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Swedish Radiation Safety Authority

Research

Analysis of Radon Levels in Swedish Dwellings and Workplaces

2021:28

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Report number: 2021:28
ISSN: 2000-0456
Available at: www.ssm.se

SSM perspective

Background

Exposure to radon is considered the second most important cause of lung cancer next to smoking and is estimated to account for about 500 lung cancer cases per year in Sweden. For this reason, it is important to lower radon concentrations in indoor air, particularly where levels exceed the reference level 200 Bq/m^3.

In order to be able to update calculations on number of lung cancer cases, which are caused by radon, it is necessary to estimate the average radon level in indoor air. It is also essential to estimate how many dwellings and workplaces there are which exceed the reference level 200 Bq/m^3. This study focuses on single-family houses but also includes analysis for some workplaces and multi-family houses. The radon measurement data for single-family houses in the database of the company Radonova consists of about 340 000 measurements.

In the database, there are more measurements in areas with well-known radon problems and in houses which include the radioactive building material blue concrete. However, in the analysis it is possible to compensate for a number of such background factors to reduce bias. This enables estimation of a national average for the radon level in dwellings, which should resemble results based on a representative sample.

In order to be able to prioritize supervision of both dwellings and workplaces it is important to understand which background factors are associated with radon levels exceeding the reference level. Suggested factors for such analysis include building year, ventilation type, building material (blue concrete), region, uranium level in the ground and type of soil.

Results

Based on the analysis of a large amount of measurements the national average of radon concentration in single-family houses was estimated. For the measurement season 2007/2008 it was assessed to 128 Bq/m^3 and for 2008/2009 to 136 Bq/m^3. These two time periods were believed to provide the most reliable results since offers for measurements were distributed widely to house-owners during those years. The results in the study for average radon level in Swedish single-family houses are in good agreement with a previous national survey within the so-called BETSI project. That project reported a national average of 124 Bq/m^3 for the corresponding time period and type of dwelling.

It was also estimated that about 19% of single family houses during the time period 2007-2009, corresponding to 370 000 units, have radon levels above the reference level 200 Bq/m^3. This number is considerably higher than in some other studies (BETSI and ELIB studies). For radiation protection purposes the number of houses exceeding 200 Bq/m^3 is important since it shows how many single-family houses there are that need to lower radon concentrations. Based on the result 370 000 and analysis of number of mitigated houses and new houses since 2008, it was estimated that in 2021 there are about 330 000 single-family houses with radon levels exceeding 200 Bq/m³. This corresponds to 16% of the number of single-family houses in 2021.

In the study there are also some results for workplaces, but since these are based on long-term average measurements around the clock, these results are usually not representative for working hours. This is because ventilation often is reduced during non-working hours causing increased radon levels during those times. Thus radon levels during working-hours can be substantially lower than the levels reported in this study.

In this study, it was shown that single family houses built in more recent years have substantially lower radon levels than in older houses. The same clear pattern of decreasing radon levels in newer buildings was however not observed for workplaces.

The radon concentration in single-family houses was highly correlated to the uranium level in the ground based on a limited subset of the database. In the corresponding analysis for workplaces some correlation was also observed but less pronounced.

Relevance

New regulations regarding radon in workplaces was implemented 2018 in response to the revised European Basic Safety Standards (BSS). Since then the Swedish Radiation Safety Authority has a new responsibility to perform supervision of workplaces regarding radon. In order to prioritize efforts for supervision it is important to know which background factors are most important for risk of elevated radon concentrations in buildings. The analysis in this research project includes quantitative estimation of a number of such potential risk factors.

For the purpose of risk assessment for lung cancer in the population due to radon exposure it is necessary to determine the national average radon concentration in indoor air. In this study this average is estimated for single-family houses. Thus additional analysis of studies in other indoor environments is necessary to determine a comprehensive assessment of the national average radon level.

The number of single family houses with radon levels exceeding the reference limit 200 Bq/m³ is of great interest as an indicator of the size of the radon problem in Sweden. The corresponding assessment for workplaces is also important, but this study is based on long-term measurements around the clock, which often results in overestimation of radon levels during working-hours.

Need for further research

It would be worthwhile to initiate a new study to assess the current national average of radon level and fraction of buildings exceeding the reference level 200 Bq/m³. This kind of study should be based on selecting a representative sample of dwellings and workplaces.

In the large dataset of measurement results from Radonova it was indeed possible to estimate a national average. However, despite efforts to control for factors that bias results to resemble a representative selection, it is difficult to rule out some remaining bias. This is particularly valid for recent measurement years but presumably also for possible future studies.

For workplaces, it would be very useful to add follow up measurements to determine radon levels during working hours to complement current results based on long-term measurements. This is because long-term measurements around the clock in workplaces often overestimate the radon levels during working hours.

It would also be of interest to study the long-term sustainability of measures to reduce radon concentrations in buildings. Furthermore, studies to provide additional scientific background for current recommendations regarding methods to measure radon in both dwellings and workplaces would be valuable.

Project information

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Reference: SSM2020-5864 / 7030350-00

SSM perspektiv

Bakgrund

Exponering för radon anses vara den viktigaste orsaken till lungcancer näst efter rökning och beräknas orsaka omkring 500 lungcancerfall årligen i Sverige. Därför är det viktigt att sänka radonhalten i inomhusluften, speciellt om nivån överstiger referensnivån 200 Bq/m³.

För att kunna uppdatera beräkningar av antal lungcancerfall som årligen orsakas av radon är det nödvändigt att uppskatta medelhalten av radon i inomhusluften. Det är också viktigt att uppskatta hur många bostäder och arbetsplatser som har radonhalter överstigande referensnivån 200 Bq/m³. Den här studien fokuserar på småhus, men inkluderar också analyser för en del arbetsplatser och flerfamiljshus. Mätdata för radon i småhus i mätföretaget Radonovas databas består av omkring 340 000 mätningar.

I databasen finns det fler mätresultat i områden med välkända problem med förhöjda radonhalter och i hus som innehåller blåbetong. Det är emellertid möjligt att kompensera för ett antal olika sådana bakgrundsfaktorer för att därigenom reducera snedvridande inverkan av dessa på resultaten. Detta möjliggör att beräkna ett nationellt medelvärde för radonhalten i småhus som bör efterlikna en studie med ett slumpvist urval av småhus.

För att kunna prioritera tillsynsinsatser för både bostäder och arbetsplatser så är det viktigt att känna till vilken effekt olika bakgrundsfaktorer har på risken för förhöjda radonhalter. Föreslagna faktorer för analys inkluderar byggnadsår, ventilationstyp, byggnadsmaterial (blåbetong), region, uranhalt i marken och jordart.

Resultat

Baserat på analys av en stor mängd data uppskattades det nationella medelvärdet för radonhalten i småhus. För mätsäsongen 2007/2008 uppskattades det till 128 Bq/m³ och för 2008/2009 till 136 Bq/m³. Dessa två mätsäsonger ansågs ge mest tillförlitliga resultat eftersom erbjudande om mätningar då skickades ut i stor omfattning till husägare. Resultaten för nationellt medelvärde av radonhalt i småhus stämmer väl överens med en tidigare stickprovsundersökning inom BETSI-projektet, som rapporterade 124 Bq/m³ för motsvarande tidsperiod.

I studien uppskattades också att omkring 19 % av småhus under tidsperioden 2007-2009, motsvarande 370 000 stycken, beräknades ha radonhalter över referensnivån 200 Bq/m³. Det här antalet är avsevärt större än resultaten i några andra studier (BETSI och ELIB). Antalet småhus med radonhalt som överstiger referensnivån är viktigt ur strålskyddssynpunkt, eftersom det visar hur många hus som bör sänka radonhalten. Baserat på resultatet 370 000 och analys av antalet radonsanerade hus och nytillkomna hus sedan 2008, uppskattades att antal småhus 2021 med radonhalt överstigande 200 Bq/m³ är omkring 330 000. Detta motsvarar omkring 16 % av antalet småhus 2021.

I denna studie finns det även en del resultat för arbetsplatser, men eftersom dessa baseras på medelvärde för långtidsmätningar dygnet runt, så är resultaten ofta inte representativa för radonnivåer under arbetstider. Detta beror på att ventilationen ofta reduceras eller stängs av utanför arbetstid vilket då leder till ökande radonhalter. Därför kan radonhalter under arbetstider vara avsevärt lägre än vad som rapporteras i denna studie.

I denna studie visades att småhus byggda under senare år har avsevärt lägre radonhalter än i äldre hus. Samma tydliga tendens av minskande radonhalter i nyare hus observerades inte för arbetsplatser.

Radonhalten i småhus var tydligt korrelerad till uranhalten i marken baserat på analys av en mer begränsad mängd mätningar. Motsvarande analys för arbetsplatser visade också viss korrelation men inte lika uttalat.

Relevans

Nytt regelverk för radon på arbetsplatser infördes 2018 mot bakgrund av EU:s reviderade Basic Safety Standards (BSS). Sedan dess har Strålsäkerhetsmyndigheten ett nytt ansvar att utöva tillsyn för radon på arbetsplatser. För att underlätta prioritering av tillsynsinsatser är det viktigt att känna till vilka bakgrundsfaktorer som är viktigast som markörer för risk för förhöjda radonhalter i byggnader. Analyser i detta forskningsprojekt inkluderar kvantitativa bestämningar av sådana potentiella riskfaktorer.

För att kunna uppdatera beräkningar av antal lungcancerfall som årligen orsakas av radon är det nödvändigt att uppskatta medelhalten av radon i inomhusluften. Eftersom det nationella medelvärdet i denna studie enbart avser småhus krävs det ytterligare analyser och studier av andra inomhusmiljöer för att få en mer heltäckande uppskattning av ett nationellt medelvärde.

Antalet småhus med radonhalt som överstiger referensnivån 200 Bq/m^3 är av stort intresse, eftersom det är en indikator på omfattningen av radonproblemet i Sverige. Även motsvarande resultat för arbetsplatser är viktigt, men denna studie baseras på långtidsmätningar dygnet runt, vilket oftast resulterar i en överskattning av radonhalter under arbetstid.

Behov av vidare forskning

Det vore värdefullt att initiera en ny studie för att bestämma det nationella medelvärdet för radonhalten i byggnader och även andel byggnader med radonhalt som överstiger referensnivån 200 Bq/m^3. En sådan studie bör baseras på ett representativt urval av bostäder och arbetsplatser.

I den omfattande mängden av radonmätningar i Radonovas databas var det möjligt att utvärdera ett nationellt medelvärde för småhus. Det är dock svårt att helt utesluta någon snedvridning av resultaten trots kompensation för olika bakgrundsfaktorer för att efterlikna ett representativt urval. Detta gäller framförallt för mätningar under senare år, men förmodligen även för eventuella nya analyser under kommande år.

För arbetsplatser vore det värdefullt att addera uppföljningsmätningar som komplement till långtidsmätningar för att utvärdera radonhalten under arbetstid. Långtidsmätningar dygnet runt på arbetsplatser överskattar ofta radonhalter under arbetstid.

Det vore också av intresse att studera hållbarhet över tid av åtgärder för att sänka radonhalter. Dessutom vore det värdefullt med studier som analyserar vetenskapligt stöd för rådande rekommendationer i metodbeskrivningar för radonmätning i såväl bostäder som på arbetsplatser.

Projektinformation
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Date: December 2021
Report number: 2021:28 **ISSN:** 2000-0456
Available at www.stralsakerhetsmyndigheten.se

Summary

In the present radon database of Radonova, there are more than 340’000 long-term average measurements in Swedish single-family houses and more than 440’000 measurements in multi-family houses. The main part (55 %) of the measurements in single-family houses were performed during 2005-2010 and the largest part (43 %) of measurements in multi-family houses were performed during 2015-2020.

