BOOSTING AGRO-METEOROLOGY STATIONS BY MONITORING LARGE SCALE SOIL MOISTURE WITH INNOVATIVE NON-INVASIVE SENSORS

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POTENZIAMENTO DI STAZIONI AGRO-METEOROLOGICHE MONITORANDO L'UMIDITÀ DEL SUOLO SU AMPIA SCALA CON INNOVATIVI SENSORI NON INVASIVI

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Abstract
In this study, new non-invasive soil moisture sensors have been installed and calibrated at three experimental sites. The sensors have been easily installed and data is regularly transmitted to an on-line platform. At the specific conditions of the sites, the measurements represent average soil moisture over an area of around 5 hectares down to 25 cm in the soil. The soil moisture dynamic detected by the sensor is well in agreement with the monitored local conditions (precipitation) and with the soil moisture simulated by the agro-hydrological model CRITERIA-1D. Overall, these detectors show to be an effective solution for soil moisture monitoring that can be integrated into current agro-meteorologic networks. Additional assessments are planned at different agro-environmental conditions.

Parole chiave
umidità del suolo, raggi cosmici, neutroni, monitoraggio della siccità

Keywords
soil moisture, cosmic-rays, neutrons, drought monitoring

Introduction

Soil moisture is an important variable for understanding hydrological processes at different spatial and temporal scales (Vereecken et al., 2008). It is a key factor in weather and climate by controlling the exchange and partitioning of water and energy fluxes at the land surface. The correct characterization of temporal and spatial soil moisture dynamics is of primary importance in agricultural and irrigation management practices, precision agriculture, flood forecasting and landslides prediction.

Several methods have been developed for soil moisture estimations (Corradini, 2014). These methods can be classified as invasive point-scale soil moisture, near-surface proximal sensing or remote sensing. Among these different methods, point-scale soil moisture sensors remain the widest ground-true method in many applications ranging from environmental monitoring to precision agriculture (Domínguez-Niño et al., 2020). However, point-scale observations suffer from inherent soil spatial variability. As such, many sensors should be installed when a representative field average condition is requested. In addition, they need relatively regular maintenance or re-installations to allow agricultural activities. For this reason, the integration of soil moisture observations into long-term operational agro-meteorology stations is still very limited.

Therefore, agricultural soil moisture drought monitoring is still often conducted based on the integration of agro-hydrological models of different complexity or remote sensing products (Saha et al., 2021).

In the last decade, soil moisture estimation based on the so-called cosmic-ray neutron sensing (CRNS) emerged as a promising method for detecting soil moisture non-invasively at a large scale of hectares and integration depth down to 50 cm (Zreda et al., 2008).

This method relies on the inverse correlation of natural neutrons generated by cosmic-rays fluxes and soil moisture. The detector is installed above ground with no contact with soil and it requires low maintenance. The method has been tested in many conditions all around the World showing good performance in comparison to averaged point-scale measurements (Franz et al., 2012; Hawdon et al., 2014; Nasta et al., 2020; Rivera Villarreyes et al., 2011; Vather et al., 2018; Zhu et al., 2016). This technique has started to be integrated into some national observation networks with the acronyms of COSMOS network, i.e., COSMOS-US (Zreda et al., 2012), COSMOz (Hawdon et al., 2014), COSMOS-UK (Cooper et al., 2021), COSMOS-India (Upadhyaya et al., 2021). To some extent, the integration and use of this method have been limited to research groups due to the relatively high cost of the detectors and the complexity of corrections to be implemented in the signal.

To overcome these limitations, more recent efforts have been dedicated on developing new instruments and standardized analyses that can be easily integrated into on-line processing. Among them, Stevanato et al. (2019) developed a new lighter detector that shows good performance in comparison to commercial probes. In addition, it shows several advantages by measuring additional particles than neutrons like muons and gammas that can be used for further improvements of the signal. The detector underwent further improvements for the optimization of the signal and to minimize energy consumption (Stevanato et al., 2020). As such, it is positioning as a competitive detector that can be easily integrated into current operational agro-meteorological networks for, e.g., drought monitoring, remote sensing calibration or integration into hydrological models.

In the present study, we show the activities to integrate such sensors into three agro-meteorological stations operated by the Regional Environmental Protection Agencies (ARPA). The preliminary results are presented and discussed.

Materials and Methods

The experimental sites are located in the Po plain, northern Italy (Fig. 1): this area is well known for its agricultural importance and it can be threatened by drought spells in summer. Each site hosts a weather station of ARPA's hydrometeorological network, equipped with world meteorological organization compliant meteorological sensors for monitoring atmospheric conditions.

