Monitoring of natural radionuclides in soils as a tool for precision farming - methodical aspects

Michael Tauchnitz[1], Detlev Degering[2], Carsten Pretzschner[1], Thomas Wonik[3], Juergen Boess[4]

[1] TU Bergakademie Freiberg, Institute of Applied Geophysics, Gustav-Zeuner-Straße 12, D-09599 Freiberg/Sa., Germany
[2] Saxon Academy of Sciences at Leipzig, Quaternary Geochronology section at the TU Bergakademie Freiberg, B.-v.-Cotta-Str. 4, D-09599 Freiberg/ Sa., Germany, E-mail: degering@physik.tu-freiberg.de
[3] Leibniz Institute for Applied Geosciences (GGA), Germany
[4] Geological Survey of Lower Saxony (NLfB), Germany

Abstract. The use of natural radionuclide contents for the evaluation of soil quality data was tested by field logs and additional laboratory analyses on vertical profiles. The latter proved a well mixing of soil material in the uppermost 30 cm by ploughing. A mathematical procedure for the consideration of soil moisture and the determination of the "information depth" is presented and lead to good agreement between field and laboratory data.

Introduction

The future environmental requirements as well as the development of the business environment force the trend to an economical use of fertilisers, sowings, plant protectants etc. in agriculture. Highly resolved soil data are an important prerequisite for sustainable cultivation. The soil texture determines the basic fertilisation with K, P, Mg as well as the depth of ploughing (Voßhenrich 2003). Therefore, GPS controlled farming, often referred to as *precision farming,* will play a growing role in modern agriculture.

Techniques used for the collection of soil data must correspond to the needs for high resolution, reliability and inexpensive realisation. Based on the close relationship to the clay content, radiometric measurements provide the opportunity to draw a relation between the content of natural radionuclides and the different soil types.

In the present paper we report first results of radiometric logging on farmland conducted by gammaspectrometric investigations on the vertical distribution of

radionuclides and by methodical considerations on the relation between radionuclide analysis in the laboratory and field data.

Experimental

All measurements displayed here were made at an investigation area near Hörsingen, Saxony-Anhalt. The local soil is characterised by underlying variegated sandstone and in the upper parts by glacial material.

Field logging was carried out in two different ways at the surface of the acre: by measurements on a regular grid using a portable Gamma ray spectrometer and by continuous tracking of a borehole probe along defined profiles.

The portable spectrometer GS-512 (Geofyzika 1998) contains a 3'' x 3'' NaI(Tl) scintillation detector. For the determination of the radionuclide contents three energy ranges of the gamma rays were used: around 1461 keV (^{40}K) for Potassium, around 1764 keV (^{214}Bi) for Uranium and around 2614 keV (^{208}Tl) for Thorium. The integration time amounted to 25 s, the grid spacing was 10 m. The correlations between the pulse rates and radionuclide concentrations were determined by calibration pads of known K, U and Th content (IAEA 2003).

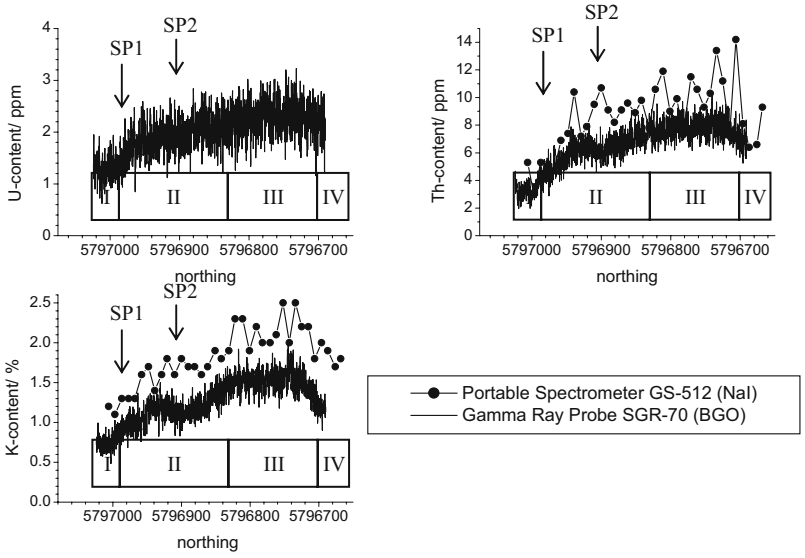

Fig. 1. Contents of Uranium (top left), Thorium (top right) and Potassium (down left) at a section on area Hörsingen as measured by different equipments. The Roman numerals in the boxes denote different soil types: I - moist similigley, II - pelosol soil, III - pelosol-braunerde, IV - gley colluvium. SP 1 and SP 2 give the positions of the two sampling points for laboratory γ-spectrometry.

