings was initiated. The origin of radon formed in the soil air of the ground under buildings and assessing the actual radon risk level after erecting a building are of primary importance. Namely, these data determine usefulness and efficiency of measures designed for radon risk mitigation.

The first Estonian radon monitoring site was set up in 2005 for studying the causes of this problem. Additional three study areas were established in 2009 (Jüriado et al., 2010; Jüriado et al., 2011).

MONITORING SITES

The first radon monitoring site in 2005 was set up in a high radon risk area in Tallinn, Kadaka Road 82. Sites added in 2009 were in Suurupi (area of very high radon risk), Kahala and Viljandi (areas of high radon risk).

When choosing monitoring sites (Fig. 1), it was taken into account that the Estonian territory has been affected by repeated glaciations. As a result, the Quaternary deposits are lithologically different from the underlying bedrock, and the eU concentration in these deposits may be drastically different. The Quaternary cover, including the topsoil, is young, only slightly weathered and radium migration in the soil is modest. The soil has been developed in circumstances, when the average monthly temperature is 18.0 °C in June–July and falls to –7.6 °C during January–February. The ground starts freezing intensively in October.

The Tallinn monitoring site

The Tallinn monitoring site is located on the SW slope of the some 2 km wide Harku ancient buried valley. Glacial and glacioaqueous sediments filling the valley are covered by sand and silt of the Litorina Sea, and the latter in turn by a 20–30 cm silty (Table) topsoil layer of man-made origin. The eU

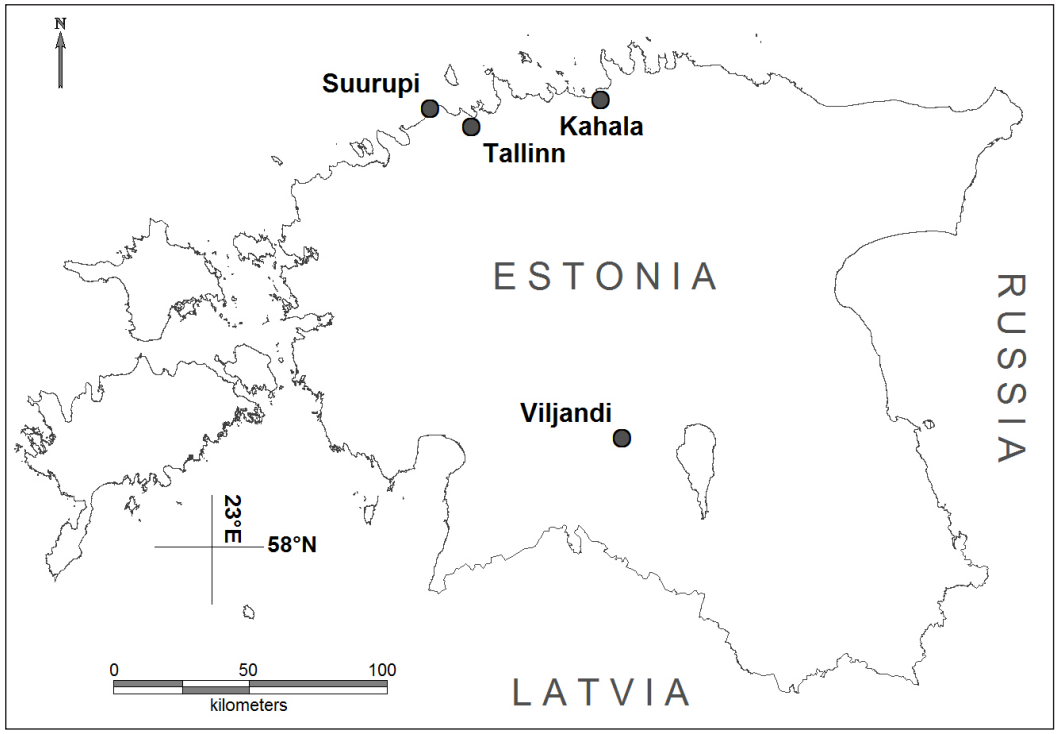

Fig. 1. Location of the monitoring sites
1 pav. Monitoringo vietos

concentration in soil is uniform and higher than the average of Estonian topsoil (2.1 mg/kg, Petersell et al., 2005). The thickness of Quaternary deposits exceeds 30 m. The groundwater level has subsided due to underground pipelines and lies at a depth greater than 3 m below the ground level. Uranium-rich graptolite argillite crops out in the top part of the buried valley, some 400 m to the south-west of the monitoring site. The closest weather observation site of the Estonian Environment Agency in Harku is located about 4 km to the west of the monitoring site. Its observations were used in interpreting the radon measurements.

The Suurupi monitoring site

The Suurupi monitoring site is located within the North Estonian Klint zone, on a ca 150 m wide terrace between escarpments. The bedrock in the terraces is represented by uranium-rich (U 30–120 mg/kg) graptolite argillite with a thickness of 4–4.5 m. Graptolite argillite is covered by 1–3 m of glaciolacustrine clay and silt with clay mineral content increasing with depth. The latter ones contain variable amounts of fines and detritus of graptolite argillite and phosphatic matter, and are rich in eU. The eU concentration increases with depth, up to 17 mg/kg (Table).

