Gamma-ray sensor for topsoil mapping; the Mole

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Abstract

Soil plays an important role in crop growth and in general farmers use soil sample analysis and their experience for crop management related decision-making. The introduction of precision agriculture on a farm has implications for the soil information that is required for decision-making. At present, soil data are not at the appropriate level of detail because traditional soil sample techniques are too costly for the information required for precision agriculture. Several sensor techniques are available that provide high-resolution soil maps. This paper presents a sensor technology that is used for quantitative mapping of physical and chemical soil properties of the tillage layer. The method is highly sensitive and is used to make high-resolution maps for precision agriculture. The Soil Company shows that accurate sensor technology and precision agriculture techniques contribute to yield improvement.

Keywords: gamma-ray sensor, precision agriculture, high resolution digital soil mapping

1. Introduction

Precision agriculture needs high-resolution maps of physical and chemical soil properties together with yield and crop biomass maps to enable operational decision support in crop management and to conjure variable rate application (VRA) maps. This information should be accurate and provide quantitative information. The University of Groningen (RUG), Medusa Explorations and The Soil Company (Netherlands) have developed a technique (called the Mole) that is used commercially for high resolution mapping of physical and chemical soil properties. The method is based on measurements of (natural) gamma radiation and a proper field, or regionally based calibration.

The fact that gamma radiation carries information on mineral- or soil composition has been known for long. Already in the early 1930s, gamma detectors were built and used for mineral (uranium) prospection (de Meijer, 1998). With the advent of scintillator crystals, replacing the early Geiger-Muller counter based systems, it became possible to deconvolute the measured radiation into a series of constituents, the naturally occurring radioactive elements like potassium (^{40}K), thorium (^{232}Th) and uranium (^{238}U).

However, it has taken researches until the early 1990s to jump from a qualitative interpretation in terms of nuclide concentrations, to a quantitative interpretation in terms of soil or mineral properties. A number of coincident developments were needed to achieve this.

First of all, proper calibration methods were devised allowing for field systems to measure absolute concentrations of radionuclides. At the same time, several studies were done on correlations between radionuclide concentrations and mineral properties of soil and sediment samples taken during carborne and underwater radiometric surveys (de Meijer, 1998). Strong correlations were discovered between for instance the ^{232}Th radionuclide concentration and the clay content of soil. As a general rule it was found that different soil- and sediment types are characterized by unique fingerprints (van Wijngaarden et al., 2002); i.e. typical concentrations (C_K, C_U, C_{Th}) of naturally occurring nuclides ^{40}K, ^{238}U and ^{232}Th. Some years later it was found that not only relationships exist between radionuclides and physical soil properties (texture, grain size, etc.) but also between radionuclides and chemical soil properties (heavy metal pollution, fertilizers, etc.) (van der Graaf et al, 2007).

Parallel to the development of intricate analysis methods and the fingerprinting method, also smaller and better acquisition systems were developed. Measurement systems for radioactivity are converted into true sensors for radioactivity related soil properties. This paper describes how The Soil Company uses this sensor to provide relatively low cost high resolution soil maps to farmers and how they use them together with precision agriculture techniques for yield improvement.

2. Equipment and data analysis methods

Historically, most outdoor gamma ray logging systems are build of NaI scintillation crystals and use a Windows full spectrum analysis to determine the concentration of the radionuclides. Our innovations have highly improved the quality of gamma measurements (Koomans et al., 2007), such that detailed and accurate maps of gamma radiation can be produced. These innovations are in the type of detector material used and in the method of data analysis.

2.1 Hardware

Traditionally used crystals like NaI are not the most efficient capturer of gamma radiation. Commercially available alternatives are BGO and CsI. BGO has a low peak resolution, which prohibits use in cases where man-made nuclides (like the ^{137}Cs present in nuclear fallout) are subject of interest. Furthermore, the material is rather expensive and prone to temperature instability. CsI is a very robust alternative to NaI and BGO. The density of CsI is higher than NaI, yielding better efficiency, especially for smaller crystal sizes. The Soil Company utilizes a 70x150 mm CsI crystal coupled to a photomultiplier unit and a 512 channel MCA system. The system stores the full spectral information to enable post processing of spectral data at a later stage.

