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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

Stefano Gianessi[1,a], **Matteo Polo**[2,b], **Luca Stevanato**[2], **Marcello Lunardon**[2,3], **Till Francke**[4], **Sascha E. Oswald**[4], **Hami Said Ahmed**[5], **Arsenio Toloza**[5], **Georg Weltin**[5], **Gerd Dercon**[5], **Emil Fulajtar**[6], **Lee Heng**[6], **and Gabriele Baroni**[1]

[1]Department of Agricultural and Food Science, University of Bologna, 40127 Bologna, Italy
[2]FINAPP s.r.l., Montegrotto Terme, 35036 Padova, Italy
[3]Department of Physics and Astronomy, University of Padova, 35100 Padova, Italy
[4]Institute of Environmental Science and Geography, University of Potsdam, Potsdam, Germany
[5]Soil and Water Management and Crop Nutrition Laboratory, Joint FAO/IAEA Centre of Nuclear Techniques in Food and Agriculture Vienna, Vienna, Austria
[6]Soil and Water Management and Crop Nutrition Section Joint FAO/IAEA Centre of Nuclear Techniques in Food and Agriculture Vienna, Vienna, Austria
[a]now at: FINAPP s.r.l., Montegrotto Terme, 35036 Padova, Italy
[b]now at: Department of Industrial Engineering, University of Trento, Trento, Italy

Correspondence: Gabriele Baroni (g.baroni@unibo.it)

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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 on a new scintillator-based sensor especially designed to jointly measure neutron counts, muons and total gamma rays. The neutron signal is first compared against two conventional gas-tube-based CRNS sensors at two locations. The estimated soil moisture is further assessed at four agricultural sites, based on gravimetric soil moisture collected within the sensor footprint. Muon fluxes are compared to the incoming neutron variability measured at a neutron monitoring station and total gammas counts are compared to the signal detected by a gamma ray spectrometer. The results show that the neutron dynamic detected by the new scintillator-based CRNS sensor is well in agreement with conventional CRNS sensors. The derived soil moisture also agreed well with the gravimetric soil moisture measurements. The muons and the total gamma rays simultaneously detected by the sensor show promising features to account for the incoming variability and for discriminating irrigation and precipitation events, respectively. Further experiments and analyses should be conducted, however, to better understand the accuracy and 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 and to 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, an accurate monitoring of this variable is crucial in many applications, ranging from agricultural water management (Lichtenberg et al., 2015), runoff generation 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 hydro-

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logical 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 available nowadays, ranging from invasive point-scale soil moisture sensors to remote sensing methods with larger coverage (Babaeian et al., 2019; Corradini, 2014; Ochsner et al., 2013). More recently, 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 advantage of estimating soil moisture over an intermediate scale (10–200 m radius) and at subdaily 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 shown good performance in several environmental conditions like natural ecosystems (Franz et al., 2012), meadows (Zhu et al., 2016), cropped fields (Rivera Villarreyes et al., 2011; Coopersmith et al., 2014) and forests (Heidbüchel et al., 2016; Jeong et al., 2021). This technique relies on the negative correlation between natural neutron fluxes in a specific energy range (0.5 eV–100 keV) and hydrogen pools at and in the ground, providing the base for monitoring soil moisture (Zreda et al., 2012), snow (Schattan et al., 2017; Tian et al., 2016) and biomass (Baroni and Oswald, 2015; Jakobi et al., 2018).

It is noteworthy that this negative correlation has been detected for a long time but mostly considered a nuisance 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 were presented only some years 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 the need for a better understanding of the interaction of these neutron fluxes and soil moisture led to its investigation (Zreda et al., 2008). In this context, the neutron detector had been installed aboveground, and the signal agreed well with soil moisture over an area of several hectares and down to a depth of several decimeters (Franz et al., 2012; Köhli et al., 2015), providing a new prospective monitor of hydrological variables at the land surface (Desilets et al., 2010). Nowadays, this aboveground CRNS method is used by many research groups worldwide, and it is integrated into some national monitoring systems to provide a better understanding of hydrological processes and to support 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; Evans et al., 2016).

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 pave the way for 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 the detected neutron counts with conventional gas-tube-based CRNS instruments at two experimental sites, (ii) a comparison of the derived soil moisture with independent gravimetric soil moisture measurements at four additional experimental sites, (iii) a comparison of detected muons with incoming neutrons measured at a neutron monitoring station, and (iv) a comparison of total gamma counts with a conventional gamma ray spectrometer at one experimental site. The added value of muons and gamma particles simultaneously recorded by the sensor are also explored and discussed.

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 based on helium-3 or boron trifluoride, respectively. Moreover, the flexibility in manipulating the detecting material (e.g., thin layers) allows us to optimize the sensitive area and to develop relatively efficient but 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 a unique property, in comparison to inorganic scintillators, in that they release 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), which exploits the different profiles at the time of the signals. Among others, a typical parameter used in this analysis is the so-called pulse shape discrimination parameter (PSD), which is 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 Fig. 1a, which shows how different particles (here thermal neutrons and cosmic muons) populate very different regions in the PSD vs. integrated-charge plane. For more details on the analysis and on the parameters used for the identification of the single events, we refer to more specific studies (e.g., Cester et al., 2016).