The Kahala monitoring site

The Kahala monitoring site is located on the limestone plateau, about 3 km to the south from the North Estonian Klint. The bedrock is covered by pebble rich grey till, which has an overburden of glaciolacustrine sand. The latter is comparably heterogeneous, and rich in carbonate and phosphatic matter, which contain eU up to 8 mg/kg (Table). The thickness of Quaternary deposits exceeds 10 m.

Humus horizon is absent at the monitoring point in an area of some 80 m^2, and topsoil is represented by sand. Approximately 30 m to the west, the same sand is covered by a 20–30 cm thick layer of humus-rich topsoil.

The Viljandi monitoring site

The Viljandi monitoring site was established in the area of Devonian sand- and siltstones, with slightly undulating topography. The Quaternary deposits are represented by reddish-brown till, mainly with the thickness of 2–3 m. The thickness of topsoil is 20–25 cm. The till and overlaying topsoil is comparably clay-rich at the site. Its eU concentration increases with depth and is up to 2.9 mg/kg (Table).

The Suurupi, Kahala and Viljandi monitoring sites are located more than 10 km from weather observation stations and they could not be directly

Table. **The eU concentration in soil and the average radon concentration in soil at the monitoring sites, and chemical composition of the soil**

Lentelė. **eU ir vidutinis radono kiekis dirvožemyje bei cheminė dirvožemio sudėtis monitoringo vietose**

Site	Depth, cm	eU*, mg/kg	Rn*, kBq m^{-3}	Rn/ eU	Oxides, %							
					SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	P_2O_5
Tallinn	30	3.7	48	13.5	88.86	1.61	0.37	0.39	3.22	0.20	0.53	0.62
	55	3.6	72	20.6	94.48	1.46	0.27	0.04	0.92	0.18	0.45	0.09
	80	3.7	96	26.8	83.58	1.86	2.85	0.14	1.31	0.18	0.47	1.84
Suurupi	30	10.7	120	11.2	72.39	5.90	2.79	0.40	3.90	0.30	2.93	3.1
	55	15.0	142	9.7	70.71	7.19	3.55	0.57	4.63	0.46	3.44	3.44
	80	17.0	146	8.6	62.15	9.76	6.65	0.79	2.82	0.27	5.12	2.18
Kahala	30	2.5	10	3.6	57.73	4.18	3.98	2.56	11.01	0.52	1.42	3.35
	55	4.8	14	2.9	87.68	2.76	0.88	0.13	3.47	0.46	0.66	2.44
	80	8.0	16	2.3	79.18	2.37	1.51	0.20	7.62	0.44	0.74	5.49
Viljandi	30	1.3	35	30.8	72.88	7.86	2.14	0.80	2.05	0.95	2.83	0.25
	55	2.5	50	20.4	77.88	9.39	2.67	0.79	1.06	1.12	3.23	0.13
	80	2.9	53	18.6	73.73	10.64	3.71	1.00	1.15	1.11	3.27	0.12

* when establishing the monitoring.

* – vykdant monitoringą.

applied in the monitoring result analysis due to regional and temporal irregularities in precipitation.

STUDY METHODS

When establishing the monitoring sites, eU concentration was measured in soil once at every location with the gamma spectrometer GR 320 (Detector model GPX-21A; Exploranium). This was done at the bottom of an approximately 20 cm wide hole at the depths of 30 cm, 55 cm and 80 cm. As the gamma spectrometer is adjusted for a 2 π configuration (an infinite flat surface), the recorded values required conversion from 4 π to 2 π configuration with a factor of 0.63 for the depths of 55 cm and 80 cm, and 0.75 for the depth of 30 cm. The measuring time was 300 seconds.

The soil samples were taken from the depths of 25–35 cm, 50–60 cm and 75–85 cm and sent to AcmeLabs in Canada for determining the concentration of elements (oxides in Table).

Radon in the soil air was determined with the emanometer Markus-10 (Gammadata, Sweden). At each site the soil air was sucked via a steel pipe into the emanometer. Radon concentration of the sampled air was then analysed by the instrument measuring the decay of radon daughter polonium (^{218}Po) for 15 minutes. To monitor changes in the radon concentration in soil at different depths, three steel pipes were sunk into the ground at the depths of 30 cm, 55 cm and 80 cm in the monitoring sites near the pit, at an average distance of 1 m from each other. Upper ends of the pipes were sealed for measurements with an airtight, removable cap. Tubes were installed in the soil for carrying out repeated measurements with Markus 10. Changes in radon concentration in soil air were monitored at three different depths after 26–40 days of the previous measurement, by conducting one measurement at each of the three depths. At the Tallinn site until 2009 radon concentration in soil air was measured only with one tube at the depth of 80 cm. Atmospheric temperature was measured at midday during each radon measurement. Resulting temperatures are generally higher than average daily temperatures and especially higher than the nightly temperature.