Figure 1. The Mole system of The Soil Company consisting of detector, GPS and laptop.

2.2 Data analysis

The reduction of the measured spectral information into concentration of radionuclides, is mostly done using the Windows analysis method (Grasty, 1985). In Windows, the activities of the nuclides are found by summing the intensities of the spectrum found in a certain interval surrounding a peak. In “classic” windows, three peaks are used to establish the content of ^{232}Th, ^{238}U and ^{40}K. A major flaw of the Windows method is the limited amount of spectral information that is incorporated into the analysis. Another weakness is the inherent use of ‘stripping factors’ to account for contributions of radiation from nuclide A into the peak of nuclide B (figure 2).

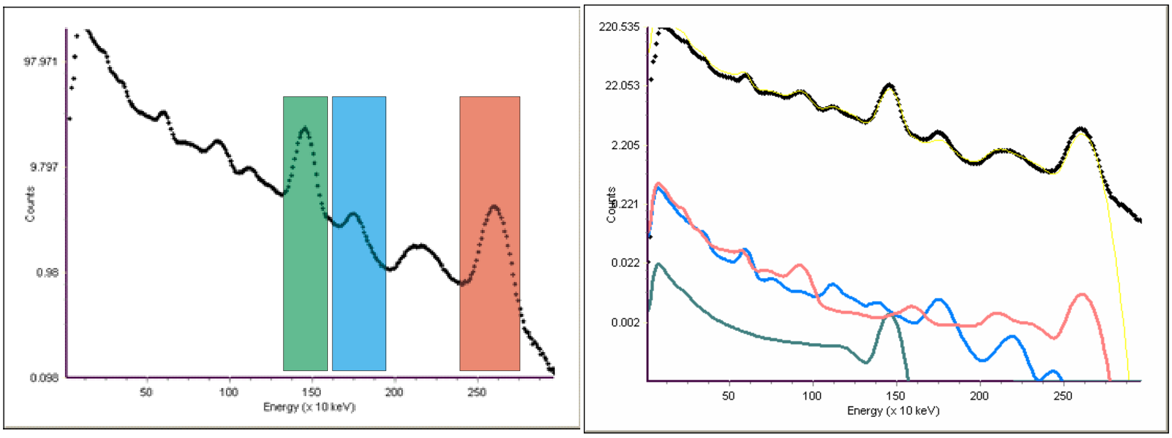

Figure 2. Left hand picture: windows surrounding the ^{40}K, ^{238}U and ^{232}Th peaks (from left to right). Right hand picture: FSA analysis of a natural gamma spectrum. The measured spectrum (black dots) is approximated by a fitted curve (yellow). The green, blue and red curves are the Standard Spectra for ^{40}K, ^{238}U and ^{232}Th respectively.

The Mole system incorporates a different method to analyze gamma spectra. In contrast to the "Windows" method described before, our Full Spectrum Analysis (FSA) method incorporates virtually all of the data present in the measured gamma spectrum. In FSA, a Chi-squared algorithm is used to fit a set of "Standard Spectra"[1] to the measured spectrum (see figure 2). The fitting procedure yields the multiplication factors needed to reconstruct the measured spectrum from the standard spectra of the individual nuclides. The multipliers equal the actual concentrations of the radionuclides that led to the measured spectrum. The method is described in detail in Hendriks et al. (2001). Hendriks shows that the uncertainty in the FSA method is at least a factor of 1.7 lower compared to the Windows method.

2.3 Fingerprinting and soil sampling

During measurements, the Mole is placed on a tractor and carried over the field. Each second a reading of the gamma spectrum and of the GPS position is stored on a computer. A constantly updated map shows on-the-go the variation of gamma radiation in the field.

