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Testing a novel sensor design to jointly measure cosmic-ray neutrons, muons and gamma rays for non-invasive soil moisture estimation

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Abstract. Cosmic-ray neutron sensing (CRNS) has emerged as a reliable method for soil moisture and snow estimation. However, the applicability of this method beyond research has been limited due to, among others, the use of relatively large and expensive sensors. This paper presents the tests conducted to a new scintillator-based sensor especially designed to jointly measure neutron counts, total gamma-rays, and muons. The neutron signal is firstly compared against two conventional gas-tube-based CRNS sensors at two locations (Austria and Germany). The estimated soil moisture is further assessed at four agricultural sites in Italy based on gravimetric soil moisture collected within the sensor footprint. The results show that the signal detected by the new scintillator-based CRNS sensor is well in agreement with the conventional CRNS sensors and with the gravimetric soil moisture measurements. In addition, the muons and the total gamma-rays simultaneously detected by the sensor show promising features for a better correction of the incoming variability and for discriminating irrigation and precipitation events, respectively. Further experiments and analyses should be conducted, however, to better understand the added value of these additional data for soil moisture estimation. Overall, the new scintillator design shows to be a valid and compact alternative to conventional CRNS sensors for non-invasive soil moisture monitoring that can open the path to a wide range of applications.

1 Introduction

Soil moisture plays a key role in the hydrological cycle controlling water and energy fluxes at the land surface (Seneviratne et al., 2010; Vereecken et al., 2008). For this reason, a correct monitoring of this variable is crucial in many applications, ranging from agricultural water management (Lichtenberg et al., 2015), runoff generations and floods (Bronstert et al., 2011; Saadi et al., 2020), and landslide prediction (Abraham et al., 2021; Zhuo et al., 2019). The main challenges in monitoring this variable are related to its strong spatial and temporal variability driven by the different hydrological processes at the land surface (Haghighi et al., 2018) and further aggravated by human activities like irrigation and drainage (Domínguez-Niño et al., 2020).

Several instruments for monitoring soil moisture are nowadays available ranging from invasive point-scale soil moisture sensors to remote sensing methods with larger coverage (Babaeian et al., 2019; Corradini, 2014;

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Ochsner et al., 2013). More recently, the attention has been paid to the development and assessment of the so-called proximal soil moisture sensors (Bogena et al., 2015). These non-invasive near-ground detectors have the advantages to estimate soil moisture over an intermediate scale (10 - 200 m radius) and at sub-daily resolutions providing a new perspective for hydrological observations (Ochsner et al., 2013).

Among these non-invasive techniques, cosmic-ray neutron sensing - CRNS (Zreda et al., 2008) - has showed good performance in several conditions (Baatz et al., 2014; Coopersmith et al., 2014; Franz et al., 2012; Heidbüchel et al., 2016; Jeong et al., 2021; Rivera Villarreyes et al., 2011; Sigouin et al., 2016; Zhu et al., 2016). This technique relies on the inverse correlation between natural neutron fluxes in a specific energy range (0.5 eV – 100 keV) and hydrogen pools at and in the ground, providing a favourable option for monitoring soil moisture, snow and biomass (Baroni and Oswald, 2015; Desilets et al., 2010; Jakobi et al., 2018; Schattan et al., 2017; Tian et al., 2016).

Noteworthy, this inverse correlation has been detected since long time but mostly considered noise in space weather monitoring (Hands et al., 2021; Hendrick and Edge, 1966) and rock dating (Gosse and Phillips, 2001). First studies showing the value of this signal for hydrological applications have been presented only some decades later based on a neutron detector installed below the ground (Kodama et al., 1979). Its application, however, remained limited to some integrations into long-term observation networks for snow estimation (Morin et al., 2012). A strong contribution to the development and spread of this technique was provided only more recently when a better understanding of the interaction of these neutron fluxes and soil moisture was investigated (Zreda et al., 2008). In this context, the neutron detector had been installed above-ground and the signal well agreed with soil moisture over an area of several hectares and down to a depth of several decimetres (Franz et al., 2012) providing a new prospective to monitor hydrological variables at the land surface (Desilets et al., 2010). Nowadays, this above-ground CRNS method is used by many research groups worldwide and it is integrated into some national monitoring systems for providing a better understanding of hydrological processes and supporting water management and assessments (Andreasen et al., 2017b; Bogena et al., 2022; Cooper et al., 2021; Hawdon et al., 2014; Upadhyaya et al., 2021; Zreda et al., 2012).

Initially, all the CRNS detectors were based on proportional gas tubes filled in with helium-3 or boron trifluoride (Schrön et al., 2018; Zreda et al., 2012). Alternative sensors are now emerging that could also open the path to new and wider applications (Cirillo et al., 2021; Flynn et al., 2021; Patrignani et al., 2021; Stevanato et al., 2019; Stowell et al., 2021; Weimar et al., 2020; van Amelrooij et al., 2022). In this context, the scintillator-based neutron detector design showed a good capability to measure neutrons with different energies (Cester et al., 2016). A first prototype specifically for soil moisture estimation was developed and tested showing good performance in comparison with independent soil moisture observations (Stevanato et al., 2019). This detector was further improved by, e.g., reducing environmental temperature effects on the recorded signal and reducing its energy consumption (Stevanato et al., 2020). First comparisons with independent data confirmed the good performances of these devices (Gianessi et al., 2021) with the additional advantage of measuring muons for on-site incoming neutron correction (Stevanato et al., 2022).