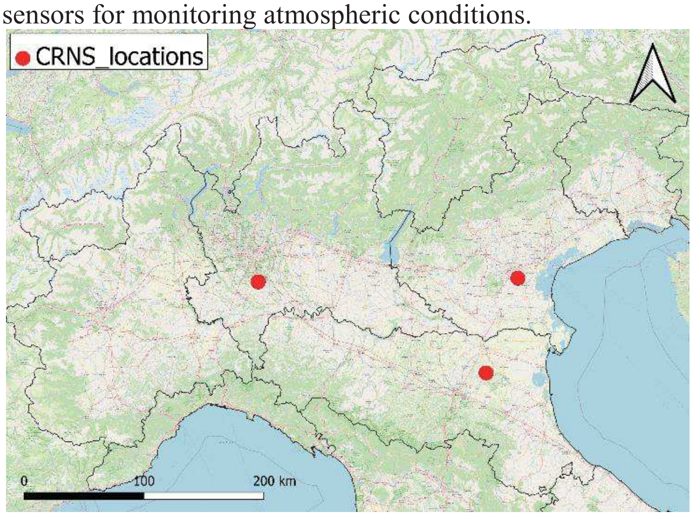

Fig. 1. Posizione delle stazioni agro-meteorologiche in cui è stato installato un sensore CRNS

Fig. 1. Locations of the agro-meteorological stations equipped with CRNS sensor

At each site, a CRNS sensor (https://www.finapptech.com/) has been installed (Fig. 2aFig. 1). In the present configuration, the sensors are autonomous with a relatively small solar panel and they transfer the data via GSM. Alternative configurations depending on the specific conditions can be foreseen, i.e., the sensor can be integrated into an existing data logger and connected to local energy supply. Detected neutrons have been further corrected based on standard approaches for atmospheric pressure, incoming neutron variability and air humidity (Zreda et al., 2012).

At each site, soil samples have been collected for the calibration of the sensor based on a standard sampling design that accounts for the spatial sensitivity of the signal (Fig. 2b). A total of 72 undisturbed soil samples have been collected (i.e., 18 locations and four depths down to 5, 15, 25 and 35 cm). Each sample has been analyzed in the laboratory for gravimetric soil moisture (SM) and bulk density (ρ_{bd}). A composite soil for each soil depth has been further analyzed for organic matter (OM) and lattice water (LW). OM and LW are both determined by the loss-on-ignition method in two separate steps. First, samples are weighted after heating for 16 h at 500°C. Secondly, they are weighted after 12 h at 1000°C (Scheiffele et al., 2020). The results of the laboratory analyses are shown in Tab. 1. These values are used for the calibration (eq.1). On the same day of the survey, manual surface (0-5cm) soil moisture values have been detected at around 500 locations around the sensor based on TDR measurements (Field Scout 350) (data not shown).

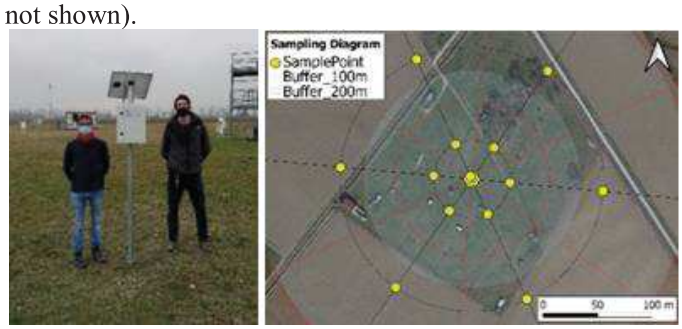

Fig. 2. (a) Tipica installazione del sensore CRNS e (b) disegno di campionamento di suolo per la calibrazione e area indagata dal sensore

Fig. 2 (a) Typical installation of CRNS sensor and (b) sampling design for calibration and sensor footprint

Tab. 1. Parametri medi del terreno per ogni sito sperimentale

Tab. 1. Soil samples parameters average for each experimental site

Site	Capofiume	Landriano	Legnaro
Latitude WGS84	44.653655	45.3216877	45.3473971
Longitude WGS84	11.623476	9.2674271	11.9521693
Altitude [m]	8.5	87.5	6.8
Survey date	3/15/2021	3/22/2021	3/29/2021
Gravimetric SM [g/g] =	0.119	0.198	0.165
Dev st. SM σ =	0.036	0.037	0.021
Gravimetric OM [g/g] =	0.028	0.038	0.044
Gravimetric LW [g/g] =	0.084	0.0073	0.152
Bulk Density [g/cm^3] =	1.43	1.37	1.46

The following equation is used to invert corrected neutrons intensity to soil moisture (Zreda et al., 2012):

$$\theta(N) = \left(\frac{0.0808}{\frac{N}{N_0} - 0.372} - 0.115 - \theta_{offset}\right) \cdot \frac{\rho_{bd}}{\rho_w}$$

where N is the corrected neutron intensity [counting per hours cph], θ is the volumetric soil moisture [cm^3 cm^{-3}], N_0 is the specific parameter to be calibrated [cph], θ_{offset} is the additional hydrogen pool (i.e., lattice water + soil organic matter) [cm^3 cm^{-3}] and ρ_{bd} and ρ_w are the bulk density and density of the water respectively [g cm^{-3}].

