Assessment of new non-invasive mobile sensing techniques for mapping soil spatial variabilities

S. Gianessi[1*], J. Niederbacher[1], R. Mazzoleni[1], L. Morselli[2], L. Stevanato[2], G. Baroni[1]

[1]*Department of Agricultural and Food Sciences (DISTAL), University of Bologna, Bologna, Italy*

[2]*FINAPP s.r.l, Montegrotto Terme (PD), Italy*

* stefano.gianessi2@unibo.it

Abstract

In the present contribution, a comparison between cosmic ray neutron sensing (CRNS) and gamma-ray spectroscopy (GRS) for soil spatial mapping is shown. The experiments have been conducted in a walnut field situated in Bondeno (Ferrara), Northern Italy, characterized by a relatively strong soil texture spatial variability ranging from sandy to clay soil from north to south. Data acquired are compared to ground portable time domain reflectometry (TDR) observations and regional soil classification maps. Results show good performance in distinguishing the two main soil type zones. For these reasons, the results support the applicability of these methods (i) to obtain preliminary maps for specific soil sampling design, (ii) to have a qualitative understanding of soil texture and moisture variability of the field, and (iii) to divide the field into sectors with similar hydrological properties. Further experiments and analyses should be performed however to understand the effect of the different spatial footprints of each detector and the best timing for performing the survey.

Keywords: Soil mapping, non-invasive mobile sensing techniques, gamma-ray spectroscopy, cosmic ray neutron sensing, proximal sensing

Introduction

In agricultural fields, soil spatial physical variables such as soil texture, clay content, moisture content, bulk density, pH, and nutrient availability have a big impact on productivity (Gebbers and Adamchuk, 2010). For this reason, a correct characterization and management of this variability during the growing season is a key factor to maximize the yield and minimize inputs and environmental impacts (Garré et al., 2021).

Variations in soil characteristics and crop production can be measured by direct soil sampling or by utilizing remote sensing products. More recently, proximal sensing tools such as electrical or electromagnetic induction (EMI) sensors, optical sensors (Vis-NIR), gamma-ray spectrometer sensors (GRS) and cosmic ray neutron sensor (CRNS) represent a new opportunity for real-time field scale monitoring integration in precise agriculture practices. The non-invasive near-ground detectors have the advantage that they can be moved easily on the soil surface while sensing the at different deep (Bogena et al., 2015). In particular, emerging technologies such as CRNS and GRS installed on moving platforms, can be used to map the moisture condition of the soil and soil texture variabilities, respectively. For CRNS, the negative correlation between epithermal neutrons and hydrogen molecules is the basis for the estimation of the field soil moisture conditions. For GRS, the natural gamma radiation emission from the soil is mainly correlated with the mineralogy of the soil (Becker et al., n.d.; Pätzold et al., 2020; Vather et al., 2019). The combination of these technologies can also provide some more insight into supporting precision agriculture.

Comparison studies are however limited. For this reason, in the present contribution, a field campaign is presented to compare the main characteristics of new proximal soil sensors in detecting soil spatial variability. The results are compared with TDR point-scale soil moisture observations and with the regional web map services (WMS) soil texture map of the upper soil (about 0-30 cm depth).

Materials and methods

Instrumentation and measurements

In this study, three mobile instruments have been used (Figure 1). The first instrument is a CRNS probe, model "Finapp5" by Finapp s.r.l (https://www.finapptech.com, Montegrotto Terme - Italy), an inorganic plastic scintillator-based neutron detector (Stevanato et al., 2020, 2019) with an efficiency of about 2800 neutron counts per hour (cph) at sea level. The second instrument is a GRS probe, model "gSMS" by Medusa (https://medusa-online.com, Groningen - Netherlands), a 100 ml cesium iodide (CsI) crystal scintillator which absorbs incoming energy and records total gamma spectra (0-2800 keV). This can be further analyzed into different radionuclide counts using "GAMMAN" software provided by the same company. The last instrument used for the geophysical survey is a portable TDR model "FieldScout350" by Spectrum Technologies (https://www.specmeters.com, Aurora – United States of America), with 12 cm long steel rods. All sensors are equipped with an individual GNSS unit. This overall mobile sensing setup allowed the measurement of neutrons, gamma radiations, and point scale volumetric water content simultaneously along with time and position of each observation with the aim to assess the relationship between soil moisture and texture. Although each sensor differentiates in horizontal and vertical footprint, as reported in Table 1, observations acquired are compared to show the relationship between the signals detected and soil properties.