In this study, we present a comprehensive description and assessment of this new scintillator-based CRNS detector. The assessment is performed based on (i) a comparison of neutron counts detected by conventional gas-tube-based CRNS instruments at two experimental sites and (ii) a comparison to independent soil moisture measurements at four additional experimental sites. The added value of muons and gamma particles simultaneously recorded by the sensor are also explored and discussed.

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2 Materials and methods

2.1 The detector assembly

Scintillators have been identified as a promising alternative to proportional gas tubes for measuring neutrons in many applications (Peerani et al., 2012). The main advantages are the use of cheaper and safer materials than proportional gas tubes and the capability to develop relatively compact sensors. The scintillators are made of plastic or organic materials that emit photons in the visible or near ultraviolet (UV) region when hit by radiation. The scintillator materials used for neutron detection, in particular, have the special property to release the light in different ways when hit by different particles. The identification of the type of particle or ray is achieved by means of Pulse Shape Analysis (PSA), exploiting the different profile in time of the signals. A typical parameter used in these analyses is the so-called pulse-shape-discrimination parameter (PSD), given by the ratio of the integrated charge in the tail of the signal with respect to the total integrated charge. An example is shown in Figure **1**a, left panel, which shows how different particles (here thermal neutrons and cosmic muons) populate very different regions in the PSD vs. integrated-charge plane in the used sensor. For more details we refer to more specific studies (e.g., Cester et al., 2016).

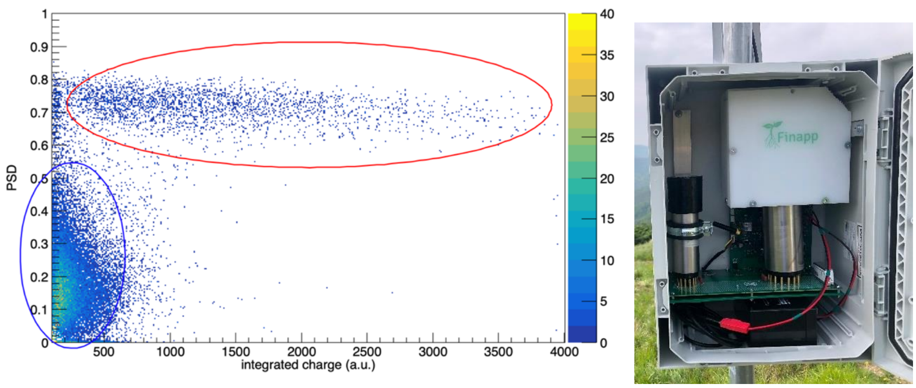

Figure 1: (left) typical PSD *vs.* integrated charge plot for a FINAPP3 detector. Red and blue ovals indicate the neutron and muon region respectively; (right) scintillator-based sensor FINAPP3 with board, photomultiplier, and the two main detectors.

In the present study we use the scintillator-based sensor FINAPP3 developed by FINAPP.srl (finapptech.com/en). The main parts of the sensor are shown in Figure 1b. The sensor hosts two main detectors. The first one (with the white polyethylene shield in the top-right of the box) is a multi-layer Zinc Sulfide Ag-doped scintillator mixed with Lithium-6 Fluoride powder embedded in a silicone-based matrix. Epithermal neutrons are further moderated by the polyethylene shield and brought to thermal energies (around 0.026 eV) where neutron capture cross section on Li-6 is maximum. The output of the neutron capture reaction is the emission of an alpha particle and a tritium nucleus with total kinetic energy of almost 5 MeV, easily detected by the ZnS(Ag) scintillator. This detector can measure cosmic-ray induced muons too (in the energy of around 4 GeV) distinguished by a real-time PSD. The second main detector is a small EJ200 plastic scintillator 2” dx 2” (the black cylinder on the left side of the box). This sensor can measure muons as the main detector but also the total gamma rays fluxes in the energy range between 0.3 MeV and 3.0 MeV. Two commercial photomultipliers (from Hamamatsu Photonics, Hamamatsu, Japan) are used to transform the light (visible photons) to electric pulse. The sensor is further integrated with air pressure, air temperature and air humidity sensors. A single

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electronics board takes care of detector signal acquisition, real-time data processing and data logging to a remote server. All the components of the detector are in a box of about 40 x 30 x 20 cm with a total weight of 8 kg. Energy consumption is minimized to 0.4 Watt (35 mA at 12 V) and it is supplied by a relatively small solar panel (20 Watt) installed above the sensor.

2.2 From neutron counts to soil moisture estimation

Since first publications (Desilets et al., 2010; Zreda et al., 2008), the CRNS method has seen a fast development with many research groups contributing to the better understanding of the detected signal and proposing new equations and corrections (Baatz et al., 2015; Köhli et al., 2021; Scheiffele et al., 2020). In this study, the current state-of-the-art of data processing is used and briefly described below.