The data from the single-family houses were compared with the previous national surveys BETSI 2007-2009 and ELIB 1991-1992. The estimated national average values obtained in this study is 128 Bq/m^3 for the measurement season 2007/2008 and 136 Bq/m^3 for the measurement season 2008/2009, which are in very good agreement with the value of 124 Bq/m^3 obtained in the BETSI survey. The estimate of 370’000 (280’000 – 440’000) houses with radon levels above 200 Bq/m^3 in this study is higher than both the ELIB and BETSI studies but closer in agreement with the estimates 300’000 (280’000-320’000) in the old ELIB survey compared with the BETSI survey which estimated 250’000 (125’000-375’000). Using the estimated number of 370’000 for 2007-2009 together with an estimated number of successfully mitigated houses since 2008 and an estimated number of new-built houses above the reference level, 330’000 single-family houses above 200 Bq/m^3 is estimated for the year of 2021. This corresponds to 16 % of the number of single-family houses in 2021.

Radon data from more than 3000 workplaces with 5 or more measurement points each were also investigated and compared with data from about 5500 multi-family houses. Under-ground workplace types have significantly higher radon levels compared to other workplaces. Older (built before 1900) workplace buildings as well as buildings with natural ventilation also have significantly higher values. Radon levels above the reference level of 200 Bq/m^3 can be found in any type of workplace and on any floor level. For all types of workplaces, 19 % or more of the workplaces had average radon values from long-term measurements above 200 Bq/m^3. The radon levels in basements are in average about 2.5 times higher than on the higher floors in the building. The large decrease in radon levels for new-built buildings observed for single-family and multi-family houses could not be observed for workplaces. Since most workplaces have a time-controlled ventilation, radon levels are usually much lower during working hours. A future study of radon levels in workplaces during working hours would be interesting.

The correlations between radon levels and Uranium (U) concentration in the soil were also studied as well as correlations with different soil types. The radon levels in single-family houses are significantly higher in areas with high U-concentration in the soil. It should be noted that in all areas, most of the houses are well below the reference level and that very high radon levels can be found in all areas. The correlations between indoor radon concentrations and U concentrations were smaller for workplaces and multi-family houses.

From the analysis of measured radon levels in about 7000 single-family houses in the municipalities of Uppsala and Östhammar, the highest radon levels were found in clay soil types. Sometimes, clay soil types are regarded as “lower radon risk” areas due to an expected lower permeability. The data from this study contradicts such assumptions.

Sammanfattning

I Radonovas radondatabas finns resultat från mer än 340’000 årsmedelvärdesmätningar i enfamiljshus och från mer än 440’000 mätningar i flerfamiljshus. De flesta (55 %) av mätningarna i enfamiljshus gjordes under tidsperioden 2005–2010 medan den största delen (43 %) av mätningarna i flerfamiljshus gjordes under tiden 2015–2020.

Radondata från mätningarna i enfamiljshus jämfördes med de tidigare nationella kartläggningarna BETSI 2007–2009 och ELIB 1991–1992. Det uppskattade nationella genomsnittsvärdet i denna studie är 128 Bq/m^3 för mätsäsongen 2007/2008 och 136 Bq/m^3 för mätsäsongen 2008/2009, vilket stämmer väl överens med uppskattningen på 124 Bq/m^3 i BETSI-undersökningen. Uppskattningen på 370’000 (280’000 – 440’000) hus med radonhalter över 200 Bq/m^3 i denna studie är högre än i både ELIB och BETSI undersökningarna men stämmer bättre överens med uppskattningen på 300’000 (280’000-320’000) i ELIB jämfört med BETSI uppskattningen på 250’000 (125’000–375’000). Det uppskattade antalet av 370’000 för 2007-2009 tillsammans med ett uppskattat antal lyckade radonåtgärdade hus efter 2008 samt ett uppskattat antal nybyggda hus över referensnivån, ger en uppskattning för år 2021 på 330’000 enfamiljshus över 200 Bq/m^3. Detta motsvarar 16 % av antalet enfamiljshus 2021.

Mätdata från mer än 3000 arbetsplatser som mätt i 5 eller fler mätpunkter jämfördes med data från cirka 5500 flerfamiljshus. Arbetsplatser under jord har signifikant högre radonhalter än andra arbetsplatser. Gamla (byggda före 1900) arbetsplatsbyggnader och arbetsplatser med självdragsventilation har också signifikant högre radonhalter. Radonhalter över referensnivån på 200 Bq/m^3 kan dock påträffas i alla typer av arbetsplatser och på alla olika våningsplan. Bland alla arbetsplatstyper hade 19 % eller fler genomsnittliga halter från långtidsmätningar över 200 Bq/m^3. Radonhalterna i källarplanet var i allmänhet cirka 2,5 gånger högre än på högre våningsplan i byggnaden. Den stora nedgången i radonhalter för nybyggda bostadshus kunde inte observeras för arbetsplatser. Man kan räkna med att arbetsplatser har betydligt lägre radonhalter under arbetstid eftersom de oftast har en tidsstyrd ventilation. En framtida studie rörande radonhalter på arbetsplatser under arbetstid vore därför värdefull.

Sambandet mellan radonhalter inomhus och uran (U) koncentrationen i marken studerades samt även sambanden med olika jordartstyper. Radonhalterna i enfamiljshus var signifikant högre i områden med högre U-koncentrationer. Det ska dock noteras att i samtliga områden så har de flesta husen halter under referensnivån men att man också i samtliga områden hittar hus med radonhalter högt över referensnivån på 200 Bq/m^3. Sambandet mellan radonhalter inomhus och U-koncentration i marken var mindre för arbetsplatser och flerfamiljshus.

Från ca 7000 mätningar i enfamiljshus i Uppsala och Östhammar studerades sambandet mellan radonhalt inomhus med olika jordartstyper. Ibland betraktas lera som ”lågriskmark” på grund av förväntad lägre luftgenomsläpplighet. Data från denna studie motsäger sådana antaganden.

Content

1. Background and objectives

In the present radon database of Radonova, there are more than 340’000 long-term average measurements in Swedish single-family houses and more than 440’000 measurements in multi-family houses. These measurements are performed during the heating season October 1- April 30 and can therefore risk to overestimate a “true” annual average radon concentration. This is because indoor radon concentrations typically are higher during the heating season. The first measurements in the database are from 2004. The total number of measurements in the database correspond to about 16 % of all Swedish single-family houses and 17 % of all apartments in multi-family houses in the year 2020 [5]. Since the measurement protocol [1] for multi-family houses require measurements in 20 % of the apartments without ground contact (all apartments with ground contact should be measured), it can be concluded that the data from multi-family houses covers a large fraction of all multi-family houses in Sweden. For the multi-family data in Table 21, 25 % of the measured apartments had ground contact. The database also includes measurements from remeasured houses, so the actual number of unique measured dwellings are lower than the numbers given above.

The main part, 55 % of the measurements in single-family houses, were performed during 2005-2010 which can be compared with 19 % for measurements during 2015-2020. This difference can be explained through large radon information campaigns from authorities around 2005. On the other hand, the largest part, 43 % of measurements in multi-family houses were performed during 2015-2020 which can be compared with 26 % during 2005-2010. This latter increase can be explained with increased requirements from municipality authorities on multi-family house owners during recent years. The last Swedish national radon survey was performed within the BETSI [2] project 2007-2009 which was conducted by the Swedish National Board of Housing, Building and Planning.

An important purpose of this project is to improve the knowledge of the radon situation in Swedish dwellings. This knowledge should give valuable input for improving strategies to the work with reducing the radon exposure of the Swedish population and thereby decreasing the number of radon-induced lung cancer cases. In the project, the national average radon concentration in single family houses is evaluated. In addition, various factors of importance for radon levels in dwellings will be analysed. These factors include building year, region, measurement year, impact of so-called blue concrete, uranium level in the ground and type of soil. In addition to single-family houses some analysis will also be included for multi-family houses.

Some parts of the project will be performed as pilot studies based on available radon data and will also give suggestions of possible future studies.
Measurements in workplaces have increased during the last years, partly due to new regulations concerning radon in workplaces [3,4]. The data from these measurements will also be evaluated.

2. Radon concentrations in Swedish single-family houses

The Radonova radon data could be skewed since more measurements most likely have been performed where radon problems are well known and thus anticipated. This could be the case in municipalities with substantial and well-known radon problems or in houses built with the light-weight concrete building material which is based on alum shale “Blue concrete”. Newly built houses are also expected to be more frequently measured. For all analysed measurement seasons, data exist for 95 % of the municipalities in Sweden so the possibilities to correct for regional differences as well as differences in measurement frequency depending on building year are quite good. However, corrections for skewed data in a municipality will be difficult if measurements only are performed in a specific area in the municipality which could be an area with known very high radon levels.

Data from the period 2007-2020 is evaluated in this project. During 2007-2010 most measurements in single-family houses were performed through buying addresses from the Swedish Building Register and sending out letters with radon measurement offers to all single-house owners in a municipality. During this period, it is expected that data for different municipalities will be more similar to a representative sample of all the dwellings. However, the winters during 2009/2010 and 2010/2011 were unusually cold, see Figure 1, which could give increased radon levels during the measurements. Therefore, it is expected that the measurement seasons 2007/2008 and 2008/2009 should give the best estimates for the radon concentrations. During these years, the BETSI survey [2] was also performed to which comparisons can be made.

Measurements in single-family houses after 2010 were usually made through larger mitigation companies or direct orders from private persons. It is therefore a higher risk that these measurements are less representative and could be more biased both towards buildings where high levels are expected as well as new-built houses where low levels are expected.

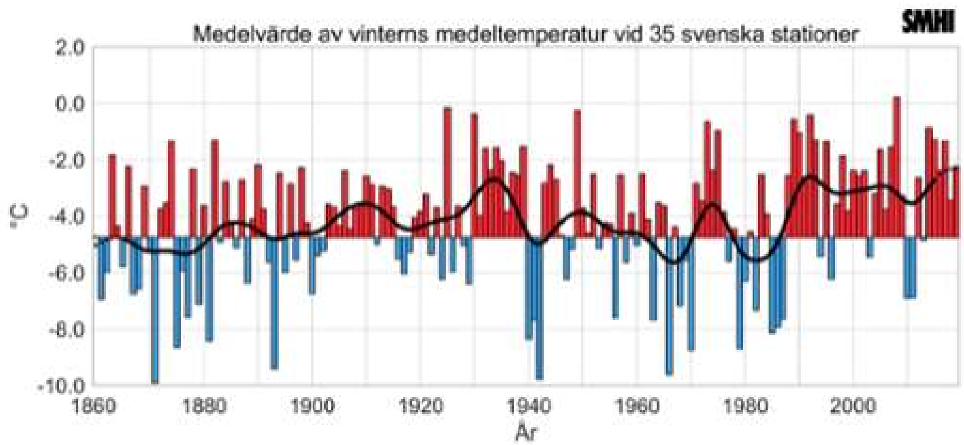

Figure 1, Variation of Swedish winter temperatures.

Method for evaluation & Results

The radon detectors used by Radonova for long-term measurements is the Radtrak[2] detector. Radonova is accredited (ISO 17025) for radon measurements with this detector. Radonova has developed a method to evaluate very high radon exposures so the measurement range for a 3-months measurement is large: 20-25’000 Bq/m^3. The uncertainty for a 3-month measurement is estimated to be 6 % (standard uncertainty k = 1) or 12 % (expanded uncertainty k = 2) for a radon concentration of 200 Bq/m^3. The largest contribution to this uncertainty is the calibration uncertainty. The uncertainty in a calibration chamber is in the order of 7 % (SSM - expanded uncertainty k = 2). Radonova has taken part in more than 140 different radon intercomparison exposures during the last 20 years. The average absolute deviation from the given exposure has been 3.9 %. When “SD” is mentioned in text and tables, it refers to the standard deviation in the data set.

The process to check and correct for skewness in the radon data were performed in several steps using statistical information about Swedish dwellings which are available from Statistics Sweden (SCB). Information about number of houses in a certain region or municipality grouped by building years can be downloaded from their database [5]. That information is needed to check how representative the radon measurements are for the Swedish dwelling stock. To do this evaluation, it must be known in which municipality and region the measurement was performed. This information can be obtained through the postal code of the measurement site.