Main data for analysing the behaviour of radon concentration in soil air at the monitoring sites are presented in Table.

RESULTS AND DISCUSSION

The Tallinn monitoring site

The first 2005–2008 years time series of the monitoring site showed that the concentration of radon preserved in soil air at 80 cm depth varied during the summer months in the range of 50–70 kBq m^{-3} and during the winter months 90–110 kBq m^{-3}. Thus, the maximal radon concentration in the

winter period is up to 2.2 times higher than the minimal concentration in summer (Fig. 2).

Comparison between the three-year time series of radon concentrations and weather observations shows a strong negative correlation between the radon concentration and air temperature (Fig. 3). The correlation between the precipitation and radon concentration is absent or is weakly positive (Jüriado, Petersell, 2010). The principal factor behind a periodic change of the radon concentration is temperature.

Precipitation causes irregular variations in the graph shown in Fig. 3, superimposed on the general temperature-dependent trends. It can be observed that an increase in soil air radon starts in autumn when the amount of precipitation and air humidity increases and ground evaporation decreases, in accord with the temperature decrease. Soil starts to wet and freeze when the temperature drops. With less favourable radon emission circumstances in the background, its concentration continues to increase and reaches its maximum during the coldest period, or slightly after, when the upper frozen soil creates a screen and rainwater infiltration is virtually absent. Precipitation falls as snow during that period, and radon emission is obstructed by frozen ground (principally the topsoil). When snow melts and soil thaws in spring, soil aeration and radon emission increase and radon concentration in soil air decreases. Aeration reaches its maximum and radon concentration reaches its minimum during the spring–summer period with little precipitation.

When the Tallinn monitoring site was rearranged in 2009, the measuring pipe at the depth of 80 cm was moved 5 m to the south of the former location. This did not have any effect on radon variation. Time series of the variation are analogical to those at the initial monitoring site but have considerable difference between different depths in regard to the level of radon concentration (Fig. 4). Maximum concentrations were registered at every depth in late winter when snowmelt began. During this period, the concentration of radon in soil air at the depth of 80 cm increased up to 129 kBq m^{-3}, at the depth of 50 cm up to 105 kBq m^{-3}, and at the depth of 30 cm up to 78 kBq m^{-3}, respectively. This occurred despite the observation that eU concentration in soil at these depth levels is similar (Table). Differences in the concentration of radon at different depths persisted also during all the periods of the time series. Relative intensity of aeration from different depth levels

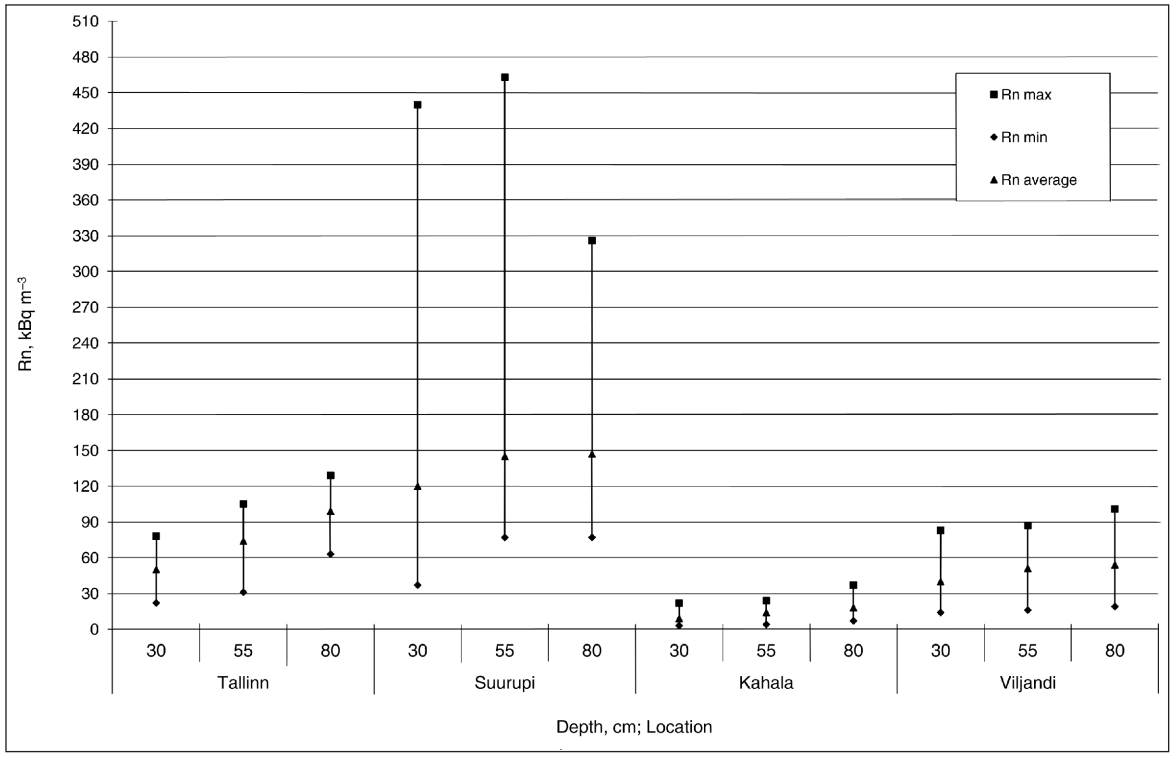

Fig. 2. Radon maximum, minimum and average concentrations for the monitoring sites at depths of 30, 55 and 80 cm