The measured neutron count rates N are affected by local atmospheric conditions. For this reason, some corrections are commonly applied to the raw signal to allow relating the corrected signal N_c to soil moisture. Specifically, N is corrected for air pressure (f_p), variability of incoming neutron flux (f_i) and air vapour (f_v) based on the following correction factors (Zreda et al., 2012):

$$f_p = exp\left(\beta\left(p - p_{ref}\right)\right) \tag{1}$$

$$f_i = \frac{I_{ref}}{I} \tag{2}$$

$$f_v = 1 - \alpha\left(h - h_{ref}\right) \tag{3}$$

$$N_c = N \cdot f_p \cdot f_i \cdot f_v \tag{4}$$

where, β = 0.0076 [mb^{-1}], α = 0.0054 [m^3 g^{-1}], p and h are air pressure [mb] and absolute humidity [g·m^{-3}], I is the incoming flux of cosmic-ray neutrons induced by galactic primary particles in the Earth's atmosphere [counts hour^{-1}, cph], h_{ref}, p_{ref} and I_{ref} are the mean values of air pressure, absolute air humidity and incoming neutron flux during the measuring period, respectively. Air pressure and relative air humidity are generally measured locally (or taken from a weather station nearby) and the latter can be converted into absolute air humidity using measured air temperature. In contrast, data of the incoming fluctuations are commonly downloaded (e.g. from https://www.nmdb.eu/nest/) from dedicated neutron incoming monitoring stations located at some places globally (Simpson, 2000). For the specific case study, data from JUNG station at Jungfraujoch (Switzerland) are used for the correction as commonly adopted in many applications in central Europe.

Finally, the corrected neutron count rate N_c is transformed to volumetric soil moisture θ based on Desilets equation (Desilets et al., 2010):

$$\theta(N_c) = \left(\frac{0.0808}{\frac{N_c}{N_0} - 0.372} - 0.115 - \theta_{offset}\right) \cdot \frac{\rho_{bd}}{\rho_w} \tag{5}$$

where ρ_{bd} and ρ_w are the soil bulk density (kg·m^{-3}) and water density (kg·m^{-3}), respectively; θ_{offset} is the combined gravimetric water equivalent of additional hydrogen pools, i.e., lattice water (*LW)* and soil organic carbon (*SOC*), and N_0 is approximately the counting rate of the detector at a site during very dry soil conditions. The value N_0 can be calibrated based on independent soil sampling campaigns as suggested in different studies (Schrön et al., 2017; Franz et al., 2012). A simple spreadsheet for the processing of the data according to the steps described above is available from (Baroni, 2022b). For a more advanced data processing integrating also additional external data-sets readers can refer to Power et al. (2021).

Measuring cosmic muons and environmental gamma rays on top of neutrons is a unique feature of the scintillator-based sensors. The use of muons has been shown to be an alternative for incoming correction since they are produced from the same cascade as cosmic-ray induced neutrons in the atmosphere (Stevanato et al., 2022). We also test this approach in the present study and for sake of clarity we report here the main data-processing steps. Specifically, muons are first corrected to account for air pressure and air temperature effects as follows:

$$f_{p\_M} = exp\left(\beta_M\left(p - p_{ref}\right)\right) \tag{6}$$

$$f_{T\_M} = 1 - \alpha_M\left(T - T_{ref}\right) \tag{7}$$

$$M_c = M \cdot f_{p\_M} \cdot f_{T\_M} \tag{8}$$

where Eq. (6) is analogous to the pressure correction for neutron flux (see Eq. 1), p and T are the air pressure [mb] and air temperature [°C], respectively, and p_{ref} and T_{ref} are the mean value of air humidity and air temperature during the measuring period. The corrected muon flux M_C is then used for local incoming corrections in Eq. (2) instead of using neutron counts from space weather monitoring stations (https://www.nmdb.eu/nest/). The parameters $\beta_M = 0.0016$ mbar^{-1} and $\alpha_M = 0.0021$ °C^{-1} are taken from literature (Stevanato et al., 2022). These values have been estimated based on a recursive analysis conducted on a relative long time series collected at the same area. For this reason, the values are considered representative also for the experimental sites of the present study. Refinements of these values could be considered but this is beyond the scope of the present study.

Finally, the measurements of gamma ray has been shown to be a valid approach for soil moisture estimation at relative small scale, i.e., tens of meters (Baldoncini et al., 2018) or for identifying irrigation events at agricultural sites (Serafini et al., 2021). More specifically, gamma-rays measured above the ground (e.g., by a detector installed about 2 meters from the ground) are mainly produced by radionuclides in the soil. The gamma-ray fluxes are also attenuated by the presence of water in the soil, due to the increased average absorption coefficient of the wet soil with respect to the dry soil. For this reason, the gamma-ray signal (i.e., the ^{40}K full-energy peak at 1.46 MeV or, anyhow, high energy gamma-rays in this energy region) shows an inverse correlation with the amount of water in the soil and thus this relation can be used to estimate soil moisture dynamic (Strati et al., 2018). In contrast, gamma-rays in the energy range of ^{214}Pb (352 keV), a radon progeny, has a much stronger volatility and it is also present in the atmosphere. Thus, a fast increase in the gamma-rays in the energy of this photopeak can be detected during precipitation events due to the effect of radon atmospheric deposition. In contrast, during an irrigation event, no such behaviour is expected. The added value of these signals is also analysed in the present study based on the data collected at the experimental sites.

2.3 Comparison to other conventional CRNS sensors at two sites (Austria and Germany)

The comparison to other conventional gas-tube-based CRNS detectors has been conducted at two experimental sites (Figure **2**). The first site is located at Marchfeld (near Vienna, Austria, N48.24, E16.55). The second site is located at Marquardt (near Potsdam, Germany, N52.45, E12.96). The recorded time series cover the period of seven months starting from May 2021 when, in both sites, a FINAPP3 detector was installed.