In the present study, we use the scintillator-based sensor FINAPP3 developed by FINAPP s.r.l. (http://finapptech.com/en, last access: 14 January 2024). The main parts of the sensor are shown in Fig. 1b. The sensor hosts two main detectors. The first detector (detector 1 in Fig. 1b) is a multilayer 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 the neutron capture cross section on Li-6 is the maximum. The Li-6 embedded inside the detectors has a large cross section for neutron capture. When a Li-6 nucleus captures a neutron, then a nuclear reaction occurs, and the compound Li-7 breaks into an alpha particle (He-4) and a triton (H-3), with a large energy release of almost 5 MeV. This energy is converted into light (a flash of optical photons) by the ZnS(Ag) crystals. The energy release in the thin layers of the scintillator (a few hundreds of microns) is strong for local interactions coming from the neutron–Li capture reaction products, providing a large electrical signal that is well above the voltage threshold used to cut the instrument noise. This detector can also measure cosmic-ray-induced muons (in the energy range of around 4 GeV) that are distinguished by a real-time PSD, as described above. The possibility to detect muons in the same device was proven by the comparison with standard muon telescopes (patent no. IT102021000003728). The second main detector (detector 2 in Fig. 1b) is a small (2 in. × 2 in.; 5.08 cm ×5.08 cm) commercial organic scintillator (EJ200 from Eljen Technology Inc.). Due to the low effective atomic number Z_{eff}, typical of organic materials, gamma rays interact with this scintillator mainly by Compton scattering, providing the spectrum shape of the Compton continuum from zero to the Compton edges. In the energy range above 3.0 MeV, no gamma rays are present but only signals with a larger energy deposit (e.g., 10 MeV); this is mainly due to cosmic muons. For this reason, this second detector can not only measure muons as the first detector but also the total gamma ray fluxes in the energy range between 0.3 and 3.0 MeV. For more details about the detected signals, we refer to more specific studies (Boo et al., 2021; Ford et al., 2008). Finally, two commercial photomultipliers (PMTs in Fig. 1b) from Hamamatsu Photonics (Hamamatsu, Japan) are used to transform the light (visible photons) to an electric pulse. The sensor can be further integrated with air pressure, air temperature and air humidity sensors. A single 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 × 30 × 20 cm, with a total weight of 8 kg. Energy consumption is minimized to 0.4 W (35 mA at 12 V), and it is supplied by a relatively small solar panel (20 W) installed above the sensor. Overall, the new sensor assembly provides neutrons, muons and gamma counting rates that can be further corrected and elaborated on to retrieve soil moisture, as described in the next sections.

2.2 From neutron counts to soil moisture estimation

The measured neutron count rates N are corrected for air pressure (f_{p}), variability in the incoming neutron flux (f_{i}) and air vapor (f_{v}) to account for local atmospheric effects based on the following correction factors (Zreda et al., 2012):

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

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

$$f_{\mathrm{v}} = 1 + \alpha\left(h - h_{\mathrm{ref}}\right) \tag{3}$$

$$N_{\mathrm{c}} = N \cdot f_{\mathrm{p}} \cdot f_i \cdot f_{\mathrm{v}}, \tag{4}$$

where $\beta = 0.0076\,(\mathrm{mb}^{-1})$, $\alpha = 0.0054\,(\mathrm{m}^3\,\mathrm{g}^{-1})$; p and h are air pressure (mb) and absolute humidity ($\mathrm{g\,m^{-3}}$); I is the incoming flux of cosmic-ray neutrons induced by galactic primary particles in the Earth's atmosphere (counts per hour, cph); and h_{ref}, p_{ref} and I_{ref} are reference values (here the average is taken) 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/, last access: 14 January 2024) 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 (Bogena et al., 2022).

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

$$\theta\left(N_{\mathrm{c}}\right) = \left(\frac{0.0808}{\frac{N_{\mathrm{c}}}{N_0} - 0.372} - 0.115 - \theta_{\mathrm{offset}}\right) \cdot \frac{\rho_{\mathrm{bd}}}{\rho_{\mathrm{w}}}, \tag{5}$$

where ρ_{bd} and ρ_{w} are the soil bulk density ($\mathrm{kg\,m^{-3}}$) and water density ($\mathrm{kg\,m^{-3}}$), 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,

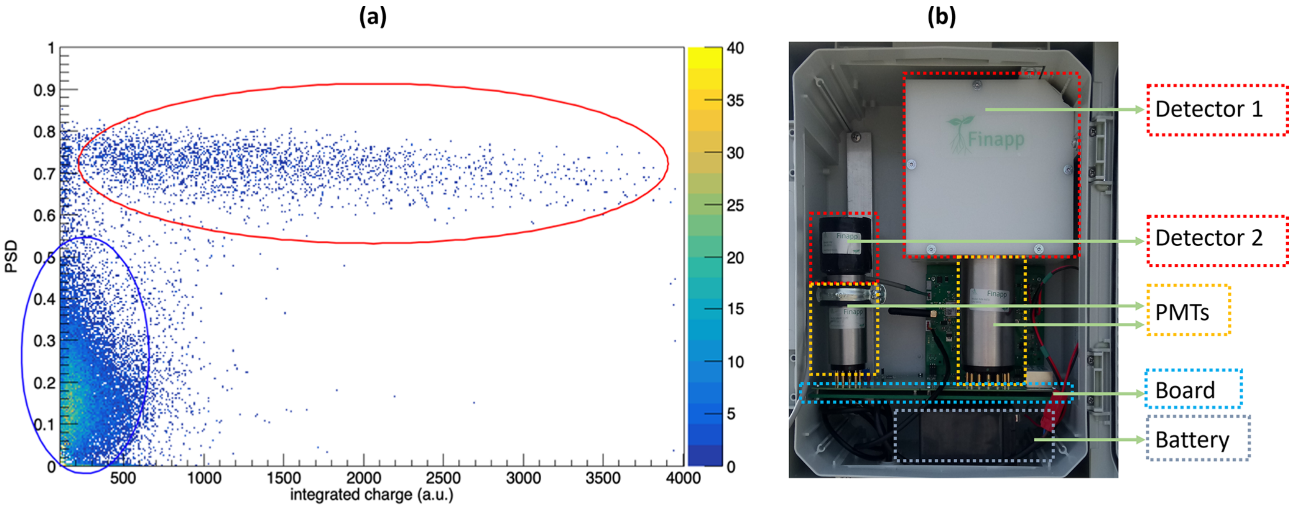

Figure 1. **(a)** Typical pulse shape discrimination (PSD) vs. integrated-charge plot for a FINAPP3 detector. Red and blue ovals indicate the neutron and muon region, respectively. **(b)** Scintillator-based sensor FINAPP3, with the two main detectors, photomultiplier (PMTs), board and battery.