2 pav. Maksimalūs, minimalūs ir vidutiniai radono kiekiai monitoringo vietose 30, 50 ir 80 cm gylyje

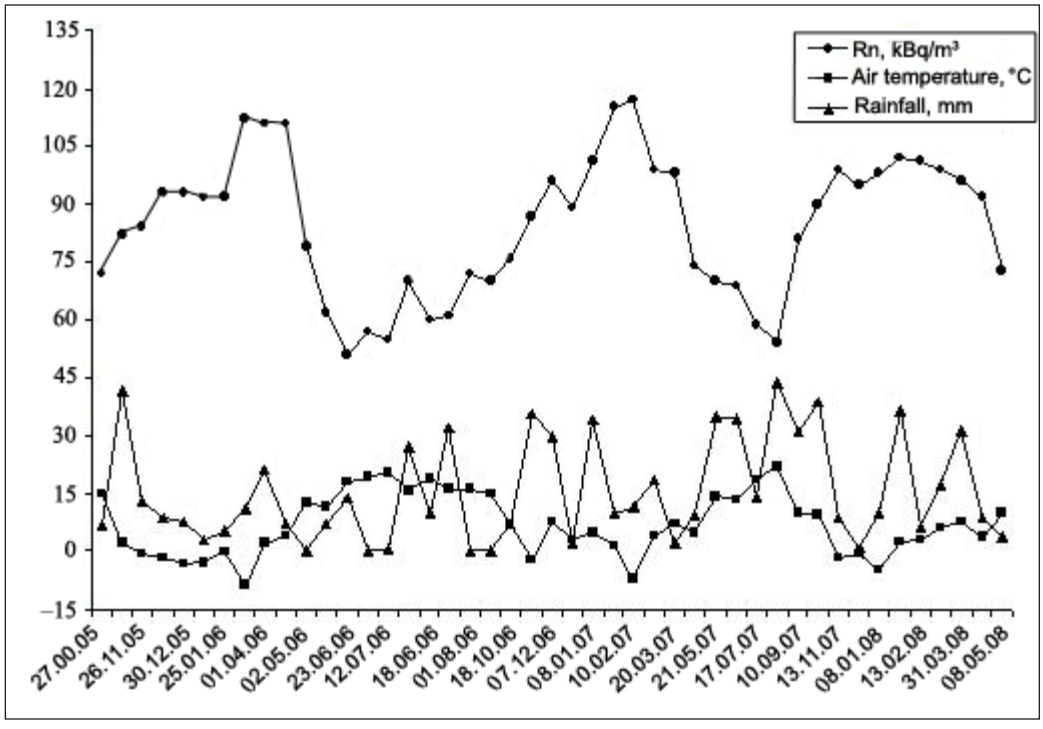

Fig. 3. Measurement results of the 2005–2008 radon concentration time series at the Tallinn monitoring site

3 pav. 2005–2008 metų radono kiekio matavimų laiko eilutės Talino monitoringo vietoje