At Marchfeld experimental site, the FINAPP3 sensor is compared with a CRS2000, a boron-10 trifluoride proportional gas tube produced by Hydroinnova LLC (www.hydroinnova.com) that has been used in many

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studies (Andreasen et al., 2016; Baroni and Oswald, 2015; Hawdon et al., 2014). At the Marquardt site, several CRNS sensors of different design are available for comparison. In the present study we selected a sensor based on two boron trifluoride proportional gas tubes (a double CRNS sensor system type called BF3-C-4) from "Lab-C" LLC, sold by Quaesta Instruments (www.quaestainstruments.com). This sensor provides a high sensitivity for neutron detection, thus good signal-to-noise ratio, which can promise potential for estimating soil moisture at even about hourly time resolution (Fersch et al., 2020).

All the detectors have been installed at a height of around 1.5 m above the ground and less than a few meters distance between FINAPP3 and the other selected CRNS detectors. Considering the large footprint of the signal detected, this horizontal difference is considered negligible for the comparison (Rivera Villarreyes at al., 2011). All the detectors have been equipped with a solar panel and with GSM data transmission for supporting long-term and real-time observations.

Figure 2. Experimental sites (left) Marchfeld (near Vienna, Austria) and (right) Marquardt (near Potsdam, Germany)

2.4 Comparison with independent gravimetric soil sampling campaigns (Italy)

A second assessment of the FINAPP3 sensor was carried out by a series of independent gravimetric soil sampling campaigns. The experiments were conducted at four experimental sites located in the Po river plain, northern Italy (Figure **3**). At San Pietro Capofiume (N44.65, E11.64, near Bologna, Italy, Figure 3, top left) and at Legnaro sites (N 45.34, E11.96, near Padova, Italy, Figure 3, top right), the sensors were installed over a grassland with low biomass that is surrounded by agricultural cropped fields. Conversely, at Ceregnano (N45.05, E11.86, near Rovigo, Italy, Figure 3, bottom left) and at Landriano (N45.31, E9.26, near Pavia, Italy, Figure 3, bottom right), the sensors were installed in the middle of agricultural fields where fast biomass growth and irrigation took place. More specifically, at Landriano, sorghum was cropped and irrigated by a sprinkler system. At Ceregnano, soybeans were cultivated and irrigated by a variable rate irrigation ranger system. The soil texture at the experimental sites is quite homogenous over the main area investigated by the sensors (approximately 100 m radius) except for Ceregnano, where a sandy fluvial deposit crosses the loamy field.

At each site, weather data were collected by meteorological stations operated by the Regional Environmental Protection Agencies (ARPA) at the same positions where the CRNS sensors were installed or located in close distance (few km). In these cases, the meteorological observations have been considered representative for the local conditions. Moreover, three field campaigns were conducted during the vegetation season to collect soil samples for the calibration and assessment of the CRNS signal. The sampling took into account the sensitivity of the signal decreasing with distance from the sensor. Specifically, undisturbed soil samples were collected at 18 locations (white circles in Figure **3**) and at four different depths (0-5 cm, 10-15 cm, 20-25 cm and 30-35 cm from the soil surface) for a total of 72 soil samples. Gravimetric water content for each soil sample was

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measured by dry-oven method (105° for 24 h). A mixed soil sample was further prepared at each site to measure soil organic carbon (SOC) and Lattice Water (LW). These two parameters have been measured by a Loss On Ignition (LOI) method respectively with a cycle of 24 h at 500° C and 12 h at 1000° C (Barbosa et al., 2021). All the values have been processed to account for the spatial sensitivity of the neutrons detected based on the most recent methods (Schrön et al., 2017). A simple spreadsheet where these weighting functions have been implemented is publicly available (Baroni, 2022b). The results are summarized in Table 1 in the appendix.