Figure 1. Experimental instrument setup with, starting from the left of the photo: portable TDR in the hands of the operator, CRNS, and GRS probes mounted on wheels

Table 1. Characteristics of the geophysical probes used during the experimental study

Sensor	Physic characteristic detected	Physic characteristic investigated	Horizontal / Depth footprint
CRNS	Cosmic rays generated epithermal neutrons interaction with *H*	Soil moisture	50 m / 25 cm
GRS	K-40 gamma emission from the soil due to its natural decay in time	Clay content	15 m/ 15 cm
TDR	Travel time of a high-frequency electromagnetic pulse through the soil	Soil moisture	1-2 cm around the rods / 12 cm into the soil

Study site

The experimental site chosen for this study is an agricultural field with walnut production in the Po plain near Bondeno (FE), Emilia Romagna region (Italy), with a particular soil texture variability ranging from silty clay loam to silty clay as reported by the regional soil map services ().

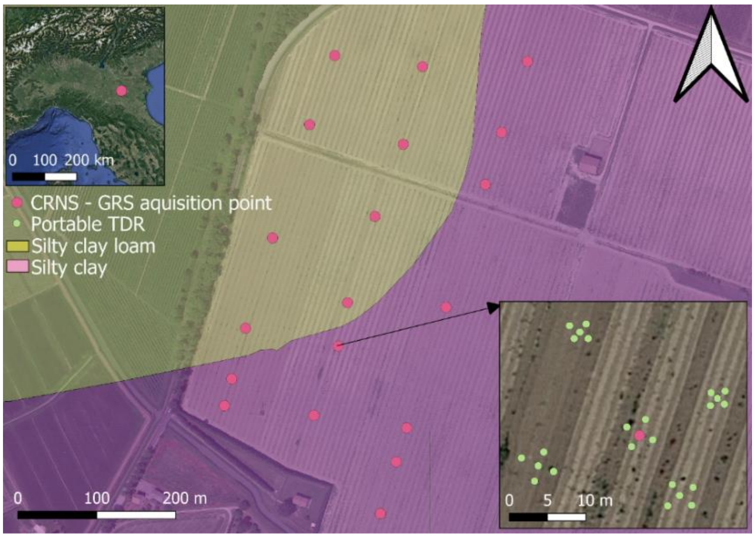

Figure 2. Study area location and overview along with regional WMS soil texture map (higher clay content in purple) and the stationary position of CRNS and GRS probes as the TDR scheme pattern example nearby the position itself.

To detect the variability with mobile geophysical sensors, a stop-and-go measurements scheme was applied at several points of the field with 10 minutes stationary at each point of interest, with incremented number of observations close to the expected soil boundary. At the same time, in each point investigated, invasive soil moisture observations at 12 cm depth were taken with a portable TDR in an area of 15 m x 15 m.

The survey was conducted on the 15th of July 2022, period marked by high temperatures and little precipitations at the beginning and end of the month (Figure 3).

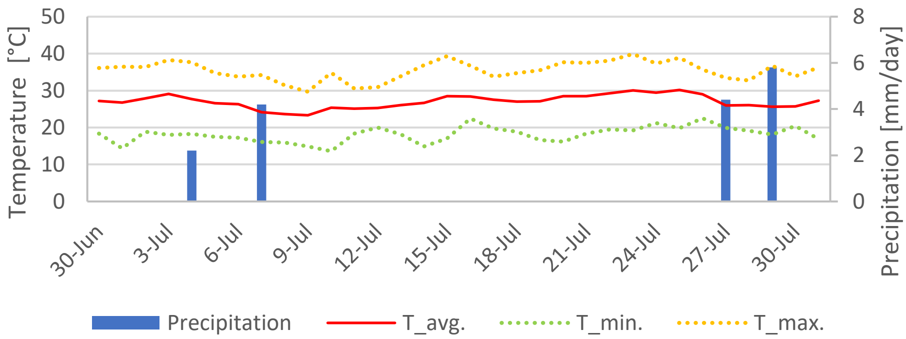

Figure 3. Weather data downloaded by the Emilia-Romagna regional environmental agency (ARPAe) at Mirabello, the closest weather station from the field *(simc.arpae.it/dext3r/)*.

Results

All observations acquired have been displayed in the open-source GIS software "QGIS" and processed with an inverse distance weighting (IDW) interpolation tool to understand spatial variability and the relationships between thematic maps. However, we acknowledge that the signal detected by different sensors has different footprints, and for this reason, a more accurate interpolation should have considered such scale mismatch (Bocchi et al., 2000; Morari et al., 2009). This aspect will be considered in further analyses.