The borehole probe SGR-70 (ANTARES, Stuhr) is equipped with a BGO crystal in a robust housing. At a logging velocity of 3 m/ min every 5 cm a 512 channel γ-spectrum was recorded. The evaluation software allows the analysis of the K, U and Th concentrations using the same γ-lines as indicated above. Calibration was performed in borehole geometry.

Samples for gammaspectrometric investigations were taken at two vertical profiles on this area. Each sample represents a range of 10 cm in depth. At position SP 1 the maximum depth was 60 cm, at position SP 2 only 40 cm. We used a high resolution low level gammaspectrometer equipped with a 38 % n-type HPGe detector. The dried sample material was filled into gas-proof so called Marinelli beakers which cover the cylindrical detector on each side. Measuring times up to 24 h were necessary in most cases. The effect of self attenuation was taken into account for the activity calculation. Generally, the following long living natural radionuclides could be determined (in some cases by using gamma emitting short living daughter nuclides): ^{238}U, ^{226}Ra, ^{210}Pb from ^{238}U decay series, ^{228}Ra, ^{228}Th from ^{232}Th series and ^{40}K. ^{137}Cs from the atmospheric nuclear weapons tests and the Chernobyl accident was detected down to 50 cm depth.

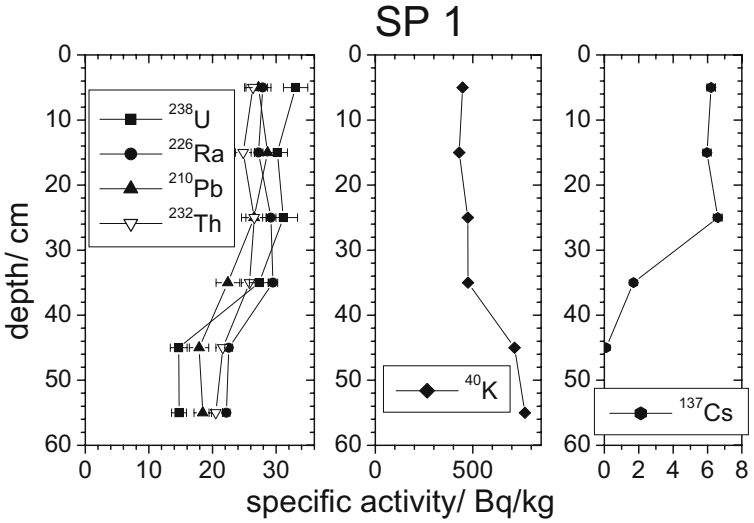

Fig. 2. Depth profile of the specific activities of members of the ^{238}U decay series and the ^{232}Th series (left), ^{40}K (middle) and ^{137}Cs (right) at sampling point SP 1.

Results

Fig.1 shows the field logs. Along the section the soil type varies in a definite way: Part I is sandy to loamy moist similigley, part II contains a loamy to sandy pelosol whereas in part III slightly loamy, partly clayey pelosol-braunerde was found. The last segment IV is a sandy colluvium with gley properties.

Due to a technical defect no Uranium values were recorded by the GS-512 spectrometer. For Thorium and Potassium the trends of the concentrations correlate between the two equipments but their total values differ by a factor of 1.2 to 1.5. Note the position of the two sampled profiles SP1 and SP2 which are situated in areas of different radionuclide concentrations and soil types.

The laboratory gammaspectrometric measurements of the samples from SP 1 (Fig. 2) and SP 2 (Fig. 3) show almost constant values of the geogenic activities (^{238}U and ^{232}Th series as well as ^{40}K) in the uppermost 40 cm. No disequilibrium between ^{228}Ra and ^{228}Th was found in both profiles. Therefore, their mean value is quoted as ^{232}Th in all diagrams. A distinct change of the contents appears beneath the upper layer (investigated just at sampling point SP 1). The Potassium concentration increases whereas Uranium and Thorium are reduced. Similar effects were found at SP 1 for the ratios between the nuclides: ^{238}U/^{226}Ra varies between 1.1 and 1.2 in the upper part and lies at 0.7 at the lower one, ^{238}U/^{232}Th falls from about 1.2 to 0.7 whereas ^{226}Ra/^{232}Th remains nearly constant at 1.1 over the whole profile.

