On the combined use of static and mobile cosmic-ray neutron sensors for monitoring spatio-temporal variability of soil water content in cropped fields

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***Abstract*—The primary aim of precision agriculture is to optimize crop yield while minimizing the usage of production inputs (in particular water and energy). This entails understanding and effectively managing the spatial variability of soil moisture within agricultural fields. This study present the performance of a combinated system of static and mobile Cosmic Rays Neutron Sensing (CRNS) probes installed in site and mounted onto a tractor for monitoring the temporal variability and mapping the spatial distribution of soil moisture in a cropped field. The use of CRNS entails different benefits, firstly, it allows for the collection of valuable information regarding soil water content in depth, reaching tens of centimeters. Moreover, the large footprint coverage, spanning approximately 5 hectares, provides a comprehensive understanding of soil moisture distribution over a significant area. The installation of CRNS probes on tractor allows for an efficient coverage of a large area and capturing dynamic changes in soil moisture over time. In order to achieve a comprehensive understanding of the soil moisture distribution, a total of four field mappings were conducted at key agronomic intervention points during the growing season of a plot cropped with tobacco.**

***Index Terms*—CRNS, Soil Moisture, Mapping, Field Scale**

I. INTRODUCTION

In the last decades, the use of non-invasive geophysical methods for agricultural applications has increased significantly [1]. Among others, electromagnetic induction sensing (EMI), ground penetration radar (GPR) or gamma-ray spectrometer (GRS) have been exploited showing good performance in several studies [2]. In this context, cosmic-ray neutron sensing (CRNS) has also emerged as a robust non-invasive soil water content sensor that is nowadays used in several networks all around the World [3]. The use of the same sensor in a mobile mode has also been tested showing promising applications [4], [5]. Similarly, the combined use of static and mobile sensors has been previously proposed showing the possibility to cover soil moisture in space and time. The studies conducted so far cover however large catchment areas [6]. Similarly, the use of CRNS in mobile mode for agricultural applications has been previously assessed but only for relatively large cropped fields [7]. Considering the high number of smallholder farms all over the world (e.g., $\leq$ 10 ha), additional tests should be conducted to understand the feasibility of this technology for relatively small cropped fields. In this contribution we report some research activities conducted with the final aim to assess the combined use of static and mobile CRNS systems at smallholder farms. Specifically, a static CRNS sensor has been installed to assess soil water content dynamics over time. The comparison with precipitation and irrigation is then performed. In addition, a mobile CRNS system has been used to detect spatial variability and different possible management zone within the field. The mobile system has been installed on a tractor while carrying out seasonal activities to avoid any additional farm activities and to reduce the operation costs.

II. CASE STUDY

A. Test site & Instrumentation

The experimental site is a 5 ha field with a sub-irrigation system cultivated with tobacco plants, located in Umbria (Italy) (Fig. 1).

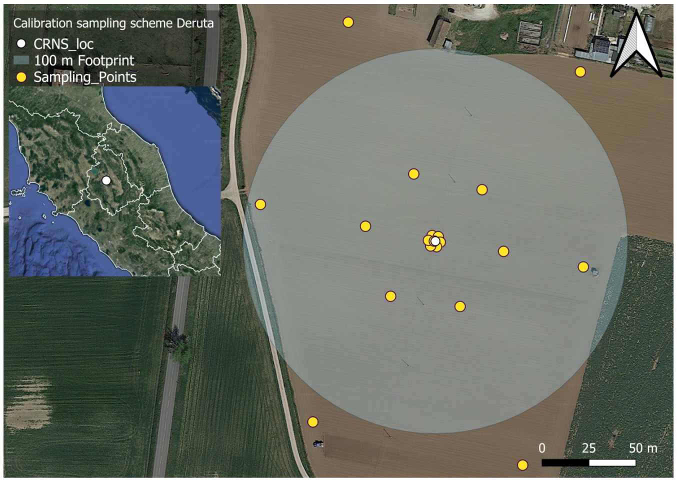
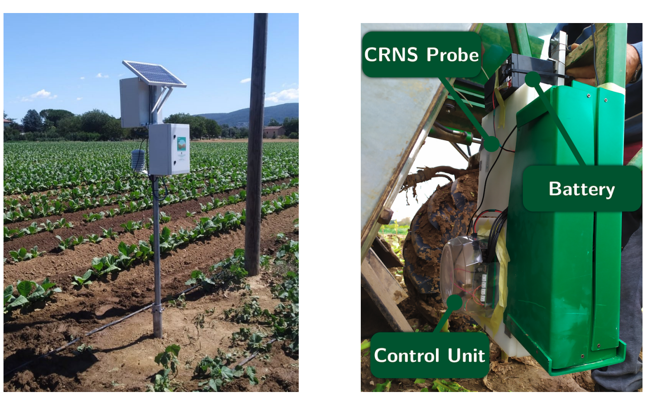