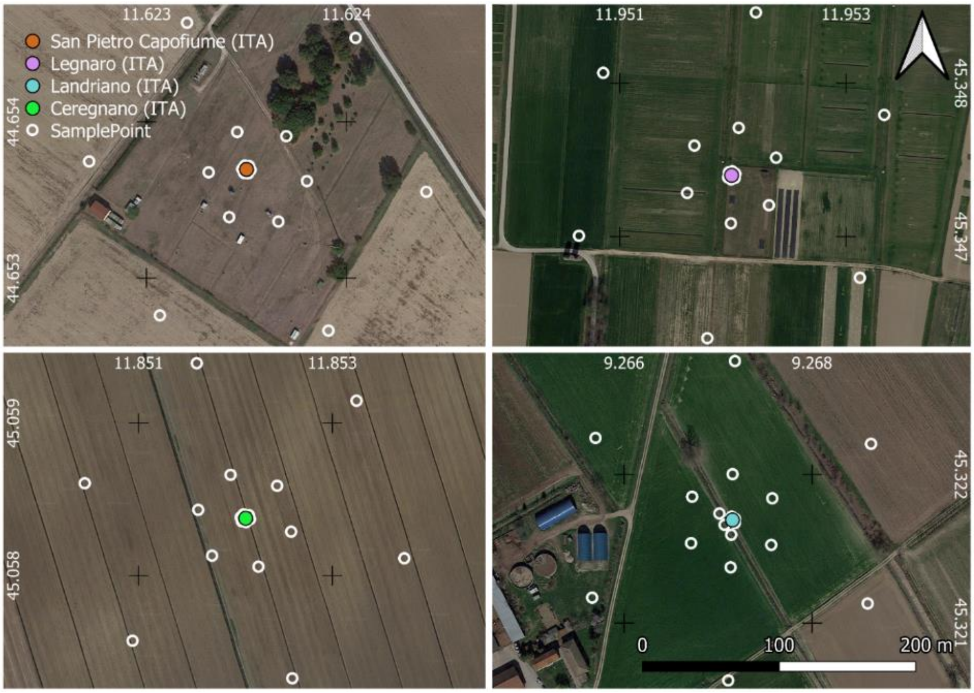

Figure 3. Experimental sites with FINAPP3 sensor (colored points) and locations where gravimetric soil samples (white open circle) have been collected for comparison.

3. Results

3.1 Comparison to conventional CRNS sensors

The corrected hourly neutron count rates measured by the different sensors are shown in Figure **4**. The results show a very good agreement of the signal detected by the FINAPP3 sensor. As expected, the sensors have different sensitivities with mean neutron counting rate over the period at Marchfeld of 1279 cph and 1797 cph, for FINAPP3 and CRS2000, respectively and at Marquardt of 1187 cph and 8387 cph, for FINAPP3 and Lab-C, respectively. Accordingly, the relative lower sensitivity of FINAPP3 and CRS2000 produced a higher amount of statistical noise (and, thus, lower correlation) for the same integration period of 1 hour, when compared to the pairing of FINAPP3 and Lab-C. However, this difference is less substantial when the signal is smoothed over six hours (Figure **4**c, d). For this reason, the FINAPP3 sensor can be considered reliable for many applications while it is suggested to employ a more sensitive detector for especially demanding settings, e.g., when focusing on fast hydrological processes like canopy interceptions (Andreasen et al., 2017a; Baroni and Oswald, 2015) or roving applications (Jakobi et al., 2020).

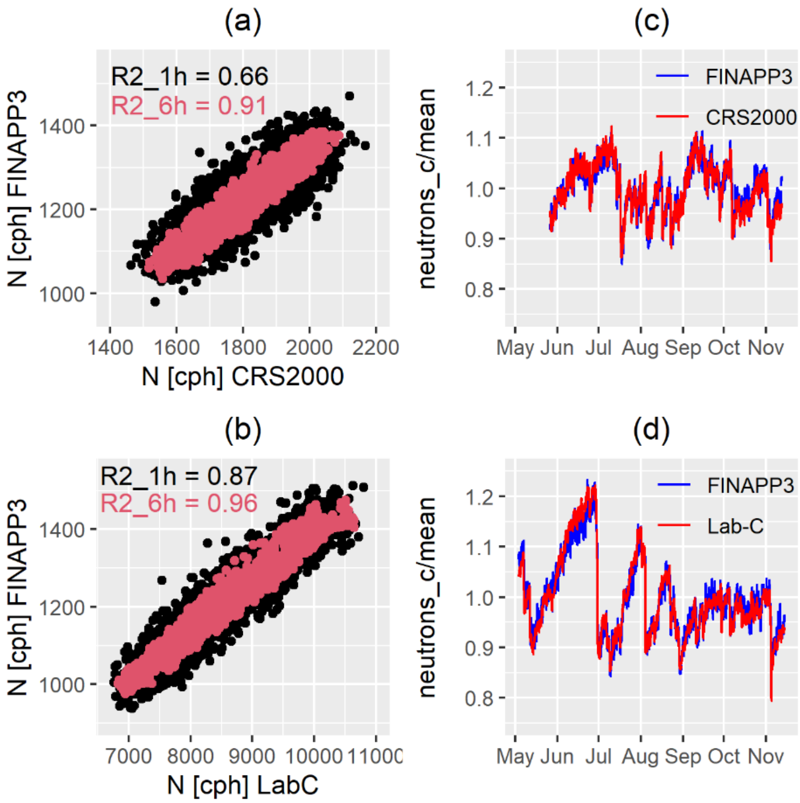

Figure 4. Comparison of measured neutrons at Marchfeld site (Vienna, Austria) and Marquardt site (Potsdam, Germany) by the two different sensor pairs (CRS2000 and FINAPP3; Lab-C and FINAPP3). Plots (a) and (b) show the hourly values in black and the based on a running average of 6 hours (brown). Plots (c) and (d) show the neutron fluxes corrected for air pressure and with a running average of 6 hours. Neutron counts in (c) and (d) were normalized for comparison.

3.2 Comparison with independent gravimetric soil sampling campaigns

The time series collected at the four experimental sites in Italy are shown in Figure **5**. The neutron counts were transformed to volumetric soil moisture as described in section 2.2 using all the soil samples for the calibration of the parameter N_0. The hourly values were smoothed with a Savitzky-Golay filter to decrease the random fluctuations at short time period as suggested in literature (Franz et al., 2020).

As it is shown, the FINAPP3 signal was regularly recorded and transmitted over the entire period. Only few data gaps were experienced, and they are related to short periods of low power supply by the solar panel during wintertime. At all the sites, the estimated soil moisture dynamic corresponds well to precipitation events; and in general, the values are in good agreement with the gravimetric soil moisture (green dots). For this reason, the results show how FINAPP3 can be considered a reliable soil moisture sensor to be integrated in long-term monitoring networks, as proposed by (Cooper et al., 2021; Zreda et al., 2012).

