Review of developments in airborne geophysics and geomatics to map variability of soil properties

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Abstract.

Over the past 40 years, airborne geophysics and geomatics has become an effective and accepted technology for mapping various signatures on the Earth's surface and sub-surface. But so far, its airborne application in agriculture is perceived as sub-practical and/or its real value unknown to most stakeholders. In this paper, we are reviewing major technical and commercial achievements and latest developments to date, but also potentials for new developments and applications, of airborne geophysics (and geomatics) for soil variability mapping. The contribution of airborne agri-geophysics/geomatics is based on the efficient and versatile integration of four main components: carriers; sensors; data/information; and knowledge. The use of a small and stable airborne multi-sensor data measurement platform, resulting in versatile and highly flexible surveys flown at low/reasonable cost of operation, is the recurring wish of many stakeholders in the agriculture industry. The past years GyroLAG brought to reality the next generation of advanced and innovative light airborne remote sensing platforms with specially designed gyrocopters and also light fixed-wing aircraft. Sensors allow the recording of meaningful information for the critical end product (*i.e.* knowledge). New technologies and combinations of those technologies must be enhanced from the traditional off-the-shelves offers by manufacturers or traditional airborne geophysics service providers which are expensive, heavy, not necessarily fit for purpose and definitely not integrated, or capable of being so, for multi-sensor application to agricultural problems. Those sensors include notably: (a) fluxgate magnetic; (b) CsI gamma spectrometer; (c) thermal cameras; (d) NIR hyper-spectral camera; (e) portable SWIR camera; (f) use of reflected GNSS data; and (g) electromagnetic. The above airborne geophysics/geomatics tool box allows collection of soil data such as: potassium, thorium and uranium concentrations; conductivity and/or resistivity values; total magnetic intensity; temperature; and moisture. Through further value-adding on their own or in combination with other data, that information can then be converted into knowledge such as: soil types; soil zoning; soil variability; soil physical parameters (porosity, density, magnetic susceptibility, etc); soil depth; soils clay content; ground faults location; soil moisture; soil erosion risks; nematodes preferential habitat imaging; and soil chemistry.

Keywords. *airborne, geophysics, geomatics, agriculture, soil properties, soil variability*

Introduction

The farmers' awareness regarding spatial heterogeneity of soil properties has existed for generations. Technology to handle systematically and efficiently the within-field variability became available with the advent of civilian use of GPS and satellites in the late 80s. The identification and understanding of the root causes of within-field variability is however a larger challenge which is nowadays often eluded by remote sensing imaging of various plant-physiology status. Those are however only a snapshot in time and a too late record of a problem with the crop and yield. Ultra-high-resolution imaging and understanding of the identification, conditions, textural and chemical characteristics of soils into which the crop is rooted and from which it is extracting nutritional elements is usually a neglected approach in precision farming. The collection of soil data presents obvious problems arising from sampling a dense, opaque and very heterogeneous medium. But over the past 40 years, airborne remote sensing, and particularly airborne geophysics, has become an effective and accepted technology for mapping various signatures on the Earth's surface and sub-surface (mainly in the natural resources exploration industry). Its application to the agriculture industry has only be sub-practical to date for a number of reasons such as (enhanced from George and Woodgate, 2002): (i) impractical character of traditional airborne geophysics; (ii) lack of definition of key biophysical data sets required; (iii) heavy payload; (iv) limitation of some geo-technologies; (v) lack of understanding of geophysical technologies and data by most agronomists; (vi) user unawareness of the technology availability and capability; (vii) lack of demonstration of tangible economic benefits to the farmer's profit and loss planning; (viii) time and expertise required for data/image interpretation; (ix) large time gap between acquisition and interpretation of data (no real time); (x) general cultural impediments to the adoption of radical new technology; (xi) effective demonstration of suitable application of the interpretations to land/farm management problems; (xii) effective size of investigated farm lands; (xiii) cost and utility of repeat monitoring (4D); (xiv) lack of or inadequacy of integrated multi-sensor types (geophysics vs. geomatics) mapping solutions; and (xv) commercial practices and strategies by equipment manufacturers and service providers. Many of those reasons/perceptions are however no longer valid. The precision agriculture industry presently does not embrace the full advantage and potential of nowadays available airborne sensing toolboxes and capabilities.

In this paper, we are reviewing major technical and commercial achievements and latest developments to date, but also potentials for new developments and applications, of airborne geophysics (and geomatics) for soil variability mapping. Examples and arguments are drawn from a paper by Ameglio and Jacobs (2015), in-house research and development at GyroLAG (www.gyrolag.com), and a review of publicly available information worldwide from academic, scientific and commercial sources.

Airborne agri-geophyics/geomatics solutions for soil mapping

LiDAR, laser altimeter and ortho-photos – soil topography and drainage

A case study (see www.precisionagriculture.com.au) over a 140-ha paddock (in Australia) showed that up to 50 ha (*i.e.* 36% of the surface) of that area suffered from waterlogging damages (see Fig. 1b). Over a single season, 36 ha of canola was lost due to waterlogging. Improving drainage on farm land is usually performed by first collecting elevation data. Airborne, this is done via either LiDAR or ortho-photos to obtain measured (LiDAR) or calculated (ortho-photo - see Fig. 1d) point clouds. The point cloud is then used to establish topographic contour maps (see Fig. 1a). Engineering firms can then design drainage solution across a paddock with scrapers and excavators to cut the drain and terraform the paddock ground surface. In the Australian specific case related above, after drainage, the average area of crop loss from waterlogging was reduced to only 5 ha (*i.e.* 4% of the paddock surface). It is also reported that a substantial 1890 % return on investment (ROI) was achieved for that farmer on that specific land drainage case (the topographic data was however not acquired airborne which cost might impact the ROI figures indicated).

