Application of airborne radiometric surveys for large-scale radon potential classification

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Contents

1 Data

1.1 Ireland (RoI and NI)

Read grid cells of 1km x 1 km (same grid cells where Ireland has population data just in case we would need to link the RP radon map with population density).

```
Grids1km <- read_sf("Rdata/Grids1km/IR_NI_Grids_1km.shp")

Ireland <- Grids1km %>%
  group_by(Id) %>%
  summarise(N = n()) %>%
  ungroup()
```

1.2 Airborne (eU)

We have aggregated the initial data (with a resolution of 50 x 50 m; i.e. *Tellus radiometric merged grd, tiff and gxf (981.9 MB)* - Tellus) in grid cells of 1x1 km (after running a separate script, i.e. *Average_eU_grid_cells_1km2*). Here we read directly the aggregated map (*eU_Grids1km*), and we use the initial map (*eU_50m*) only for comparison (Figure 3).

```
eU<-"Rdata/Radiometrics/RAD_MERGED_GRIDS/GXF/Tellus_RAD_eU_MERGE_2019.gxf"
eU_50m  <- read_stars(eU) %>% st_set_crs(st_crs(Grids1km))

eU_Grids1km <- read_sf("Rresults/eU_Grids1km.shp")

eU_50m_tbl <- eU_50m %>%
#as.tbl_cube() %>%
as.data.frame() %>%
drop_na()

cbind(tibble(Resolution = c("50 m","1 km")),
      rbind(summary(eU_50m_tbl$Tellus_RAD_eU_MERGE_2019.gxf),
            summary(eU_Grids1km$eU_AM)
      )
) %>%
  mutate_if(is.numeric, ~round(., 2)) %>%
  knitr::kable(format = "latex", booktabs=TRUE) %>%
  kableExtra::kable_styling(position = "center")
```

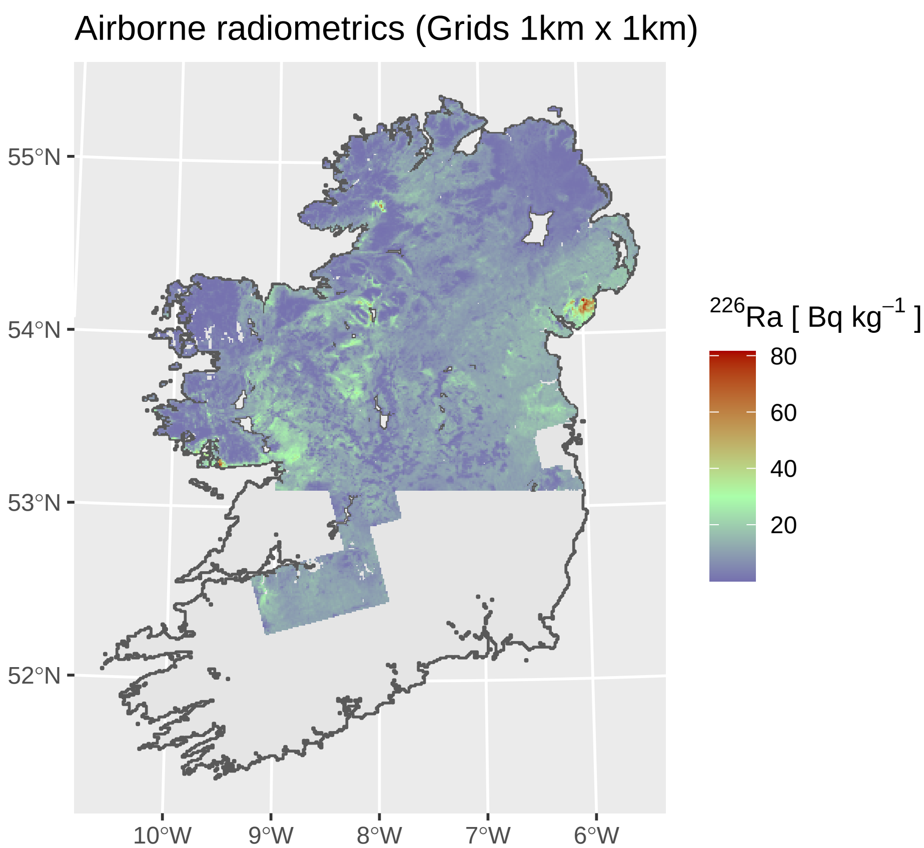
Resolution	Min.	1st Qu.	Median	Mean	3rd Qu.	Max.
50 m	0	0.33	0.72	0.71	0.99	10.0
1 km	0	0.39	0.73	0.73	0.97	6.6

1.3 Radium predictions (Ra-226)

- Radium (Ra-226) activity in Bq/kg
- Equilibrium with eU (1 ppm eU = 12.35 Bq/kg)

```
eU_Grids1km <- eU_Grids1km %>%
  mutate(AM_Ra226 = 12.35*eU_AM,
         SD_Ra226 = 12.35*eU_SD)
```

```
ggplot() +
  geom_sf(data = Ireland) +
  geom_sf(data = eU_Grids1km, aes(fill = AM_Ra226), colour = NA) +
  scale_fill_gradient2(
  name = expression(""^226*Ra * " [ " * "Bq "* kg^-1 * " ]"),
  midpoint = 30,
  low    = "#0000AA",
  mid    = "#AAFFAA",
  high   = "#AA0000") +
  ggtitle("Airborne radiometrics (Grids 1km x 1km)")
```



1.4 All-Ireland Quaternary map (scale 1:500.000)

```
QG <- read_sf("Rdata/GSI_Quaternary_500k/QG_500k.shp") %>%
  mutate(Sediment_5 = as_factor(Sediment_5)) %>%
  group_by(Sediment_5) %>%
  summarise(N = n(),
            area_sq_km = sum(area_sq_km),
            label = first(label)) %>%
  ungroup()
```

1.5 Aquifer Type

```
AQ <- read_sf("Rdata/Groundwater/IRL_AQUIFER_BEDROCK_ITM.shp") %>%
    rmapshaper::ms_simplify(keep = 0.01, keep_shapes = TRUE) %>%
    st_make_valid()

  Karst <- AQ %>%
    group_by(AQUIFERCAT) %>%
    summarize(AQUIFER_DE = first(AQUIFER_DE)) %>%
    ungroup() %>%
    filter(AQUIFERCAT != "Lake" & AQUIFERCAT != "Unclas") %>%
    mutate(Karst = case_when(
      AQUIFERCAT == "Lk"      ~ "TRUE",
      AQUIFERCAT == "LkNI"    ~ "TRUE",
      AQUIFERCAT == "Ll"      ~ "FALSE",
      AQUIFERCAT == "LlNI"    ~ "FALSE",
      AQUIFERCAT == "Lm"      ~ "FALSE",
      AQUIFERCAT == "LmNI"    ~ "FALSE",
      AQUIFERCAT == "NI_Un*" ~ "FALSE",
      AQUIFERCAT == "PINIl"   ~ "FALSE",
      AQUIFERCAT == "Pl"      ~ "FALSE",
      AQUIFERCAT == "PlNI"    ~ "FALSE",
      AQUIFERCAT == "Pu"      ~ "FALSE",
      AQUIFERCAT == "PuNI"    ~ "FALSE",
      AQUIFERCAT == "Rf"      ~ "FALSE",
      AQUIFERCAT == "Rf/Rk"   ~ "TRUE" ,
      AQUIFERCAT == "RfNI"    ~ "FALSE",
      AQUIFERCAT == "Rk"      ~ "TRUE",
      AQUIFERCAT == "Rkc"     ~ "TRUE",
      AQUIFERCAT == "RkcNI"   ~ "TRUE",
      AQUIFERCAT == "Rkd"     ~ "TRUE",
      AQUIFERCAT == "RkNI"    ~ "TRUE",
      TRUE ~ as.character(AQUIFERCAT))
    ) %>%
```

```r
  group_by(Karst) %>%
  summarise(N = n()) %>%
  ungroup()
```