To translate this gamma field data into soil maps, the data need to be calibrated to the desired soil parameters. Therefore, soil samples are taken from a depth up to 25-30 cm, within a 2 m radius from the sensor. At this location, a gamma spectrum is measured for 5 minutes. The locations of the samples are based on the on-the-go map of gamma variation in such a way that the sample location selection should reflect the overall soil variation in the field. The

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1 A standard spectrum is the pure response of the detector system used on a 1 Bq/kg source of a given radionuclide in a given geometrical setting.

samples are analysed in the lab and the soil parameters are related to the corresponding gamma readings by regression analysis. By means of the resulting regression equations the gamma readings can be translated into soil properties. Sampling is done during the same field visit as the gamma sensing of the field. Gamma spectrum analysis, regression, interpolation, map calculation and quality control are performed at the office.

In agricultural applications, soil nutrient levels are influenced by management. Therefore calibration for soil nutrient maps has to be based on general knowledge rules and samples of that specific field or farm. Physical soil properties and their natural gamma readings however can be compared regionally. The fingerprints of soil types and properties depend among others on parent material, soil forming processes and age.

Throughout the years The Soil Company has built a large database of soil samples and their gamma readings. This functions as a knowledgebase to derive general behavioural patterns of different soil properties and provides ‘extra’ regional sample data for correlation of nuclides with the physical soil properties and often organic matter and magnesium. As an example the soil samples and their gamma readings of an 800 ha farm in Zeeland, Netherlands on marine clays are depicted in figure 3. Comparable plots can be made of other physical and chemical soil properties.

In general, correlation plots have an R^2 ranging from 0.6 to 0.95. Lower quality regression analysis is not used in the prediction of a soil property.