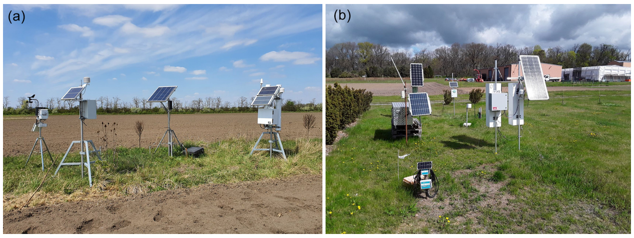

Figure 2. Experimental sites at **(a)** Marchfeld (near Vienna, Austria) and **(b)** Marquardt (near Potsdam, Germany).

as suggested in different studies (Schrön et al., 2017; Franz et al., 2012). The data processing described above has been implemented in a simple spreadsheet available from Baroni (2022b). For a more advanced data processing that also integrates additional external datasets, readers can refer to Power et al. (2021).

2.3 Assessment of neutron counts 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 (Fig. 2). The first site is located at Marchfeld (near Vienna, Austria; 48.24° N, 16.55° E). The second site is located at Marquardt (near Potsdam, Germany; 52.45° N, 12.96° E). The recorded time series covers the period of 7 months, starting from May 2021, when a FINAPP3 detector was installed at both sites.

At Marchfeld experimental site, the FINAPP3 sensor is compared with a CRS2000 device, a boron-10 trifluoride proportional gas tube produced by Hydroinnova (https://www.hydroinnova.com, last access: 14 January 2024) and that has been used in many studies (Andreasen et al., 2016; Baroni and Oswald, 2015; Hawdon et al., 2014). At the Marquardt site, several CRNS sensors of different designs are available for comparison (Heistermann et al., 2023). 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 (https://www.quaestainstruments.com, last access: 14 January 2024). This sensor provides a high sensitivity for neutron detection and thus a good signal-to-noise ratio, which promises potential for estimating soil moisture at even about hourly time resolutions (Fersch et al., 2020).

All the detectors have been installed at a height of around 1.5 m above the ground and placed at a distance of a few meters distance apart. Considering the large footprint of the signal detected, this horizontal difference is considered negligible for the comparison (Rivera Villarreyes et al., 2011; Patrignani et al., 2021; Schrön et al., 2018). All the detectors have been equipped with a solar panel and with GSM (Global System for Mobile Communications) data transmission for supporting long-term observations and real-time monitoring.

2.4 Assessment of derived soil moisture 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 in 2021 at four experimental sites located in the Po river plain, northern Italy (Fig. 3). At the San Pietro Capofiume (44.65° N, 11.64° E; near Bologna, Italy) and Legnaro sites (45.34° N, 11.96° E; near Padova, Italy), the sensors were installed over a grassland with low biomass that is surrounded by agricultural cropped fields. Conversely, at Ceregnano (45.05° N, 11.86° E; near Rovigo, Italy) and at Landriano (45.31° N, 9.26° E; near Pavia, Italy), 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 at which the CRNS sensors were installed or located in close proximity (a few kilometers). In these cases, the meteorological observations have been considered representative of 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 (red points in Fig. 3) and at four different depths (0–5, 10–15, 20–25 and 30–35 cm from the soil surface) for a total of 72 soil samples. Gravimetric water content for each soil sample was measured by oven-drying method (105 °C 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 in which these weighting functions have been implemented is publicly available (Baroni, 2022b). The results are summarized in Table A1 in the Appendix.

2.5 Assessment of muons counting rate

The use of muons has been shown to be a possible alternative to the use of the neutron monitoring stations 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 signal in the present study, and for sake of clarity we report here on the main data-processing steps. Specifically, muons are first corrected to account for air pressure and air temperature effects as follows:

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

$$f_{T\_\mathrm{M}} = 1 - \alpha_{\mathrm{M}}\left(T - T_{\mathrm{ref}}\right) \tag{7}$$

$$M_{\mathrm{c}} = M \cdot f_{\mathrm{p\_M}} \cdot f_{T\_\mathrm{M}}, \tag{8}$$

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 reference value (here the average is taken) of air pressure and air temperature during the measuring period. In contrast to the neutrons, the effect of air vapor on the muon counting rate has been not identified so far (Dorman, 2004; Maghrabi and Aldosary, 2018), and it is also not considered in the present study. It is noteworthy that the whole air temperature profile should be considered for the correction. This would better represent the atmospheric condition, and it would better capture the effect on muons. Some studies, however, have shown how the use of air temperature measured at 2 m height provides a good approximation of the muon effect (de Mendonça et al., 2016). This approach is used also in this study, but it should be further tested in future research.