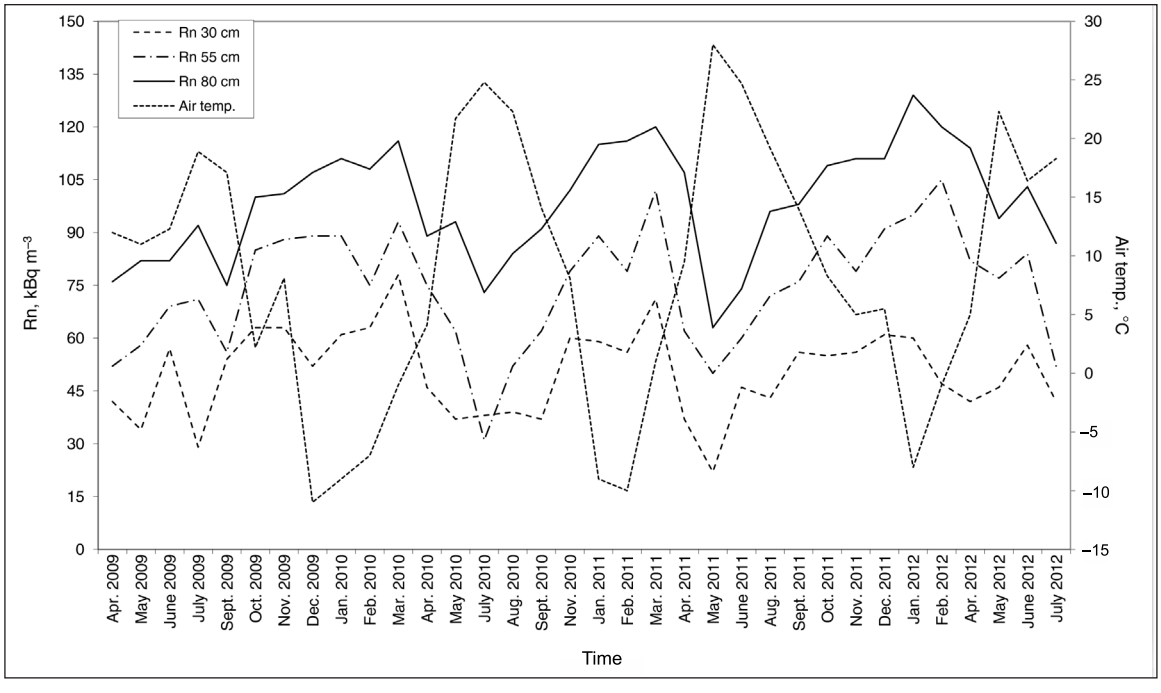

Fig. 4. Time series of changes in the radon concentration in soil air at the Tallinn monitoring site

4 pav. Radono kiekio kaitos dirvos ore laiko eilutės Talino monitoringo vietoje

is quite stable. Therefore it can be assumed that aeration does not cease even in winter when conditions for it are least favourable.

The relationship between the average radon concentration in soil air and the eU concentration in soil is high (>12) (Table) and increases with

depth. This indicates the presence of additional radon emission from a depth greater than 80 cm. For controlling this issue, the eU concentration was measured in a hole at the depth of 1.8 m. The soil becomes rich in graptolite argillite fines at this depth and the eU concentration rises at the levels of 8–9 mg/kg.

The Suurupi monitoring site

The site is located in an area of very high radon risk. Comparably clay-rich soil at the site contains variable amounts of detritus and fines of graptolite argillite and phosphorite. Soil is rich in eU, the concentration of which increases with depth from 10.7 to 17 mg/kg (Table). Radon emission from soil is intensive and variable (Fig. 5).

Characteristically, concentrations of radon in soil air here are almost similar at three different depth levels. But in comparison with the Tallinn monitoring site, the relationship between the summer minimum and winter maximum is considerably higher, up to 4.2 at 80 cm depth, and even higher at greater depth (Fig. 2). Despite the fact that eU concentrations in soil increase with depth (Table), concentrations of radon were higher at levels closer to the surface. For instance, in April 2010 it was 463 kBq m^{-3} at 55 cm depth. This was essentially higher than the radon concentration in soil air at 80 cm depth at the same time. The ground was covered by a few centimetre high ice layer at the time of high concentration. This blocked soil aeration and brought the radon emission into minimum. As the ground was frozen and measurement of radon in soil air with Markus 10 unhampered, it was not possible that additional moisture would have been entered the soil. It is likely that additional radon was coming from graptolite argillite at a few metres depth, having the maximal eU concentration above the limit of 80 mg/kg.

The soil air radon concentration decreased at all depth levels in December 2011 and was only 90 kBq m^{-3}. The reason for this situation was an anomalous temperature rise in the atmosphere when the ground surface thawed, causing soil aeration and radon emission circumstances similar to the summer period.

The Kahala monitoring site

At the Kahala monitoring site the humus horizon is absent and top- and subsoil are represented by quartz-carbonate sand. In addition, there is uranium-rich phosphatic matter, and, as a result, the P_2O_5 concentration in soil varies in 2.44–5.49%.

