COMPARISON OF TWO ELECTROMAGNETOMETERS FOR SURVEYING SOIL ELECTRICAL CONDUCTIVITY: CMD MINI-EXPLORER AND SOIL EXPLORER

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Abstract. Several natural or anthropogenic factors can induce electromagnetic variations that affect agricultural management strategies. The Frequency Domain Electromagnetic (FDEM) techniques are measurement methods for detecting variations in electromagnetic fields, that can be exploited for the detection of characteristics of the surrounding environment. Among FDEM techniques, the most widely employed in agriculture is Electromagnetic Induction (EMI), which calculates the potential difference using a low-frequency generator and a receiver coil. This technique gives useful information on agricultural soils, such as physical characteristics, presence of contaminants and moisture content. This paper compares two EMI-based instruments to detect the electrical conductivity of soil. The first analyzed instrument is the CMD mini-explorer, an electro-magnetometer capable of surveying at 3 different depths simultaneously. The second instrument is the SoilXplorer, an electro-magnetometer capable of detecting 4 different depths. Both tools allow the georeferencing of the survey, enabling the creation of maps that can be used in precision agriculture. The data collected by the two instruments, after being processed, were compared and validated with chemical-physical laboratory analyses on soil samples taken from the test field. The results showed that both instruments provided values very close to those obtained in the laboratory; the sensors detected an electrical conductivity at a depth of 25 cm of 34 $mS \cdot m^{-1}$ for the CMD Mini-Explorer, 24 $mS \cdot m^{-1}$ for the SoilXplorer comparable with the 32 $mS \cdot m^{-1}$ detected by the laboratory analysis. As a result, the use of EMI-based instruments to detect the physical condition of soil in a non-invasive and destructive way is an effective approach to optimize agricultural management strategies. This technique improves the understanding of soil characteristics and provides a solid basis for the development of more sustainable and targeted precision farming practices.

Keywords: electromagnetic induction, soil electrical conductivity, CMD mini-explorer, SoilXplorer, soil physical characteristics.

Introduction

Soil is a natural resource that plays a fundamental role for a sustainable life on Earth [1], having a key role for 95% of food production and 25% of biodiversity, thus the detailed knowledge of its chemical and physical properties is essential to better preserve it. [2]. The increase of the world population and the strong reduction of cultivated areas require an increase in crop yields per hectare [3].

Therefore, a key challenge is to produce safe and nutritious food for the growing and wealthier population taking care of the planet [4]. To do so, it is essential to know the potentiality of the soil in which the crops are grown. Soil physical properties are essential for good agricultural productivity and environmental health [5; 6]. An accurate knowledge and interpretation of the spatial distribution of soil physical properties is essential to correctly plan agricultural practices and to preserve the environment [7; 8]. Soil is a system in continuous evolution with other environmental components that allows it to dynamically evolve [9; 10].

Static soil properties (e.g. soil texture, mineral composition, bulk density, and porosity), which are strictly correlated to the soil capability to product [6], show generally slight variability over time and are not significantly influenced by localized and short-term environmental conditions [11]. On the contrary, dynamic soil properties (e.g. soil moisture, salinity and temperature) exhibit strong temporal variability and are influenced by local environmental factors. These properties have a significant impact on soil conditions (i.e. fertility, nutrient cycling, and carbon sequestration) [11], making them central in agricultural management practices [12]. Static properties provide a baseline for soil characterization, while dynamic properties offer insights into the responsiveness of the soil to different environmental conditions [6]. Detailed knowledge of the soil static and dynamic characteristics is a key factor in improving agricultural production quality. Thanks to the improvements in technology and equipment, the assessment of soil parameters has become easier, more accurate and faster [13].

This scenario made possible implement at field scale precision agriculture [14] an emerging practice which employs site-specific information for decision-making, taking advantages from precise data on soil properties [15]. In this way, farmers can optimize natural input, such as water for irrigation and fertilizers for fertilization [16]. Traditional mapping techniques for soil properties [7; 17] involve laborintensive field surveys and sampling campaigns, in which soil samples are collected at several locations within the area under study. In this case, laboratory analysis is necessary to determine the static and dynamic properties of the sampled soil. These data are then elaborated and interpolated to create detailed soil maps, that provide insights about the spatial distribution of the different soil properties [8].

The non-invasive geophysical methods to determine soil properties, such as electromagnetic induction (EMI) for electrical conductivity, can offer efficient and high-resolution mapping capabilities [18; 19]. Multi-coil and/or multi-frequency EMI instruments allow simultaneous measurement of soil properties at several depths. The acquired data can be elaborated and interpreted to provide the underlying distribution of electrical conductivity in $mS \cdot m^{-1}$ [20]. Electromagnetic induction is among the most useful and easy techniques used to obtain the spatial distribution of electrical conductivity; this property strongly influences crop productivity [21; 22].