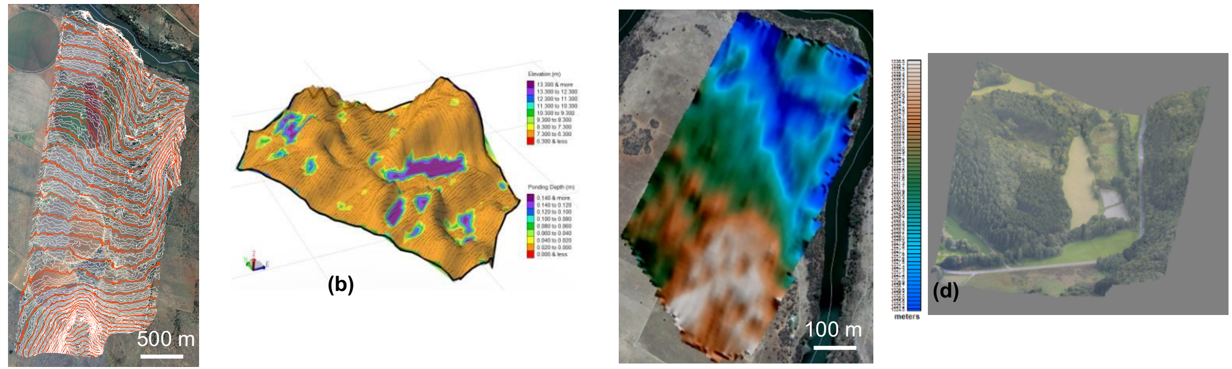

Fig. 1 (a) Contour map established from an airborne LiDAR point cloud acquired over a farm (North-West region, South Africa) by GyroLAG onboard a gyrocopter (Fig. 11a). Sub 30 mm accuracy in x, y and z. Major contours (red) and minor contours (white). (b) Waterlogging assessment (geographically unrelated to Fig 1a) pre-drainage work (from www.precisionagriculture.com.au). (c) Topographic map (sub meter in x,y and 25 cm in z) of a farm (South Africa) established with the laser altimeter (elevation amplitude over the whole land surveyed is 12 m) used for navigation on GyroLAG aircraft. (d) 3D rendering of ortho-photo of farm and forestry lands in Germany (from Bongartz et al. 2015).

Gamma-ray spectrometry – Soil zoning and variability

Gamma-ray spectrometry is limited to approximately the first 30 cm of the ground surface. As such, it is a very powerful tool for surface soil zooming and variability mapping. Results of a low-level flying airborne gamma spectrometry survey flown over a farm land (~ 153 ha) in the North-West region of South Africa is presented in Fig. 2. The survey was flown on board GyroLAG's gyrocopter (see Fig. 11a) at 20 m agl (above ground level), 20 m line spacing and 120 km/hr speed. A total of ~ 67 000 measurement points were collected in less a than 2 hours work and providing a resolution of 438 point/ha or 23 point/m^2.

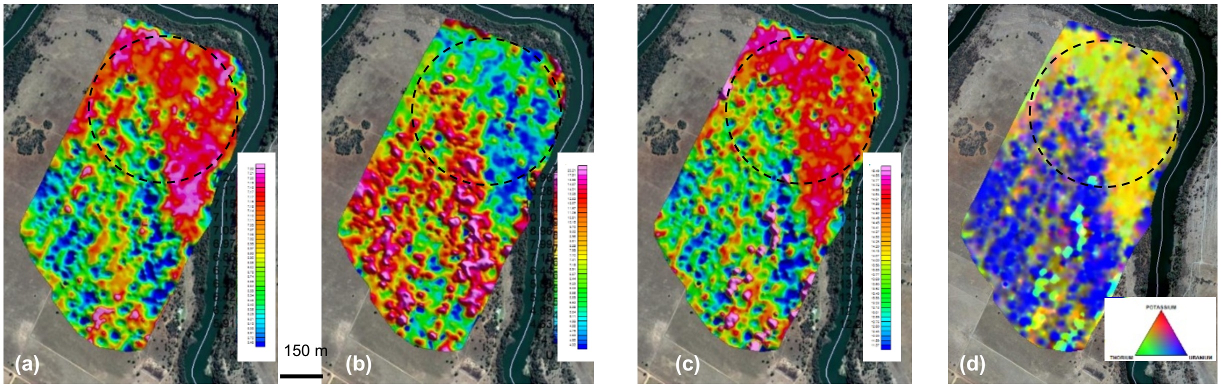

Fig. 2 Soil variability airborne gamma-ray spectrometry mapping (survey flown onboard GyroLAG gyrocopter (see Fig. 11a) at 20 m line spacing, 20 m above ground level and 120 km/hr). Black dashed line: outline of pivot farm in Fig. 3. All maps at same scale. (a) Potassium (K) concentration (%). (b) Uranium (U) concertation (ppm). (c) Thorium (Th) concentration (ppm). (d) Ternary plot of K, U and Th. Each map contains ~ 67 000 measurement points collected in less a than 2 hours work. Resolution of 438 point/ha or 23 point/m^2. See also Fig. 6 for the magnetic data flown over the same area at the same time than gamma-ray spectrometry.