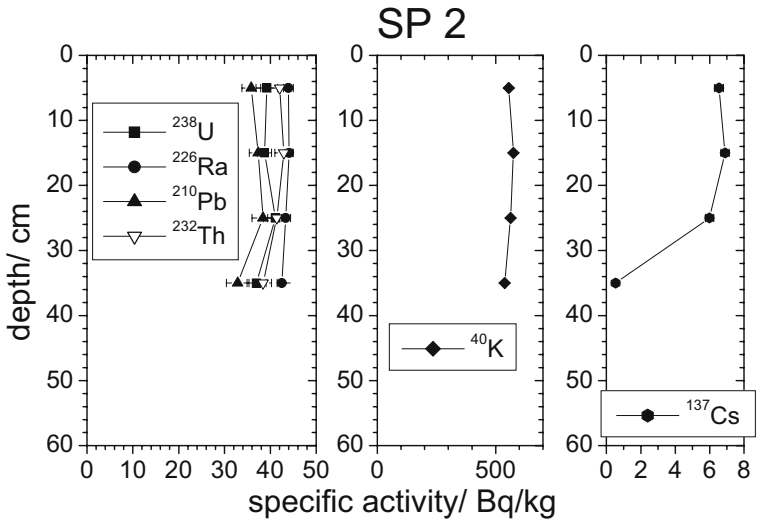

Fig. 3. Depth profile of the specific activities of members of the ^{238}U decay series and the ^{232}Th series (left), ^{40}K (middle) and ^{137}Cs (right) at sampling point SP 2.

Unlike this, ^{137}Cs activities show a sharp decrease below 30 cm depth at both sections. This step parallels to an increase of the ^{226}Ra/^{210}Pb ratio from about 1.0 to 1.3.

Discussions

The most evident conclusion of the laboratory analyses is the determination of the ploughing depth to about 30 cm. The contents of the geogenic nuclides as well as that of the airborne ^{137}Cs are homogenous in this region which indicates a well mixed soil. The further run of the ^{137}Cs curve indicates the downward migration with time. For the nuclear weapons fraction, the European Comission (1998) estimates the ^{137}Cs contamination for 1986 in the region of Hörsingen of about 2 kBq/m². For the Chernobyl fraction, BGA (1991) gives values of 2.0 -3.5 kBq/m². From the measured ^{137}Cs profile we estimate an actual total amount of about 3.1 kBq/m² which corresponds to 4.8 kBq/m² in 1986. This result points at a nonessential ^{137}Cs loss by migration or plant uptake.

The step in the radionuclide composition at 40 cm depth is thus not linked to the ploughing depth but rather to a change in the parent material of the soil from glacial sediments to variegated sandstone. In this context the decrease of the ^{238}U/^{226}Ra ratio suggests an enrichment of the alcaline earth element Radium in the lower soil probably caused by a displacement from the upper part. The constant ^{226}Ra/^{232}Th ratio is then astonishing but may be explained by the fact that ^{232}Th is analyzed via its daughter nuclides ^{228}Ra (half life 5.75 a) and ^{228}Th (1.91 a). So the ^{232}Th profile is rather that of ^{228}Ra which behaves chemically like ^{226}Ra.

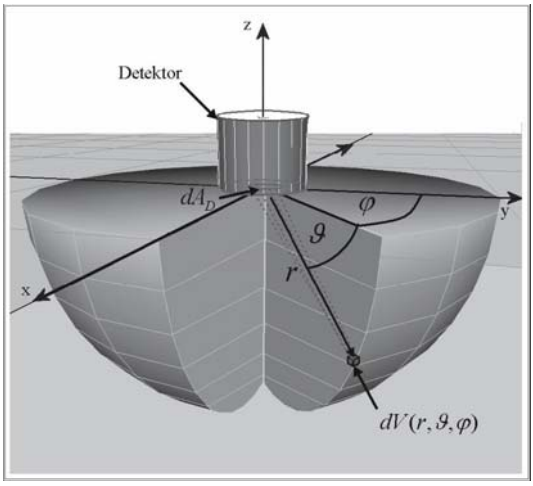

Fig. 4. Sketch of the geometrical relations and the variables used for the calculation of the moisture correction of the count rates.