The resulting interpolated map (Figure 4) of about 500 TDR measurements showed an increase in soil moisture in the N-S direction in correspondence with the clay zone. The wide variability of volumetric soil moisture values, ranging from 5 to 35 VWC% in the upper 12 cm of soil, shows an extreme spatial variability of soil moisture even at the smallest scale of a meter. This shows the difficulty in having representative moisture observations with punctual and invasive instruments.

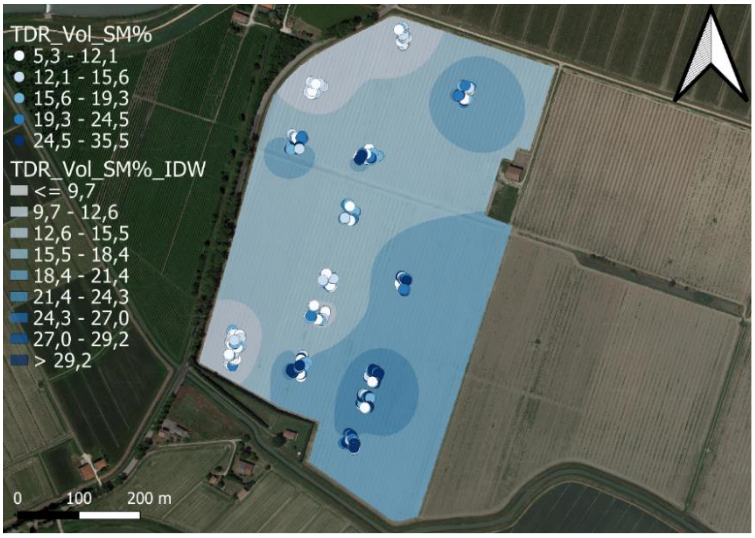

Figure 4. IDW interpolation of volumetric soil water content observations acquired with the portable FieldScoutTDR350.

For the gamma-ray spectroscopy, data acquired have been integrated with two past surveys conducted respectively on the 26th of April and the 3rd of June. The insufficient amount of data during the main survey on the 15th of July to cover all the field was due to a lack of power supply after a few hours of activity. K-40 (1440 $\pm$ 40 keV) cpm has been analyzed from the raw total gamma spectra acquired. The interpolation of potassium counts (Figure 5) identifies two macro areas with different radioactivity. Low counts in the northern part of the field indicate an area with relatively less clay content while the opposite happens with higher counts in the southern one. Results suggest a positive correlation between K-40 radionuclides and clay confirming the feasibility of this technique in identity areas with different clay content.

Figure 5. K-40 counts acquired by the gSMS during different days of surveys and data interpolation.

CRNS-Rover raw data have been averaged during the stationary period of 10 minutes for every point (Figure 6) to obtain a representative mean value of neutron counts in each position. The negative correlation between neutrons and hydrogen present in the soil allowed the description of a dryer northern portion of the field in correspondence with higher neutron counts. In contrast, a higher moisture content area in the southern part is characterized by lower counts, distinguishing the two macro areas representative of the field characterized by different water retention capacities. The neutron and TDR thematical maps both identify the same moisture behavior of the field, except for the central and top right positions where conditions are diverging.

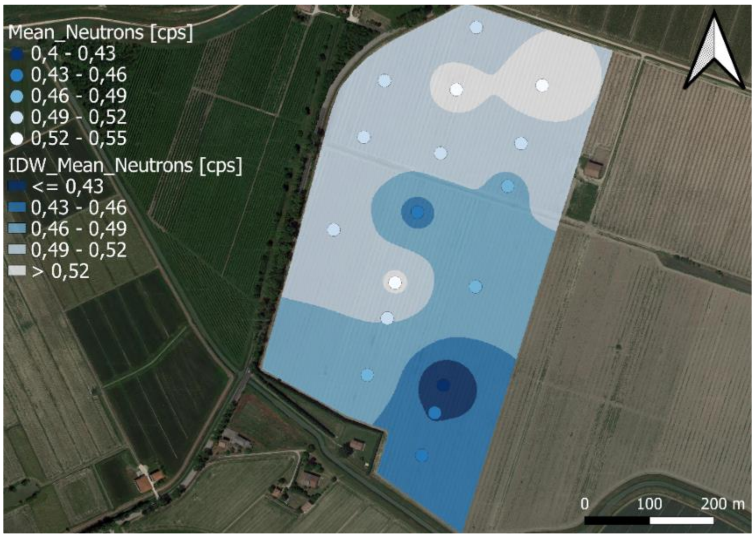

Figure 6. CRNS-Finapp5 observed data and IDW point interpolation result.