The soil survey ground investigation (Jasper and Ameglio 2018) of the northern pivot (dashed line circle in Fig. 2) revealed two distinct soil types/bodies. Along the river the parent material is alluvium with an average silt and clay content of 28%. Further away from the river the soil is deep eolian sand with less than 10% silt and clay content. The limit between those two soil zones is represented in Fig. 3a (dotted line). The total count map (Fig. 3b) also identifies two major soil zones in the airborne data. One soil zone, S-SW of the pivot, is depleted in K and Th and richer in U and corresponds to gravel/sandy soil. The other soil zone, N-NE of the pivot, is rich in K and Th and corresponds to a clayish soil. The ternary plot of K, Th and U (Fig. 2d) shows that both zones also display a substantial degree of lateral variability of the soil which is not fully imaged on the single elements maps (Fig. 2). This high variability is further enhanced in the map of Th over K (Fig. 3c). Analysis of all of the airborne data over that pivot (potassium, uranium, thorium - Fig. 2 a to c - but also ratios of those elements) allow to however identify four soil zones (Fig. 3a). This study (part of ‘X-farm’ research program - see Appendix) is still on-going at North West University (NWU) in South Africa with the identified soil zones being subjected to ground truthing with also soil laboratory analyzes.

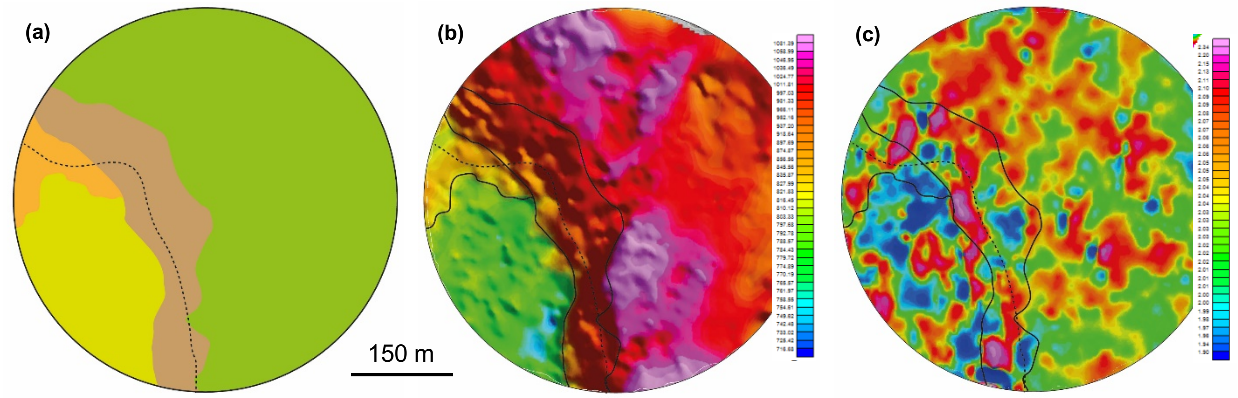

Fig. 3 Soil zones identification and lateral variability over a farming pivot in South Africa. (a) Four soil zones are identified with airborne data (mainly K, Th, U, Total Count and various ratios such as Th/K and K/U). The doted line separates the only two soil zones identified by ground investigation. (b) Airborne gamma-ray spectrometry total count map. (c) Airborne gamma-ray spectrometry Th/K ratio distribution. For (b) and (c) the airborne survey was flown at 20 m line spacing, 20 m above ground level and 120 km/hr. Soil zones limits of Fig. 3a also overlaid on Fig. 3 b and c (solid lines - airborne soil zones; dotted line - ground soil zones).

Gamma-ray spectrometry – Soil lateral variability and nematodes distribution

Preliminary results of nematodes in soil analyses performed by NWU over the same pivot as in Fig. 3 show that the total abundance (*i.e.* measure of the total number of individual nematodes at each sampling site) (Fig. 4a) and the total biomass (*i.e.* all sizes and mass of all combined nematodes at each sampling site) (Fig. 4b) distributions are spatially related to the major soil zones identified with airborne gamma-ray spectrometry (most nematodes ‘activity’ being located over the more clayish soil - western half of the pivot). Student project at NWU are presently further analyzing the distribution of nematodes species and quantifying their spatial relations with soil zones and types established with the airborne survey. Wyse-Pester et al. (2002) also demonstrated such distribution between species of nematodes and soil distributions of organic matter, clay, sand and silt. Achieving the combination of rapid airborne soil zoning and variability mapping and the understanding of related nematode types and distributions will provide in the near future a powerful site-specific management tool for the agriculture industry.