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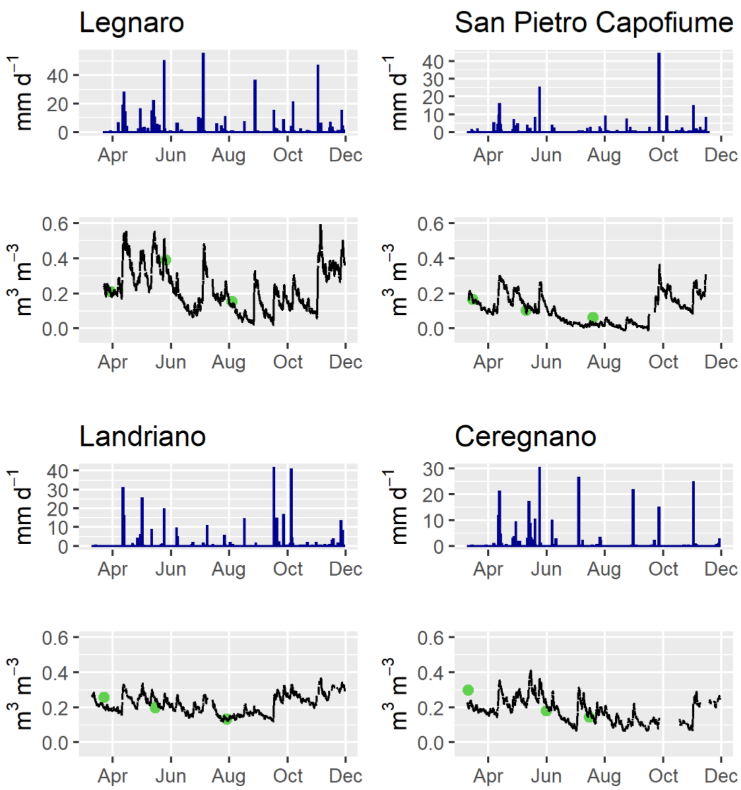

Figure 5. Estimated volumetric soil moisture (m^3 m^{-3}) by FINAPP3 at the four experimental sites (black line) compared to weighted average soil moisture based on soil samples and gravimetric methods (green dots). At each site, the precipitation is also shown (blue bars).

Noteworthy, some relevant differences between FINAPP3 and gravimetric soil moisture are still detected. To better highlight these differences, the calibration curves obtained based on all the gravimetric soil samples are shown Figure **6** (dashed black lines) together with some performance metrices between estimation and observation (coefficient of determination R^2 and RMSE). Moreover, calibration curves based on the data collected during only one single soil sampling campaign are added to better visualize the differences (grey lines). At the Legnaro site, the calibration curve aligned well the observations with a high goodness of fit ($R^2 > 0.9$; RMSE = 0.006 g g^{-1}). In contrast, at the other three sites, the goodness of fit deteriorated. These results can be explained in relation i) to the effect of other hydrogen pools like biomass (Baatz et al., 2015; Franz et al., 2015) and ii) to the contributions to the signal from remote areas (Schattan et al., 2019; Schrön et al., 2017). Specifically, the very good fit at Legnaro site can be explained considering that the FINAPP3 sensor has been installed at a grass site with low biomass and the surrounding areas are characterized by relatively small agricultural fields (see Figure **3**). In these conditions, the soil samples well represent the average soil moisture within the footprint and no additional hydrogen pools are relevant. As such, the results support the sufficiency of one single calibration campaign and the accuracy of the detected signal when these conditions are met. At San Pietro Capofiume, the FINAPP3 sensor was also installed at a grass site with low biomass. This area, however, reached very low soil moisture values during the summer. In contrast, the remote areas are large, irrigated maize cropped fields (i.e., with much higher expected soil moisture). As recently discussed (Schrön et al., 2022), in these particularly heterogeneous conditions, the sensor can detect soil moisture changes at more remote distance than the actual footprint and the gravimetric soil samples collected during the field campaigns could be not representative of the average soil moisture condition detected by the sensor. On the one hand, this can explain the unrealistic apparent negative soil moisture values estimated during August. On the other hand, it supports the need of additional soil samples at the irrigated areas to provide a soil moisture basis more representative for this CRNS footprint and to allow for a better calibration and overall assessment of the signal. Finally, at Ceregnano and at Landriano, the FINAPP3 sensors were installed at the centre of a homogenous cultivated field where the contribution of the fast biomass growth to the detected signal should be expected. Thus, the apparent overestimation of soil moisture towards the peak of the growing season at both sites is very plausible. Some corrections to the signal to account for the biomass contribution have been suggested in literature (Baatz et al., 2015; Franz et al., 2015) but it is beyond the aim of the present study to assess these approaches.