An EMI sensor is composed of a transmitter coil located at one end of the instrument, which induces circular eddy-current loops in the soil with magnitude directly proportional to the electrical conductivity of the soil in the neighborhood of that loop. Each current loop generates a secondary electromagnetic field proportional to the current flowing within the loop. A fraction of the secondary induced electromagnetic field from each loop is intercepted by the receiver coil of the instrument. The sum of these signals is amplified and transformed into an output voltage proportional to the depth-weighted bulk soil electrical conductivity. The receiver coil measures the amplitude and phase of the secondary magnetic field, thus the apparent electrical conductivity (ECa) is measured. These will differ from those of the primary field because of soil properties (e.g. clay content, water content, and salinity), spacing of the coils and orientation, frequency, and distance from the soil surface [23].

Materials and methods

The field tests were carried out on an area of 1 ha in the experimental farm "Martucci" of the University of Bari, in the municipality of Valenzano (BA), Fig. 1. The surface, bare at the time of the tests, is characterised by a clayey soil with low skeleton content, according to the USDA Soil Taxonomy classification.

Fig. 1. **Soil on which the tests were performed**

During the field tests, two different EMI sensors were tested to detect the electrical conductivity of the soil.

- The CMD Mini-Explorer probe (GF Instruments, s.r.o., Brno, Czech Republic): its probe is a cylindrical tube 1.3 m long, with a 30-kHz transmitter coil and three receiver coils positioned at 0.32 m, 0.71 m, and 1.18 m from the transmitter, for measuring the ECa at three different depths simultaneously. The effective penetration depths are 0-0.25 m, 0-0.5 m, and 0-0.9 m in the vertical coplanar mode (VCP) and 0.5 m, 1 m, and 1.7 m in the horizontal coplanar mode (HCP) coil configurations, respectively. Before starting the measurements, the sensor was warmed up for about 15 minutes to allow for proper calibration of the instrument. Data were collected in continuous measurement mode by setting a measurement period of 1 s. A global positioning system (GPS), incorporated in the device, allows georeferencing all sample points. The survey was carried out by a walking operator holding the device as close to the ground as possible to reduce interference. The transects were drawn 1 m apart in the east-west direction over the entire surface, and the device was moved at a constant speed in the north-south direction. The dataset obtained from the instrument was post-processed using the Origin 2018 software and plotted with MATLAB 2024, to create geo-referenced maps of ECa.
- SoilXplorer (AgXtend, Geoprospectors GmbH, Traiskirchen, Austria) TSM instrument, provides the ECa value at four soil depth: 0-25 cm, 0-60 cm, 0-95 cm and 0-115 cm. The survey was carried out with the instrument hooked onto the front of a New Holland T5 120 tractor, at a height of 70 cm above ground. The survey was carried out in continuous mode following transects of 2 m apart in the east-west direction over the entire surface, moving at a constant speed of 1 m·s^{-1} in the north-south direction. The acquired data were processed with the Topsoil Mapper software which allows the elaboration of georeferenced maps of ECa.

The data of the electrical conductivity obtained by these two instruments of the soil were validated with the data obtained from laboratory analyses carried out on 12 soil samples taken in the field at 4 sampling points. These were chosen based on the maps generated by the EMI sensors, taking into consideration the 4 areas with the greatest variability. For each sampling point, 3 different samples were taken at depths of 25 cm, 50 cm and 1 m.

Results and discussion

The comparison of the data obtained from the two EMI sensors, the CMD Explorer and the SoilXplorer, and the results of laboratory analysis on the 12 soil samples, was performed. The elaborated georeferenced maps show the distribution of ECa at the different depths provided:

- Fig. 2 and Fig. 3 show the maps obtained at a depth of 25 cm for the CMD Mini Explorer sensor and the SoilXplorer sensor, respectively.
- Fig. 4 and Fig. 5 show the maps obtained at a depth of 50 cm for the CMD Mini Explorer sensor and the SoilXplorer sensor, respectively.
- Fig. 6 and Fig. 7 show the maps obtained at a depth of 100 cm for the CMD Mini Explorer sensor and the SoilXplorer sensor respectively.