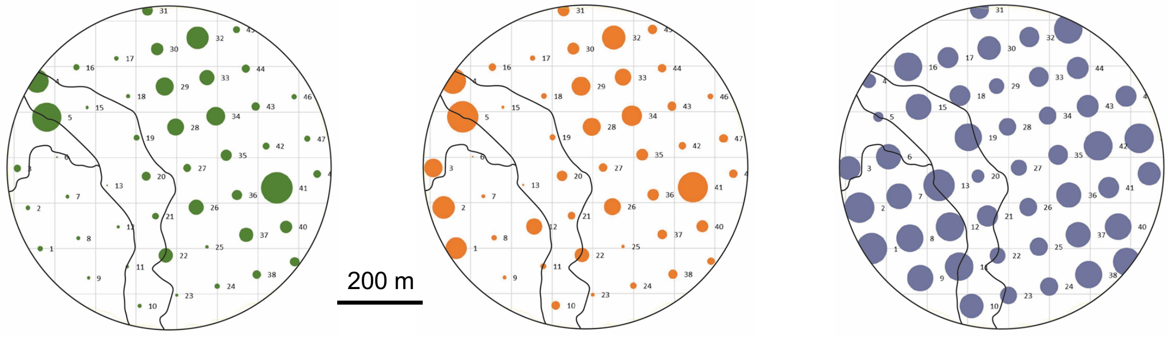

Fig. 4 Nematodes indicators distribution and relationship with soil zones (delineated by solid lines) established by airborne gamma-ray spectrometry survey (see Fig. 3). (a) Abundance index. (b) Total biomass index. (c) Shannon diversity index. Work in progress at North West University (NWU) in South Africa (part of ‘X-farm’ collaborative research program - see Appendix).

Gamma-ray spectrometry – Soil clay content

A work by van Egmond et al. (2010) collected soil samples (measuring notably soil clay % and Mg content) and ground-based gamma-ray spectrometry 232Th readings on a land of 800 ha

(Netherlands) over three subsequent years. Correlation between the soil samples and gamma-ray spectrometry data provided a regression equation ($R^2 > 0.7$) for clay% which, when applied to the measured gamma spectrometric thorium concentration maps of the area, led to establish a clay percentage soil zoning map presented in Fig. 5.

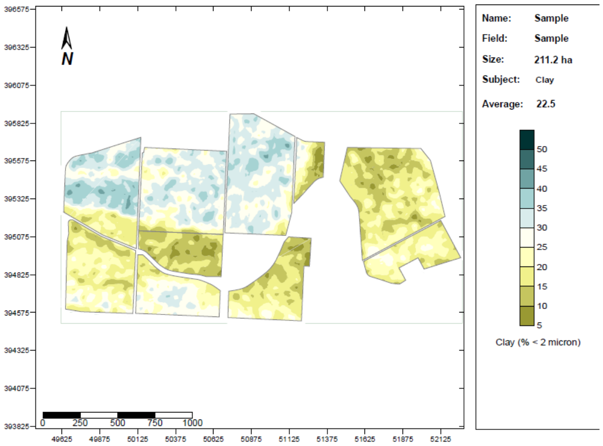

Fig. 5 Soil clay content (%) of multiple plots (all together 211 ha) in Netherlands extrapolated from soil thorium concentration measured using a ground gamma spectrometer. From van Egmond et al. (2010).

There will most probably be no linear relationship between the soil encountered in van Egmond et al. (2010) case study in the Netherlands and soils elsewhere in the world. But such systematic approach of soil sampling over soil zones identified with airborne gamma-ray spectrometry would provide a useful database for fast and efficient automatic extrapolation of thorium concentration airborne map into clay % soil map over large areas in agricultural regions.

Gamma-ray spectrometry – Soil depth estimate?

Wong et al. (2007) presented a method to estimate soil depth in commonly occurring sandy soil over lateritic cemented gravels/rock landscapes based on attenuation of gamma radiation due to the thickness of the soil layer. The method was tested using both ground and airborne gamma spectrometric surveys coupled with in-situ soil depth measurements. Theoretical versus measured values of soil depth showed a reasonable degree of confidence. The maximum measurable soil depth of the method was indicated to be 45 cm. This is in fact very much the maximum representative depth of any gamma-ray spectrometric measurements. The applicability of this method to solve farming problem remain uncertain and might well be limited to the definition of 'soil depth'.

Electromagnetic – Airborne soil vertical profiling dream?

Soil depth affects plant available soil water storage capacity. This storage capacity is critical for notably grain yield, drainage, nitrate leaching and also for the available space for root formation (particularly in orchards). The depth of investigation required here goes well beyond the sole top soil (30-40 cm) but does not need to go beyond 30-40 m below ground level (bgl). Airborne electromagnetic (AEM) is a very powerful method for mineral (and water too) exploration. It can image down to depth of 700+ m bgl. But it lacks the adequate resolution for imaging the first 25+ m bgl for agricultural purposes. Nevertheless, Street (1992) demonstrated that AEM can be useful for land management planning and soil salinity assessment. AEM is however a very expensive technology (~ US$ 70-115 per line kilometer flown). New developments to provide the required resolution for soil vertical profiling in the 0 to 25 m bgl range will also be time and budget intensive. So, for the foreseeable future, there is little expectation that such development would be engaged on light airborne platform. It would however be a major technological and application innovation in the agriculture industry since electromagnetic, a very powerful tool on the ground for soil characterization (see Doolittle and Brevik 2014), could be flown together with magnetic and gamma spectrometry. A possible step-in workable solution might come in the form of already established ground electromagnetic tools being carried by UAVs (once such carriers will become reliable and cost effectively while also capable of embarking a payload of ~ 15 kg).