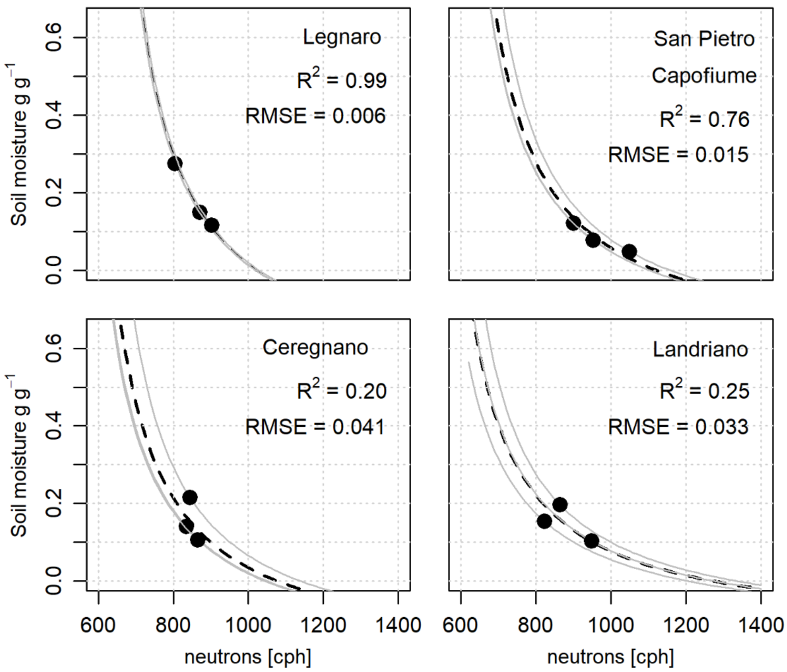

Figure 6. Calibration curves obtained at each site (Legnaro, San Pietro Capofiume, Ceregnano and Landriano) using data collected during one single field campaign (gray lines) or based on the best fit over all the samples (dashed line).

3.3 The use of muons for incoming corrections

The use of locally-measured muons simultaneously obtained by the FINAPP3 sensor has been recently suggested as a promising alternative approach for incoming correction of the signal (Stevanato et al., 2022). During most of the monitoring period no substantial incoming fluctuations have been detected. Thus, no differences can be identified between the use of muons or the conventional approach during these periods (data not shown). One relevant event, however, has been recorded at the beginning of November. During this period, a

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strong precipitation event with atmospheric instability occurred that was observed especially at some experimental sites. Thus, during this period there is a relevant difference between using neutron fluxes from neutron data bases (i.e., from JUNG at Jungfraujoch) and the local muons. During these conditions (Figure **7**), the use of muons well capture the soil moisture increases due to the precipitation events. In contrast, the common correction using incoming fluctuations from JUNG station (Switzerland) completely fails to capture a soil moisture increase during the second precipitation event. Despite additional analyses with longer time series and continuous independent soil moisture records should be considered for better understanding the value of local muon correction, these results support previous findings that muon detection can be a promising approach to better account for local atmospheric conditions.

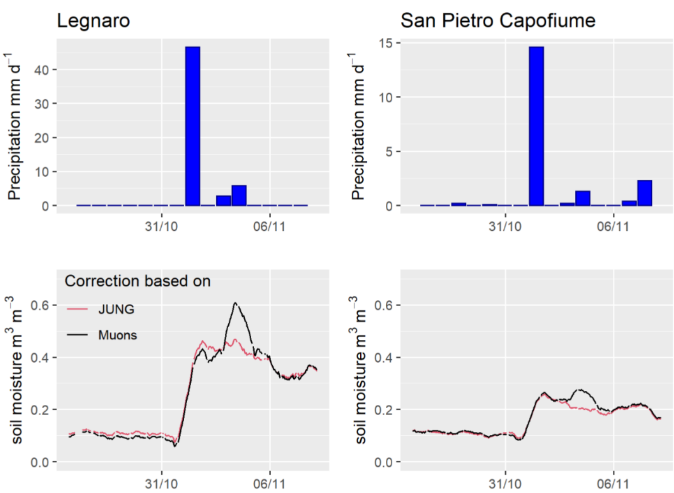

Figure 7. The plots in the top row show the precipitation during the period. The plots at the bottom row show the estimated soil moisture using two different approaches for the incoming correction of the signal: based on the standard approach of data from neutron data base (e.g., JUNG plotted as red line) and using locally detected muons (black line).

3.4 The use of gamma rays for estimating soil moisture and discriminating irrigation

Figure 8 shows total gamma radiation measured at Ceregnano experimental site by the FINAPP3 sensor, as example. The results show a negative correlation with the soil moisture dynamic estimated based on the neutron counts. More specifically, the results confirm how the total gamma fluxes are attenuated by the presence of water in the soil providing the scientific basis to develop a gamma-ray sensor for soil moisture estimation (Strati et al., 2018). However, the correlation is weak suggesting that further experiments and analyses should be conducted to better understand the added value of this signal. In particular, the weak correlation can be attributed to the smaller footprint of the gamma fluxes (<25 m radius) in comparison to the neutron (100 m radius) and a dedicated soil sampling campaign within the theoretical gamma footprint should be performed for better assessment. Noteworthy, however, a peak in the total gamma radiation generated by the deposition of atmospheric radon during the precipitation events is clearly identifiable. In contrast, no such peaks occur during the irrigation events. For this reason, while the use of total gamma radiation for soil moisture estimation will require additional refinements, this sensor can well be used for discriminating the increase of soil moisture due to irrigation in contrast to precipitation events as shown in other studies using more dedicated gamma-ray spectrometers (Serafini et al., 2021).