The minimum measurement time during the heating season is two months although three months is recommended. It is of interest to examine if the results differ much depending on when during the measurement season the measurement was performed. To check that, single-family house measurements in the month of January and April were compared. In the analysis of the 30647 measurements in January 28.2% were above 200 Bq/m^3 and the corresponding analysis of 55531 measurements in April 26.2 % had an average value above 200 Bq/m^3. It can therefore be concluded that differences when the measurements were performed during the heating season will not affect the analysis of the measurement data.

In the skewness correction calculations, the following variables have been used:

- g = region
- y = building year period
- n_g = number of measurements in a region
- n_y = number of measurements in a region for the building period y
- N = total number of Swedish single-family houses
- N_g = the number of single-family houses in a region
- N_B = the number of single-family houses built 1931-1980
- N_{yg} = the number of Swedish single-family houses in region g for the building period y
- n = total number of measurements
- n_B = total number of measurements in houses built 1931-1980
- A_g = average radon concentration in a region
- R_g = region correction, $R_g = (N_g/N)/(n_g/n)$
- Y_g = regional building year correction, $Y_g = (N_{yg}/N_g)/(n_y/n_g)$
- A_r = region corrected national average. $A_r = (1/21)\sum_{g=1}^{21} Ag * Rg$
- A_{ry} = building year corrected national average. $A_{ry} = (1/21)\sum_{g=1}^{21} Ag * Rg * Yg$

- C_Y = correction for non-representative number of measurements for the building year period 1931-1980. $C_Y = (N_B/N)/(n_B/n)$
- R_{Blue} = the average radon concentration in houses when the customer has answered Yes on the question about "Blue Concrete" and the house was built during 1931-1980.
- R_{Not_Blue} = the average radon concentration in houses when the customer has answered No on the question about "Blue Concrete" and the house was built during 1931-1980.
- $R_{Not\_Blue\_All}$ = the average radon concentration in houses when the customer has answered No on the question about "Blue Concrete".
- $R_{Blue\_Unknown}$ = the average radon concentration in houses when the customer has answered Unknown on the question about "Blue Concrete".
- $Frac_{Blue}$ = the fraction of measurements performed in houses in "Blue Concrete" which usually is higher than the fraction of about 6 % in the Swedish building stock.
- C_B = is overestimated radon concentration due to non-representative number of measurements in houses with "Blue Concrete.
  $C_B = C_Y*(R_{Blue} - R_{Not\_Blue}) * (Frac_{Blue}-0.06)$
- R_{Mit} = the average radon concentration in mitigated houses when the customer has not answered Yes on the question about "Blue Concrete".
- R_{Not_Mit} = the average radon concentration in non-mitigated houses when the customer has not answered Yes on the question about "Blue Concrete".
- $Frac_{Mit}$ = the fraction of measurements performed in mitigated houses.
- Mit_{Swe} = estimated fraction of mitigated houses in Sweden.
- C_M is the overestimated radon concentration due to non-representative number of measurements in mitigated houses. $C_M = (R_{Mit} - R_{Not\_Mit}) * (Frac_{Mit} - Mit_{Swe})$.

The evaluation and correction for non-representative measurement distributions (skewness) was performed in several steps:

1) "**Regional level correction**" In some of the 21 Swedish regions, more measurements are performed than in others. The first correction R_g in data is in the number of measurements (n_g) for each region (g) so that number reflects the true distribution in the Swedish building stock. The values in column "Average – region corrected" in Table 2 is calculated by taking the weighted average of the regional average values in Table 7: N_g and N are obtained from the building data of SCB. With this correction a post-stratified estimate for the whole population of Swedish houses can be obtained.

2) **"Building year correction"** Within each region, different building year periods could be more frequently measured than others. Typically, more measurements are made in newly-built houses and houses from the period 1960-1980 (many houses built with "Blue Concrete") and less measurements are made in very old houses and houses which are 10-20 years old. A correction Y_g for this skewness in building year period was made on the regional summarized data so that the building year distribution represented the actual situation in the building stock of each region. Regional building year distributions like the national ones (example in Table 6) were used in this correction. The post-stratified values in the column "Average – building year corrected" in Table 2 and the column "Above 200 Bq/m^3 region and building year corrected" in Table 3 are obtained by correction for the skewness in data due to building year and the regional weighting factors described in point 1 above.

3) **“Municipality correction”** Within a region, municipalities with more radon problems are more likely to measure than municipalities with less problems. To correct for this effect, the weight of each municipality in a region was corrected so that it represented the true relation between number of houses in the municipalities in which measurements were performed. The average values in each municipality were calculated in this process and through the municipality weights, a municipality weighted region average was obtained. Since not all municipalities in a region had measurements, the total number of houses in a region was corrected so that only municipalities with measurements were included. The relative difference between this region average and the original non-corrected regional average was used as a correction factor on the region data in point 2 to obtain the region weighted average in the column “Average – municipality corrected” in Table 2 and “Above 200 Bq/m^3 municipality corrected” in Table 3.

4) **“Outlier correction”** Measurements in some regions during some measurement seasons could give regional averages which differ from most of the other measurement seasons in that region. It is not expected that average concentrations should be much different from one year to another. If the average differs more than two standard deviations from the average of all seasons (2007/2008 – 2019/2020), the average is regarded as an “outlier” and are not used in the analysis. This usually happen in regions with very few measurements and where the measurement might have been done in small areas with known high radon concentrations. If the number of measurements in a region is so low that regional correction R_g would be higher than 10, these data points are also regarded as “outliers”. It should be noted that “outliers” are not incorrect measurements, they are non-representative values for a certain region at some measurement season. The risk if “outliers” are not considered is that non-representative values could get too high weight in the analysis. Instead of the “outlier” value, the average (2007/2008 – 2019/2020) value is used for that region. This correction for “outliers” is the last one on a regional level and the resulting average values are shown in column “Average – outliers removed” in Table 2. The identified outliers were also regarded as outliers when the measurements above 200 Bq/m^3 were estimated. This outlier handling has been done on all type of corrected values shown in Table 3.

5) **“Blue concrete correction”** More measurements are performed in houses containing “Blue Concrete” so the fraction of these measurements (15-20 %) will not be representative for the true number of “Blue Concrete” houses in the Swedish building stock which is estimated to be 6-7 % [2,6] The measurements in houses with “Blue Concrete” have on average higher radon levels than the ones without this building material during the building period in which “Blue Concrete” could be used.

6) **“Mitigated correction”** In most mitigated houses, a follow-up measurement will be performed to check the mitigation. The number of measurements in mitigated houses will not be representative for the total fraction of mitigated houses in Sweden. Although the mitigated houses have got significantly decreased radon levels, they still on average have higher radon levels than an average Swedish house. As a last step in the corrections, the overestimations due to “Blue Concrete” and “Mitigated” measurements were estimated and subtracted. In order not to double count, only “Mitigated” houses without “Blue Concrete” were included in the

corrections for "Mitigated" houses. These corrections are shown in detail in Table 11 where also the separate effect of "Blue Concrete" is shown. As can be seen in Table 1, the correction for the combined effect of blue concrete and mitigation is the largest correction. In particular, it is large for the estimate of measurements above 200 Bq/m^3 which is understandable since radon concentrations often can be around 200 Bq/m^3 in houses with "Blue Concrete" and/or mitigated houses.

Table 1, Average amount of skewness corrections applied in the average radon concentration and number of measurements above 200 Bq/m^3.

Parameter	**Region & Building Year correction**	**Municiplaity correction**	**Outliers' correction**	**Correction for "Blue Concrete" & "Mitigated" measurements**
Average conc.	-1.9 %	-2.4 %	-4.6 %	-8.1 %
Above 200 Bq/m^3	-0.2 %	-3.0 %		-15.6 %

The final estimates of the average Swedish radon concentrations are shown in the Column "Average final" in Table 2 below. The details in the evaluations and regional data are presented in the last parts of this chapter. As discussed in the beginning of this chapter, the results for measurement seasons 2007/2008 and 2008/2009 are expected to get the best representative values for the Swedish average concentrations in the data set for single-family houses. The average for these two seasons is 132 Bq/m^3. For reasons discussed earlier, the estimates from the following measurement seasons have a higher risk to be overestimated due to some possible remaining bias in selection of buildings despite a number of corrections. The average of all measurement seasons is 140 Bq/m^3 with a standard deviation of 8 Bq/m^3. Taking this standard deviation and the measurement calibration uncertainty (5 %, standard uncertainty k = 1) in the uncertainty calculations for 2007/2008 and 2008/2009 would give a national average of 132 ± 20 Bq/m^3 where the uncertainty is given as expanded uncertainty k = 2. All calculated average values are arithmetic mean values.

Table 2, Average radon concentrations (Bq/m^3) in Swedish single-family houses.

Measurement season	**Number of measurements**	**Average - non-corrected**	**Average - region corrected**	**Average - building year corrected**	**Average - municipality corrected**	**Average - outliers removed**	**Average -final**
2007/2008	32556	171	154	149	144	142	**128**
2008/2009	28490	156	146	149	150	149	**136**
2009/2010	22088	175	171	172	181	169	**149**
2010/2011	14802	189	171	166	161	157	**143**
2011/2012	12428	183	164	161	156	158	**146**
2012/2013	10516	177	168	162	154	156	**142**
2013/2014	14567	162	151	146	145	141	**130**
2014/2015	11487	157	151	159	154	154	**142**
2015/2016	12678	147	141	146	144	144	**136**
2016/2017	10624	153	153	160	158	151	**140**
2017/2018	10330	145	142	165	168	143	**132**
2018/2019	11383	166	164	181	188	169	**158**
2019/2020	12505	138	136	159	168	142	**133**

Another interesting parameter is the number of houses which have radon concentrations above the reference level of 200 Bq/m^3. National estimates of these numbers are shown in Table 3 (last column to the right). For the measurement seasons 2007/2008 and 2008/2009 combined, the average value is 19.0 %. In this estimate, mitigated houses without “Blue Concrete” with levels above 200 Bq/m^3 have been removed since it is assumed that mitigated houses above the reference level probably have not fully completed the mitigation work. This could be compared with a corresponding value of 17.5 % if all measurements with “Blue Concrete = YES” or “Mitigated = YES” (18.8 % for 2007/2008 and 16.2 % for 2008/2009) were removed and with 20.8 % when applying corrections for mitigated houses instead of removing them in the analysis. Among answer alternative “UNKNOWN” on these questions, there are probably measurements which are more representative for the numbers in the Swedish building stock.

The average of all measurement seasons in Table 3 is 19.9 % with a standard deviation of 1.9. Combining this uncertainty estimate of the skewness in the data with the measurement calibration uncertainty (5 %, standard uncertainty k = 1) in the uncertainty calculations for 2007/2008 and 2008/2009, a national value of 370’000 (280’000 – 440’000, expanded uncertainty k = 2) houses above 200 Bq/m^3 is obtained. A total value of 1.94 million single-family houses were used in these calculations. The relative measurement calibration uncertainty estimate was obtained by counting the number of houses above 190 Bq/m^3 and 210 Bq/m^3 respectively and comparing this with the number of houses above 200 Bq/m^3. It should be noted that measured radon values don’t have a normal distribution and therefore, the lower uncertainty region will be wider than the upper.
This value could be compared with the lowest value obtained if using the data from measurement season 2008/2009 and removing all measurements in mitigated and blue concrete houses. In that case (16.2 % above), an estimate of 310’000 (250’000 – 380’000) houses above the reference level of 200 Bq/m^3 would be obtained. The “Blue Concrete” correction in Table 3 is a subtraction of the N_A / N_T value in Table 11 and the “Mitigation” correction is a subtraction of the N_M / N_T value in Table 11. The “Not Mitigated” correction is a subtraction of the $Frac_{Mit} * H_{Mit}$ value in Table 11. During 2008-2020, Radonova has 30’300 measurements in mitigated single-family houses with annual average below 200 Bq/m^3. Assuming a Radonova market share of 2/3, it can be estimated that about 45’000 which had values above 200 Bq/m^3 2008 have been mitigated. Based on the number of new-built houses and that about 4 % of these have annual average values above the reference level, it is assumed that about 5000 new houses above the reference level have been built. Therefore, an estimate of the current number of single-family houses above 200 Bq/m^3 based on these assumptions would be 370’000-45’000+5000 = 330’000. This corresponds to 16 % of the number of single-family houses in 2021.