1.6 Subsoil permeability

Load *SP_GW_naQG.shp* file; output of the R-script: *SP_Groundwater_recharge.R*.

```r
SP <- read_sf("Rresults/Soil_Permeability/SP_GW_naQG.shp") %>%
  rename(Perm = PERM) %>%
  mutate(Perm = factor(Perm,
                       levels = c("H", "M", "L"),
                       ordered = TRUE))
```

Rasterize: convert Subsoil Permeability shapefile (SP) to a raster file with a resolution of 1km x 1 km).

a) Make grids equal to the cell grids of eU data (1km x 1km)

```r
grd_res_x <- 1000 # m
grd_res_y <- 1000 # m
grd <- st_as_stars(st_bbox(eU_Grids1km),
   nx = (st_bbox(eU_Grids1km)[3] - st_bbox(eU_Grids1km)[1]) / grd_res_x,
   ny = (st_bbox(eU_Grids1km)[4] - st_bbox(eU_Grids1km)[2]) / grd_res_y,
   xlim = c(st_bbox(eU_Grids1km)[1], st_bbox(eU_Grids1km)[3]),
   ylim = c(st_bbox(eU_Grids1km)[2], st_bbox(eU_Grids1km)[4]),
   values = NA_real_)
```

b) Rasterize

```r
SP_Raster <- stars::st_rasterize(SP["Perm"], grd) %>%
  mutate(Perm_class = case_when(
    ID == 1   ~ "H",
    ID == 2   ~ "H",
    ID == 3   ~ "H",
    ID == 4   ~ "H",
    ID == 5   ~ "H",
    ID == 6   ~ "M",
    ID == 7   ~ "M",
    ID == 8   ~ "M",
    ID == 9   ~ "M",
    ID == 10  ~ "M",
    ID == 11  ~ "M",
    ID == 12  ~ "L",
    ID == 13  ~ "L",
    ID == 14  ~ "L",
```

```r
    ID == 15  ~ "L",
    is.na(ID) ~ "NA" )) %>%
  mutate(Perm_class = factor(Perm_class,
                             levels = c("H", "M", "L", "NA"),
                             ordered = TRUE)) %>%
  st_crop(eU_Grids1km)
```

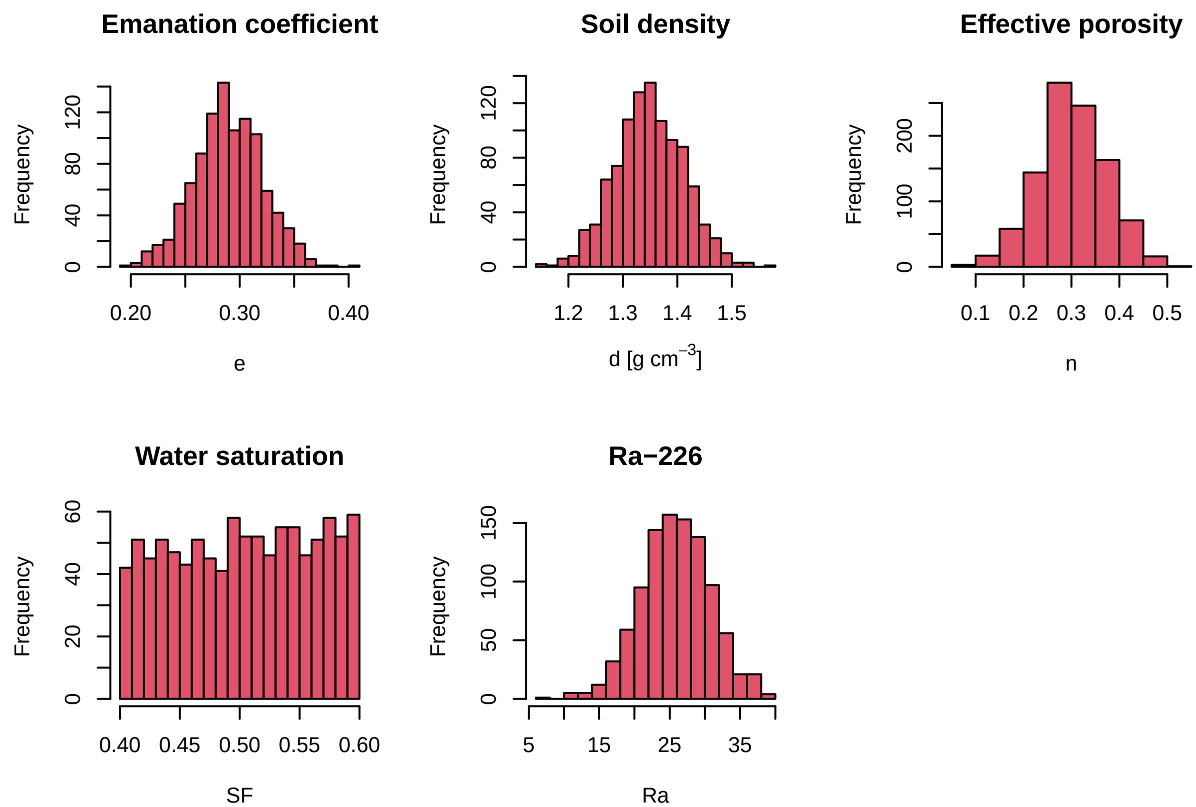
2 Results

2.1 Soil-gas radon predictions based on airborne radiometrics (eU)

a) Soil Parameters:

- e ~ N(0.29, 0.03); Yu et al 1993: Range approx. from 0.13 to 0.37
- d ~ N(1.35, 0.06); Yu et al 1993: Range dry density 1.1 - 1.6; Creamer et al 2016 (Irish soils) bulk density mainly 1.1-1.3 and >1.4 g m-3
- n ~ N(0.30, 0.07); Yu et al 1993: Effective Porosity range approx. from 0.02 to 0.53
- Water influence (SF) ~ uniform distribution on the interval from min (0.4) to max (0.6)

```r
set.seed(1) # Make the analysis reproducible

e  <- rnorm(1000, mean = 0.29, sd = 0.03)
d  <- rnorm(1000, mean = 1.35, sd = 0.06)
n  <- rnorm(1000, mean = 0.30, sd = 0.07)
SF <- runif(1000, min = 0.4, max = 0.6)
id <- "g90164"
Ra <- rnorm(1000,
            mean = eU_Grids1km[eU_Grids1km$SP_ID == id, ]$AM_Ra226,
            sd   = eU_Grids1km[eU_Grids1km$SP_ID == id, ]$SD_Ra226
            )

par(mfrow = c(2,3))
hist(e, col = 2, breaks = 15, main = "Emanation coefficient")
hist(d, col = 2, breaks = 15, main = "Soil density",
     xlab = expression(d * " [" *g *" "* cm^-3 * "]"))
hist(n, col = 2, breaks = 15, main = "Effective porosity")
hist(SF, col = 2, breaks = 15, main = "Water saturation")
hist(Ra, col = 2, breaks = 15, main = "Ra-226")
```