Results and Discussion

The CRNS sensors correctly register the neutrons since the installation. The data is transmitted to the on-line platform. Data have been downloaded and further analyzed as previously described. The results at the San Pietro Capo Fiume experimental site are presented in figure 3. The results show a consistent soil moisture dynamic well in agreement with precipitation events. Preliminary analyses show a footprint of 5 ha and a penetration depth of 20 cm. The comparison with soil moisture over the first 25 cm simulated with the agro-hydrological model CRITERIA-1D previously calibrated at the same locations (Tomei et al., 2007) also confirms the good agreement of the soil moisture dynamics. Differences are in the range of the spatial variability detected at the site (data not shown).

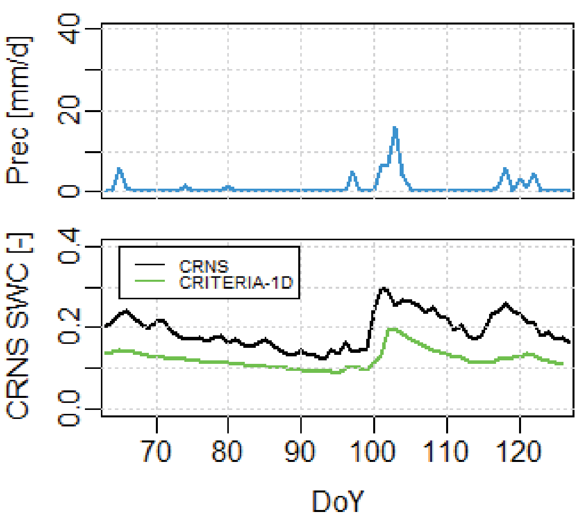

Fig. 3. Dati raccolti a San Pietro Capofiume (alto) precipitazione, (basso) umidità del suolo stimata dalla sonda CRNS e dal modello agro-meteorologico CRITERIA-1D.

Fig. 3. Data from San Pietro Capofiume: (top) precipitation, (bottom) soil moisture estimated based on CRNS and CRITERIA-1D.

The results obtained at the other two experimental sites are illustrated in figure 4. Also for these sites, soil moisture dynamic is well in agreement with precipitation events.

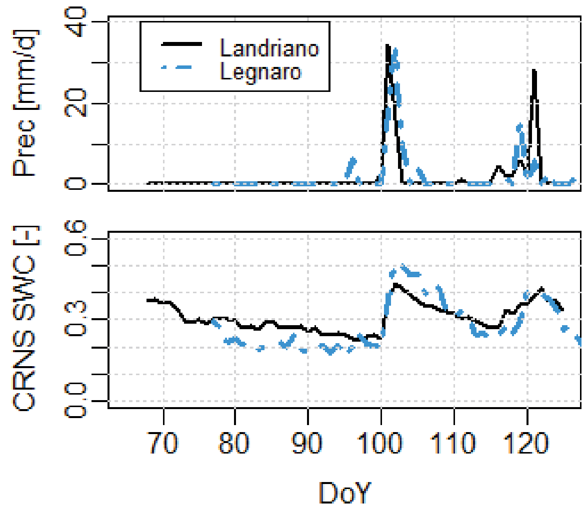

Fig. 4. Dati raccolti alla stazione di Landriano e di Legnaro: (top) precipitazioni; (bottom) umidità del suolo stimata dalla sonda CRNS.

Fig. 4. Data from Landriano and Legnaro experimental sites: (top) precipitation (bottom) CRNS soil moisture.

Specifically, higher precipitation events occurred at these sites in comparison to San Pietro Capofiume, which are reflected in a higher soil moisture dynamic detected by the sensor, with values reaching up to 0.5 volumetric soil moisture [cm^3 cm^3]. Noteworthy, two main precipitation events occurred during the monitored period but with a short time shift between the sites. This time shift is well in agreement with the soil moisture dynamic detected by the sensors.

Conclusions

This contribution presents the installation, calibration and preliminary results obtained with innovative cosmic-ray soil moisture sensors CRNS (https://www.finapptech.com/). The detectors have been installed at three locations where standard agro-meteorological stations are operated by the Environmental Protection Agencies (ARPA). These detectors have been easily installed, they showed a robust data transmission capacity and they have provided reliable soil moisture estimation since the beginning of their operation. Therefore, these preliminary results, indicate that they can represent an effective and viable solution for non-invasive soil moisture estimation that can be easily integrated into agro-meteorological stations. These boosted observation systems can provide the basis for ground-truth drought monitoring, remote sensing and modeling calibration. Further assessments are planned based on additional soil surveys and the comparison with other commercial CRNS detectors. The application of the same sensor for snow monitoring is also under investigation (Schattan et al., 2017), with two additional sensors installed in two alpine sites (in Veneto and Piemonte regions), once again in collaboration with ARPA.

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