Table 3, Single family house above 200 Bq/m^3.

Measure-ment sea-son	Above 200 Bq/m^3 non-corrected	Above 200 Bq/m^3 region & building-year corrected	Above 200 Bq/m^3 munici-pality corrected	Above 200 Bq/m^3 "Blue Concrete & "Mitigated" corrected	Above 200 Bq/m^3 "Blue Concrete corrected" & "Not Mitigated"
2007-2008	27.5 %	25.3 %	25.5 %	21.6 %	**19.7 %**
2008-2009	24.3 %	23.6 %	24.1 %	20.1 %	**18.2 %**
2009-2010	26.8 %	26.3 %	28.5 %	24.0 %	**21.5 %**
2010-2011	32.9 %	30.7 %	29.3 %	24.8 %	**19.9 %**
2011-2012	31.7 %	30.3 %	29.6 %	24.6 %	**20.3 %**
2012-2013	36.8 %	29.3 %	28.2 %	22.9 %	**18.8 %**
2013-2014	27.1 %	25.8 %	24.8 %	21.3 %	**18.7 %**
2014-2015	25.6 %	26.3 %	25.9 %	22.0 %	**19.4 %**
2015-2016	22.8 %	23.2 %	22.6 %	19.6 %	**17.9 %**
2016-2017	25.3 %	25.5 %	24.2 %	20.3 %	**18.2 %**
2017-2018	23.0 %	25.5 %	25.3 %	21.0 %	**18.9 %**
2018-2019	33.1 %	30.2 %	31.4 %	26.5 %	**24.3 %**
2019-2020	22.0 %	26.1 %	28.1 %	24.5 %	**22.7 %**

Dependences on building year

The data can also give information about the differences in radon concentrations for different building year periods. Since the differences are the most important information here, only "non-corrected" values will be used in this analysis. The results are shown in Table 4. As can be seen, average radon concentrations are much lower in newly built houses. This has also been observed (see Table 5) and presented by Radonova at the AARST Symposium 2018 [7]. In the data presented at the AARST symposium an analysis was made on houses built 2002-2004 and measured between 2005-2016, to investigate if radon concentrations might increase with time. No such significant increases were observed, Kruskal-Wallis test (p-value = 0.416).

Table 4, Average values per measurement season in Swedish single-family house grouped by building year.

Period	07-08	08-09	09-10	10-11	11-12	12-13	13-14	14-15	15-16	16-17	17-18	18-19	19-20	To-tal
< 1931	159	183	180	208	207	188	164	192	182	183	218	244	215	194
1931-1940	183	164	174	203	206	176	166	200	159	196	172	235	206	188
1941-1950	171	156	187	193	186	179	189	179	181	190	174	217	180	183
1951-1960	210	201	209	235	223	216	221	207	209	201	189	233	215	213
1961-1970	224	199	222	231	233	226	208	214	192	209	186	229	213	214
1971-1980	178	159	183	191	190	183	173	177	165	174	182	187	161	177
1981-1990	108	92	123	136	125	118	90	90	90	119	97	101	83	106
1991-2000	72	63	85	106	92	125	69	65	54	82	86	78	55	79
2001-2010	55	54	75	73	69	76	71	55	65	67	107	93	75	72
2011-2020					41	39	34	41	36	43	48	56	48	43

Table 5, Radon concentrations in Swedish single-family house grouped by building year. Date from measurements performed 2015-2017. Presented at the AARST Symposium 2018 [7].

Building year	Number of measurements	Average radon conc. (Bq/m^3)	Highest value (Bq/m^3)	Above 200 Bq/m^3
1950-1980 (all)	7495	185	4290	33 %
1950-1980 (“blue concrete”)	1886	252	3330	53 %
1950-1980 (no “blue concrete”)	2519	163	4070	27 %
1980-2000	8099	89	4550	11 %
2000-2010	2332	63	1920	6.1 %
2014-2016	2255	41	6100	2.0 %

The building year of Swedish single-family houses are not uniformly distributed. A very large fraction of houses was built during 1960-1980 which can be seen in Table 6 below where the number of single-family houses [5] as it was 2019 is shown in the column “Dwellings 2019”. During these years, a lot of buildings were built with “Blue Concrete” and the awareness that such houses could have radon problems can be observed in the relative measurement excess, compared with the building stock distribution, for these building years (skewness > 1). However, the largest relative measurement excess is usually found in newly-built houses which might be explained by recommendations to measure in newly built houses. The “skewness” in Table 6 is the factor with which the number of measurements should be divided in order to get a building year distribution which is similar to the distribution of all single-family houses in Sweden.

Table 6, Distribution of houses and radon measurements on building year periods.

Period	Average (Bq/m3)	SD	Dwellings 2019	Skewness 2007	Skewness 2019
Before 1931	194	24	415629	0.56	0.30
1931-1940	188	22	141016	0.84	0.51
1941-1950	183	14	137962	0.97	0.67
1951-1960	213	13	164559	1.16	1.09
1961-1970	214	15	289868	1.57	1.23
1971-1980	177	11	427591	1.11	0.79
1981-1990	105	17	214935	0.83	1.77
1991-2000	79	20	99279	0.81	1.68
2001-2010	72	15	114546	1.24	0.73
2011-2020	43	7	73735		3.89

Comparisons with previous studies

To compare with previous Swedish national radon surveys, it is important to estimate how much the average radon concentrations are expected to change from year to year. As is seen in Table 6, about 10’000 new single-family houses were built yearly during the last 30 years. The average radon concentration for building years before 2001 as shown in Table 6 is 177 Bq/m^3 which can be compared with an average of 67 Bq/m^3 for the building years between 1991 and 2020. This difference of about 100 Bq/m^3 would correspond to a yearly decrease of the average radon concentrations with 0.5 Bq/m^3 yearly due to the increased stock of newly built houses.

Radonova has previously studied how effective radon mitigation has been by comparing measured radon concentrations before and after radon mitigation. This study was made on 1640 Swedish single-family houses and the results were presented at the 13th IRPA International Congress, 2012 [8]. A table with results presented at that congress is shown in Figure 2. As seen from the results, the average decrease in radon concentration is 337 Bq/m^3. Assuming 3000 yearly radon mitigations, the national radon average is estimated to decrease about 0.5 Bq/m^3 per year. This estimate assumes that Radonova performs about 2/3 of the radon measurements in Sweden and is based on the number of measurements from 2013 and onward. During the period 2007-2012, the corresponding numbers are 5000-6000 yearly mitigations which agree with the number of 5600 given in the BETSI report [2]. Before 2005, significantly less measurements were performed and consequently also less mitigations can be assumed. In the following comparisons, it is estimated that 1000 yearly mitigations were performed during 1992-2000 and 2000 yearly mitigations during 2001-2006. These values are used together with the total number of single-family houses to estimate the fraction Mit_{Swe} of radon mitigated houses.

The first Swedish radon survey was the ELIB survey 1991-1992. The estimated national average for single-family houses in that survey was 141 Bq/m^3 and the number of houses with radon levels above 200 Bq/m^3 was estimated to be 280’000-320’000 (16-18 %) [9]. The expected average decrease in radon levels to 2008 from the assumptions above (0.5 Bq/m^3 yearly decrease) would be about 12 Bq/m^3 which would give a value 129 Bq/m^3 in comparison with the value of 124 Bq/m^3 obtained in the BETSI survey [2]. The national average values obtained in this study was 128 Bq/m^3 for the measurement season 2007/2008 and 136 Bq/m^3 for season 2008/2009. Considering measurement uncertainties, all these results are in good agreement with each other.

It could be noted that if the upper detection limit of the detector used is about 2500 Bq/m^3 (usually upper limit for counting individual tracks), the estimated nation average could be slightly underestimated. From the Radonova data of 2007/2008, removing the 0.13 % measurements above 2500 Bq/m^3, will cause a decrease of about 5 Bq/m^3 in the average value.

The estimate of 370’000 (280’000 – 440’000) houses above 200 Bq/m^3 in this study is closer in agreement with the findings in the ELIB survey compared with the BETSI survey which estimated 250’000 (125’000-375’000). It is estimated that about 150’000 new houses were built during the years between the ELIB and BETSI studies of which about 10’000 houses are estimated to be above the reference level. However, the estimate of 370’000 in this study is very sensitive to measurements around 200 Bq/ m^3 which often is the case in mitigated houses and/or “blue concrete” houses. Removing these measurements gave an estimate of 310’000 (16 %) houses for measurement season 2008/2009.

Parameters	All data	>1000 Bq/m³ before remedia-tion	With "blue con-crete"	Without "blue concrete"
Number of dwellings	1640	123	647	749
Average levels before remediation	521	1632	509	538
Average levels after remediation	184	315	218	161
< 200 Bq/m³ after remediation	64 %	48 %	54 %	72 %
< 100 Bq/m³ after remediation	34 %	31 %	14%	48 %
Reduction with more than 90 %	18 %	41 %	4 %	28 %
Reduction with more than 80 %	32 %	61 %	15 %	45 %
Higher levels after remediation	6 %	3 %	6 %	7 %

Figure 2, Comparison from 2012 between radon concentrations before and after radon mitigation in Swedish single-family houses.

Possible future studies

Since the radon market for single-family houses has changed a lot the last 10 years, it is more difficult to obtain representative values from the measurement laboratories since it is no longer possible (answer rates too low) to send offer of radon measurements to all house owners in a municipality. Good estimates must probably be based on a new randomized survey with large enough measurements to get good statistics.
If future national survey studies are planned, it would be important to evaluate the measurement performance of the chosen radon detectors such as the measurement range of the detectors. It is also recommended to make blind quality control measurements of the supplier laboratory. Only requirements of accreditation should not be enough. Quality control measurements within the project should be performed and results from them should be included in the uncertainty calculations in the survey report. The quality control routines used in the US and Canada could serve as good examples for this. In larger radon projects there, it is required that 10% of the detectors should be used for blind control measurements. These quality control measurements can be divided in SPIKE (detectors exposed in a radon chamber), DUPLICATE (side-by-side detectors) and BLANK (un-exposed detectors).

A possible new study would be a new evaluation of the efficiency of radon mitigations. The last such study [8] by Radonova was performed 2012 so a new similar study 2022 is recommended.

Regional level corrections

This section describes the detailed regional data which are used for the different corrections applied.

The non-corrected average values for each Swedish region are shown in Table 7. In some regions, measurements have been performed more frequently, such as in the region of Stockholm. Other regions such as Gotland, Västerbotten and Norrbotten have relatively few measurements. To correct for this non-representative distribution of measurements, correction factors, see Table 8, for the "number of measurements" in each region are applied to get a distribution which represent the true distribution of buildings between the regions. If the correction factors are higher than 10 (marked in yellow), it is a risk that the influence of the few measurements will get too high weight which might cause outliers (usually with a too high corrected average results since measurements in known local high-risk areas could get too much weight). To avoid this effect, the corresponding regional average values are replaced with overall average value for that region (column "average +/- SD" in Table 9).

Table 7, Regional average radon concentrations (Bq/m^3) in Swedish single-family houses, non-corrected.