b) Simulations

Radon concentration in soil-gas:

$$C_{Rn}[kBqm^{-3}] = \frac{C_{Ra}[Bqkg^{-1}] \times e \times \rho[gm^{-3}]}{n} \times \frac{1}{1 - S_F + S_F K_{W/Air}}$$

```
set.seed(1) # Make the analysis reproducible

rep <- 1000
SG_MCS <- matrix(NA, nrow = dim(eU_Grids1km)[1], ncol = rep+1)
for (i in 1:rep) {
  Ra <- rnorm(dim(eU_Grids1km)[1],
              eU_Grids1km$AM_Ra226,
              eU_Grids1km$SD_Ra226)
  e  <- rnorm(dim(eU_Grids1km)[1], 0.29, 0.03)
  d  <- rnorm(dim(eU_Grids1km)[1], 1.35, 0.06)
  n  <- rnorm(dim(eU_Grids1km)[1], 0.30, 0.07)
  SF <- runif(dim(eU_Grids1km)[1], 0.40, 0.60)
  SG_MCS[ ,i+1] <- (Ra*e*d/n)*(1/(1-SF+(0.25*SF)))
}
SG_MCS <- as.data.frame(SG_MCS)
```

```r
names(SG_MCS) <- c("SP_ID", c(1:rep))
SG_MCS$SP_ID <- eU_Grids1km$SP_ID

SG_MCS <- as_tibble(SG_MCS)
SG_MCS
```

c) Percentiles:

```r
SG_MCS_T <- t(SG_MCS[,2:rep])

SG_MCS_P95 <- matrix(NA, nrow = dim(eU_Grids1km)[1], ncol = 8)
for (i in 1:dim(eU_Grids1km)[1]) {
  SG_MCS_P95[i,2] <- quantile(SG_MCS_T[,i], 0.025)
  SG_MCS_P95[i,3] <- quantile(SG_MCS_T[,i], 0.05)
  SG_MCS_P95[i,4] <- quantile(SG_MCS_T[,i], 0.25)
  SG_MCS_P95[i,5] <- quantile(SG_MCS_T[,i], 0.50)
  SG_MCS_P95[i,6] <- quantile(SG_MCS_T[,i], 0.75)
  SG_MCS_P95[i,7] <- quantile(SG_MCS_T[,i], 0.95)
  SG_MCS_P95[i,8] <- quantile(SG_MCS_T[,i], 0.975)
}

SG_MCS_P95 <- as.data.frame(SG_MCS_P95)
names(SG_MCS_P95) <- c("SP_ID","Rn_P025","Rn_P05","Rn_P25",
                       "Rn_P50","Rn_P75","Rn_P95","Rn_P975")
SG_MCS_P95$SP_ID <- SG_MCS$SP_ID
SG_MCS_P95 <- as_tibble(SG_MCS_P95)

eU_Grids1km <- left_join(eU_Grids1km, SG_MCS_P95, by = "SP_ID")
eU_Grids1km
```

d) Soil gas radon classification based on eU (Rn predictions - percentile 75%):

- Extremely High: >= 100
- Very High: 70 - 100
- High: 50 - 70
- Moderate: 30 - 50
- Low: 10 - 30
- Very Low: < 10

```r
eU_Grids1km <- eU_Grids1km %>%
  mutate(Rn_class = case_when(
    Rn_P75 >= 100               ~ "EH",
    Rn_P75 >= 70 & Rn_P75 < 100 ~ "VH",
    Rn_P75 >= 50 & Rn_P75 <  70 ~  "H",
    Rn_P75 >= 30 & Rn_P75 <  50 ~  "M",
    Rn_P75 >= 10 & Rn_P75 <  30 ~  "L",
```

```
    Rn_P75 <  10                ~ "VL",
    TRUE ~ as.character(Rn_P75)
  )
  ) %>%
  mutate(Rn_class = factor(Rn_class,
                           levels = c("EH", "VH", "H", "M", "L", "VL"),
                           ordered = TRUE
  )
  )
```

2.2 Radon Potential map

a) Merge Rn_class and SP in one dataset (by grids of 1km x 1km):

- Create a dataframe with *Rn* values (Rn_class)
- Transform SP_Raster to points (*Perm* value at the centroid)
- Add points to the Grids1km (st_join - inner join)

b) Assign values of Rn and Perm
c) Estimate RP

$$RP = \frac{C_R n}{(-log_{10}(k) - 10)}$$

d) RP classification (RP_class)

- High: RP   30
- Moderate-High: 22.5 <= RP < 30
- Moderate-Low: 10 <= RP < 22.5
- Low: RP < 10

```
RP_Grids <- eU_Grids1km %>%
  select(Rn_class)

SP_Points <- st_as_sf(SP_Raster, as_points = TRUE, merge = FALSE) %>%
  drop_na() %>%
  select(Perm_class) %>%
  rename(Perm = Perm_class)

RP_Grids <- st_join(RP_Grids, SP_Points,
                    join = st_intersects,
                    left = FALSE
)

RP_Grids  <-  RP_Grids %>%
  mutate(Rn = case_when(
```

```
    Rn_class == "EH" ~ 110,
    Rn_class == "VH" ~  85,
    Rn_class == "H"  ~  65,
    Rn_class == "M"  ~  50,
    Rn_class == "L"  ~  25,
    Rn_class == "VL" ~   5
  )) %>%
  mutate(logk = case_when(
    Perm == "H" ~ 11,
    Perm == "M" ~ 12,
    Perm == "L" ~ 13
  )) %>%
  mutate(RP = (Rn/(logk - 10))) %>%
  mutate(RP_class = case_when(
    RP >= 30                  ~  "H",
    RP >= 22.5 &  RP <  30    ~ "MH",
    RP >= 10   &  RP <  22.5 ~ "ML",
    RP <  10                  ~  "L"
    )) %>%
  mutate(RP_class = factor(RP_class,
                          levels = c("H", "MH", "ML", "L"),
                          ordered = TRUE)
  )


write_sf(RP_Grids, "Rresults/RP_Grids1km.shp")
```

3 In-situ soil-gas measurements

```
Soil_Rn <- readxl::read_xlsx("Rdata/data.xlsx",
                            sheet = "DATA (MeanReplica_NoNA)") %>%
  rename(SoilRn = "Rn-222") %>%
  select(Grid, Point, Day, X_ITM, Y_ITM, SoilRn) %>%
  st_as_sf(coords = c("X_ITM", "Y_ITM")) %>%
  st_set_crs(st_crs(eU_Grids1km)) %>%
  st_intersection(eU_Grids1km)
```

Summary

```
SG_Sum <- Soil_Rn %>%
  group_by(Grid) %>%
  summarize(N = n(),
          Rn_Min = min(SoilRn),
```

```
            Rn_GM = exp(mean(log(SoilRn))),
            Rn_AM = mean(SoilRn),
            Rn_Max = max(SoilRn),
            Rn_RMD = 100 * mean(abs(SoilRn - mean(SoilRn)))/mean(SoilRn),
            Ra_AM = mean(AM_Ra226),
            Ra_SD = mean(SD_Ra226),
            Rn_P025 = mean(Rn_P025),
            Rn_P50 = mean(Rn_P50),
            Rn_P75 = mean(Rn_P75),
            Rn_P975 = mean(Rn_P975)
            ) %>%
  ungroup()

SG_Sum %>%
  mutate_if(is.numeric, ~round(., 0)) %>%
  as_tibble() %>%
  select(-geometry) %>%
  knitr::kable(format = "latex", booktabs=TRUE) %>%
  kableExtra::kable_styling(latex_options = "scale_down")
```