For the muon assessment, first the parameters β_{M} and α_{M} are derived, based on the data collected within this study to evaluate the effect of air pressure and air temperature on the muon signal. These values are then compared with $\beta_{\mathrm{M}} = 0.0016\,\mathrm{mbar}^{-1}$ and $\alpha_{\mathrm{M}} = 0.0021\,°\mathrm{C}^{-1}$ provided by 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 (1-year time series collected at around 200 km distance). For this reason, the values can also be representative of the experimental sites of the present study. Refinements of these values should be expected in case of application in different locations. The corrected muon flux M_{C} is then compared to the incoming variability measured at the neutron monitoring station usually adopted for CRNS incoming correction (https://www.nmdb.eu/, last access: 14 January 2024). Finally, the effect of using a muon signal instead of using neutron counts from a neutron monitoring station for the incoming correction (Eq. 2) and soil moisture estimation is also presented and discussed.

2.6 Assessment of total gamma rays

The measurements of gamma rays have 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 m 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, in any case, in the energies between about 1.0 and 2.5 MeV) shows a negative correlation with the amount of water in the soil, and thus this relation can be used to estimate the 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

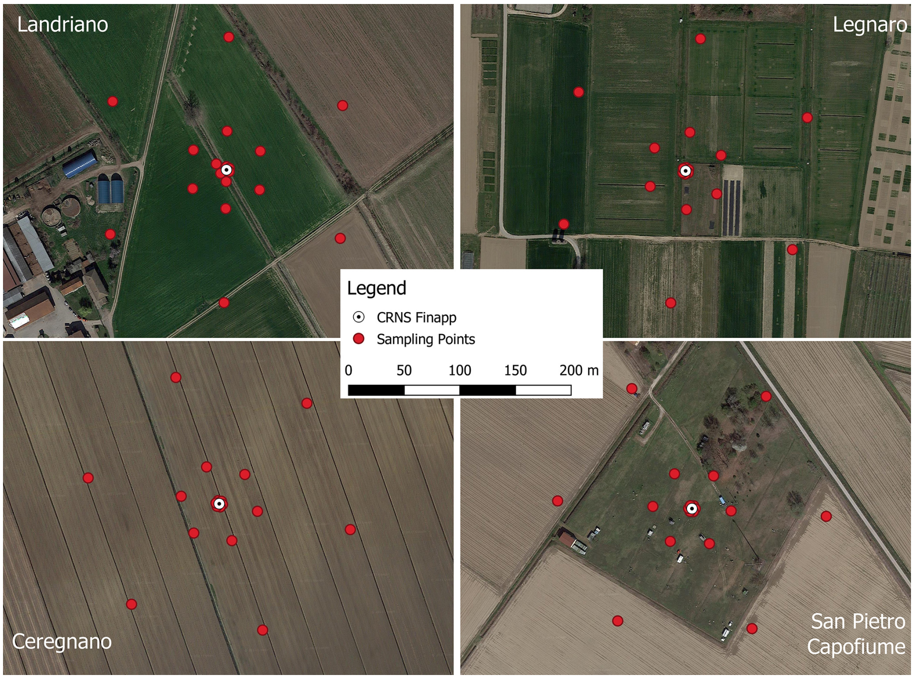

Figure 3. Experimental sites with FINAPP3 sensor (white points) and locations where gravimetric soil samples (red points) have been collected for comparison (pictures from © Google Earth). At Ceregnano site, a gamma ray spectrometer (Medusa Radiometrics gSMS) was also installed few meters from the CRNS sensor.

rays in the energy range of this photo peak 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. It is noteworthy that the gamma signal should not be corrected for other effects (i.e., air pressure, air temperature and air humidity). For these reasons, it can provide some advantages when using neutrons for soil moisture application.

For the assessment of the gamma signal measured by FINAPP3, a stationary cesium iodide (CsI) gamma ray spectrometer (gSMS, Medusa Radiometrics, https://www.medusa-radiometrics.com/, last access: 14 January 2024) has also been installed at Ceregnao site in 2021, a few meters away from the CRNS location. A direct comparison between total gamma fluxes measured by the two sensors is performed. The capability of the signal to discriminate precipitation and irrigation events is also explored in the present study, based on the data collected at the experimental sites.

3 Results

3.1 Comparison between neutrons detected by FINAPP3 and conventional CRNS sensors

The corrected hourly neutron count rates measured by the different sensors are shown in Fig. 4. As expected, the sensors have different sensitivities, with a mean neutron counting rate over the period at Marchfeld of 1279 and 1797 cph for FINAPP3 and CRS2000, respectively, and at Marquardt of 1187 and 8387 cph for FINAPP3 and Lab-C, respectively. Accordingly, the relative lower sensitivity of FINAPP3 produced a higher amount of statistical noise when compared to its benchmark (CRS2000 or Lab-C, respectively). However, this difference is less substantial when the signal is smoothed over a longer time interval. Specifically, the analysis shows a good agreement of the detected signals ($R^2 = 0.66$) at a 1 h integration time. The performance improves ($R^2 = 0.91$) when the values are already integrated over a 6 h interval. The good correlation can also be appreciated by looking at a fast drop of the neutron counting rates during a short timescale (Fig. 4c, 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 (e.g., hourly) hydrological processes like canopy interceptions (Andreasen et al., 2017a; Baroni and Oswald, 2015) or mobile applications (Jakobi et al., 2020).