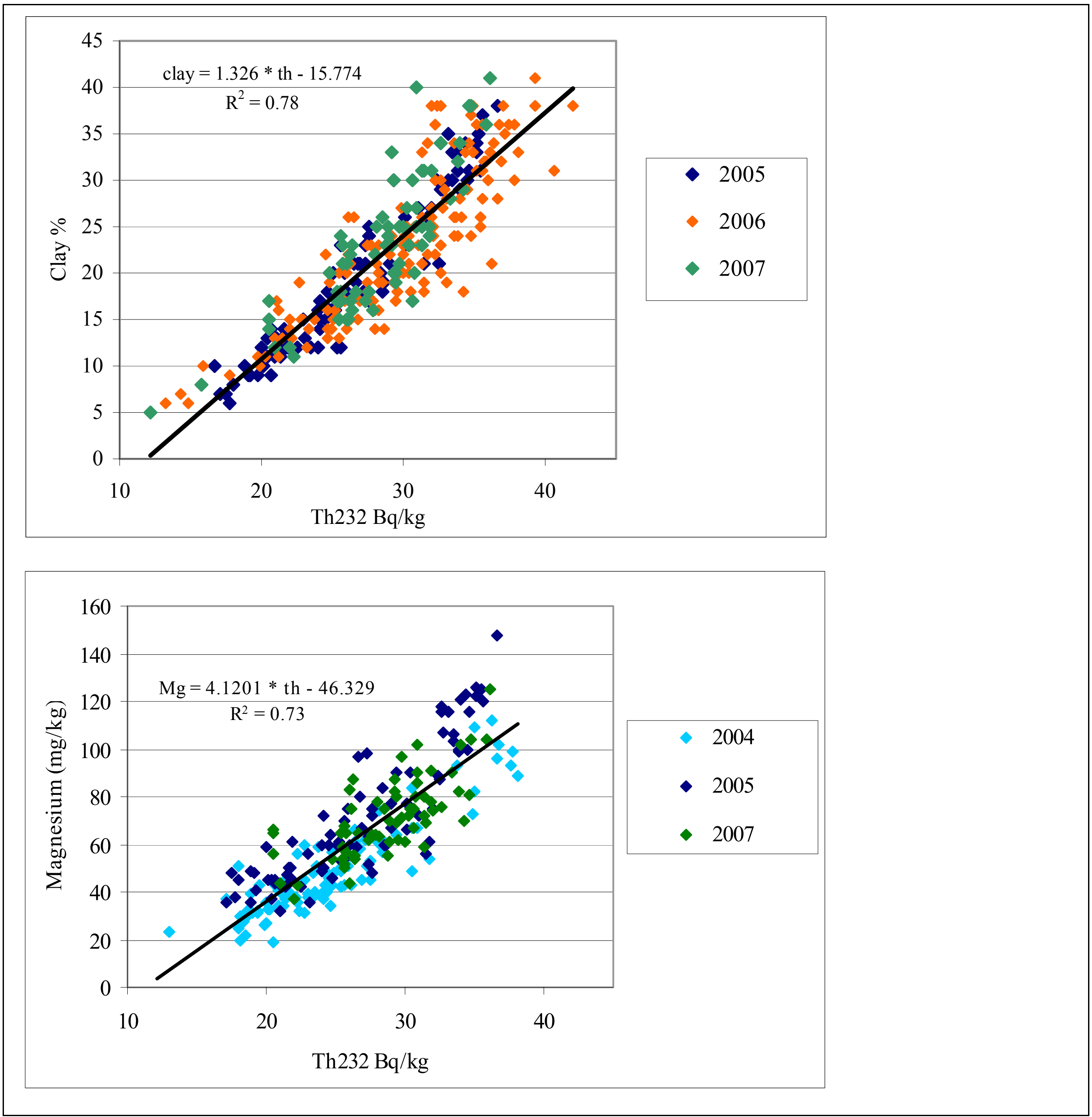

Figure 3. Soil samples versus ^{232}Th readings of an 800 ha farm (Zeeland, Netherlands) taken in 3 subsequent years. Top: Clay %, Bottom: Magnesium

The field sampled gamma data are interpolated using Inversed-Distance-Weighing and the interpolated maps of gamma readings are translated into the soil maps by means of the derived regression equations. Applying the regression equation of figure 3 to some of the gamma maps of this farm yields the map in figure 4.