Ground penetrating radar – in the infentile stage of airborne application

Ground penetrating radar (GPR) is a non-invasive on-site measurement technique with which a more accurate and complete underground information can be gathered. Though GPR has been widely used in civil engineering, geosciences, and forestry, some of the advanced methods have not been adopted or trialed by agricultural soil research. Xiuwei et al. (2016) provide a review GPR for underground sensing in agriculture (mainly root zones). Airborne application of GPR is however in its early stage of research and development around the world.

Magnetics – Soil zoning

Airborne magnetic (together with gamma spectrometry) is an effective technology for mapping various signatures on the Earth's surface and sub-surface. Results of a low-level flying airborne magnetic survey flown over a farm land (~ 153 ha) in the North-West region of South Africa is presented in Fig. 6 (see also Fig. 2 for the gamma-ray spectrometry results over the same area flown concomitantly to the magnetics). The survey was flown on board GyroLAG's gyrocopter (see Fig. 11a) at 20 m above ground level, 20 m line spacing and 120 km/hr speed. Magnetic imaging is a more complex affair than gamma-ray spectrometry imaging for surface soil zoning and variability mapping. This is due to the fact that the magnetic signal (see Fig. 6b, pivot with dashed white outline) incorporates the effect of multiple sources (hence wavelength) at depth of several kilometers. There are multiple data enhancement techniques allowing for isolation of the magnetic signal related to the top soil itself (see Figure 6d, pivot with dashed white outline and compare with Figure 6b). Work is undergoing on that magnetic dataset to enhance its value and notably also ground truth/calibrate magnetic susceptibility values calculated from the airborne data. Magnetic signal content can also be severely impacted by human artifacts (see Fig. 6a - spraying system in the western half of the white circled pivot, and also an underground drain and/or water supply pipeline crossing the northern black circle pivot). Most of those human artifacts can be however removed from the airborne dataset as shown when comparing Fig. 6 a and b for the white circled pivot.

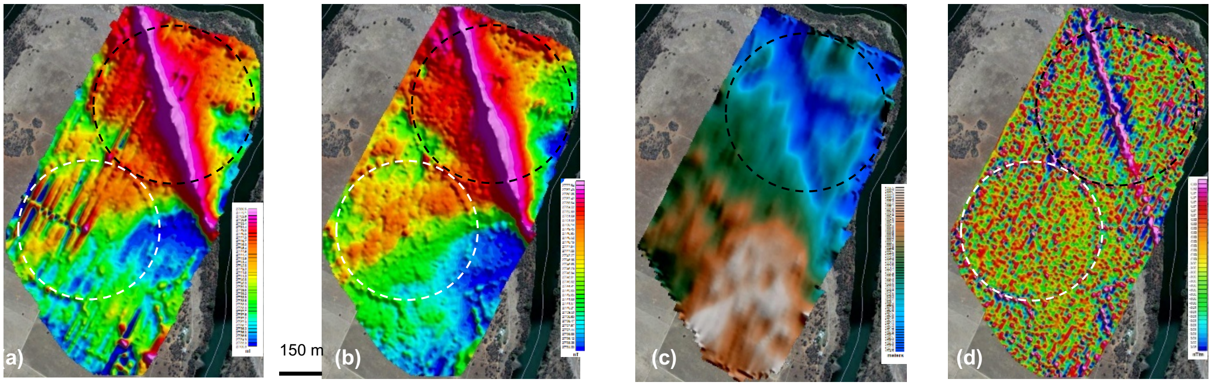

Fig. 6 Soil zoning and variability airborne magnetic mapping (survey flown onboard GyroLAG gyrocopter (see Fig. 11a) at 20 m line spacing, 20 m above ground level and 120 km/hr). Black dash line: outline of 600 m diameter pivot. White dash line: outline of 500 m diameter pivot (a) Total Magnetic Intensity Reduced To the Pole (TMI RTP) with cultural artefacts. (b) TMI RTP with most cultural artefacts removed. (c) Topography from laser altimeter with NNW-SSE topographic gutter (black circle pivot) corresponding to the position underground of a water supply pipeline/drain (see large magnetic anomaly of same direction in Figure 6b). (d) TMI RTP second vertical derivative (2VD). See also Fig. 2 for the gamma spectrometry data flown over the same area at the same time than magnetic.

Magnetic – Soil erosion index

A detailed field and laboratory study by Nazarok et al. (2014) on a small (less than 1 ha) agricultural land in Ukraine demonstrated the applicability of magnetic methods (measuring Magnetic Susceptibility, MS) in soil erosion estimation (in the particular case of strongly magnetic parent material). The study showed that soil MS had a high degree of statistical relationship with erosion index and humus content and MS was used to establish an erosion index of the area (see Fig. 7). The automatization of such approach to airborne magnetic dataset would allow for a fast and cost-effective assessment of soil erosion level over large surfaces (from individual farm to an entire agricultural region and also at a basin scale).

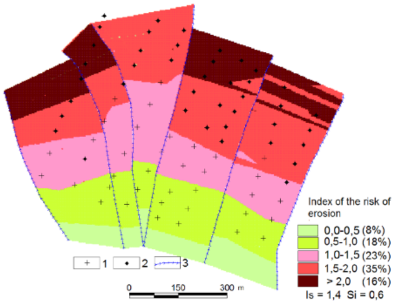

Fig. 7 Mapping of soil risk erosion using ground magnetic susceptibility measurements. From Nazarok et al. (2014).