3.2 Assessment of the derived FINAPP soil moisture with independent gravimetric soil samples

The neutron counts collected at the four Italian experimental sites were transformed to volumetric soil moisture, as described in Sect. 2.2, using all the soil samples for the calibration of the parameter N_0 (Eq. 5). Before the transformation, the corrected hourly neutron values were smoothed with a

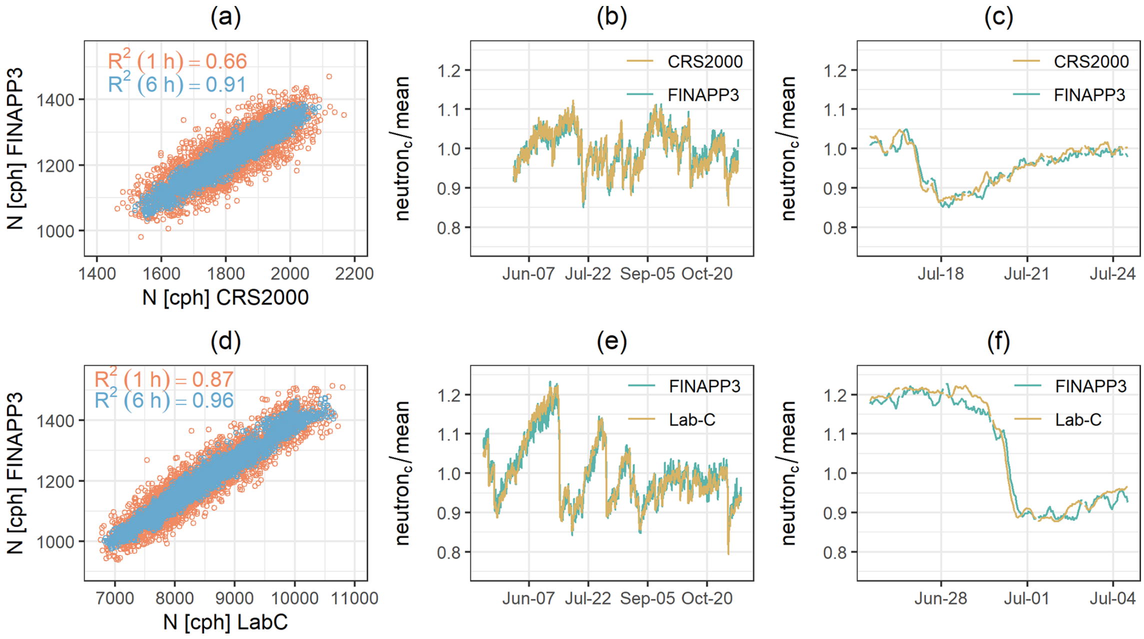

Figure 4. Comparison of measured neutrons in 2021 at the **(a–c)** Marchfeld site, Vienna, Austria, and the **(d–f)** Marquardt site, Potsdam, Germany, by the two different sensor pairs (CRS2000 and FINAPP3; Lab-C and FINAPP3). Panels **(a)** and **(d)** show the hourly values (in orange) and are based on a running average of 6 h (in blue). Panels **(b)** and **(e)** show the neutron fluxes corrected for air pressure, with a running average of 6 h. The relative counts over the mean are shown for comparison. Panels **(c)** and **(f)** show a zoom-in during a fast drop in the neutron counts.

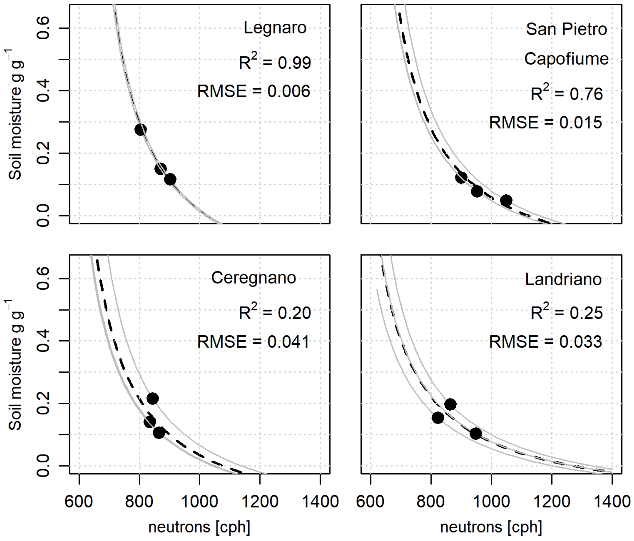

Figure 5. Calibration curves obtained at each site (Legnaro, San Pietro Capofiume, Ceregnano and Landriano) using data collected during one single field campaign (gray lines) or based on the best fit over all of the samples (dashed black line).

Savitzky–Golay filter to decrease the random fluctuations at a short time period, as suggested in the literature (Franz et al., 2020). The calibration curves obtained, based on all the gravimetric soil samples, are shown in Fig. 5 (dashed black lines), together with some performance metrics 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 (gray lines).

At the Legnaro site, the calibration curve aligned well the observations, with a high goodness of fit ($R^2 > 0.9$; RMSE $= 0.006\,\mathrm{g\,g^{-1}}$). In contrast, at the other three sites, the goodness of fit deteriorated, with the worst case obtained at Ceregnano site ($R^2 > 0.2$; RMSE $= 0.041\,\mathrm{g\,g^{-1}}$). These performances are in agreement with studies conducted with other conventional CRNS sensors (e.g., Franz et al., 2012), and they can be explained in relation (i) to the effect of other hydrogen pools like biomass (Baatz et al., 2015; Franz et al., 2015; Jakobi et al., 2018) 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 the 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 Fig. 3). In these conditions, the soil samples represent the average soil moisture within the footprint well, 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., 2023), in these particularly heterogeneous conditions, the sensor can detect soil moisture changes at a 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 for additional soil samples at the irrigated areas to provide a soil moisture basis more representative of this CRNS footprint. Finally, at Ceregnano and at Landriano, the FINAPP3 sensors were installed at the center 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 the literature (Baatz et al., 2015; Franz et al., 2015; Jakobi et al., 2018), but it is beyond the scope of the present study to assess these approaches. The use of more recently proposed soil moisture–neutron relation could also be tested in future studies to see possible compensations for these effects (Köhli et al., 2021). Anyway, these results confirm the need to conduct, when possible, more than one calibration campaign to account for some of these effects (Heidbüchel et al., 2016; Iwema et al., 2015).