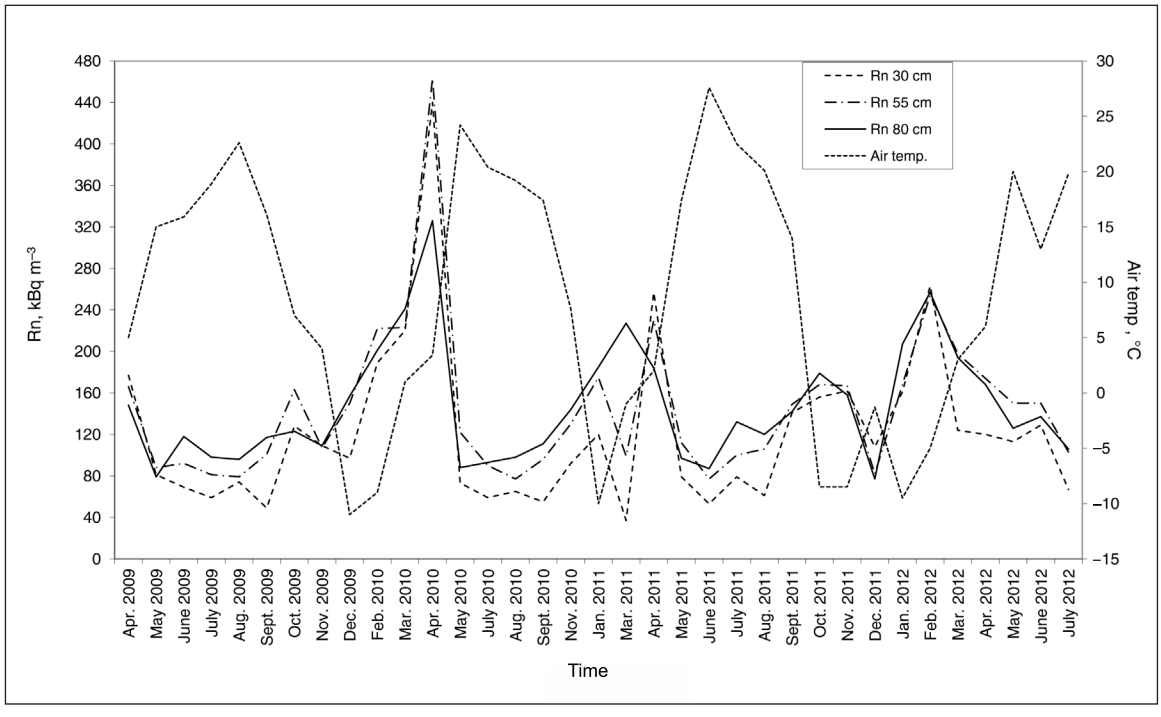

Fig. 5. Time series of changes in the radon concentration in soil air at the Suurupi monitoring site
5 pav. Radono kiekio kaitos dirvos ore laiko eilutės Suurupi monitoringo vietoje

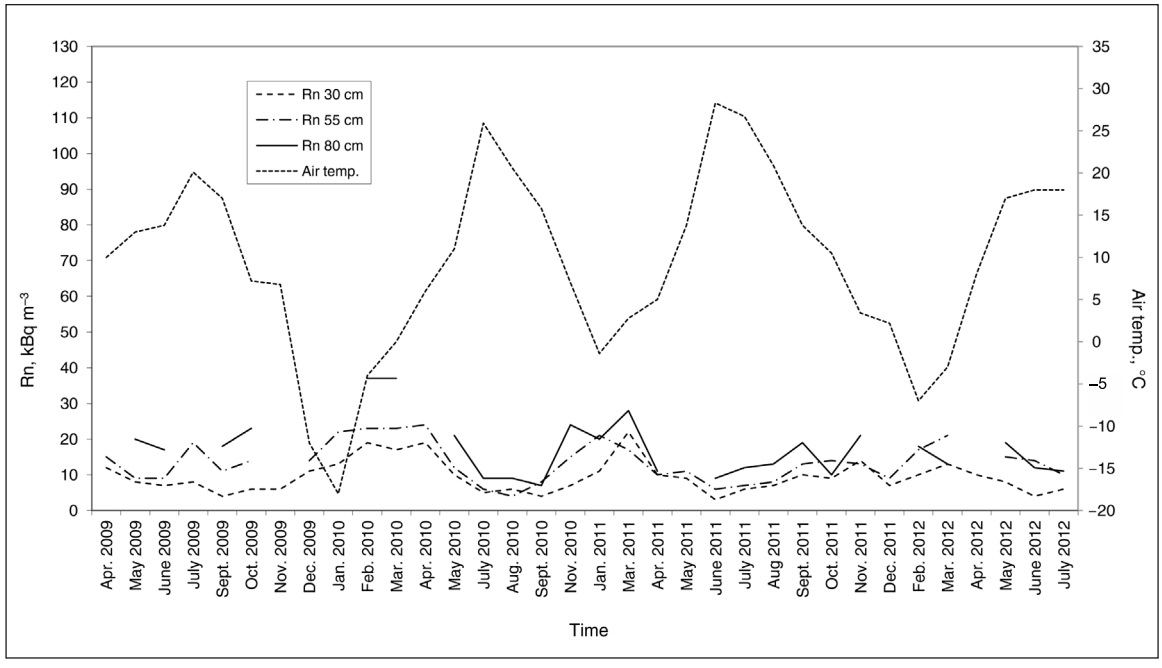

Fig. 6. Time series of changes in the radon concentration in soil air of the Kahala monitoring site
6 pav. Radono kiekio kaitos dirvos ore laiko eilutės Kahala monitoringo vietoje

The eU concentration is high and increases with depth from 2.5 up to 8 mg/kg (Table). Observations of radon concentration changes in soil air at three different depths were sometimes hindered by high groundwater level (up to 50 cm from surface; Fig. 6). Despite this they show higher values at deeper levels almost all year round. It is notable that although the concentration of radon in soil air increased during the cold winter period, it was still much smaller than the eU concentration would indicate (Table). The relationship between the radon and eU concentration is also very low,