Fig. 1: Gravimetric sampling diagram of the experimental site. White dot represent the fixed CRNS probe position while yellow ones denote the soil sampling points. Buffered 100 m radius area is where the biggest contribution of the static CRNS signal is coming from.

The site is characterized by a silty clay loam soil with an estimated bulk density of 1.48 $\mathrm{g/cm^3}$ based on collected soil samples. In the center of the field, a CRNS-Finapp3 sensor is installed (www.finapptech.com) for real-time and long-term soil moisture monitoring of the entire field (Fig. 2 (a)). This scintillator-based sensor measures epithermal neutrons and has shown good performance in comparison to other commercial CRNS probes [8]. Data collection of the soil moisture signal we present goes from the day of installation on 15$^{\text{th}}$ of July 2022 and until 31$^{\text{st}}$ of December 2022. In addition to that, two Finapp-5 have been installed on a tractor for mobile survey (Fig. 2 (b)).



(a) (b)

Fig. 2: Static CRNS-Finapp3 sensor installed 2 m above ground at the center of the field (a). Mobile CRNS sensor installed on a tractor at about 50 cm from ground(b).

These scintillator-based CRNS probes used for mobile application and manufactured by Finapp are similar to the ones used for static applications. However, the active area of the Finapp-5 is 1.5 times bigger than the Finapp-3, allowing for the detection of around 1600 neutrons per hours at sea level for each sensor. Moreover, the two sensors are controlled by a dedicated electronic board also equipped with GNSS for the geolocation of particle counts, which is a key requirement for the roving application. The whole system is compact, having a total volume of 0.2 m^3, making it easy to install onto tractors. It allows to map the soil moisture conditions of the field while carrying out typical seasonal agronomic practices such as phytosanitary treatments and collection of basal, intermediate and apical leaves. Four mobile surveys have been conducted on August 31$^{\text{st}}$, September 22$^{\text{th}}$, October 26$^{\text{th}}$ and December 21$^{\text{th}}$ 2022.

B. Calibration & data analyses

For soil moisture monitoring over time, raw neutrons counts (N) have been corrected for pressure, incoming and atmospheric correction factors and transformed to volumetric water content (VWC) based on the procedure proposed in literature [9]. Specifically, the neutrons counts are converted in VWC using the following equation:

$$\theta(N)\ [\mathrm{m^3/m^3}] = \left(\frac{a_0}{\frac{N}{N_0} - a_1} - a_2 \right) \cdot \rho_{\text{bulk}} \tag{1}$$

where $a_0 = 0.0808$, $a_1 = 0.372$, $a_2 = 0.115\ \mathrm{m^3 m^{-3}}$, ρ_{bulk} is the soil bulk density and N_0 represent the probe neutrons count on dry soil condition. The value for N_0 was obtained from a dedicated soil sampling campaign conducted on December 21$^{\text{st}}$. The sampling design (see Figure 1) has followed the protocol currently suggested in literature to account for the spatial sensitivity of the signal [10]. Specifically, a set of 72 soil samples were collected. These samples were distributed at 18 points every 60° to the north (Fig. 1), at a distance of 3-35-120 m from the probe, at four average depths of 2.5-12.5-22.5-32.5 cm from surface. The soil moisture for each sample was assessed via the gravimetric method and will be used also for a qualitative validation of the rover soil moisture map variability in the field. In order to accurately compare the point-scale value obtained from soil samples, the values were weighted, taking into account the CRNS probe footprint sensitivity.