Finally, the time series collected at the four experimental sites in Italy are shown in Fig. 6. The FINAPP3 signal was regularly recorded and transmitted over the entire period. Only a 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 responds well to precipitation. As previously discussed, the derived soil moisture values are in good agreement with the gravimetric soil moisture (green crosses). For these reasons, the results show how FINAPP3 can be considered a reliable soil moisture sensor that can be integrated in long-term monitoring networks, as proposed by other studies (Cooper et al., 2021; Zreda et al., 2012; Bogena et al., 2022).

3.3 On the use of muons for incoming corrections

Muons have been recorded simultaneously by the detector at all of the experimental sites. Some malfunctions in the pulse shape discrimination integrated in the electronic board and on the data transmission have, however, been initially identified. These malfunctions were later fixed, but some data have been corrupted. For this reason, the muon time series cover a shorter period in comparison to the neutron counts (i.e., June–November). Figure 7 shows the muon counting rates collected at Legnaro site, for example, but similar results have been detected in the other experimental sites. As expected, the results show a strong relation between measured muon counting rates and air pressure (Fig. 7a). The slope of the relation (-0.0018) is also very similar to the value obtained by Stevanato et al. (2022) (i.e., -0.0021). In contrast, within the present study, no relation is detected between the pressure-corrected muons and air temperature (Fig. 7b). The behaviour is attributed to the relatively short time series and the small temperature range ($\pm 5^\circ$). However, the representativeness of air temperature measured at 2 m height in comparison to the need for a whole-atmosphere air temperature profile is also questionable, and it should be further investigated (de Mendonça et al., 2016). The residual spread in the relationship suggests that the influence of factors to the signal other than cosmogenic muons cannot, however, be excluded, and it should be considered in further studies.

The muon counting rate is further analyzed by comparing its dynamic to the incoming neutron fluxes measured at a neutron monitoring station (Jungfraujoch) and based on the effect on the derived soil moisture (Fig. 8). During most of the monitoring period, the main fluctuations are clearly visible in both muon and incoming neutron (JUNG) time series (Fig. 8c). On some days (e.g., on 5 July, when a precipitation event occurred), some differences are detected that might be attributed to different local atmospheric conditions between the experimental sites and Jungfraujoch, where the incoming neutron fluxes are measured. However, these differences do not propagate into significant differences in derived soil moisture. For this reason, the analysis within the present study is not conclusive, but longer time series (e.g., years) with stronger incoming variability are needed to test the use of muons for the incoming correction.

It is noteworthy that one single relevant event has been recorded at the beginning of November (Fig. 8d). During this period, a fast drop in the incoming fluxes has been detected, producing an $\sim 8\,\%$ increase in the incoming correction (if neutron monitoring is concerned). In contrast, the fluctuations in the muons are much smoother. At the current stage, the reasons for these differences have been not identified, but only some hypotheses are formulated. First, the FINAPP3 muons count rate is relatively low, and the recorded signal is smoothed over a relatively long time period (days) to reduce the statistical errors. For this reason, short-term dynamics cannot be captured. Second, the muon detector is also not directional (e.g., as a telescope looking upward), but it measures muon particles that are scattered in all the directions. These characteristics could produce some differences in comparison to the directional detector when these fast and strong events are considered. For this reason, the need for a bigger or directional muon detector could be considered for further developments to detect events that occurs during relatively short period. Still, it is interesting to note the propagation of these different corrections into soil moisture estimation. Specifically, a precipitation event was observed over all the Italian sites during this strong incoming neutron vari-

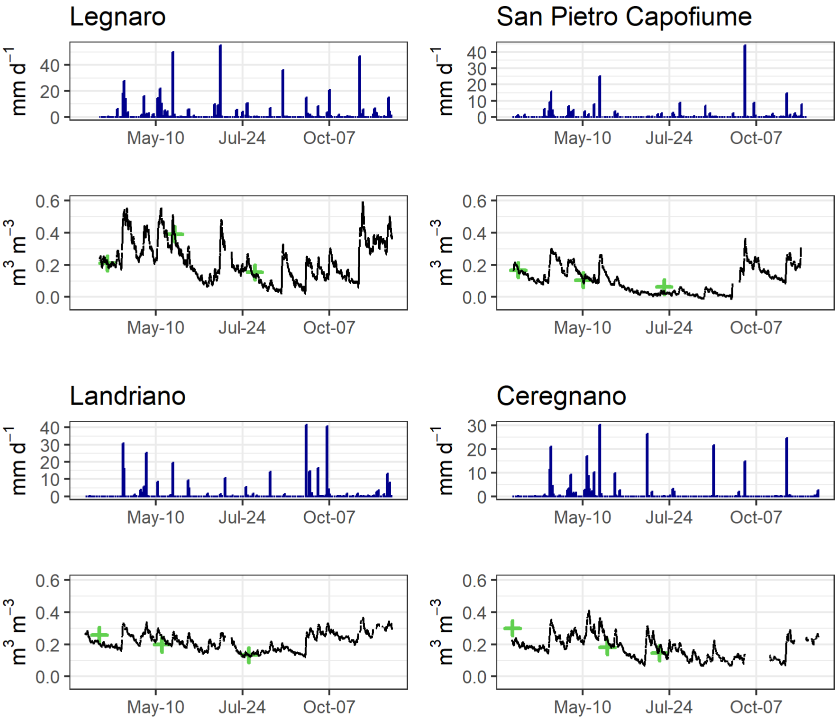

Figure 6. Estimated volumetric soil moisture (m^3 m^{-3}) by FINAPP3 in 2021 at the four experimental sites (black line) compared to the weighted average soil moisture, based on soil samples and gravimetric methods (green crosses). At each site, the precipitation is also shown (blue bars).