Hyperspectral SWIR – towards airborne soil mineralogy and chemistry

Aircraft based acquisition of hyperspectral reflectance imagery (900-2500 nm) can currently provide the necessary data to map soils mineralogy in an efficient and rapid manner. Future improvements in sensor technology are expected to improve the signal-to-noise ratio and spatial resolution of the imagery. The high cost of hyperspectral cameras is however still a major entry barrier. But as they become more readily available and at a lower cost, the application of new soil spectra reflectance data processing will provide effective method for calculating high-resolution raster map of soil mineralogy and some other properties like texture, pH and various chemical components such as C, silt, Fe and Al as demonstrated by Hively et al. (2011) (see Figure 8). The combination of hyperspectral SWIR imaging with gamma spectrometry and magnetic would be an ideal trio of sensors for airborne soil mapping removing the long, expensive and ground access constraints of the traditional ground soil sampling and laboratory analyses.

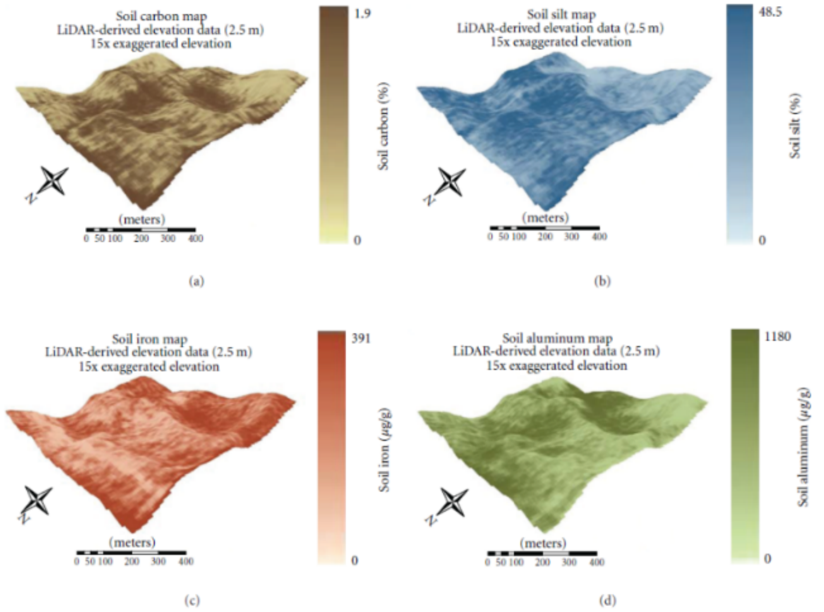

Fig. 8 Map of predicted values for selected soil chemical components (C, Silt, Fe and Al) using an airborne imaging spectrometer (400-2450 nm) overlaid over LiDAR topographic information over a field in USA. From Hively et al. (2011).

Thermal infrared – Farm management and soil zoning tool

Thermal remote sensing measures emitted radiations from a target surface or object. This differs from optical remote sensing (previous section of this paper) that measures reflected radiations of the target (see Prakash, 2000). Everything above absolute zero emits radiation in the infrared range (IR) of the electromagnetic spectrum. Hence, over 80% of the energy thermal sensors received in the thermal wavelength region (8 - 14 µm) is emitted by land surface. This makes surface temperature a practical variable to extract from the thermal infrared (TIR) signal. TIR imaging has been growing fast and starts to play a role in various fields of agriculture such as: nursery monitoring; irrigation scheduling; soil salinity stress and plants disease detection; yield estimation; and maturity evaluation and bruise detection of fruits and vegetables (see review in Ishimwe et al. 2014). A TIR survey performed by GyroLAG over a pivot farm North of Potchefstroom (South Africa) (Fig. 9) shows significant lateral variation of temperatures with the coolest related to dark grey clayish soil (qualitative assessment). Additional research work is presently performed over that farm to identify the type of soil related to the TIR zones.