Raw neutron counts measured in the mobile survey, sampled at 1 Hz and tagged with a GNSS location (see Figure 3), are spatially aggregated using a grid with a pixel size of 10 m; hence each pixel contains a number of neutron counts, normalized by the total elapsed time inside the pixel, which depends on the vehicle velocity. In order to ensure a good signal-to-noise ratio, the vehicle velocity was constrained to about 5 km/h. After this aggregation, the neutron counts rate in each cell is smoothed by taking an average on all the cells within 30 m as follows:

$$N(i,j) = A^{-1} \sum_k \sum_l \delta^{(i,j)}_{(k,l)}\ N(k,l) \tag{2}$$

where $N(i,j)$ is the neutrons counts rate at the cell (i,j), $\delta^{(i,j)}_{(k,l)}$ is a function that takes a value of 1 if the distance, between

Fig. 3: CRNS-Rover track during the December campaign. The following paths were dictated by the vehicle agronomical activity, planned for that day and field geometry.

cell (i,j) and cell (k,l) is less than 30 m otherwise it returns 0, and A is the number of cells within the radius of 30m, namely:

$$A = \left(\sum_{k} \sum_{l} \delta_{(k,l)}^{(i,j)} \right) \tag{3}$$

The same N_0 used for the static CRNS probe has also been used for the mobile sensors by accurately scaling for the different detection efficiency between Finapp3 and Finapp5, i.e., the two sensors have been intercompared in the laboratory by acquiring the signal and quantifying the relative efficiency.

C. Results and discussion

The static CRNS-Finapp3 sensor recorded and transmitted the data regularly during the monitored period (Figure 4). The signal reacted well to irrigation and precipitation events confirming previous studies conducted on the use of static CRNS probes for agricultural applications [11]. The average soil moisture detected by the mobile-CRNS sensor is also compared with the static soil moisture signal during the season. Apart from the first rover campaign during August 31^{st}, where only one Finapp-5 was used for the mapping, the other surveys are in good agreement with the static probe. This may be linked to the fact that the rover campaign does not cover all the static probe footprint and thus the mobile average could be different from the static one. However, this hypothesis needs further investigation.

Noteworthy, a strong precipitation event occurred at the end of September producing a strong increase in soil water content (SWC). This was regularly monitored by the static CRNS probe during the whole period capturing the soil drying down.

The maps of soil water content variability are shown in Figure 4. By visual inspection, it is possible to see some hot spots; these were attributed to depressions in the surface of the field such as a drainage channel situated in the center of the field from W-E in correspondence with the entrance to the field, or to the leakage of the sub-irrigation system as reported by local farmer due to worm activities that lacerate the drip irrigation pipe causing a consequent concentration of water in a small area.

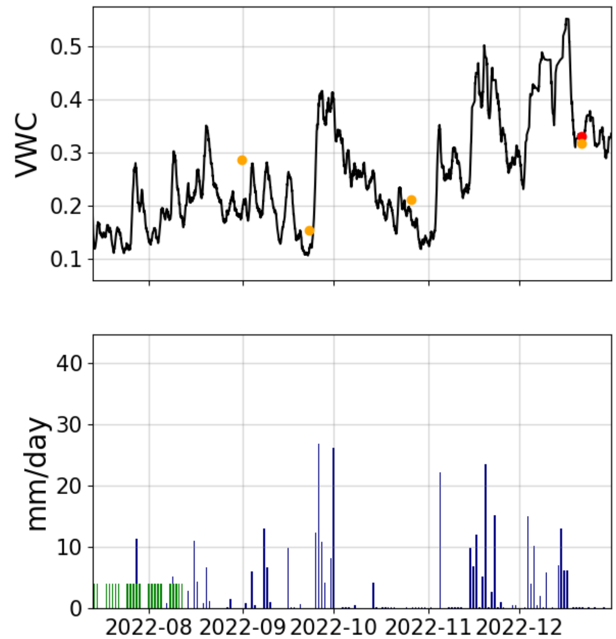


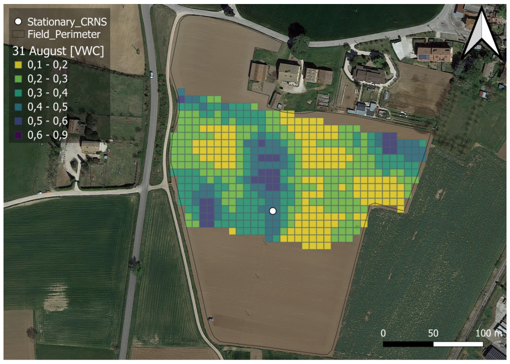
Fig. 4: Upper panel shows volumetric soil moisture (VWC [m^3 m^{-3}]) estimated by the static CRNS installed at the field. Soil moisture during the calibration date is shown in red dot. The average of the results of the mobile surveys are also added (orange dots). The bottom panel shows irrigation (green bars) and precipitation (blue bars).