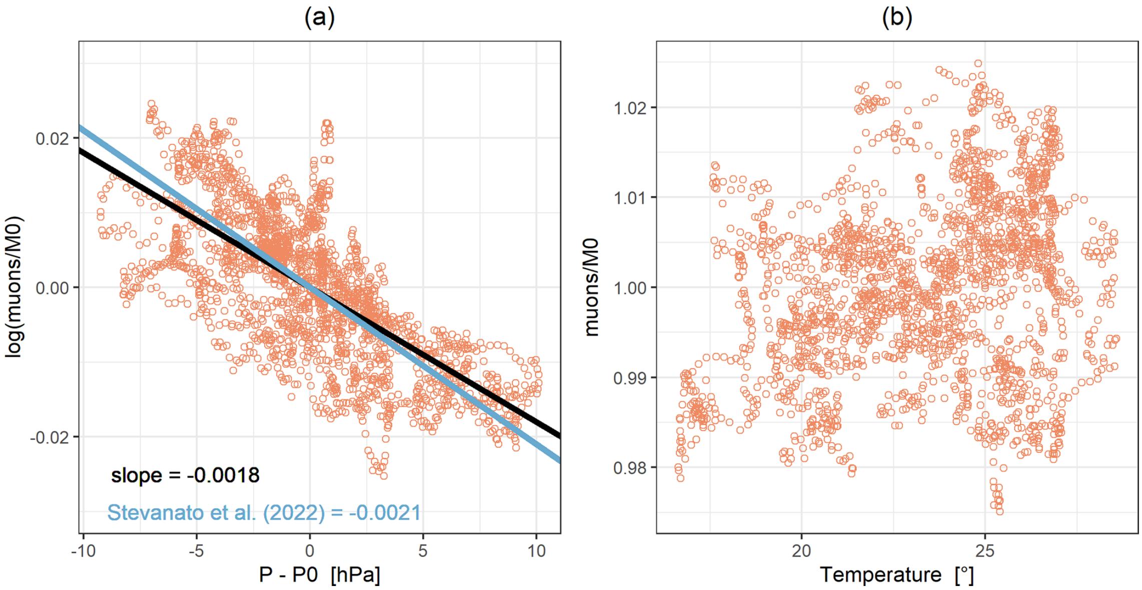

Figure 7. Comparison of data collected at Legnaro site. **(a)** Relative air pressure vs. muon counting rate. **(b)** Air temperature vs. pressure-corrected muon counting rate.

ability. Accordingly, soil moisture should have increased to some degree. The effect of the incoming correction based on the neutron monitoring station, however, smoothed this effect, and the soil moisture remained constant or even started to dry down. In contrast, by using the muon signal, the soil moisture increased. While the magnitude of this increment is, in some cases, questionable if compared, for instance, to the increment recorded during the earlier precipitation event,

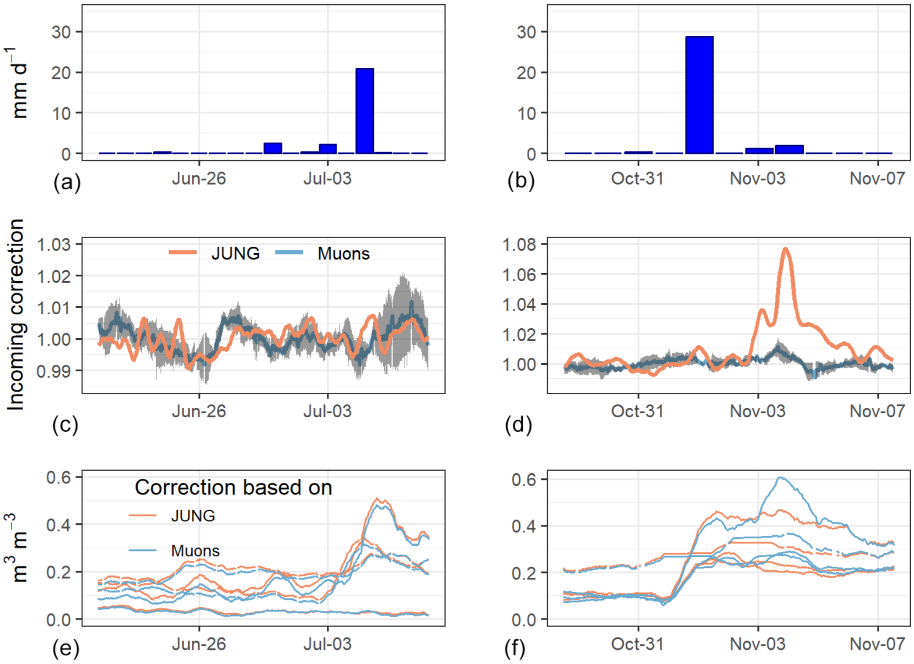

Figure 8. (a, b) The average precipitation over the four Italian experimental sites. **(c, d)** The incoming correction based on neutron monitoring station (JUNG) and based on the average muon detected at the four experimental sites (Muons).The standard deviation is also shown as gray area. **(e, f)** Estimated soil moisture using the 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 an orange line) and using locally detected muons (blue line). The measurements refer to the year 2021.

these results support previous findings that muon detection can be a possible approach to better account for local atmospheric conditions. In this context, FINAPP3 can be considered a valuable sensor for collecting new data for further testing this hypothesis. The use of continuous independent soil moisture measurements should, however, be designed for benchmarking.