For a correlation of the laboratory and the field measurements two items must be considered: (i) the connection between count rate and soil moisture and (ii) the thickness of the soil layer that governs the measured count rate in the field logs.

The mathematical treatment uses the geometric relations shown in Fig. 4. The gamma ray detector is put directly onto the soil surface. Spherical coordinates are chosen for symmetry reasons.

A volume element dV at the surface of a hemisphere with radius r has the activity

$$dA = A_{sp} \cdot \frac{\rho_m}{(1-M)} \cdot dV$$

with

A_{sp} - specific activity, determined on a dry sample
ρ_m - density of moist soil
M - moisture, ratio of mass of water to dry mass

The total gamma quanta rate emitted by the hemisphere is then

$$d\dot{n}_{H\gamma}(r) = \int_0^{\pi/2}\int_0^{2\pi} A_{sp} \cdot p \cdot \frac{\rho_m}{(1-M)} \cdot r^2 \cdot \sin\vartheta d\vartheta \cdot d\varphi \cdot dr$$

$$= A_{sp} \cdot p \cdot \frac{\rho_m}{(1-M)} \cdot r^2 \cdot 2\pi \cdot dr$$

with

p - number of quanta of a certain gamma energy emitted per decay

The fraction of the gamma rate emitted into the direction of a detector cross section element dA_D including the gamma ray attenuation in the soil is

$$d\dot{n}_H(r) = A_{sp} \cdot p \cdot \frac{\rho_m}{(1-M)} \cdot \frac{1}{2} \cdot e^{-\mu_M \cdot \rho_m \cdot r} \cdot dA_D \cdot dr$$

where μ_M is the mass attenuation coefficient of the moist soil for the observed gamma energy. The coefficient is defined only for narrow parallel beams without any scattering. Since scattering leads to an energy loss and the detector shall count only quanta of the full gamma energy, the condition is fulfilled.

Integration over the half space (r = 0 ... ∞) and normalisation to the rate of a dry soil gives the ratio of "moist count rate" to "dry count rate", the correction factor C_m:

$$C_m = \frac{d\dot{n}}{d\dot{n}_D} = \frac{1}{(1-M)} \cdot \left(\frac{\mu_{MD}}{\mu_M} \right)$$

where $d\dot{n}_D$, μ_{MD} and $d\dot{n}$, μ_M denotes count rate and mass attenuation coefficient for the dry and the moist soil, respectively.

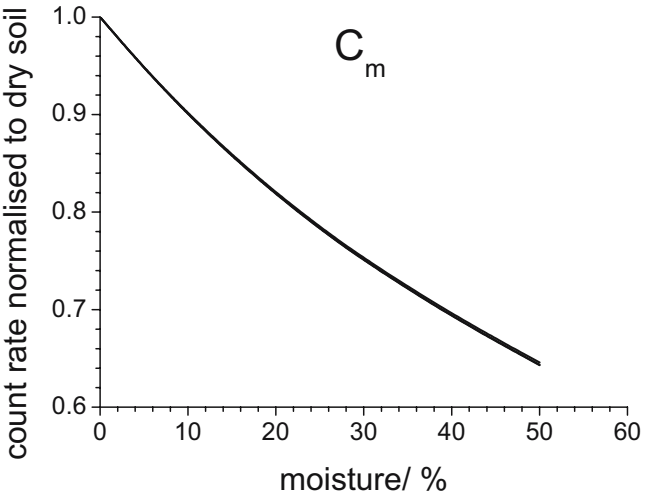

Fig. 5. Calculated ratio C_m of the gamma count rate received from a moist soil to the count rate of a dry soil. The curves for the three γ-peaks at 1461 keV, 1764 keV and 2614 keV, respectively, coincide within the width of the drawn lines.

Values of the mass attenuation coefficient were calculated using the software PHOTCOEF (Buecherl 1994) for the simplified system SiO_2 (soil) plus H_2O and different moisture contents at the gamma energies used in the field measurements. The derived moist-to-dry count rate ratio C_m presented in Fig. 5 shows negligible differences between the three gamma energies. The necessity of correcting the count rates for moisture effects is obvious: e.g. a moisture M = 17 % as found in the above 30 cm of the vertical profiles leads to a reduction of the count rate compared to a dry soil of 16 %.