During the first two mapping campaigns in August and September, it is possible to notice a larger variability concerning the one acquired in October; this was linked to the prevailing rainfall during that period. The gravimetric soil moisture obtained from the samples obtained for N_0 calibration was used to do a preliminary validation of the CRNS-rover mobile patterns. As can be seen in Figure 6 the soil moisture obtained from soil samples has a lower degree of variability (σ_{SMgrav} = 2.18 $m^3 m^{-3}$) with respect to the soil moisture map obtained. This suggests that these maps should be used only to appreciate soil spatial variability more than the absolute soil moisture value. Overall, results show that mobile CRNS can serve farmers in determining critical zones, such as wet or dry spots that can lead to a lower yield or quality of the final product.

III. Conclusions & future perpsective

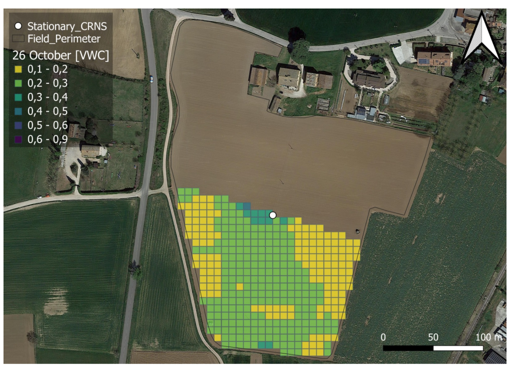
This study presents the results acquired through a CRNS system based on the combination of static and mobile sensors on a farm of 5 ha.

The static sensor has demonstrated its utility in providing valuable insights for real-time monitoring of soil moisture at field-scale since its signal is well-correlated with irrigations as



(a) August 31^{st} 2022

(b) September 22^{nd} 2022



(c) October 26^{th} 2022

(d) December 21^{st} 2022

Fig. 5: Mobile-CRNS soil moisture variability maps.

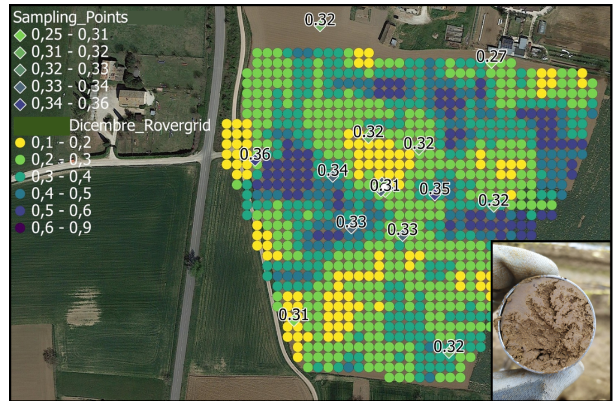


Fig. 6: Comparison between soil moisture map obtained by CRNS-Rover and gravimetric soil moisture in different sampling points within the field.

well as precipitation patterns. This correlation enables farmers and land managers to make informed decisions regarding irrigation scheduling and water management strategies.

The mobile sensor has proven to be a viable choice for mapping soil water content variability. By identifying and mapping these variations, farmers can implement site-specific strategies such as targeted fertilization, irrigation, or pest control measures.

Overall, the combined use shows promising applications for a relatively small size field.

This research paves the way for future investigations, the assessment of this technique will be carried out by using more than two probes in order to find a cost-effective configuration ensuring an optimized signal-to-noise ratio. In addition to this, the effect of the aggregation procedure will be investigated more in detail by trying to average over all the cells by weighting them with the distance from the cell of interest. Finally, the stability of the observed patterns will be studied using dedicated statistical techniques like Empirical Orthogonal Functions (EOF) analysis.

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