Region	07-08	08-09	09-10	10-11	11-12	12-13	13-14	14-15	15-16	16-17	17-18	18-19	19-20
Stockholm	184	157	209	196	186	179	164	161	144	145	141	180	149
Uppsala	198	207	195	209	208	199	208	206	197	188	129	183	112
Södermanland	251	295	319	273	292	293	248	239	280	276	229	273	210
Östergötland	146	183	195	160	178	170	171	172	178	172	169	149	161
Jönköping	128	135	145	173	177	209	156	160	171	155	122	147	124
Kronoberg	131	109	142	141	123	141	123	122	129	95	98	152	151
Kalmar	222	126	177	176	180	212	144	179	184	152	159	236	122
Gotland	54	43	55	79	34	92	45	76	51	58	98	84	40
Blekinge	107	89	133	115	124	118	149	140	127	139	142	98	105
Skåne	91	94	104	114	100	103	98	94	92	114	76	78	63
Halland	57	61	78	107	54	80	60	58	49	55	66	40	37
Västra Götaland	171	147	173	149	170	186	143	134	113	145	173	156	138
Värmland	97	129	110	102	148	140	122	125	121	116	112	179	134
Örebro	214	194	274	237	225	229	206	242	185	196	156	241	212
Västmanland	170	231	261	275	226	231	230	249	243	241	213	261	211
Dalarna	189	195	215	311	260	217	198	190	208	205	209	231	204
Gävleborg	160	165	188	182	168	188	174	155	182	183	170	171	172
Västernorrland	183	165	200	225	207	202	161	191	162	241	265	121	160
Jämtland	125	187	167	141	148	137	157	177	104	108	149	468	185
Västerbotten	140	115	104	151	116	117	110	81	108	169	87	207	216
Norrbotten	181	109	159	172	106	90	198	214	113	175	90	152	118

Table 8, Regional distribution correction factors (R_g) for non-representative number of measurements. Cells marked in yellow denote correction factors above 10 which are replaced by average for that region as shown in Table 9

Region	**07-08**	**08-09**	**09-10**	**10-11**	**11-12**	**12-13**	**13-14**	**14-15**	**15-16**	**16-17**	**17-18**	**18-19**	**19-20**
Stockholm	0.45	0.42	0.59	0.36	0.38	0.38	0.55	0.49	0.53	0.47	0.37	0.45	0.41
Uppsala	0.48	0.67	0.49	0.38	0.46	0.50	0.88	0.88	0.90	0.77	0.64	0.62	0.34
Södermanland	0.55	1.94	1.28	0.66	0.50	0.70	0.64	0.73	0.79	0.77	0.63	0.62	0.54
Östergötland	0.72	1.17	1.74	1.29	1.22	1.15	0.97	1.54	1.14	1.40	1.97	1.08	1.75
Jönköping	1.05	1.19	0.72	1.32	1.27	2.11	1.04	1.02	0.89	0.93	1.33	1.49	2.02
Kronoberg	1.21	8.22	2.30	3.11	4.25	3.00	1.52	3.99	1.49	1.30	2.34	2.43	2.53
Kalmar	2.36	1.15	1.42	1.70	0.99	1.54	1.10	1.14	1.24	1.39	2.44	2.18	1.52
Gotland	14.09	16.90	0.77	12.07	16.90	42.26	21.15	21.05	8.38	10.49	41.92	7.61	7.58
Blekinge	3.19	1.56	0.74	3.51	2.34	1.14	1.63	2.72	1.58	0.76	0.94	0.87	1.29
Skåne	2.63	0.97	2.06	2.16	2.41	1.36	1.62	2.43	2.26	2.18	1.42	1.20	1.43
Halland	2.80	2.58	0.70	3.85	1.13	0.94	1.44	0.70	0.58	0.85	1.62	1.16	0.77
Västra Götaland	1.29	1.70	1.27	1.90	1.95	2.20	1.44	0.96	0.82	0.97	1.40	1.55	1.49
Värmland	1.78	1.59	0.75	0.84	3.25	2.56	1.02	0.70	1.21	1.37	1.79	1.91	2.77
Örebro	1.38	0.50	1.32	0.82	0.87	1.00	0.66	0.99	0.80	0.89	0.81	0.89	1.56
Västmanland	0.42	0.78	2.11	0.56	0.67	0.62	0.65	0.66	0.62	0.51	0.67	0.46	0.73
Dalarna	0.52	1.16	0.46	1.37	1.22	1.19	0.80	1.08	1.00	1.29	1.33	1.16	0.92
Gävleborg	0.79	0.61	0.79	0.70	0.62	0.51	0.62	0.70	2.54	1.06	1.04	1.22	2.16
Västernorrland	7.45	4.17	2.43	2.72	4.53	5.22	2.20	4.04	4.42	4.62	8.11	1.09	2.63
Jämtland	4.05	2.20	2.12	1.66	0.86	1.96	0.79	1.60	2.68	2.64	1.64	1.88	2.44
Västerbotten	31.21	22.29	1.33	9.18	8.21	9.75	2.62	2.79	5.71	12.91	11.09	11.90	11.85
Norrbotten	35.82	2.15	13.43	7.86	4.30	7.01	2.35	12.83	5.06	6.28	1.84	7.57	4.58

Table 9, Regional distribution of single-family houses in the Swedish building stock. The column "Average +/- SD (outliers removed)" shows the values obtained for 2007-2020 after removing the outliers marked in Table 10. Cells marked in yellow has some regional outlier result replaced with the average value shown in the column "Average +/- SD".

Region	**Single-family houses (number of)**	**Single-family houses (fraction)**	**Average +/- SD (outliers removed) (Bq/m^3)**
Stockholm	279254	0.134	161 +/- 16
Uppsala	71249	0.034	205 +/- 18
Södermanland	61784	0.030	250 +/- 26
Östergötland	94941	0.045	164 +/- 16
Jönköping	87177	0.042	132 +/- 15
Kronoberg	53327	0.026	120 +/- 19
Kalmar	69068	0.033	181 +/- 22
Gotland	17400	0.008	53 +/- 9
Blekinge	43774	0.021	126 +/- 19
Skåne	281269	0.135	100 +/- 12

Halland	89587	0.043	71 +/- 13
Västra Götaland	350972	0.168	149 +/-13
Värmland	75770	0.036	119 +/- 10
Örebro	67746	0.032	217 +/- 25
Västmanland	55356	0.027	225 +/- 33
Dalarna	82486	0.040	227 +/- 36
Gävleborg	75156	0.036	180 +/- 21
Västernorrland	63629	0.030	182 +/- 28
Jämtland	37744	0.018	158 +/- 43
Västerbotten	64338	0.031	102 +/- 18
Norrbotten	65938	0.032	149 +/- 26

The final regional corrected results are shown in Table 10. Results which differ with more than the 2*SD (marked in yellow) from the average value shown in Table 9 is regarded as outlier and are replaced "**Outlier correction**" with the average value from Table 9 when the national average is calculated. Results where the regional correction factors are higher than 10 (marked in orange) are also replaced with the average value from Table 9. In the values shown in Table 10, corrections from non-representative distributions between building years "**Building year correction**" as well as non-representative distributions between municipalities within a region "**Municipality correction**" are applied.

Table 10, Corrected regional average radon concentrations (Bq/m³) in Swedish single-family houses. For values marked in yellow or orange, outlier correction is applied.

Region	**07-08**	**08-09**	**09-10**	**10-11**	**11-12**	**12-13**	**13-14**	**14-15**	**15-16**	**16-17**	**17-18**	**18-19**	**19-20**
Stockholm	167	156	199	166	168	171	160	162	135	142	147	172	146
Uppsala	178	190	226	217	216	196	200	209	212	241	183	258	193
Södermanland	246	277	344	265	285	213	225	222	274	268	235	268	223
Östergötland	148	188	215	167	171	137	157	156	162	162	161	193	172
Jönköping	115	121	110	155	125	146	125	118	141	139	138	159	129
Kronoberg	91	110	161	133	120	126	112	131	130	104	106	171	174
Kalmar	176	158	201	177	176	206	148	198	193	156	164	224	177
Gotland	58	57	53	174	37	66	46	51	62	40	104	169	57
Blekinge	110	95	105	135	115	109	146	126	142	134	149	149	169
Skåne	82	90	125	88	98	111	98	98	95	131	98	136	114
Halland	47	69	73	130	49	81	77	64	67	69	84	77	93
Västra Götaland	156	147	169	142	150	159	127	160	130	136	145	157	159
Värmland	100	124	129	116	130	129	109	128	113	103	121	129	122
Örebro	191	219	316	241	259	205	205	249	179	210	234	283	199
Västmanland	190	313	307	240	247	253	228	274	245	263	232	274	252
Dalarna	192	202	218	280	288	204	184	194	224	210	247	230	284
Gävleborg	169	163	199	180	175	177	152	175	171	250	233	322	187
Västernorrland	201	183	220	226	188	182	142	166	157	258	618	153	307
Jämtland	89	209	274	112	166	160	168	218	173	127	326	604	251
Västerbotten	126	134	102	126	114	118	99	79	80	179	91	198	201
Norrbotten	194	107	196	172	90	90	283	161	156	137	147	127	188

More measurements are performed in houses containing “Blue Concrete” so the fraction of these measurements (13-20 %) will not be representative for the true number of “Blue Concrete” houses in the Swedish building stock which is estimated to be 6 % [2].

As can be seen in Table 11 below, average radon levels in houses with “Blue Concrete” from the same time period is about 100 Bq/m^3 higher than in houses without “Blue Concrete”. To correct for this source of overestimation the correction $C_B = C_Y * (R_{Blue} - R_{Not\_Blue}) * (Frac_{Blue} - 0.06)$ was subtracted from the national average estimate.

The similar overestimation of number of houses above 200 Bq/m^3 was calculated with:
$N_A = C_Y * (H_{Blue} - H_{Not\_Blue}) * (Frac_{Blue} - 0.06) * N_T$, where

- N_A is the overestimated number of measurements above 200 Bq/m^3 due to non-representative number of measurements in houses with “Blue Concrete”.
- H_{Blue} is the fraction of houses above 200 Bq/m^3 when the customer has answered Yes on the question about “Blue Concrete”.
- H_{Not_Blue} is the fraction of houses above 200 Bq/m^3 when the customer has answered No on the question about “Blue Concrete”.
- N_T is the total number of measurements.

Relatively more measurements are also performed in radon-mitigated houses which also after mitigations on average have higher radon concentrations compared to an average non-mitigated house. To correct for this source of overestimation of the national average, corrections factors are calculated based on the difference between the radon levels in mitigated houses and non-mitigated houses together with the estimated number of mitigated houses in Sweden discussed earlier in the section “Comparisons with previous studies”. To avoid double counting, mitigated “Blue Concrete” houses are not included since they are handled in the corrections for “Blue Concrete”. The radon average in the remaining mitigated houses is about 50 Bq/m^3 higher than the average in non-mitigated houses which can be seen in Table 11.
To correct for this source of overestimation the correction
$C_M = (R_{Mit} - R_{Not\_Mit}) * (Frac_{Mit} - Mit_{Swe})$ was subtracted from the national average estimate.

The similar overestimation of number of houses above 200 Bq/m^3 was calculated with:
$N_M = (H_{Mit} - H_{Not\_Mit}) * (Frac_{Mit} - Mit_{Swe}) * N_T$, where

- N_M is the overestimated number of measurements above 200 Bq/m^3 due to non-representative number of measurements in mitigated houses.
- H_{Mit} is the fraction of houses above 200 Bq/m^3 when the customer has answered Yes on the question about “Mitigated”.
- H_{Not_Mit} is the fraction of houses above 200 Bq/m^3 when the customer has answered No on the question about “Mitigated”.
- N_T is the total number of measurements.

The data in Table 11 also show that the answer “Unknown” for the question about “Blue Concrete” do not contain non-representative “Blue Concrete” houses. The average for all measurement season for “Blue Concrete = Yes” is 258 Bq/m^3 and for “Blue Concrete = No” is 142 Bq/m^3. Assuming 6 % “Blue Concrete” houses, an average of 149 Bq/m3 which could be compared with the value average value of 150 Bq/m^3 for “Unknown”.