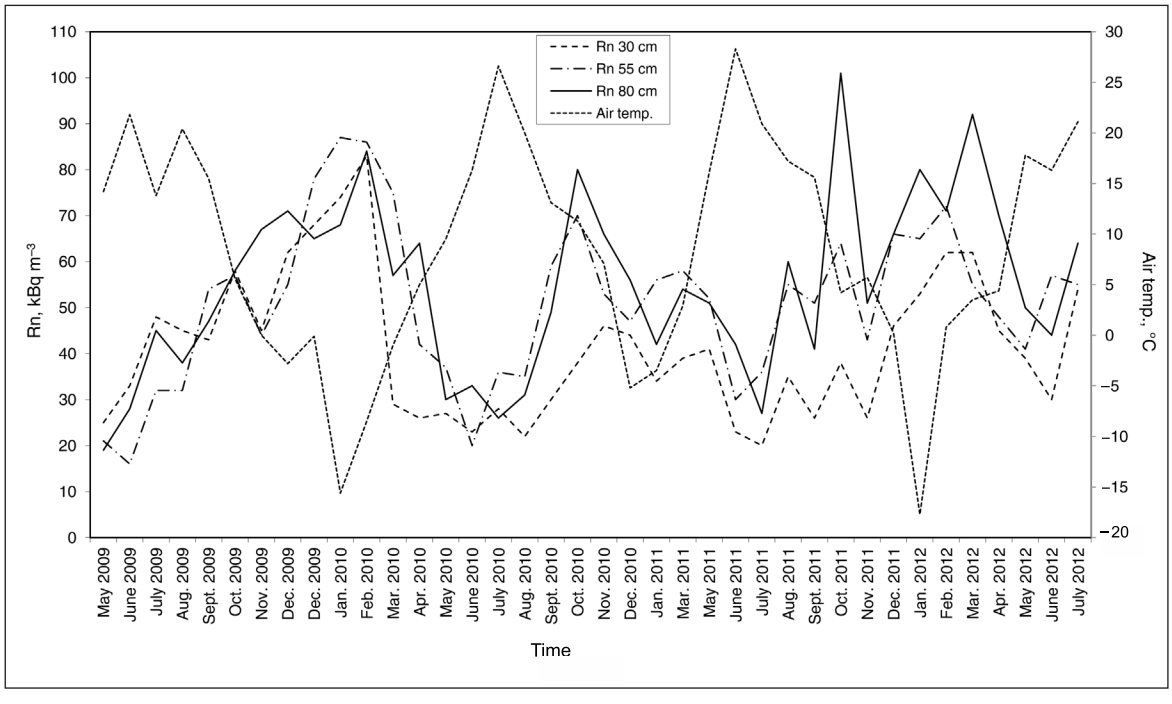

Fig. 7. Time series of changes in the radon concentration in soil air at the Viljandi monitoring site
7 pav. Radono kiekio kaitos dirvos ore laiko eilutės Viljandi monitoringo vietoje

only 2.3 at 80 cm depth (Fig. 6). This indicates the year-round intense emission of radon in soil.

The sand cover with the mineral composition typical for the monitoring site is wide in the area. The eU concentration at 80 cm depth in this sand is similar to the concentration at the monitoring site and varies in 8–10 mg/kg. The sand is covered by humus-rich topsoil. In another measuring point 40–60 m to the west the radon concentration is 85–130 kBq m^{-3} during the autumn period. At the same time it is <34 kBq m^{-3} in the monitoring point. The results from the current monitoring site show that the existence of humus horizon and the intensity of radon emission at different climatic conditions are of critical importance. In this case, for instance, even in winter, frozen wet sand does not considerably hinder emission of radon.

The Viljandi monitoring site

At the Viljandi monitoring site, soil is represented by till with elevated clay and iron content. The concentration of eU in till ranges within the background limits of Estonia (Table; Petersell et al., 2005) but increases in the depth. Temporal variation of the soil air radon concentration at 80 cm depth follows the general trends of the above-mentioned monitoring points (Fig. 7). However, the concentration at lower depths is irregularly variable at the background of the measurements at 80 cm and may be higher or lower. Also the relationship between the winter maximum and the summer minimum is at the level of another monitoring sites. The relationship between radon and eU is high, during the winter time even higher than eU concentration in the soil would indicate. It is likely that additional radon is entering from greater depths.

Comparison of the four monitoring sites

The behaviour of radon in soil air is rather uniform at all sites, although they are located in geologically different areas. A major regularity can be observed at every monitoring site. The concentration of radon in soil air starts to increase in autumn when soil aeration and possibilities for radon emission decrease as a result of wetting and freezing of the topsoil, and decreases fast in spring when the aeration capacity and conditions for radon emission are at their best. The results show that the behaviour of radon in the areas of high risk, or the areas of very high risk in particular, is similar to its behaviour in the areas of low or background-level radon risk. The latter areas have been studied by various authors (Åkerblom, 1994; Winkler et al., 2001; Sundal et al., 2004; Szabó et al., 2013).