With the deduced formulae it is also possible to estimate the radius of a hemisphere which contributes a certain fraction to the total gamma count rate. In Table 1 the radius are listed which account for 90 % of the count rate.

This "information radius" exceeds in moist soils only for Th slightly the depth over which homogenously mixed soil material was found. Radionuclide concentrations determined from count rates corrected to dry soil should therefore agree

Table 1. Radius of the soil hemisphere which contributes to 90 % of the detected count rate at the given energies and moistures. A dry soil density of 1.4 g/cm³ was used for the calculation.

	radius responsible for 90 % of the count rate/ cm		
moisture/ %	U (1764 keV)	Th (2614 keV)	K (1461 keV)
0	34.5	42.2	31.3
20	28.2	34.6	25.6

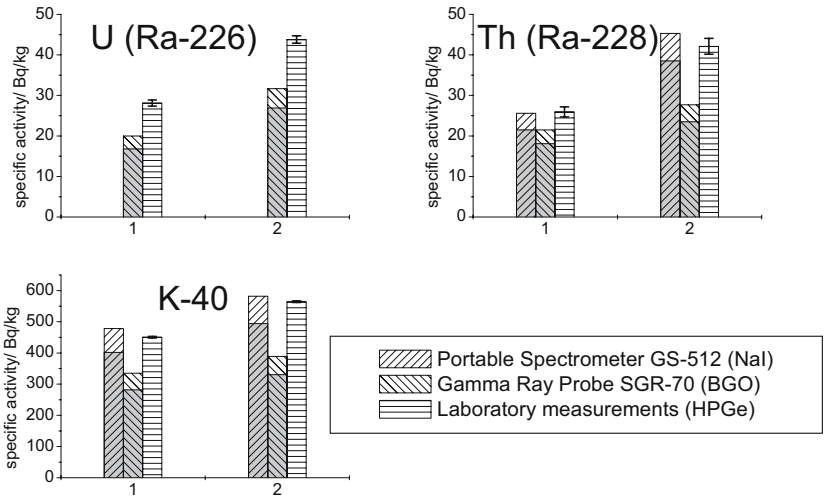

Fig. 6. Comparison of the specific activities of Uranium (top left), Thorium (top right) and Potassium (down left) at the two sampling points on area Hörsingen as measured by different equipments. The laboratory measurements were carried out on dried samples; the values for GS-512 and SGR-70 are corrected to dry soil. Uncorrected contents are marked by grey bars.

with the mean value of the specific activities in the uppermost 30 cm from laboratory measurements.

Radionuclide contents analysed by different equipments at the two vertically sampled points are summarised in Fig. 6. A fairly good agreement with the laboratory results is achieved for the GS-512 values. The lower concentrations of the borehole probe are a consequence of the unequal geometries used in calibration and field log, respectively.

The figure furthermore illustrates the must of a moisture consideration in the field data evaluation. Since the moisture distribution is currently unknown for the whole investigation area, the curves in Fig.1 are only a rough estimation of the true values. Nevertheless a relation between radionuclide and clay content is visible. Clay contents deduced from the soil classes at 15 positions on the area allow an estimation of this quantity along the logged profile. According to this, region I (cf. Fig.1) contains 8 - 12 % clay, region II 17 - 30 %, region III 45 - 65 % and region IV 8 - 12 %. These variations are mirrored in the radionuclide contents even though accurate correlations require moisture data for the whole area.

Conclusions

Field logs of the gamma radiation are suitable for a correct determination of natural radionuclide contents in agriculturally used soils. The radiation originates mainly from the well mixed ploughing depth. Only slight radioactive disequilibria were found at the investigated area in this layer but more explicitly in the bottom soil.

To achieve reliable results the count rates must be corrected for the appearing moisture content. This requires the logging of the water content for the whole area in future investigations.

References

BGA (1991) Bodenkontamination mit Cs137 im Jahr 1986, Karten erstellt auf der Grundlage von Daten des Bundesamtes für Strahlenschutz, Bundesgesundheitsamt, Institut für WaBoLu

Bücherl Th. (1994) Software PHOTCOEF, München

European Comission (1998) Atlas of caesium deposition on Europe after the Chernobyl accident, Comission of the European Communities, Luxemburg

Geofyzika (1998) Gamma Ray Spectrometer-Instruction Manual, Version 2.0. Brno

IAEA (2003) Guidelines for radioelement mapping using gamma ray spectrometry data. International Atomic Energy Agency