Table 11, Corrections for non-representative results due to too many measurements in mitigated houses and houses with "Blue Concrete".

Parameter	07-08	08-09	09-10	10-11	11-12	12-13	13-14	14-15	15-16	16-17	17-18	18-19	19-20
$Frac_{Blue}$ (%)	16.1	13.8	16.2	20.2	17.4	19.9	14.6	14.6	13.4	13.8	16.5	17.0	13.5
R_{Blue} (Bq/m^3)	284	275	271	270	266	248	262	262	245	262	237	277	248
$R_{Not\_Blue\_All}$ (Bq/m^3)	155	137	159	169	165	158	141	141	130	128	118	131	110
R_{Not_Blue} (Bq/m^3)	177	166	183	197	200	191	171	171	172	174	166	195	171
$R_{Blue\_Unknown}$ (Bq/m^3)	160	138	151	171	167	159	148	148	134	145	139	158	127
C_Y	0.85	0.87	0.85	0.81	0.84	0.83	0.86	0.86	0.98	0.97	1.00	0.95	1.11
C_B (Bq/m^3)	**9.2**	**7.4**	**7.6**	**8.4**	**6.5**	**7.6**	**6.7**	**6.6**	**5.3**	**6.7**	**7.5**	**8.6**	**6.4**
H_{Blue} (%)	55.4	56.9	57.8	55.5	55.2	52.6	55.1	54.4	51.0	54.3	47.5	57.5	49.3
H_{Not_Blue} (%)	21.2	18.7	22.4	32.2	25.9	24.3	19.8	20.2	18.5	17.7	15.8	19.0	14.9
N_A / N_T (%)	**2.9**	**2.6**	**2.9**	**2.7**	**2.9**	**3.3**	**2.6**	**2.5**	**2.4**	**2.8**	**3.3**	**4.0**	**2.9**
Mitigated not Blue C.	3284	2895	1980	2845	2630	2311	2440	1788	1256	1128	1495	1259	1611
$Frac_{Mit}$ (%)	8.0	8.7	10.7	16.0	17.8	18.0	12.8	12.7	8.0	9.1	12.5	9.9	11.1
R_{Mi} (Bq/m^3)	228	221	245	213	204	204	189	189	185	201	164	188	156
R_{Mit}- R_{Not_Mit}(Bq/m^3)	70	84	90	43	38	46	45	45	53	65	37	45	38
C_M (Bq/m^3)	**4.1**	**5.4**	**12.1**	**5.7**	**5.5**	**6.9**	**4.4**	**5.3**	**2.5**	**3.8**	**3.4**	**2.9**	**2.8**
H_{Mit} (%)	36.5	37.4	38.5	42.1	36.1	34.0	27.0	31.7	28.9	35.4	24.6	31.4	22.7
H_{Not_Mit} (%).	17.2	15.9	19.0	28.3	22.0	20.5	17.4	17.2	16.8	15.7	13.9	16.8	13.3
N_M / N_T (%).	**1.1**	**1.4**	**1.8**	**1.8**	**2.1**	**2.0**	**0.9**	**1.4**	**0.6**	**1.1**	**1.0**	**0.9**	**0.7**
$Frac_{Mit}$ * H_{Mit} (%)	**2.9**	**3.3**	**4.1**	**6.7**	**6.4**	**6.1**	**3.5**	**4.0**	**2.3**	**3.2**	**3.1**	**3.1**	**2.5**

3. Radon levels – dependence on soil type and U concentrations

Radonova has previously studied how different building parameters can affect the radon concentrations in dwellings, both in single-family and in multi-family houses. The parameters studied were: building year, foundation type, ventilation type and possible presence of the light-weight concrete building material which is based on alum shale - “Blue concrete”. The results from this study were presented at the 2018 AARST Symposium [7] and showed that the building year was the parameter with largest correlation to the radon concentrations in the house.

Radonova has not previously had any access to geological data such as Uranium concentration in the soil and the type of soil. By adding such geological data, it would be possible to evaluate the influence from geological parameters on the radon concentrations.

Method for evaluation

Information about the Uranium (U) concentrations can be obtained from maps provided by the Geological Survey of Sweden (SGU). This airborne measured Uranium data is interpolated into a 200m*200m grid. Uranium concentrations obtained from airborne measurements will always be a value representing an area, rather than a point. This area may contain soils and rocks, but also houses, roads, ponds, etc., that may cause the measured value to differ from the soil or rocks beneath houses.

SGU provides a WMS (Web Map Service) that follows the OGC standard, and information could be collected using Python. The postal codes of radon measurements were converted into latitude and longitudes using public postal code data from geonames.org and from that process, U-concentrations could be assigned to the postal codes. This work was performed by Bart Olsthoorn KTH [11], who also provided the map shown in Figure 3 where the actual postal codes with measurements are marked as black dots. The data set used in this study was from about 10’000 single-family house measurements performed during 2019/2020.

The U-concentrations connected to certain postal codes obtained in this analysis were also used to study the influence of U-concentration on radon levels measured in workplaces and multifamily house during 2017-2020. Of the 3347 workplaces and 5559 multifamily houses in that data set, 785 workplaces and 917 multifamily housed could be connected to a U-concentration through the postal code. After removing mitigated buildings and buildings with “blue concrete”, 758 workplaces and 757 multifamily houses remained in the analysis. All workplaces in this study had 5 or more measurement points and all multifamily houses had measurements in 5 or more apartments.

A more detailed study could be performed if address is used to obtain geographical coordinates from which both Uranium concentrations and soil types can be obtained from the database of SGU. SSM has access to the SGU database and could perform that type of mapping. However, from data protection reasons, Radonova cannot provide data which contain both radon values and addresses. Therefore, only pure address files can be provided to which geological data can be added for further analysis made by Radonova. Radonova has provided SSM with addresses from the municipalities of Uppsala and Östhammar which were used to test this analysis method. Measurements analysed between 2004 and 2020 were used in this analysis. After removing measurements with blue concrete and radon-mitigated houses, 7095 measurements remained in the analysis of which 61 % were analyzed before 2010. All calculated average values are arithmetic mean values.

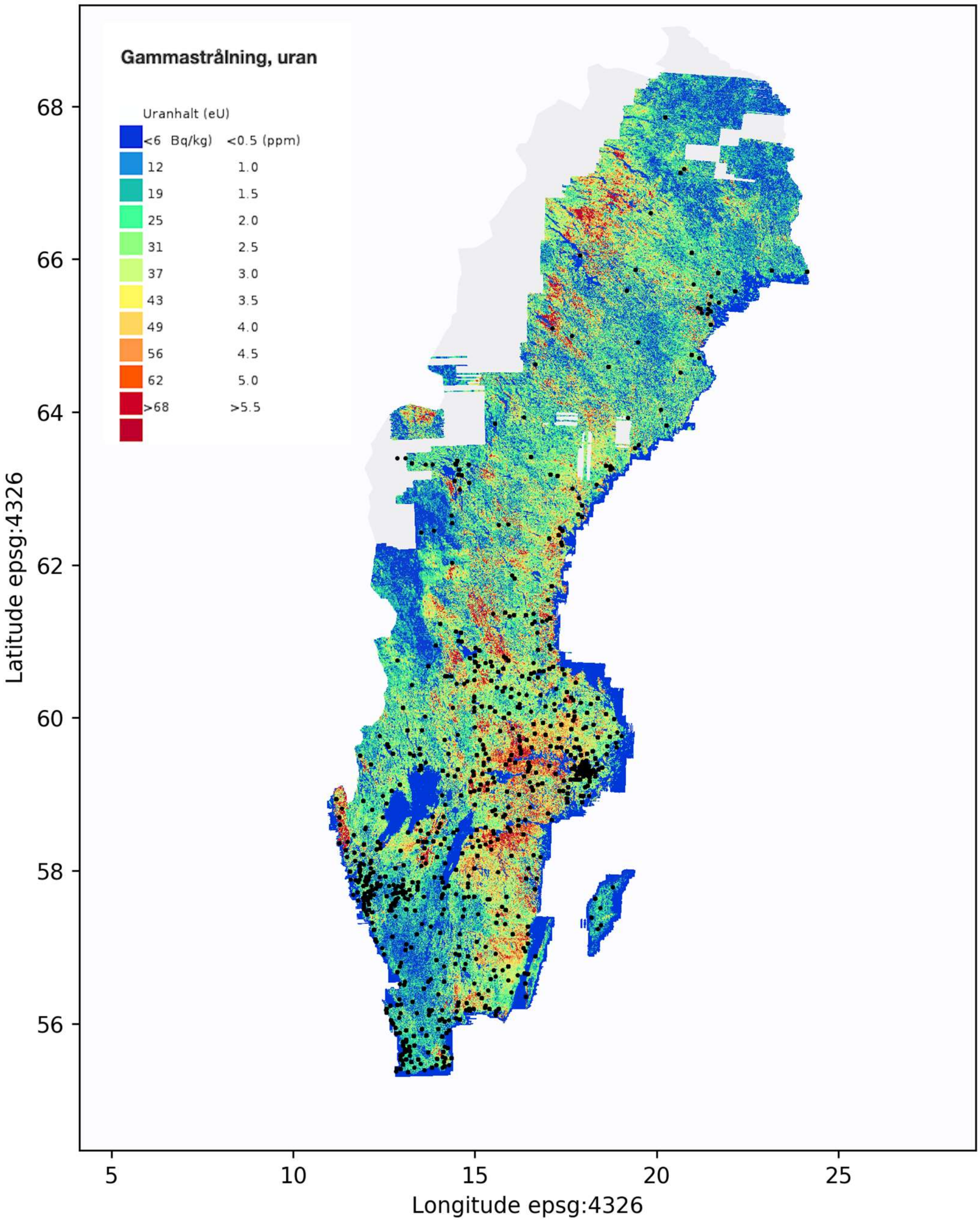

Figure 3, Surface Uranium concentrations in Sweden.

Results (single-family houses)

To test the method of obtaining Uranium concentrations from postal codes, radon measurement from the season 2019/2020 were selected. To evaluate the influence from the soil, measurements in buildings containing the radon emitting material "blue concrete" were excluded as well as measurements performed after radon mitigation. In total 8091 measurements remained in the analysis after this subtraction of measurements. The results are shown in Table 12 below. As can be seen average radon concentrations and number of houses above the reference level of 200 Bq/m^3, are significantly higher in areas with high Uranium concentration in the soil. The difference between radon levels in areas with the lowest Uranium concentrations compared with the highest is very similar as the differences found between new-built houses and older houses in Table 5. However, it should be noted that in all areas, most of the houses are well below the reference level and that very high radon levels can be found in all areas. That can only be explained through effects caused by the building which means how tight the building is against the soil. It is therefore not possible to know if an individual house is above the reference level or not unless a radon measurement is performed in the house.

Table 12, Uranium concentrations and radon levels in Swedish non-mitigated single-family houses without "Blue Concrete" building material.

U-conc (ppm)	Number of measure-ments	Average +/- SD (Bq/m^3)	Median value (Bq/m^3)	Highest value (Bq/m^3)	Measure-ments above 200 Bq/m^3
< 1.0	1409	40 ± 49	24	537	2.2 %
1.0-2.0	1487	77 ± 118	37	1957	8.5 %
2.0-3.0	2345	105 ± 207	52	6720	13.4 %
3.0-4.0	2502	135 ± 190	86	4925	20.7 %
4.0-5.0	136	142 ± 134	98	677	22.8 %
>5.0	212	209 ± 457	98	5869	25.9 %

The results from the measurements, performed between 2004 and 2020, in the municipalities of Uppsala and Östhammar are shown in Table 13. The generally higher values compared to the 2019/2020 season might partly be explained by a larger part of newly-built houses with lower radon levels in the 2019/2020 data set. Although this set of data should have a better U-concentration resolution, the correlation (looking on measurements above the reference level of 200 Bq/m^3) is smaller than in the 2019/2020 data set for the whole Sweden.