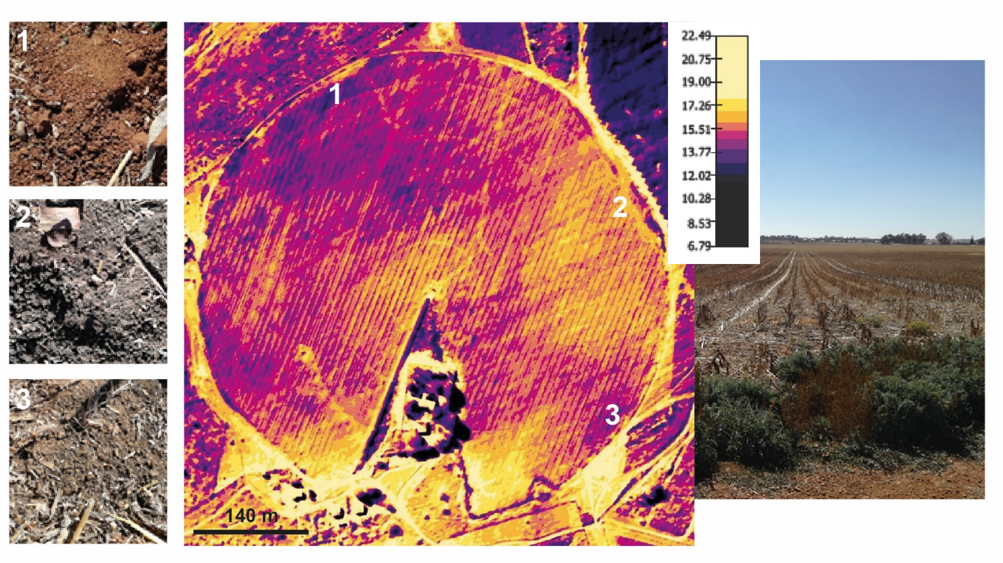

Fig. 9 Surface temperature (°C) from a TIR image acquired on board a fixed-wing aircraft (Fig. 11b) (image 20 cm pixel resolution acquired at 300 m agl) over a farm pivot in Potchefstroom (South Africa) with a Xcam combo RGB-NIR camera. Significant lateral variabilities correlate with at least 3 different types of soil (color and texture) - see point 1 to 3 and associated photos on the left-hand side. Airborne survey performed in winter (July) approx. a month after harvest (see field condition in the right-hand side photo - view full North).

GNSS-R – Airborne soil moisture

There has been a large amount of research into the general relationships between crop/plant responses and soil moisture conditions. The various stages of growth are a function of the moisture conditions (amongst other factors) with significant effects on the total growth and yield of a crop. Knowing how much water to apply to a field and when to apply it is then a fundamental management decision on which effective water management practices must be based. Furthermore, other practice such as tillage and field treatments can be optimized with real time knowledge of soil water content. Soil moisture monitoring (spatial and temporal) is consequently a critical component of agricultural production and worldwide food supply sustainability. Previous studies (*e.g.* Motte et al. 2016; Roussel et al. 2016) have demonstrated that variations of the nature of the ground/soil (*i.e.* moisture/water content amongst others parameters) modify the properties of reflected waves resulting in variations of amplitude and phase of the signal-to-noise ratio (SNR) recorded by a Global Navigation Satellite System (GNSS) receiver. Ground based studies analyzing the time variations of SNR measurements linked to dielectric constant of the surrounding soil established a method to recover local fluctuations of soil moisture content (Motte et al. 2016). This method was adapted to airborne application and trialed on low level flying light and affordable aircraft (Ameglio et al. 2017) which results are reproduced in Figure 10. A data spatial resolution of 45 m was achieved (at 120-140 km/hr flying speed and 50-100 m agl survey height) representing a 1000-fold improvement on the 35-50 km resolution obtain with satellite soil moisture imaging (*e.g.* SMOS - Kerr et al. 2010). Soil moisture acquisition has also been achieved for example with a Synthetic Aperture Radar (Baghdadi et al. 2007) and a L-band multibeam radiometer (Maggioni et al. 2006). Resolution obtained with those sensors are however at best

250 m (5x lower than with GNSS-R). Furthermore, Synthetic Aperture Radar and L-band spectrometer are more complex hardware than a simple GPS antenna and receiver.

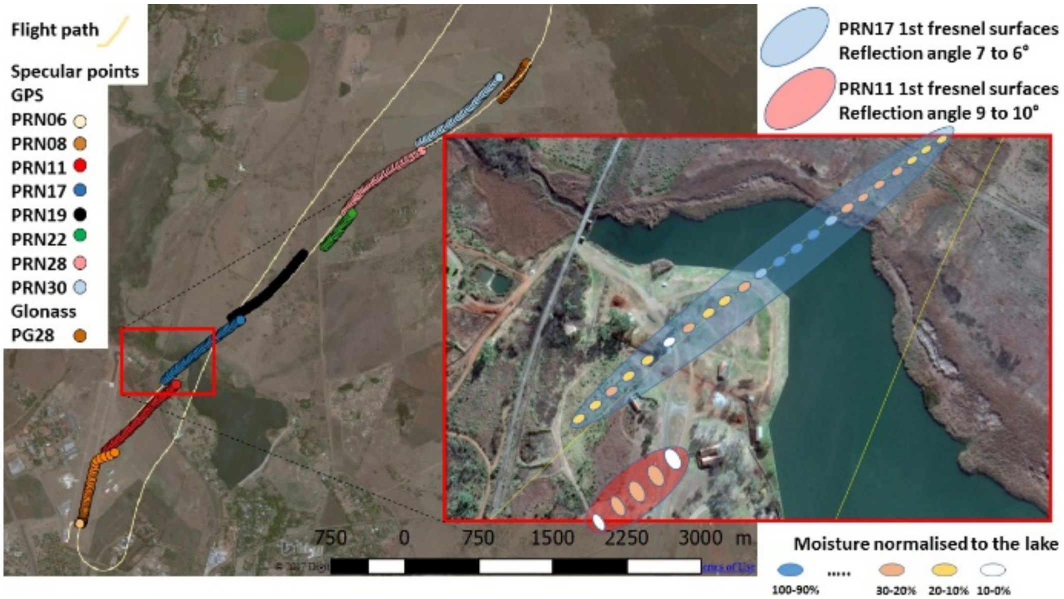

Fig. 10 Specular points over the survey flight path (yellow line) superimposed over Google Earth image. Inset: zoom into GPS PRN17 (blue) and PRN11 (red) areas with estimates of moisture content normalized to lake.