Grid	N	Rn_Min	Rn_GM	Rn_AM	Rn_Max	Rn_RMD	Ra_AM	Ra_SD	Rn_P025	Rn_P50	Rn_P75	Rn_P975
G56114	9	16	67	80	125	43	6	3	0	12	17	30
G57626	10	49	108	113	170	23	14	1	17	29	35	58
G64863	11	85	145	155	310	30	19	2	23	39	48	77
G69054	9	20	37	40	69	33	14	1	18	29	35	52
G70565	9	13	33	37	65	38	9	1	12	19	23	38
G70947	9	13	36	39	59	32	13	2	16	27	33	54
G72081	9	17	51	60	114	46	12	1	15	24	30	50
G73606	8	76	179	196	264	33	27	4	30	55	69	111
G78164	10	79	122	128	191	29	19	2	23	39	48	76
G78544	10	42	102	120	256	50	23	3	29	47	58	89
G90163	9	31	111	138	335	51	40	4	50	84	103	164
G98159	10	16	94	121	260	55	30	4	37	63	79	129
G98929	10	60	142	163	280	43	36	4	45	77	93	153

4 Indoor radon concentration

```
InRn <- readxl::read_xls("Rdata/EPA/XY_InRn_EPA_Old_New.xls") %>%
  st_as_sf(coords = c("X_ITM", "Y_ITM")) %>%
  st_set_crs(st_crs(RP_Grids)) %>% #IRENET95/Irish Transverse Mercator
  mutate(Case = if_else(Rn > 200, TRUE, FALSE)) %>%
  rename(InRn    = Rn)
```

```
Sum_New <- tibble(N = length(InRn[InRn$Survey=="New",]$InRn),
                  Prop = 100*mean(InRn[InRn$Survey=="New",]$Case),
                  Min = min(InRn[InRn$Survey=="New",]$InRn),
                  Q1 = quantile(InRn[InRn$Survey=="New",]$InRn, prob = 0.25),
```

```r
                Median = median(InRn[InRn$Survey=="New",]$InRn),
                Mean = mean(InRn[InRn$Survey=="New",]$InRn),
                Q3 = quantile(InRn[InRn$Survey=="New",]$InRn, prob = 0.75),
                Max = max(InRn[InRn$Survey=="New",]$InRn),
                SD = sd(InRn[InRn$Survey=="New",]$InRn),
                GM = exp(mean(log(InRn[InRn$Survey=="New",]$InRn))),
                GSD = exp(sd(log(InRn[InRn$Survey=="New",]$InRn)))
)

Sum_Old <- tibble(N = length(InRn[InRn$Survey=="Old",]$InRn),
                Prop = 100*mean(InRn[InRn$Survey=="Old",]$Case),
                Min = min(InRn[InRn$Survey=="Old",]$InRn),
                Q1 = quantile(InRn[InRn$Survey=="Old",]$InRn, prob = 0.25),
                Median = median(InRn[InRn$Survey=="Old",]$InRn),
                Mean = mean(InRn[InRn$Survey=="Old",]$InRn),
                Q3 = quantile(InRn[InRn$Survey=="Old",]$InRn, prob = 0.75),
                Max = max(InRn[InRn$Survey=="Old",]$InRn),
                SD = sd(InRn[InRn$Survey=="Old",]$InRn),
                GM = exp(mean(log(InRn[InRn$Survey=="Old",]$InRn))),
                GSD = exp(sd(log(InRn[InRn$Survey=="Old",]$InRn)))
)

Sum <- rbind(Sum_New, Sum_Old)

Sum %>%
  mutate_if(is.numeric, ~round(., 2)) %>%
  knitr::kable(format = "latex", booktabs=TRUE) %>%
  kableExtra::kable_styling(position = "center")
```

N	Prop	Min	Q1	Median	Mean	Q3	Max	SD	GM	GSD
6859	11.90	5.0	31.00	55	109.71	110.00	6240	204.47	62.68	2.58
31910	12.46	5.7	33.19	59	115.32	115.68	9714	219.72	65.76	2.59

4.1 t-test

```r
t.test(InRn[InRn$Survey == "New",]$InRn,
       InRn[InRn$Survey == "Old",]$InRn)

t.test(log10(InRn[InRn$Survey == "New",]$InRn),
       log10(InRn[InRn$Survey == "Old",]$InRn))
```

4.2 Binomial

```
xtabs(~ Case , data = InRn[InRn$Survey == "New", ])
  binom.test(c(816,6043))           # Prob 11.89% (11.14% - 12.69%)

xtabs(~ Case , data = InRn[InRn$Survey=="Old",])
  binom.test(c(3975,27935))           # Prob 12.45% (12.10% - 12.82%)

prop.test(c(816,3975),c(816+6043,3975+27935))
fisher.test(rbind(c(816,6043), c(3975,27935)), alternative="less")
```

4.3 Indoor radon vs. RP map

```
InRn_RP <- st_join(InRn, RP_Grids, join = st_intersects) %>%
  drop_na() %>%
  mutate(RP_class = factor(RP_class, ordered = TRUE,
                           levels = c("L", "ML", "MH", "H")))

# Intersection with 30m tolerance
  # InRn_RP <- st_join(InRn, RP_Grids, join = st_nn, maxdist = 30) %>%
  #   drop_na() %>%
  #   mutate(RP_class = factor(RP_class, ordered = TRUE,
  #                            levels = c("L", "ML", "MH", "H")))
```

```
# GM and GSD for each RP classification
  SM <- InRn_RP %>%
    group_by(RP_class) %>%
    summarize(GM  = exp(mean(log(InRn))),
              GSD = exp(sd(log(InRn)))
              ) %>%
    ungroup() %>%
    as_tibble() %>%
    mutate(RP_class = factor(RP_class, ordered = TRUE,
                             levels = c("L", "ML", "MH", "H"))) %>%
    arrange(RP_class) %>%
    select(RP_class, GM, GSD)

# Cases (InRn > 200 Bq/m3)
  CM <- xtabs(~ Case + RP_class , data = InRn_RP) %>%
    as_tibble() %>%
    spread(key = Case, value = n) %>%
    mutate(RP_class = factor(RP_class, ordered = TRUE,
                             levels = c("L", "ML", "MH", "H"))) %>%
    arrange(RP_class) %>%
```

```r
    rename(No_Case = "FALSE",
           Case =  "TRUE") %>%
    mutate(Total = No_Case + Case)

# Binomial distribution
  BTM <- matrix(NA, 4, 3)
    for (i in 1:4) {
      bt <- binom.test(CM[i,]$Case, CM[i,]$Total)
      BTM[i, 1] <- 100 * bt$estimate
      BTM[i, 2] <- 100 * bt$conf.int[1]
      BTM[i, 3] <- 100 * bt$conf.int[2]
    }
  BTM <- BTM %>%
    as_data_frame() %>%
    rename(Prob = V1,
           LCI  = V2,
           UCI  = V3)

# Total
  TM <- tibble(RP_class = "Total",
               GM       = exp(mean(log(InRn_RP$InRn))),
               GSD      = exp(sd(log(InRn_RP$InRn))),
               No_Case  = length(filter(InRn_RP, Case == FALSE)$Case),
               Case     = length(filter(InRn_RP, Case == TRUE)$Case),
               Total    = length(filter(InRn_RP)$Case)
  ) %>%
    mutate(Prob = 100 * binom.test(Case, Total)$estimate,
           LCI  = 100 * binom.test(Case, Total)$conf.int[1],
           UCI  = 100 * binom.test(Case, Total)$conf.int[2])

Table_6 <- cbind(SM, select(CM, -RP_class), BTM) %>%
    rbind(TM) %>%
    mutate_if(is.numeric, ~round(., 2))

Table_6 %>%
    knitr::kable(format = "latex", booktabs = TRUE) %>%
    kableExtra::kable_styling(position = "center")
```