Table 13, Uranium concentrations and radon levels in single-family houses in the municipalities of Uppsala and Östhammar without "Blue Concrete" building material.

U-conc (ppm)	Number of measure-ments	Average +/- SD (Bq/m^3)	Median value (Bq/m^3)	Highest value (Bq/m^3)	Measure-ments above 200 Bq/m^3
< 1.0	14	91 ± 126	67	513	7.1 %
1.0-2.0	281	129 ± 141	59	1799	17.1 %
2.0-3.0	1708	155 ± 236	101	4579	22.6 %
3.0-4.0	3143	195 ± 327	126	11046	31.7 %
4.0-5.0	1565	199 ± 235	143	3747	33.6 %
>5.0	384	174 ± 167	129	1168	32.6 %

Table 14 shows the dependence on soil types. Only soil types with more than 10 measurements have been included in the analysis. The highest values among the types with more than 100 measurements, can be found in clay soil types and the lowest in Solid rock ("Urberg") soil type. The highest of all are found in Gravelly moraine ("Grusig morän") but with only 12 measurements, the uncertainties are high.

Table 14, Soil types and radon levels in non-mitigated single-family houses in the municipalities of Uppsala and Östhammar without "Blue Concrete" building material.

Soil type	Number of measurements	Average U-conc (ppm)	Average +/- SD (Bq/m^3)	Median value (Bq/m^3)	Highest value (Bq/m^3)	Measurements above 200 Bq/m^3
Glacial clay ("Glacial lera")	2988	3.7	195 ± 231	143	4579	32.5 %
Postglacial clay ("Postglacial lera")	1347	3.7	207 ± 380	150	11046	36.7 %
Gravelly moraine ("Grusig morän")	12	4.3	485 ± 723	266	2613	50.0 %
Sandy till ("Sandig morän")	1623	3.1	167 ± 297	90	4195	23.0 %
Glaciofluvial sediment ("Isälvssediment")	52	2.8	202 ± 241	100	982	32.3 %
Glaciofluvialsediment, sand ("Isälvssediment, sand")	17	2.8	162 ± 139	108	536	29.4 %
Postglacial sand ("Postglacial sand")	356	3.4	175 ± 189	120	2231	30.3 %
Postglacial fine sand ("Postglacial finsand")	12	2.6	84 ± 89	54	283	16.6 %
"Glacial slit"	12	3.0	175 ± 112	179	372	41.7 %
Marsh peat ("Kärrtorv")	25	3.0	87 ± 77	56	290	8.0 %
Solid rock ("Urberg")	623	3.2	114 ± 161	67	2321	14.3 %

Results (multi-family houses/workplaces)

The results from the measurements in workplaces are shown in Table 15. The first step in the analysis was to calculate the average and median measured values in each workplace. The values shown in the table is the average values for all the workplaces. Very few measurements were performed where the Uranium (U) concentration was higher the 4 ppm. Two of the five workplaces with U-concentrations > 5 ppm were water plants which often can have very high radon levels. As can be seen, correlations between U-concentrations and radon levels are much smaller than in single-family houses. Lower values are observed for U-concentrations < 1.0 ppm but between 1.0 and 5.0 ppm, the differences in radon concentrations are small. To avoid too much influence of outliers, it is better to look at the median values and fraction of workplaces with some value above 200 Bq/m^3 compared to evaluation based on the average values.

Table 15, Uranium concentrations and radon levels in Swedish workplaces without "Blue Concrete" building material.

U-conc (ppm)	Number of measured workplaces	Average +/- SD (Bq/m^3)	Average median value (Bq/m^3)	Highest value (Bq/m^3)	Workplaces with some value above 200 Bq/m^3
< 1.0	48	48 ± 86	42	1125	12.5 %
1.0-2.0	144	89 ± 210	73	4850	28.5 %
2.0-3.0	303	106 ± 171	87	5103	38.9 %
3.0-4.0	245	106 ± 174	80	6429	36.3 %
4.0-5.0	13	166 ± 252	84	6198	38.5 %
>5.0	5	642 ± 1222	154	> 40000	60.0 %

The results from the measurements in multifamily houses are shown in Table 16. The first step in the analysis was to calculate the average and median measured values between the apartments in each multifamily house. The values shown in the table is the average values between the multifamily houses. As for the workplaces, lower radon concentrations were observed for U-concentrations < 1.0 ppm. However, no significant differences in radon concentrations could be observed for U concentrations between 1.0 and 5.0 ppm.

Table 16, Uranium concentrations and radon levels in Swedish multifamily houses without "Blue Concrete" building material.

U-conc (ppm)	Number of measured multifamily houses	Average +/- SD (Bq/m^3)	Average median value (Bq/m^3)	Highest value (Bq/m^3)	Multifamily houses with some apartment above 200 Bq/m^3
< 1.0	94	31 ± 25	27	598	7.5 %
1.0-2.0	167	72 ± 71	58	1478	30.0 %
2.0-3.0	193	77 ± 69	64	1201	32.1 %
3.0-4.0	244	75 ± 69	63	4451	33.2 %
4.0-5.0	30	64 ± 41	56	690	26.7 %
>5.0	29	118 ± 88	101	673	69.0 %

Comparisons with previous studies

In the governmental report *Utredning om radon i bostäder*, SOU 2001-7 [9], radon data was collected from municipalities in Sweden. Earlier, classifications had been made into different radon risk area types from geological information. The results from the collected data showed that differences between classified "low-risk" and "high-risk" areas were smaller than expected. In "low-risk" areas 20 % of the measured average values were above 200 Bq/m^3 which can be compared with 33% for the "high-risk" areas. The conclusion from that report was also that it is not possible to know if a house can have radon problem without measuring. The data from this study support these conclusions.

Possible future studies

If addresses from radon measurements in the whole of Sweden were mapped against Uranium concentrations and soil types, an improved understanding of the importance of these parameters for the in-door radon concentrations might be possible to obtain.

4. Data quality in the radon database of Radonova

Information about the radon measurements are provided by the customers who also place the detectors and return them to Radonova after the measurements. In order to evaluate the importance of different building parameters, it is important that the customer is giving that information for the measurement. To map addresses or “Fastighetsbeteckning” (Building-ID) to geographical coordinates, it is important that the address is given and correct or that the Building-ID is correct. An evaluation was made about the quality of these parameters in the radon database of Radonova. The evaluation was made from radon measurements performed 2019-2020.

Single-family houses

Total number of measurements:	14545	
Missing street address	22	(0.2 %)
Missing post office	26	(0.2 %)
Missing postal code	187	(1.3 %)
Missing or bad Building-ID	4000	(28 %)
Given Building Year, Foundation & Ventilation Type	11393	(78 %)
Given “above” & “Blue Concrete” (Yes or No)	9535	(66 %)
Given “above” & “Mitigated” (Yes or No)	6916	(48 %)

Evaluations with all building parameters can therefore be possible to perform for about half of the measurements which should give good statistics considering the large total number of measurements.
It is also clear that it is better to use addresses compared to Building-ID if additional information would be collected from the Swedish Housing Register.

Dwellings in multi-family houses

Total number of measurements:	64654	
Missing street address	147	(0.2 %)
Missing post office	2668	(4.1 %)
Missing postal code	5354	(8.3 %)
Missing or bad Building-ID	13442	(21 %)
Have post office, Building-ID and Apartment-ID	31895	(49 %)
Given Building Year, Foundation & Ventilation Type, “Blue Concrete” (Yes or No) & Postal Code	23867	(42 %)
Given “above” & “Mitigated” (Yes or No)	18753	(29 %)

For detailed evaluation of results for multi-family houses such as differences in radon levels between floors, information about post office (or postal code), Building-ID and Apartment-ID are needed. This is available for about half of the measurements which should give good statistics considering the large total number of measurements. From the Apartment-ID, accurate information about the floor for each measurement can be extracted.

5. Radon levels in workplaces and multi-family houses

To evaluate the existing measurement protocols for multi-family houses and workplaces, it is important to understand differences in radon levels between different floors. Today, one measurement is performed for each dwelling (apartment in multi-family house). For multi-family houses, it would be valuable if measurement statistics could be obtained for each building. A separate building could be identified if it has the same customer, measurement season, Building-ID ("fastighetsbeteckning") and postal code. For workplaces, measure points registered on the same measurement (report), are usually connected to a specific workplace building. The information which would be valuable to calculate and extract for buildings and floors for further analysis are:

- Type of data (Total, Ground contact, No ground contact, Highest Floor)
- Common building data such as building year, foundation type, ventilation type & "Blue Concrete"
- Floor
- Number of measurements (multi-family houses) or measurement points (workplaces)
- Average value
- Median value
- Spreading (SD) of values (1 standard deviation)
- Highest value
- Number of measurements or measure points above 200 Bq/m^3
- Number of measurements or measure points above 100 Bq/m^3
- Relation between average value on floor with no ground contact and floor with ground contact.
- Relation between average value on higher floors and ground floor with no ground contact.
- Relation between average value on the highest floor with no ground contact and lower floors with no ground contact.

Method for evaluation

Measurements analysed during 2017-2020 were included in the evaluation. All workplaces in this study had 5 or more measure points and all multi-family houses had measurements in 5 or more apartments. In total, data from 3347 workplaces and 5559 multi-family houses were used in the evaluation. In some of the measurements, the customers have not given information about building year, ventilation type and foundation type. Therefore, the sum of all parameter-specific measured buildings will be less than the total numbers given above.

The influence of parameters such as workplace type, ventilation type and building years were evaluated by taking the average values for the average, SD and median values within each building. This evaluation was made for workplaces. Evaluation about the radon level dependence on ventilation type, building year and foundation type in multi-family houses has been done before by Radonova and was presented at the AARST symposium 2018 [7].

The variation of radon levels between different floors in a building was investigated for both workplaces and multi-family houses. The variations between floors in workplaces have been presented before at the AARST symposium 2020 [10].

All measurements are integrating long-term measurements of at least two months. For workplaces with time-controlled ventilation system, these measurements will usually overestimate the radon concentrations during working hours
All calculated average values are arithmetic mean values.

Results

The radon levels in different workplace types are shown in Table 17. As can be seen, very high radon levels are found in workplaces underground (mines, water plants and tunnels). However, the number of such workplaces is quite low. The other types of workplaces show smaller differences. The lower values in "Retirement Home/Geriatric Care" could be explained by the fact the ventilation systems most probably are operating all the time in such buildings. Most workplaces have time-controlled ventilation systems which are only operating during working hours causing higher radon levels outside working hours. The relatively large number of measurements in schools and day-care could be explained by the fact that these "workplaces" also are public buildings for which Swedish municipalities are required to perform supervision. It could be noted that offices and industry as well as "workplace-general" have quite similar values and that about one third of these workplaces have some measurement point with average value above the reference value of 200 Bq/m^3. From workplace measurement analysed during 2018-2020, Radonova presented [8] results which showed that 24 % of Swedish workplaces had measured value above 200 Bq/m^3. However, that study included all workplaces, also the smaller ones with less than 5 measure points and it is obvious that the probability to find higher radon levels will increase if more points are measured in a building.

Table 17, Radon levels in Swedish workplaces for different workplace types.

Type of workplace	**Number of workplaces**	**Measure points per workplace**	**Average median value (Bq/m^3)**	**Average average value (Bq/m^3) & SD (%)**	**Some value above 200 Bq/m^3**	**Some value above 1000 Bq/m^3**	**Median value above 200 Bq/m^3**
Total	3347	12.5	79	106 (75 %)	34 %	6.2 %	7.1 %
Office	639	14.1	80	110 (78 %)	35 %	7.5 %	6.6 %
Industry	307	13.4	76	100 (75 %)	31%	4.2 %	9.4 %
School	1005	12.7	76	105 (81 %)	40 %	6.0 %	6.0 %
Daycare/ Preschool	665	9.0	62	73 (60 %)	24 %	2.4 %	4.5 %
Retirement Home/ Geriatric Care	234	13.3	35	49 (78 %)	19 %	2.6 %	2.6 %
Water Plant	25	11.3	350	630 (102%)	72 %	48 %	44 %
Tunnel	39	11.8	507	569 (69 %)	69 %	36 %	44 %
"Workplace" (in general)	433	14.5	84	119 (80 %)	39 %	8.8 %	9.7 %

The radon levels in workplaces depending on building year are shown in Table 18. The radon levels in old buildings built before 1900 are significantly higher than in buildings built after that. However, only small differences are seen for buildings built later than 1900. This is different compared to dwellings, both single-family and multi-family houses, for which new-built buildings have much lower radon concentrations [7].