Conclusions and outlook

In the present study, qualitative results acquired by non-invasive geophysical sensors (CRNS and gSMS) have been presented together with a comparison to soil texture regional maps and independent volumetric soil moisture TDR observations.

Despite these two sensors being created for a stationary application for soil moisture monitoring over large areas (Gianessi et al., 2022), we tested the possibility to obtain thematical maps by applying a stop-and-go measuring procedure. A higher counting efficiency of both sensors is required if a constant motion is wanted during the signal acquisition. The employment of the gSMS is suggested to distinguish areas with different clay content, while the CRNS allows monitoring of the soil moisture spatial variability. This information can be crucial whether the farmer wants to group the field into homogeneous sectors or have an overview of the overall moisture conditions.

Further analyses will be addressed to repeat the experiment with higher sensitive sensors avoiding the stop-and-go approach, in different soil moisture conditions, by implementing a more accurate interpolation method of the observations acquired and applying quantitative statistics to assess the relations between the methodologies applied and soil properties.

Acknowledgments

The study is partially conducted within the CRP IAEA project D12014 Enhancing agricultural resilience and water security using Cosmic-Ray Neutron Sensor. We specifically acknowledge the collaboration with Agornoceto s.r.l., with the technical and scientific support from Mauro Bruni, Pierre Marchini, and Andrea Scalabrin. We also acknowledge the colleague Prof. Moreno Toselli from the University of Bologna (Italy) for conveying the experimental site and for the availability and Finapp s.r.l for the given technical support.

References

Becker, S.M., Franz, T.E., Abimbola, O., Steele, D.D., Flores, J.P., Jia, X., et al., 2022 Feasibility assessment on use of proximal geophysical sensors to support precision management. Vadose Zone Journal 21 (6) e20228.

Bocchi, S., Castrignanò, A., Fornaro, F., Maggiore, T., 2000. Application of factorial kriging for mapping soil variation at field scale. European Journal of Agronomy 13, 295–308. https://doi.org/10.1016/S1161-0301(00)00061-7

Bogena, H.R., Huisman, J.A., Güntner, A., Hübner, C., Kusche, J., Jonard, F., et al., 2015. Emerging methods for noninvasive sensing of soil moisture dynamics from field to catchment scale: a review. WIREs Water 2, 635–647. https://doi.org/10.1002/wat2.1097

Garré, S., Hyndman, D., Mary, B., Werban, U., 2021. Geophysics conquering new territories: The rise of "agrogeophysics." Vadose Zone Journal 20, e20115. https://doi.org/10.1002/vzj2.20115

Gebbers, R., Adamchuk, V.I., 2010. Precision Agriculture and Food Security. Science 327, 828–831. https://doi.org/10.1126/science.1183899

Gianessi, S., Polo, M., Stevanato, L., Lunardon, M., Baroni, G., 2022. Comparison of cosmic-ray neutron sensing and gamma-ray spectrometry for non-invasive soil moisture estimation over a large cropped field. In: IEEE Workshop on Metrology for Agriculture and Forestry (MetroAgriFor). pp. 48–52. https://doi.org/10.1109/MetroAgriFor55389.2022.9964647

Morari, F., Castrignanò, A., Pagliarin, C., 2009. Application of multivariate geostatistics in delineating management zones within a gravelly vineyard using geo-electrical sensors. Computers and Electronics in Agriculture 68, 97–107. https://doi.org/10.1016/j.compag.2009.05.003

Pätzold, S., Leenen, M., Heggemann, T.W., 2020. Proximal Mobile Gamma Spectrometry as Tool for Precision Farming and Field Experimentation. Soil Syst. 4, 31. https://doi.org/10.3390/soilsystems4020031

Stevanato, L., Baroni, G., Cohen, Y., Fontana, C.L., Gatto, S., Lunardon, M., et al., 2019. A Novel Cosmic-Ray Neutron Sensor for Soil Moisture Estimation over Large Areas. Agriculture 9, 202. https://doi.org/10.3390/agriculture9090202

Stevanato, L., Polo, M., Lunardon, M., Marinello, F., Moretto, S., Baroni, G., 2020. Towards the optimization of a scintillator-based neutron detector for large non-invasive soil moisture estimation. In: IEEE International Workshop on Metrology for Agriculture and Forestry (MetroAgriFor). pp. 196–200. https://doi.org/10.1109/MetroAgriFor50201.2020.9277582

Vather, T., Everson, C., Franz, T.E., 2019. Calibration and Validation of the Cosmic Ray Neutron Rover for Soil Water Mapping within Two South African Land Classes. Hydrology 6, 65. https://doi.org/10.3390/hydrology6030065