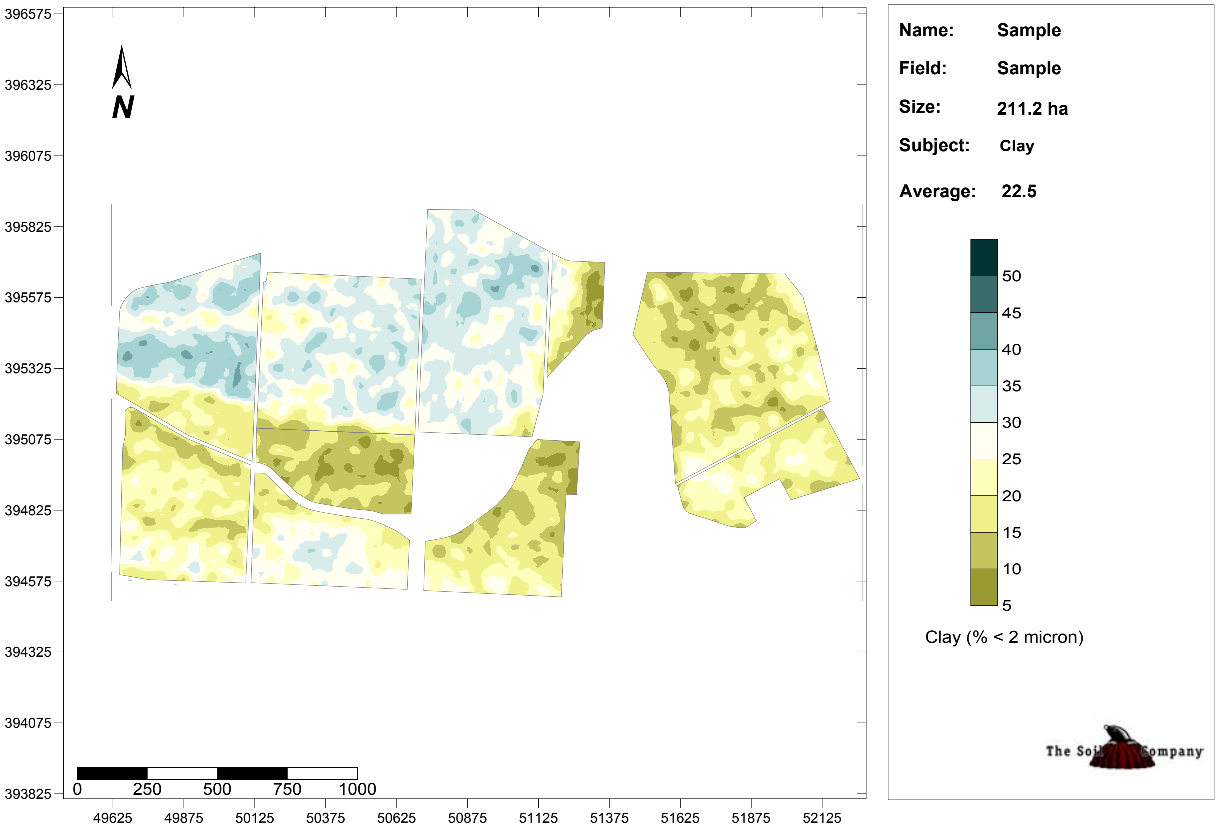

Figure 4. Gamma based map of the clay content of 10 fields, together 211 ha. Derived with equation of figure 3. Zeeland, Netherlands.

The intervals of the legend are comparable to the statistical error, variation in the maps can therefore be considered as real variation. To check the reliability of a derived soil map, the map values on the sample locations are compared with the actual (measured) soil property values. R^2 between the estimated and sampled soil property values are between 0.7 and 0.98. The image is judged by likeliness and if available compared to existing soil maps. Validation of eg. the clay map of this farm yielded a R^2 0.81. The patterns in the soil maps are recognisable to farmers and confirm their perception during tillage.

Using pedotransfer functions and the physical soil and organic matter maps, bulk density, water retention etc. maps are calculated. Based on agricultural research on the subject, maps of compaction risk (RBB, 1970), nematode risk etc. are calculated.

The set of reported maps consists of four types of maps; regionally calibrated maps of physical soil properties, field calibrated maps of chemical soil properties, calculated maps based on pedotransfer functions and calculated risk maps.

3. Applications

Although in many parts of the world the focus of precision agriculture is on reducing costs of inputs, The Soil Company believes that the focus should be primarily on improving yield and subsequent gains. In general it will be more beneficiary to improve yield by 10% then by cutting the costs of fertiliser by 10%. It has been shown that applications such as variable planting distance and nematode control can lead to great financial advantages for farmers in terms of improved yield.

In the Netherlands experience was gained with several precision agriculture applications that are derived from or based on the gamma ray based soil maps. Table 1 gives an overview of some of these applications and their general benefit.

Table 1. Tested precision agriculture strategies and their benefits in the Netherlands.

Application	Base map(s)	Desired effect	Experience
Variable planting distance	Clay content/ Water retention	Homogenous size distribution of potatoes /broccoli	5% negative up to 15% positive financial benefit
		Reducing seed sugar beets	13% reduction in cost maintaining yield
Variable fertiliser amount	Nutrient or clay content	Saving fertiliser or improving yield	Up to 60% reduction in fertiliser
			10% yield improvement consumer potatoes
Variable application compost	Organic matter	Reducing organic matter variation in field	Improved soil structure
Variable liming	pH and organic matter	More homogenous pH	Improved yield sugar beets
Variable nematode control	Trichodorus risk	Reduction in granular products	40 to 60% savings on chemicals
Variable tillage speed	Compaction risk	Less compaction due to tillage	Variable tillage patterns are highly recognisable

On the Zeeland farm clay maps are used to reduce the amount of sugar beet seed needed. A reduction in amount of seed of 13 % was obtained while maintaining yield. Another precision agriculture application is using the clay content map to achieve a more homogeneous size distribution of seed potatoes. This is an attractive perspective to a farmer because seed potatoes in the 28-55 mm size range pay more. The clay content map is translated into a variable planting distance map (figure 5). This has improved (financial) yields with on average 6 % or 230 Euro/ha in a 4 year trial.