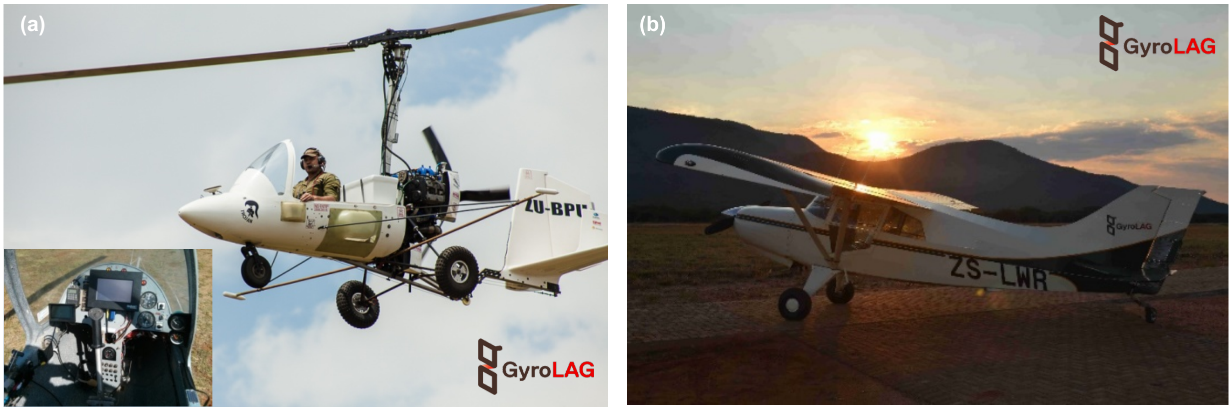

Fig. 11 (a) GyroLAG modified South African gyroplane with GyroLAG's FLAME gradient magnetic system (collaboration with UNISTRA, France). Inset: cockpit view with navigation computer (center) and data acquisition pilot display (left). (b) fixed-wing Maule M5-235 aircraft. Technical specifications of both carrier are available in Ameglio (2017).

Conclusions

New developments of operational and cost effective airborne carriers and sensors solutions are positioning the airborne geophysics and geomatics (remote sensing in large sense) support within reach of the agriculture industry. But the essence of airborne remote sensing lies in the utility of its information products. That information must be used to inform farmer decision making, support precision environmental management of agricultural fields, increase sustainable crop production, and help to reduce nutrient, sediments and carbon losses of agricultural systems. In a raw form, the remote sensing information is highly complex, and unintelligible to all but a few specialists. The goal is to convert digital numbers and 'colourful images' into biophysical and soil values of agricultural meaning and knowledge that present the opportunity to identify soil characteristics and physiological status, stress and damage in crop (or surface vegetation) at much earlier stage before problems become visually apparent (*i.e.* too late). Of course, farmers are not primarily interested in soil parameters and not even only focused on crop status. Their main concern is focused on the optimization of production by reducing its cost and stabilizing yields. This is where knowledge must then create economic benefits. That ultimate value add to the farmer is still to be demonstrated despite a myriad of research publications in precision agriculture. This lack of demonstration of tangible economic benefits to the farmer's profit and loss planning is in itself the most important entry barrier of airborne geophysics and geomatics to the agriculture industry.

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In preparation of this paper, the author has exercised reasonable skill, care and diligence. The statements, conclusions and recommendations might be based upon data and information obtained from third parties. No warranty or undertaking is made in respect of information that was obtained and used in this review and which, unknown to the author, was incorrect or incomplete. It is also possible that the author might have missed certain developments or argument factors, and possibly over or under emphasized others. It is also unavoidable that only a few selected case studies could be used to illustrate the topic at hand when keeping the length of the paper reasonable. The author would like to invite any parties to contact him to correct, debate, contribute and doing so further expand this review paper. This would provide a comprehensive development road map for both the airborne remote sensing and agriculture industries.

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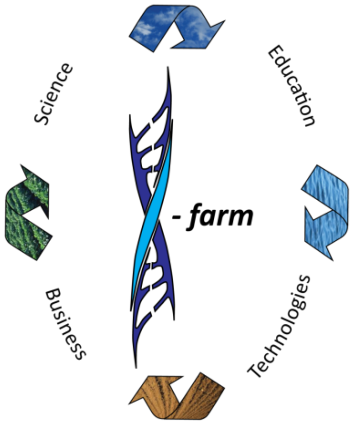
Appendix - 'X-farm' airborne agri-geophysics/geomatics collaorative research program



'X-farm' (Ameglio and Jacobs 2015) is a South African multi-disciplinary collaborative pure and applied research program set between GyroLAG (www.gyrolag.com), industry stakeholders and academic and research entities nationally and internationally. The program focuses on precision agriculture related projects developed at the interface between the Education, Technology, Business and Sciences poles of excellence.

Providing affordable ultra-high resolution airborne geophysical and geomatics data (using GyroLAG manned and unmanned platforms) and data transformation into information and knowledge, the program aims to create socio-economic benefits, business spin-offs, new technologies development and provide tangible and sustainable solutions to societal food security challenges and environmental protection issues.

The program is structured around, and contributes to four main perspectives: agronomical, technical, economic and environmental. Research projects cover engineering, geography, geology, geophysics, economic and agronomic sciences with topics linked to data acquisition (hardware and software engineering), data processing, data interpretation, data integration, knowledge transfer and economic benefits.

'X-farm' also provide a certain number of free flying hours (including geo-sensing technologies) to support research projects that meet the requirement of the program. Interested parties should contact us at laurent@gyrolag.com