RP_class	GM	GSD	No_Case	Case	Total	Prob	LCI	UCI
L	47.49	2.36	2186	142	2328	6.10	5.16	7.15
ML	57.90	2.48	6603	714	7317	9.76	9.09	10.46
MH	70.61	2.65	4549	759	5308	14.30	13.37	15.27
H	98.65	3.01	1349	486	1835	26.49	24.48	28.57
Total	63.58	2.63	14687	2101	16788	12.51	12.02	13.02

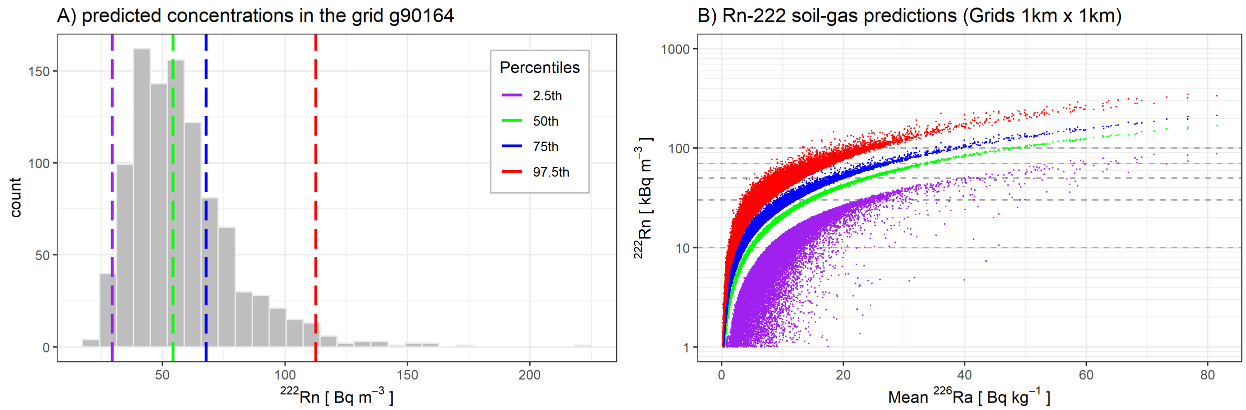
5 Figures

5.1 Figure 1

a) Example of the predicted soil-gas radon concentration in the grid G90164; b) percentiles 2.5%, 50%, 75%, and 97.5% of the simulated values for all grids covered by the Tellus gamma-ray spectrometry airborne radiometrics

```
Row <- as.numeric(rownames(SG_MCS_P95[SG_MCS_P95$SP_ID == id, ]))

cuts <- data.frame(Per = c("2.5th", "50th", "75th", "97.5th"),
                   vals = c(SG_MCS_P95[SG_MCS_P95$SP_ID == id, ]$Rn_P025,
                            SG_MCS_P95[SG_MCS_P95$SP_ID == id, ]$Rn_P50,
                            SG_MCS_P95[SG_MCS_P95$SP_ID == id, ]$Rn_P75,
                            SG_MCS_P95[SG_MCS_P95$SP_ID == id, ]$Rn_P975
                   ),
                   stringsAsFactors = FALSE)

dat_ex <- SG_MCS[SG_MCS$SP_ID == id, ] %>%
  select(-1) %>%
  t() %>%
  as_tibble()

p1 <- ggplot(data = dat_ex, aes(V1)) +
  geom_histogram(fill = "gray", color = "#e9ecef") +
  xlab(expression(""^222*Rn * " [ " * "Bq "* m^-3 * " ]")) +
  geom_vline(data = cuts,
             aes(xintercept = vals,
                 colour = Per),
             linetype = "longdash",
             size = 1,
             show.legend = T,
             key_glyph = draw_key_smooth) +
  scale_color_manual(name = "Percentiles",
                     values = c("purple",
                                "green",
                                "blue",
```

```
                                  "red")) +
  ggtitle(paste0("A) ", "predicted concentrations in the grid ",
                 SG_MCS_P95[SG_MCS_P95$SP_ID == id, ]$SP_ID)) +
  theme_bw() +
  theme(legend.key = element_rect(fill = NA),
        legend.background = element_rect(color = "gray",
                                         linetype = "solid"),
        legend.position = c(.95, .95),
        legend.justification = c("right", "top"),
        legend.box.just = "right",
        legend.margin = margin(6, 6, 6, 6))


breaks <- c(1, 10, 100, 1000)
minor_breaks <- rep(1:9, 21)*(10^rep(-10:10, each = 9))
p2 <- ggplot(eU_Grids1km) +
  geom_hline(yintercept = c(10, 30, 50, 70, 100),
             linetype = "dashed", color = "darkgrey", size = 0.5) +
  geom_point(aes(x = AM_Ra226, y = Rn_P025),
             color = "purple", size = 0.1) +
  geom_point(aes(x = AM_Ra226, y = Rn_P50),
             color = "green", size = 0.1) +
  geom_point(aes(x = AM_Ra226, y = Rn_P75),
             color = "blue", size = 0.1) +
  geom_point(aes(x = AM_Ra226, y = Rn_P975),
             color = "red", size = 0.1) +
  ggtitle("B) Rn-222 soil-gas predictions (Grids 1km x 1km)") +
  xlab(expression("Mean "*""^226*Ra * " [ " * "Bq "* kg^-1 * " ]")) +
  ylab(expression(""^222*Rn * " [ " * "kBq "* m^-3 * " ]")) +
  scale_y_log10(breaks = breaks,
                minor_breaks = minor_breaks,
                limits = c(1,1000)) +
  theme_bw()

  ggsave(file = "Rresults/Figure_1.png",
         gridExtra::arrangeGrob(p1, p2, nrow = 1),
       width = 30,
       height = 10,
       units = "cm" )
```