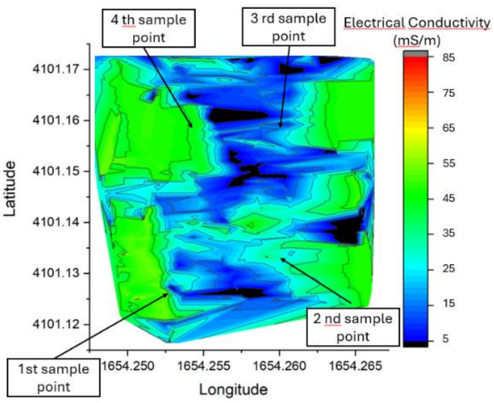

Fig. 2. **Georeferenced map of the CMD Mini Explorer at 25 cm depth**

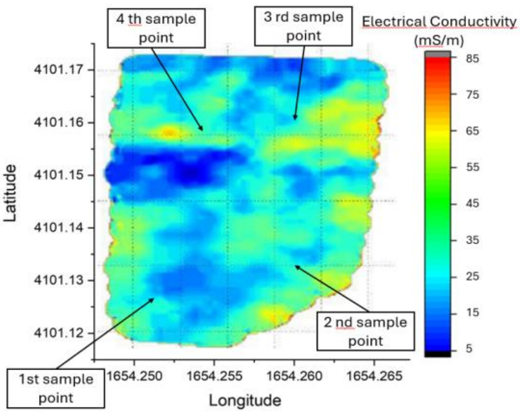

Fig. 3. **Georeferenced map of the SoilXplorer at 25 cm depth**

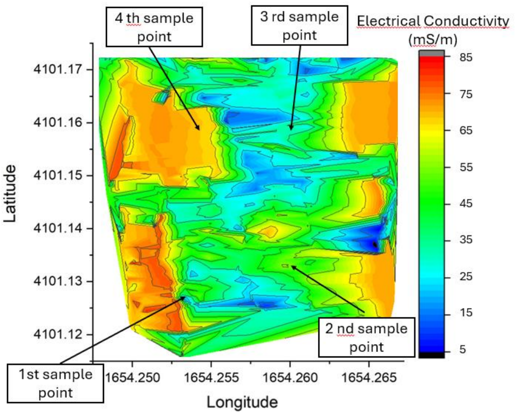

Fig. 4. **Georeferenced map of the CMD Mini Explorer at 50 cm depth**

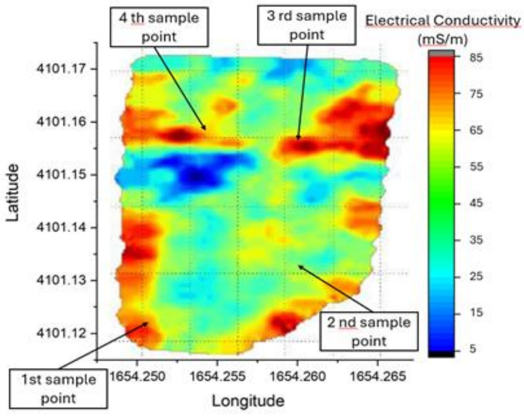

Fig. 5. **Georeferenced map of the SoilXplorer at 50 cm depth**

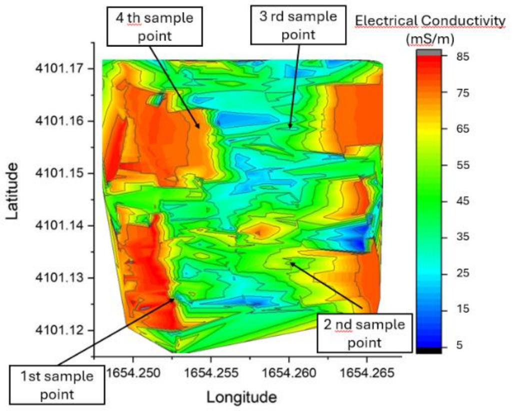

Fig. 6. **Georeferenced map of the CMD Mini Explorer at 100 cm depth**

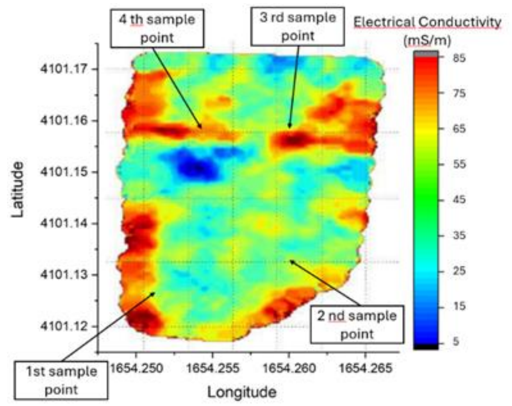

Fig. 7. **Georeferenced map of the SoilXplorer at 100 cm depth**

Fig. 8 shows the electrical conductivity values of the two EMI sensors and the values obtained by the laboratory analysis at sampling point 1 at the three depths considered. The remaining three sampling points show very similar trends.