Table 18, Radon levels in Swedish workplaces for different building years

Building year	**Number of workplaces**	**Measure points per workplace**	**Average median value (Bq/m^3)**	**Average average value (Bq/m^3) & SD (%)**	**Some value above 200 Bq/m^3**	**Some value above 1000 Bq/m^3**	**Median value above 200 Bq/m^3**
Total	3347	12.5	79	106 (75 %)	34 %	6.2 %	7.1 %
<= 1900	93	12.8	123	175 (87 %)	55 %	17.2 %	14.0 %
1901-1960	369	11.4	82	109 (82 %)	41%	5.7 %	8.9 %
1961-1980	470	12.8	73	97 (75 %)	32 %	5.7 %	7.9 %
1981-2000	282	10.8	63	75 (64 %)	23 %	2.8 %	5.0 %
2001-2010	101	12.3	57	66 (69 %)	27 %	2.0 %	4.0 %
2011-2020	376	13.1	73	88 (64 %)	21 %	4.5 %	4.3 %

The radon levels in workplaces depending on ventilation type are shown in Table 19. The radon levels in buildings with natural ventilation are significantly higher than for buildings with mechanical ventilation. However, the number of workplaces with natural ventilation is only about 5 %.

Table 19, Radon levels in Swedish workplaces for different ventilation types

Type of ventilation	**Number of workplaces**	**Measure points per workplace**	**Average median value (Bq/m^3)**	**Average average value (Bq/m^3) & SD (%)**	**Some value above 200 Bq/m^3**	**Some value above 1000 Bq/m^3**	**Median value above 200 Bq/m^3**
Total	3347	12.5	79	106 (75 %)	34 %	6.2 %	7.1 %
Exhaust air with heat recovery (FX)	79	14.5	79	96 (75 %)	39 %	3.8 %	10.1 %
Exhaust air (F)	72	11.5	77	106 (78 %)	47 %	8.3 %	12.5 %
Supply & Exhaust air (FT)	476	11.1	93	123 (72 %)	32 %	7.4 %	9.0 %
Supply & Exhaust air with heat recovery (FTX)	1344	12.6	65	86 (74 %)	31 %	5.1 %	5.3 %
Natural (S)	105	10.3	211	227 (58 %)	46 %	7.6 %	21.0 %

The radon levels in workplaces for different floors are shown in Table 20. The radon levels in basements are much higher than on any other floor. The median value for basements is about 3 times higher than the highest median value for floors above ground (ground floor on slab on grade). The variations between the other floors are much smaller. It should be noted that values above 200 Bq/m^3 could be found on any floor. The radon levels in apartments in multi-family buildings for different floors are shown in Table 21. Apart from basement values, the values are similar for workplaces and multi-family houses. For workplaces, the median values vary between 49 and 69 Bq/m^3 for non-basement floor which could be compared to 46-79 Bq/m^3 for the multi-family buildings.

Table 20, Radon levels in Swedish workplaces on different floors

Type of floor	**Number of work-places**	**Measure points per work-place**	**Aver-age me-dian value (Bq/m^3)**	**Average average value (Bq/m^3) & SD (%)**	**Some value above 200 Bq/m^3**	**Some value above 1000 Bq/m^3**	**Median value above 200 Bq/m^3**
Total	3347	12.5	79	106 (75 %)	34 %	6.2 %	7.1 %
Ground contact - all	1866	5.9	132	176 (59 %)	32 %	6.2 %	13.7 %
Ground contact - basement	547	3.5	206	244 (57 %)	44 %	8.6 %	22.1 %
Ground contact – slab on grade	887	8.2	69	86 (58 %)	22 %	2.3 %	6.0 %
No ground contact - all	1793	10.5	61	73 (61 %)	21 %	2.5 %	5.0 %
No ground contact (foundation = basement)	767	12.3	66	77 (62 %)	23 %	2.3 %	5.2 %
No ground contact (foundation = slab on grade)	481	6.5	49	56 (52 %)	13 %	0.8 %	3.1 %
Highest floor – no ground contact	1852	3.4	60	72 (42 %)	8 %	0.4 %	2.8 %

Table 21, Radon levels in Swedish multi-family houses on different floors

Type of floor	**Number of multi-family houses**	**Measured apart-ments per multifam-ily house**	**Aver-age me-dian value (Bq/m^3)**	**Average average value (Bq/m^3) & SD (%)**	**Some value above 200 Bq/m^3**	**Some value above 1000 Bq/m^3**	**Median value above 200 Bq/m^3**
Total	5559	14.4	63	79 (57 %)	31 %	0.9 %	7.4 %
Ground contact - all	990	6.7	93	108 (55 %)	31 %	1.6 %	10.3 %
Ground contact - basement	223	3.2	139	144 (53 %)	33 %	1.3 %	15.2 %
Ground contact – slab on grade	671	8.2	79	93 (55 %)	29 %	1.9 %	7.6 %
No ground contact - all	3913	12.2	68	75 (50 %)	25 %	0.3 %	6.9 %
No ground contact (foundation = basement)	2819	12.5	73	80 (50 %)	28 %	0.4 %	8.1 %
No ground contact (foundation = slab on grade)	699	10.3	46	52 (48 %)	14 %	0.1 %	2.7 %
Highest floor – no ground contact	3915	2.8	77	71 (37 %)	14 %	0.0 %	6.4 %

The differences in radon levels between different floors within each building in workplaces and multi-family houses are shown in Table 22. For about 20 % of the workplaces and multi-family buildings, higher floors have higher average values than the average values on the ground-contact floor. The column "Fraction of higher floors with higher values" in Table 22 give the percentage of buildings where the higher of the compared floor types had the highest average radon level. The decrease in radon levels with higher floors are slightly higher for multi-family houses compared to workplace buildings as can be seen for the relation (0.61 for multi-family houses and 0.69 for workplaces) between values floors with no ground contact and the ground floor for buildings with slab on grade. In a previous study [8] for large workplaces with more than 30 measure points, analysed 2018-2020, it was found that ground floors had similar radon average concentrations (78 Bq/m^3 – slab on grade, 74 Bq/m^3 – basement) and measure points above 200 Bq/m^3 (7.9 % – slab on grade, 7.0 % – basement) independent if the if the ground floor had ground contact (foundation type = slab on grade) or not (foundation type = basement). This is not in contradictions with the findings that ground contact floors have higher values than higher floors since building with basement in general have higher radon levels than buildings with slab on grade. In that study, it was also found that very high radon levels could be found independent of floor level. 15 % of the workplaces had some value above 1000 Bq/m^3 on ground contact floor and 7 % of the workplaces had some value above 1000 Bq/m^3 on higher floors.

Table 22, Differences in radon levels between different floors within each building in Swedish workplaces and multi-family houses

Relation between different floors within a building	Number of Multi-family houses	Median/ Median Multi-family houses	Fraction of higher floors with higher average value	Number of Workplaces	Median/ Median Workplaces	Fraction of higher floors with higher average value
No ground contact / Ground contact	894	0.64	24 %	133	0.49	19 %
No ground contact / Ground contact (foundation = basement)	186	0.78	39 %	475	0.40	14 %
No ground contact / Ground contact (foundation = slab on grade)	594	0.61	20 %	415	0.69	26 %
No ground contact – not ground floor / Ground floor with no ground contact	2362	0.88	38 %	834	0.85	38 %
Highest / No ground contact below highest floor	3657	0.90	39 %	1105	0.87	39 %

Possible future studies

Most Swedish workplaces have a time-controlled mechanical ventilation system which usually give significantly lower radon levels during working hours. It would be interesting to investigate how parameters such as Uranium concentration in soil, floor level, building year, foundation type and ventilation type affect the radon levels during working hours and if that differ from what was found from the long-term average measurements in the workplaces. Estimations of the radon levels during working hours should be made according to the Swedish measurement protocol for workplaces [12].

6. Conclusions and discussions

From the analysis of measured radon levels in about 7000 single-family houses, it was found that for houses on the most common soil types, the highest radon levels were found in clay soil types. Sometimes, clay soil types are regarded as “lower radon risk” areas due to an expected lower permeability. The data from this study contradicts such assumptions.

Radon levels in single-family houses are significantly higher in areas with high Uranium (U) concentration in the soil. It should be noted that in all areas, most of the houses are well below the reference level and that very high radon levels can be found in all areas. This can only be explained through effects caused by how tight the building is against the soil. It is therefore not possible to know if an individual house has radon concentration above the reference level or not unless a radon measurement is performed in the house. A similar correlation between indoor radon concentrations and U concentrations could not be observed for workplaces and multi-family houses. Lower radon levels were observed when the U concentration was < 1 ppm but only small differences were found for U concentrations between 1 and 5 ppm.

Underground workplace types have significantly higher radon levels compared to other types for which the differences in radon levels are quite small. Older (built before 1900) workplace buildings as well as buildings with natural ventilation also have significantly higher radon concentrations. It should be noted that the workplaces identified in this section for higher radon risk is a small number of the total number of workplaces, 5 % or less in this data set. It is motivated to prioritize radon measurements in these workplaces but for most workplaces, it was not possible to identify any parameters indicating a significantly higher probability for high radon levels. Radon levels from long-term measurements above 200 Bq/m^3 can be found in any type of workplace and on any floor level. Since most workplaces have a time-controlled ventilation, radon levels are usually much lower during working hours. A future study of radon levels in workplaces during working hours would be interesting.

From the large number of radon measurements in single-family houses, the national average values obtained in this study was 128 Bq/m^3 for the measurement season 2007/2008 and 136 Bq/m^3 for the measurement season 2008/2009 which are in very good agreement with the value of 124 Bq/m^3 obtained in the BETSI national survey 2007-2009. The estimate of 370’000 (280’000 – 440’000) houses above 200 Bq/m^3 in this study is higher than both the ELIB and BETSI studies but closer in agreement with the estimate of 300’000 in the old ELIB survey from 1991-1992 compared with the BETSI survey which estimated 250’000 (125’000-375’000). However, it should be noted that the estimate of the number of houses above 200 Bq/m^3 contains large uncertainties. If all houses with “Blue Concrete” and all mitigated housed were excluded, an estimate of 310’000 houses above 200 Bq/m^3 was obtained which is expected to be an underestimate but shows the large influence on this number from houses with “Blue Concrete”. Since it is no longer possible (answer rates too low) for commercial measurement suppliers to send offer of radon measurements to all house owners in a municipality, new estimates of average national radon concentrations must be based on randomized surveys. Using the estimated number of 370’000 for 2007-2009 together with an estimated number of successfully mitigated houses since 2008 and an estimated number of new-built houses above the reference level, 330’000 single-family houses above 200 Bq/m^3 is estimated for the year of 2021. This corresponds to 16 % of the number of single-family houses in 2021.

7. Acknowledgements

We would like to thank Tomas Persson at the Swedish Radiation Safety Authority (SSM) for his valuable contribution and remarks during the whole project.

We would also like to thank Cecilia Jelinek at the Geological Survey of Sweden (SGU) and Anders Pikkuniemi (SSM) for the contributions concerning uranium soil concentrations and data for different soil types in the municipalities of Uppsala and Östhammar.

We would also like to thank Ingela Düring and Tiina Orusild at Statistics Sweden (SCB) for valuable statistical discussions and Joakim Thunborg at the National Board of Housing, Building and Planning (Boverket) for valuable discussions about the BETSI project.

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E-print AB, 2021