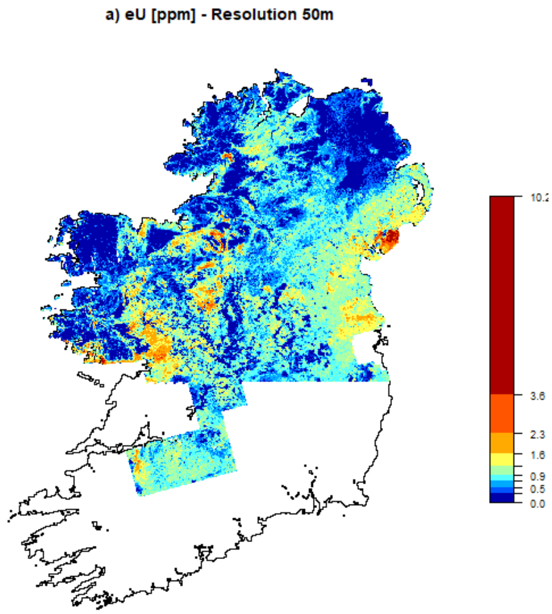


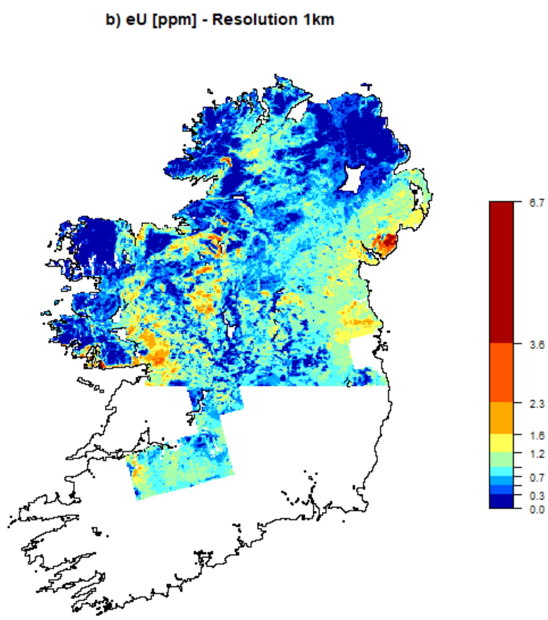
5.2 Figure 2

Equivalent uranium concentration (ppm)

```
  #round(BAMMtools::getJenksBreaks(eU_Grids1km$eU_AM, 10, subset = NULL), 1)

  colpal <- colorRamps::matlab.like(9)
  #colpal <- viridis::viridis(9)

  grDevices::png("Rresults/Figure_2a.png",
                 width  = 550,
                 height = 650,
                 unit = "px")

  nf <- layout(matrix(1:2, ncol = 2), widths = c(0.8, lcm(2)))
 {brks <- c(0.0, 0.3, 0.5, 0.7, 0.9, 1.2, 1.6, 2.3, 3.6, 10.2)
   plot(st_geometry(Ireland),
        reset = FALSE,
        main = "a) eU [ppm] - Resolution 50m")
   plot(eU_50m,
         main = "",
         col = colpal,
         breaks = brks,
         at = brks,
         add = TRUE,
         reset = FALSE,
         )
   .image_scale(brks,
               col = colpal,
               key.length = lcm(10),
               key.pos = 4,
               breaks = brks,
               at = brks,
```

```
             add.axis = F)
axis(4,at = brks, las = 2, cex.axis = 0.75)
}
dev.off()

grDevices::png("Rresults/Figure_2b.png",
               width  = 550,
               height = 650,
               unit = "px")

nf <- layout(matrix(1:2, ncol = 2), widths = c(0.8, lcm(2)))
{brks <- c(0.0, 0.3, 0.5, 0.7, 0.9, 1.2, 1.6, 2.3, 3.6, 6.7)
plot(st_geometry(Ireland),
     reset = FALSE,
     main = "b) eU [ppm] - Resolution 1km",)
plot(eU_Grids1km["eU_AM"], border=NA,
     main = "",
     pal = colpal,
     breaks = brks,
     at = brks,
     add = TRUE,
     reset = FALSE,
     )
.image_scale(brks,
             col = colpal,
             key.length = lcm(10),
             key.pos = 4,
             breaks = brks,
             at = brks,
             add.axis = FALSE)
axis(4,at = brks, las = 2, cex.axis = 0.75)
}
dev.off()
```

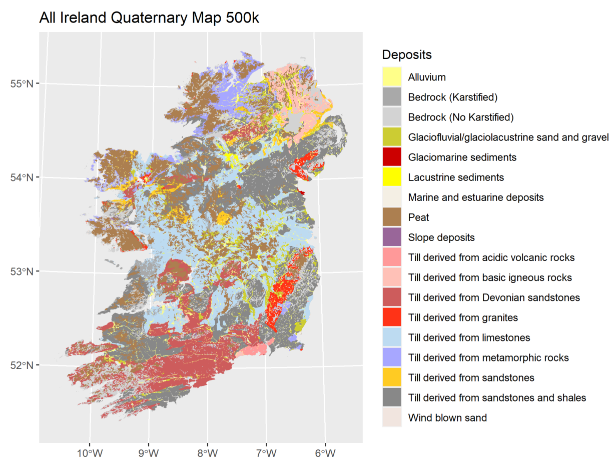


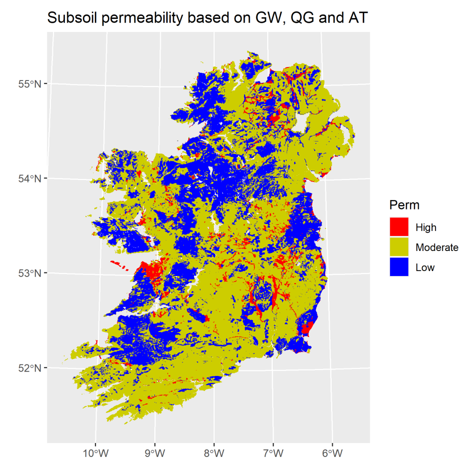


5.3 Figure 3

Subsoil permeability map of the island of Ireland (based on the All-Ireland Quaternary map)

```r
Karst <- Karst %>% mutate(Bedrock = if_else(Karst == TRUE,
                                             "Bedrock (Karstified)",
                                             "Bedrock (No Karstified)"))

QG_Colors <- c("Bedrock (Karstified)"    = "darkgrey",
               "Bedrock (No Karstified)" = "lightgrey",
               "Alluvium" = "#ffff89",
               "Glaciofluvial/glaciolacustrine sand and gravel" = "#CCCC33",
               "Glaciomarine sediments" = "#CC0000",
               "Lacustrine sediments" = "yellow",
               "Marine and estuarine deposits" = "#f4efe4",
               "Peat" = "#ac7f50",
               "Slope deposits" = "#996699",
               "Till derived from acidic volcanic rocks" = "#FF9999",
               "Till derived from basic igneous rocks" = "#ffc1b7",
               "Till derived from Devonian sandstones" = "#CD5C5C",
               "Till derived from granites" = "#ff3317",
               "Till derived from limestones" = "#bddbf1",
               "Till derived from metamorphic rocks" = "#a7a7ff",
               "Till derived from sandstones" = "#ffcb23",
               "Till derived from sandstones and shales" = "#888888",
               "Wind blown sand" = "#f1e5df"
)

p1 <- ggplot() +
  geom_sf(data = Karst, aes(fill = Bedrock), colour = NA) +
  geom_sf(data = QG, aes(fill = Sediment_5), colour = NA) +
  scale_fill_manual(name = "Deposits", values = QG_Colors) +
  ggtitle("All Ireland Quaternary Map 500k")

p2 <- ggplot() +
  geom_sf(data = SP, aes(fill = Perm), colour = NA) +
  scale_fill_manual(name = "Perm",
                    labels = c("High", "Moderate", "Low"),
                    values = c("red", "yellow3", "blue")) +
  ggtitle("Subsoil permeability based on GW, QG and AT")

ggsave(file = "Rresults/Figure_3.png",
       gridExtra::arrangeGrob(p1, p2, nrow = 1),
     width = 38,
     height = 14,
     units = "cm")
```