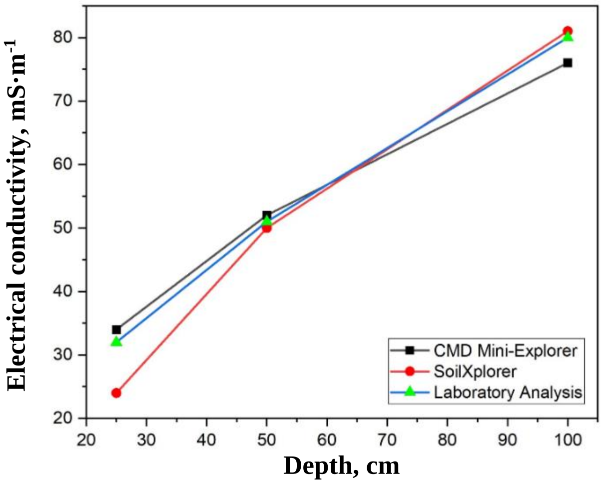

Fig. 8. **Comparison of the electrical conductivity distribution of the two sensors and laboratory analysis at different depths**

From Fig. 8 it is possible to see that the values obtained by both employed EMI sensors do not deviate much from the values determined by the laboratory analysis. In particular, the CMD Mini-Explorer sensor showed a greater sensitivity for the more superficial depths, while the SoilExplorer sensor showed a better ability to correlate data acquired for greater depth. Table 1 shows the electrical conductivity values of the sampling point 1.

Table1

Electrical Conductivity values at different depths for sampling point 1

Depth (cm)	Electrical Conductivity (mS·m^{-1})		
	CMD Mini-Explorer	SoilXplorer	Laboratory Analysis
25	34	24	32
50	52	50	51
100	74	81	80

From Table 1, the following considerations can be made:

- ECa values acquired in the first 25 cm of soil: show an average value of 34 mS·m^{-1} for the CMD Mini-Explorer sensor and 24 mS·m^{-1} for the SoilXplorer sensor, while the electrical conductivity value measured by the laboratory analysis was 32 mS·m^{-1} with an uncertainty value of ± 0.6 mS·m^{-1}.
- ECa values acquired in the first 50 cm of soil: show an average value of 52 mS·m^{-1} for the CMD Mini-Explorer sensor and 50 mS·m^{-1} for the SoilXplorer sensor, while the electrical conductivity value detected by the laboratory analysis was 51 mS·m^{-1} ± 0.6 mS·m^{-1}.
- ECa values acquired in the first 100 cm of soil: showed an average value of 74 mS·m^{-1} for the CMD Mini-Explorer sensor and 81 mS·m^{-1} for the SoilXplorer sensor, while the electrical conductivity value measured by the laboratory analysis was 80 mS·m^{-1} ± 0.6 mS·m^{-1}.

The statistical analysis conducted showed a high correlation between sensor measurements and laboratory values, with coefficients of determination of 0.88 for the Soilxplorer and 0.94 for the CMD Mini-Explorer, respectively. This study confirms the validity of the EMI-based approach as a non-invasive method for soil electrical conductivity determination, representing an effective, rapid and less laborious alternative to traditional laboratory analysis.

Conclusions

1. The investigation conducted in this study showed slight variations in the sensitivity of the two employed EMI sensors as the depth varied, confirming the ability of EMI sensors to provide an accurate estimation of soil electrical conductivity.
2. The CMD sensor was particularly effective for measurements in the first 50 cm, as the depth increases, the sensitivity of the sensor is lower.
3. The SoilXplorer provided more accurate results at depths from 50 cm to 100 cm, showing lower sensitivity in the first 25 cm.
4. This evidence suggests the importance of using such sensors to obtain detailed georeferenced maps of agricultural soil characteristics which are fundamental in the framework of precision agriculture, enabling sustainable soil management practices, efficient monitoring and optimization of natural resources.

Author contributions

Conceptualization, G.P., methodology, G.P. and A.F., software, F.V., validation, S.P., formal analysis, G.P and A.F; investigation, G.P., A.F., and F.V., data curation, G.P., A.F., writing – original draft preparation, G.P., writing – review and editing, G.P.,A.F. and S.P., project administration, G.P., All authors have read and agreed to the published version of the manuscript.

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