Variations of the radon concentration during dry spring–summer and wet autumn–winter periods differ considerably between the monitoring sites, and at 80 cm depth it differs between 2.0 to 5.3 times (Fig. 2). This difference increases towards the surface and is likely a result of lithological differences of the topsoil, as well as of meteorological circumstances – this having a larger impact closer to the surface (Figs. 3–7). It is essential to take these into account when the radon risk level is assessed for soil at the locations where buildings are going to be erected.

As mentioned, the principal factor of periodic fluctuation of radon in Estonia is temperature as a cause of ground freezing and regulating wetness. Precipitation causes only irregular variation, the general trends are temperature-dependent. It can be observed that an increase in soil air radon starts in autumn when the amount of precipitation increases and soil evaporation decreases.

Changes in the radon concentration in soil air at three different depths observed at all monitoring sites show that the concentration of radon retained in soil air depends on the lithological profile and eU concentration of the soil and bedrock. It is also dependent on the measuring depth, as shown by Åkerblom (1994). A significant role is played by the nature of the upper organic soil layer (topsoil), and its moisture content and temperature at the time of measurement. The topsoil compacts as a result of temperature decrease, and increase of precipitation and relative humidity. This is accompanied by decrease of aeration and increase of radon measured in the soil air. The process is opposite during the dry period and temperature rise above 0 °C. If there is sandy soil, with a weakly formed or missing humus horizon, soil aeration and radon emission do decrease (the Kahala site) but do not cease altogether (the Tallinn site). In addition, permeability of sandy soil without a humus horizon is very good, and the soil is well-aerated, leading to intense radon emission. This is the reason why the relationship between the average soil air radon concentration and eU is very small (Kahala, Table). As earlier stated, when a proper humus horizon was present, the soil air radon concentration in the same kind of sand was up to

and the relationship between radon and eU was 13. Sandy soil is covered with a moderate humus horizon, and there the eU concentration at 1.8 m depth is almost two times bigger than at 80 cm depth, and the radon and eU concentrations are high.

CONCLUSIONS

Monitoring sites for the following temporal variations of the radon concentration in soil air were located at natural areas of very high (Suurupi) or high (Tallinn, Kahala, Viljandi) radon risk areas. Geological sections and circumstances differed between the monitoring sites, so did the uranium concentration of the sediments (rocks) of the sections. Our radon concentration monitoring shows unequivocally that the radon level in soil air and its behaviour in Estonia are highly variable, depending on the geological construction of the monitoring sites and on the eU concentration in the soil and the bedrock. Also, it depends on the season, temperature, moisture and other meteorological factors that have an effect on soil permeability, particularly in topsoil. As these conditions change endlessly, the radon concentration in soil air vary as well, even though formation of radon (particularly, mobile radon) from radium in the soil would be stable.

However, it is necessary to consider two issues:

1) If the humus horizon at the site is frozen, it is only possible to assess radon risk basing on radon concentration. It is not possible to specify if radon originates from the ground underlying buildings or from the layers at deeper depths.

2) In the spring–summer dry periods, aeration of soils is excellent. Consequently, also the obtained radon values are essentially smaller in conditions that are unfavourable (next to blocking it) for aeration and radon emission, and do not adequately characterise the actual extent of radon inflow from deeper layers.

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RADONO KIEKIO SEZONINĖ KAITA DIRVOS ORE ESANT SKIRTINGOMS GEOLOGINĖMS SĄLYGOMS: ESTIJOS PAVYZDYS

S a n t r a u k a

Radono pavojus žmogaus sveikatai Estijoje – vienas didžiausių Europoje. Išmatuoti radono kiekiai dirvožemio ore tose pačiose monitoringo vietose ženkliai skiriasi priklausomai nuo sezono (pavasaris–vasara; ruduo–žiema). Tokie radono kiekių kaitos skirtumai dirvožemyje apsunkina šių dujų pavojaus sveikatai vertinimą. Problemai spręsti sukurta monitoringo sistema. Radono (^{222}Rn) kiekiai buvo nustatinėjami geologiniu požiūriu skirtingų dirvožemių ore, įvairiuose gyliuose, trejus metus iš eilės (kas 26–40 d.). Gauti rezultatai rodo, kad kiekvienoje monitoringo vietoje radono kiekiai priklauso nuo eU (^{238}U) kiekio kvartero nuosėdose, taip pat nuo sąlygų, kuriomis buvo matuojami, t. y. temperatūros, viršutinio dirvožemio sluoksnio aeracijos, kritulių ir atmosferos slėgio. Paaiškėjo, kad radono kiekis išauga rudenį, kai padidėja dirvožemio drėgmė. Didžiausi jo kiekiai aptikti žiemos pabaigoje, kai dirvožemis būna beveik įšalęs; mažiausi – nustatyti šiltų ir sausų vasarų laikotarpiu, kai viršutinis dirvožemio sluoksnis gerai aeruojamas, o jo skvarbumas didžiausias.

Raktažodžiai: radonas, dirvos oras, sezoniškumas, monitoringas, dirvožemio tipai