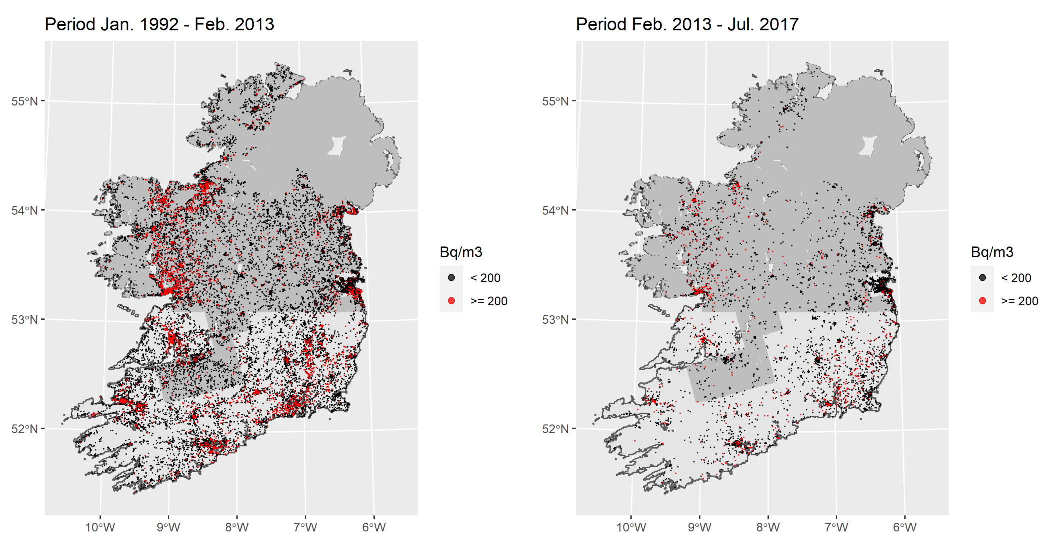


5.4 Figure 4:

Indoor radon measurements from old survey (Jan. 1992 – Feb. 2013; N = 31,910) and the new survey (Feb. 2013 – Jul. 2017; N = 6,859). Grey area: part covered by the Tellus airborne survey illustrated in this study. Note that no geolocated indoor radon data are available for Northern Ireland, as these are held by Public Health England and are not available for this study.

```r
p1 <- ggplot() +
  geom_sf(data = Ireland) +
  geom_sf(data = RP_Grids, colour = "grey") +
  geom_sf(data = filter(InRn, Survey == "Old"),
          aes(fill = Case, color = Case),
          size = 0.1,
          alpha = 0.75) +
  scale_fill_manual(name = "Bq/m3",
                    labels = c("< 200",
                               ">= 200"),
                    values = c("black",
                               "red")) +
  scale_color_manual(name = "Bq/m3",
                     labels = c("< 200",
                                ">= 200"),
                     values = c("black",
                                "red")) +
  guides(colour = guide_legend(override.aes = list(size = 2))) +
  labs(title = "Period Jan. 1992 - Feb. 2013")

p2 <- ggplot() +
  geom_sf(data = Ireland) +
  geom_sf(data = RP_Grids, colour = "grey") +
  geom_sf(data = filter(InRn, Survey == "New"),
```

```r
          aes(fill = Case, color = Case),
          size = 0.1,
          alpha = 0.75) +
  scale_fill_manual(name = "Bq/m3",
                    labels = c("< 200",
                               ">= 200"),
                    values = c("black",
                               "red")) +
  scale_color_manual(name = "Bq/m3",
                     labels = c("< 200",
                                ">= 200"),
                     values = c("black",
                                "red")) +
  guides(colour = guide_legend(override.aes = list(size = 2))) +
  labs(title = "Period Feb. 2013 - Jul. 2017")

ggsave(file = "Rresults/Figure_4.png",
       gridExtra::arrangeGrob(p1, p2, nrow = 1),
       width = 28,
       height = 14,
       units = "cm" )
```

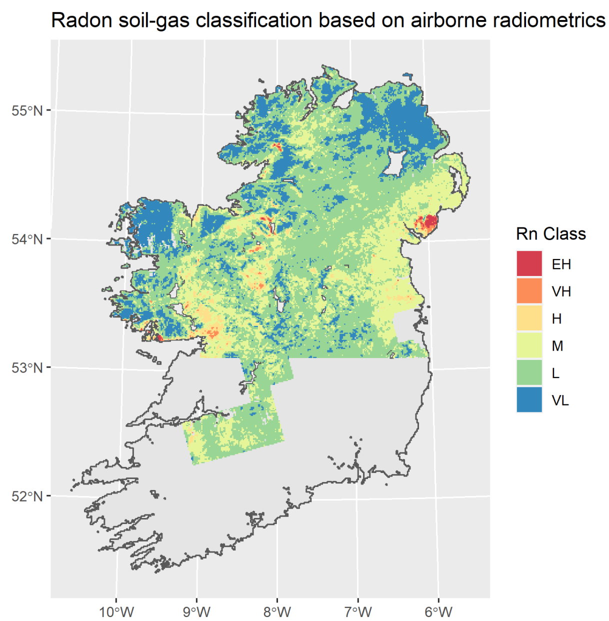


5.5 Figure 5

Radon soil-gas classification based on airborne radiometrics

```r
Col_Ramp <- RColorBrewer::brewer.pal(6, "Spectral")
p1 <- ggplot() +
  geom_sf(data = Ireland) +
  geom_sf(data = eU_Grids1km, aes(fill = Rn_class), colour = NA) +
```

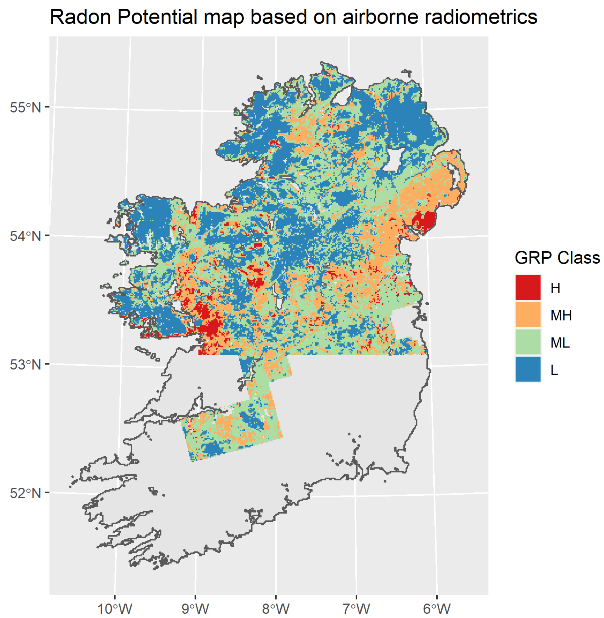
```
  scale_fill_manual(name = "Rn Class",
                    values = Col_Ramp) +
  ggtitle("Radon soil-gas classification based on airborne radiometrics")

ggsave(p1,
       file = "Rresults/Figure_5.png",
       width = 14,
       height = 14,
       units = "cm" )
```



5.6 Figure 6

Radon Potential map based on gamma-ray spectrometry airborne radiometrics and subsoil permeability

```
Col_Ramp <- RColorBrewer::brewer.pal(4, "Spectral")
p1 <- ggplot() +
  geom_sf(data = Ireland) +
  geom_sf(data = RP_Grids, aes(fill = RP_class), colour = NA) +
  scale_fill_manual(name = "GRP Class",
                    values = Col_Ramp) +
  ggtitle("Radon Potential map based on airborne radiometrics")

 ggsave(p1,
        file = "Rresults/Figure_6.png",
       width = 14,
       height = 14,
       units = "cm" )
```