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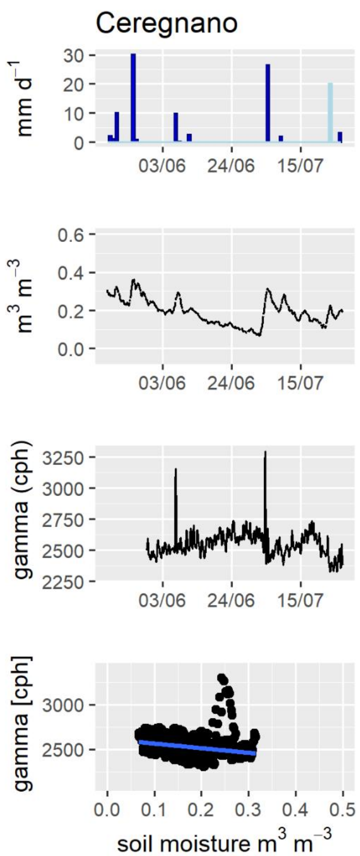

Figure 8. From top, precipitation (blue) and irrigation (light blue) (mm d^{-1}), volumetric soil moisture estimated by FINAPP3 (m^3 m^{-3}) and total gamma counts (cph). The last bottom plot shows the general negative correlation between soil moisture estimated by FINAPP3 and the total gamma fluxes.

4. Conclusions

This study presents the activities conducted to test a new sensor design based on scintillators for non-invasive soil moisture estimation. The results show that the new sensor performed well in different environmental conditions in comparison to other conventional gas-tubes-based CRNS sensors and based on several gravimetric soil moisture samples. The sensitivity of this new sensor design was found suitable for monitoring daily temporal soil moisture changes over an entire season. However, the signal noise was relatively high at hourly time scale. For this reason, a more sensitive detector should be considered when fast hydrological processes such as canopy interceptions or roving applications are targeted. However, aggregation to the 6-h-interval yielded a reasonable robustness of the signal.

Part of the new sensor design are components that simultaneously measure muons and total gamma radiation. Muons were found to be a promising alternative for incoming correction for CRNS application (Stevanato et al., 2022). On the other hand, the use of gamma-ray spectrometry was identified as an alternative method for non-invasive soil moisture estimation and irrigation discrimination (Baldoncini et al., 2018; Serafini et al., 2021). Even though additional experiments must be conducted to better understand the added value of detecting also

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these radiation forms, the data collected during this study confirm a considerable potential of these additional measurements. Specifically, the incoming correction using muons showed to better capture local atmospheric condition, affecting the incoming component of the neutron detector, and thus to improve soil moisture estimation. Total gamma radiation shows a negative correlation to soil moisture, but correlations are weak suggesting the need of additional studies and analyses. In contrast, high peaks of total gamma radiation generated by shower of radon in the atmosphere have been detected allowing a clear identification of precipitation *vs.* irrigation events.

Overall, this new sensor design can be considered a valuable alternative to more traditional CRNS detectors for soil moisture estimation. Considering that it can be built smaller than conventional neutron systems and the benefit of the additional detection of muons and total gammas, it can also open the path to new and wider applications like space weather applications (Hands et al., 2021) and for monitoring agriculture water use (Foster et al., 2020).

Appendix

Table 1. Results of the soil samples analyses at the different experimental sites. θ_a is the arithmetic gravimetric soil moisture; θ_w is the weighted average gravimetric soil moisture based on Schrön et al. (2017); N_0 is the calibrated parameter of the Eq. 5; θ_{bd} is the soil bulk density; *SOC* is the soil organic carbon and *LW* is the lattice water.

Site	Date	θ_a [g/g]	θ_W [g/g]	N_0 [cph]	ρ_{bd} [g/cm^3]	*SOC* [g/g]	*LW* [g/g]
San Pietro Capofiume	15/03/2021	0.133	0.121	1468	1.384	0.014	0.084
	10/05/2021	0.098	0.077	1466	1.373	-	-
	19/07/2021	0.049	0.048	1540	1.295	-	-
Legnaro	29/03/2021	0.174	0.149	1565	1.409	0.022	0.152
	26/05/2021	0.247	0.275	1563	1.421	-	-
	03/08/2021	0.114	0.114	1578	1.336	-	-
Landriano	22/03/2021	0.210	0.196	1413	1.322	0.019	0.007
	15/05/2021	0.200	0.154	1274	1.285	-	-
	29/07/2021	0.125	0.103	1349	1.295	-	-
Ceregnano	10/03/2021	0.209	0.215	1501	1.397	0.018	0.076
	31/05/2021	0.178	0.140	1383	1.306	-	-
	15/07/2021	0.134	0.105	1376	1.386	-	-

Code and data availability

Data collected and processed at the six experimental sites are available at the following repository (Baroni, 2022a). Two spreadsheets have been developed for data processing. The first file (CRNS_SoS.xlsm) integrates the weighting functions for processing soil samples. The second file (CRNS_PoP.xlsm) integrates the atmospheric corrections and the calibration function to transform measured row neutrons to soil moisture. The spreadsheets can be downloaded at the following repository (Baroni, 2022b).

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Author contributions

Conceptualization GB, LS, SG, design and implementation of field experiments, methodology GB, LS, SG, TF, HA, AT, GW; writing - original draft preparation SG, GB. Writing - review and editing: all the co-authors. All authors have read and agreed to the published version of the manuscript.

Competing interests

Luca Stevanato, Matteo Polo and Marcello Lunardon are of FINAPP S.r.l., 35036 Montegrotto Terme, Italy. Otherwise, the authors declare no competing interests.

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