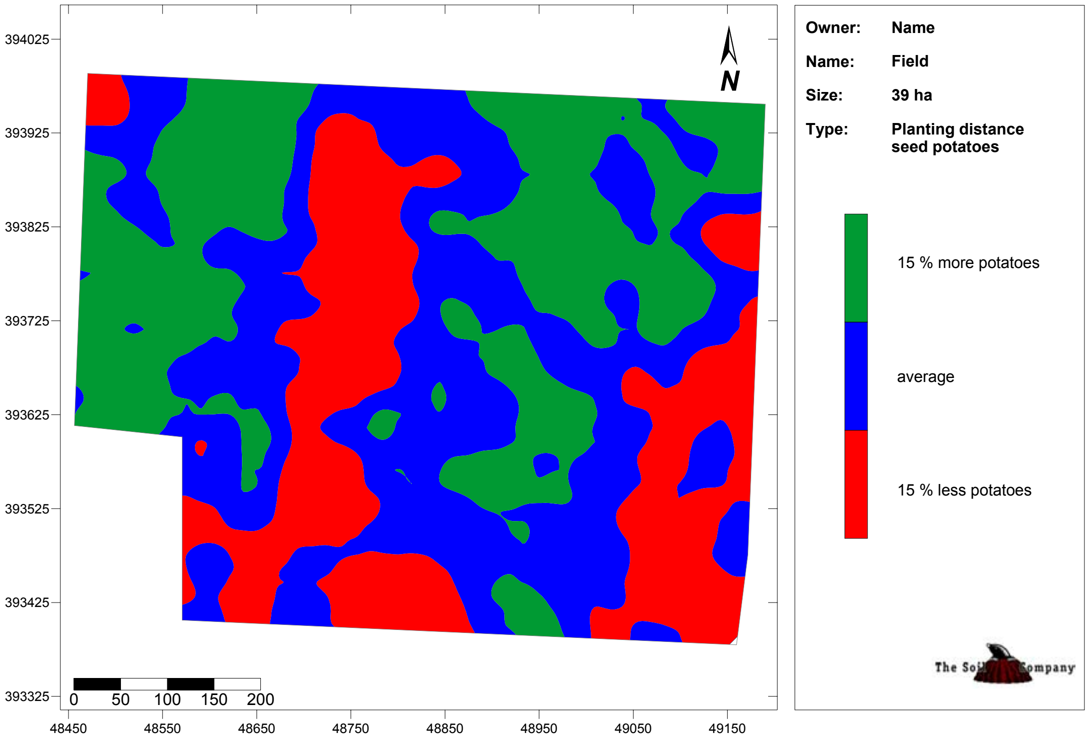

Figure 5. Variable planting distance map derived form gamma based clay content map. Zeeland, Netherlands.

At present research is conducted on the integration of gamma ray sensing with other sensor techniques like EM38. This can yield complementary data that further enhances data-based decision-making by farmers and offers new possibilities for precision agriculture.

4. Conclusions

Sensor technology based on gamma ray sensing can be used for creating quantitative topsoil maps in conventional units that farmers are familiar with. The method is highly sensitive and is used to make high-resolution maps for precision agriculture. The patterns in the soil maps are recognisable to farmers and confirm their perception during tillage. The quantitative aspect of the soil property maps enables operational decision support in crop management. The Soil Company shows that accurate sensor technology and precision agriculture contribute to yield improvement.

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