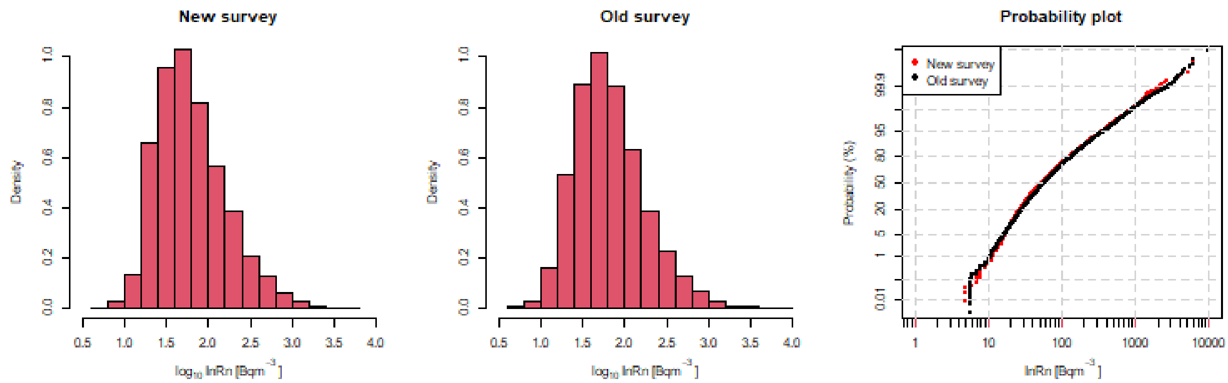
5.7 Figure 7

Histogram and probability plot of the new and old indoor radon measurements

```
df_New <- as.data.frame(qqnorm(log10(InRn[InRn$Survey=="New",]$InRn),
                               plot.it = FALSE))
df_Old <- as.data.frame(qqnorm(log10(InRn[InRn$Survey=="Old",]$InRn),
                               plot.it = FALSE))

grDevices::png("Rresults/Figure_7.png", width = 750, height = 250)

  par(mfrow = c(1, 3))
  {hist(log10(InRn[InRn$Survey == "New",]$InRn),
        xlim = c(0.5, 4),
        ylim = c(0,1),
        freq = FALSE,
        col = 2,
        main = "New survey",
        xlab = expression("log"[10] * " InRn" *  " [Bq" * m^-3 * " ]"))
   hist(log10(InRn[InRn$Survey=="Old",]$InRn),
        xlim = c(0.5, 4),
        ylim = c(0, 1),
        freq = FALSE,
        col = 2,
        main = "Old survey",
        xlab = expression("log"[10] * " InRn" *  " [Bq" * m^-3 * " ]"))

   plot(df_New$y,df_New$x,
```

```r
       ylim = c(-4, 4),
       xlim = c(0,4),
       axes = FALSE,
       frame.plot = TRUE,
       main = "Probability plot",
       xlab = "",
       ylab = "",
       pch = 19,
       col = "red",
       cex = 0.5)

points(df_Old$y, df_Old$x, col = "black", pch = 19, cex = 0.4)

ay<-c(0.01,0.1,1,5,20,50,80,95,99,99.9,99.999)
at<-qnorm(ay/100)
axis(2,labels=ay,at=at)
mtext("Probability (%)", side= 2, line=3,cex=0.7)

ax <- c(seq(0.1,1,0.1),
        seq(2,10,1),
        seq(20,100,10),
        seq(200,1000,100),
        seq(2000,10000,1000)
        )

atx <- log10(ax)
axis(1,labels = F, at = atx)

ax <- 10^(seq(-4, 4, 1))
atx <- log10(ax)
axis(1, labels = ax, at = atx, col.ticks = 2)

mtext(expression(" InRn" *  " [Bq" * m^-3 * " ]"),
      side = 1,
      line = 3,
      cex = 0.7)
abline(v = atx, h = at, lty = 2, lwd = 0.1, col = "lightgray")

legend("topleft",
       c("New survey","Old survey"),
       col = c("red","black"),
       pch = c(19,19),
       cex = 1,
       ncol = 1)
```

```
    }

dev.off()
```

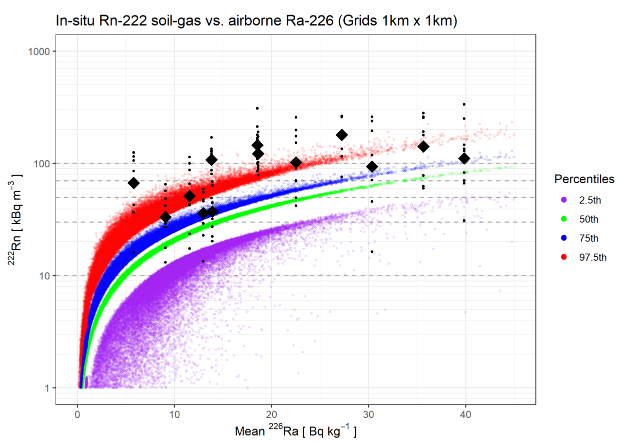


5.8 Figure 8

In-situ vs. airborne 226Ra concentration in soil (lines represent the trend lines of the percentiles 2.5th, 50th, 75th and 97.5th obtained in the simulation; the yellow points are the soil-gas radon samples; and the black points are the geometric mean of the radon measurements in each grid).

```
p1 <- ggplot(eU_Grids1km) +
geom_hline(yintercept = c(10, 30, 50, 70, 100),
           linetype = "dashed", color = "darkgrey", size = 0.5) +
geom_point(aes(x = AM_Ra226, y = Rn_P025, colour = "purple"),
           size = 0.7,
           alpha = 0.1) +
geom_point(aes(x = AM_Ra226, y = Rn_P50, colour = "green"),
           size = 0.7,
           alpha = 0.1) +
geom_point(aes(x = AM_Ra226, y = Rn_P75, colour = "blue"),
           size = 0.7,
           alpha = 0.1) +
geom_point(aes(x = AM_Ra226, y = Rn_P975, colour = "red"),
           size = 0.7,
           alpha = 0.1) +
scale_colour_identity(name = "Percentiles",
                      breaks = c("purple", "green", "blue", "red"),
                      labels = c("2.5th", "50th", "75th", "97.5th"),
                      guide = "legend") +
guides(colour = guide_legend(override.aes = list(size = 2, alpha = 1))) +
geom_point(data = Soil_Rn, aes(x = AM_Ra226, y = SoilRn),
```

```
size = 0.8,
             colour = "black") +
  geom_point(data = SG_Sum, aes(x = Ra_AM, y = Rn_GM),
             colour = "black",
             shape = 18,
             size = 5) +
  xlim(0, 45) +
  ggtitle(
    "In-situ Rn-222 soil-gas vs. airborne Ra-226 (Grids 1km x 1km)"
  ) +
  xlab(expression("Mean "*""^226*Ra * " [ " * "Bq "* kg^-1 * " ]")) +
  ylab(expression(""^222*Rn * " [ " * "kBq "* m^-3 * " ]")) +
  scale_y_log10(breaks = breaks,
                minor_breaks = minor_breaks,
                limits = c(1, 1000)) +
  theme_bw()

ggsave(p1,
       file = "Rresults/Figure_8.png",
       width = 20,
       height = 14,
       units = "cm" )
```



5.9 Figure 9

Boxplot of indoor radon measurements (InRn) in each Radon Potential class (L: Low; ML: Moderate-Low; MH: Moderate-High; and H: High). Boxes widths are proportional to the square-roots of the number of observations in each group

```
p1 <- ggplot(InRn_RP, aes(x = RP_class, y = log10(InRn))) +
  geom_boxplot(notch = TRUE, fill = "red") +
  ylab("log10(InRn)") +
  xlab("GRP")
```

```
ggsave(p1,
       file = "Rresults/Figure_9.png",
       width = 7,
       height = 7,
       units = "cm" )
```