3.4 Assessment of measured total gamma rays

The comparison between total gamma counts (TGCs) measured at the Ceregnano site by FINAPP3 and gSMS Medusa is shown in Fig. 9. On average, the sensitivity of the FINAPP3 is lower, with an average counting rate over the monitored period of 2531 counts per hour (cph). In contrast, the gSMS Medusa sensor showed higher sensitivity and an average counting rate over the monitored period of 8281 cph. The correlation between the two signals is low, at an hourly time resolution ($R^2 = 0.08$), mainly due to the presence of extreme values observed during the precipitation events. The correlation increases ($R^2 = 0.32$) with a consistent detected dynamic (Fig. 8b) when these extreme values are removed, and the time series is smoothed over a 6 h time window.

The measured total gamma counts are further compared to the soil moisture simultaneously derived by FINAPP3 and with precipitation and irrigation events (Fig. 10). Please note that a relatively shorter time series (June–September) in comparison to the neutron time series is shown due to some malfunctions of the electronic board and data transmission that have been initially deprecated the gamma signal, as also discussed for the muon signal. The collected results show a negative correlation with the soil moisture dynamic estimated based on the neutron counts (i.e., TGC increases with soil moisture decreasing, and vice versa). Thus, the results confirm how the total gamma fluxes are attenuated by the presence of water in the soil, providing the scientific basis for the development of a gamma ray sensor for soil moisture estimation (Strati et al., 2018). However, the total gamma counts show a higher dynamic at a subdaily timescale in comparison to the estimated neutron-based soil moisture, and the correlation between the signals is weak (Pearson correlation coefficient $r = -0.18$). For this reason, further experiments and analyses should be conducted to better understand the added value of this signal for soil moisture estimation. Among others, the weak correlation can be attributed to the smaller horizonal and vertical footprint of the gamma fluxes (< 25 m radius; < 15 cm depth) in comparison to the neutron (~ 100 m radius; ~ 40 cm depth). Thus, a dedicated soil sampling campaign within the theoretical soil volume detected by the gamma particles should be performed for better assessment. An exponential decrease in the sensitivity of the signal has also been suggested in the literature in both horizontal and vertical directions (Baldoncini et al., 2018).

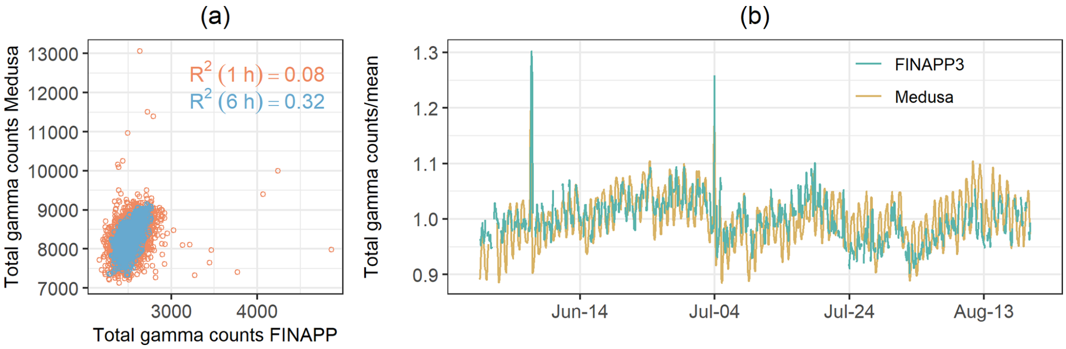

Figure 9. Comparison between total gamma counts measured by FINAPP3 and gSMS Medusa gamma ray spectrometer in 2021 at the Ceregnano site.

However, considering that the gamma footprint is strongly affected by the height of the detector installation (van der Veeke et al., 2021), further and more dedicated experiments should be performed to develop specific weighting functions and to conduct a proper assessment.

It is noteworthy, however, that 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. The results are shown in Fig. 10, where two short periods are visualized as an example. For this reason, while the use of total gamma radiation for soil moisture estimation will require additional refinement, the new sensor can be used for discriminating the increase in the 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). The use of this signal to extend existing gamma ray dosimeters can also be foreseen (Rizzo et al., 2022).

4 Conclusions

This study presents the activities conducted to test a new CRNS sensor design, based on scintillators for non-invasive soil moisture estimation. The results show that the new sensor performed very well in different environmental conditions in comparison to other conventional gas-tubes-based CRNS sensors ($R^2 > 0.9$ at 6 h integration time) and based on several gravimetric soil moisture samples (RMSE $< 0.04\,\mathrm{m^3\,m^{-3}}$). The sensitivity of this new sensor design was found to be suitable for monitoring daily temporal soil moisture changes over the long term (years). However, the signal-to-noise ratio was relatively high at an hourly timescale, and only the aggregation to a 6 h interval yielded a reasonable robustness of the signal. For this reason, a more sensitive detector should be considered when fast hydrological processes such as canopy interceptions or roving applications are targeted.

Part of the tested sensor design contains components that simultaneously measure muons and total gamma radiation. In previous studies, muons were found to be a potential candidate to support the correction for incoming cosmic rays (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 (Baldoncini et al., 2018) and irrigation discrimination (Serafini et al., 2021).

The muons measured within the present study confirmed the negative correlation with the air pressure that has been found in the literature (Stevanato et al., 2022; de Mendonça et al., 2016). The effect of the air temperature was, however, not identified, suggesting the need for longer time series and a wider temperature range. The incoming correction using muons showed some differences in the incoming variability detected by the neutron monitoring station that could be attributed to different local atmospheric conditions. In most of the period, however, the effect on the soil moisture estimation was negligible. Further analyses with longer time series should then be conducted to better understand the added value of detecting this radiation form. A comparison to other recently proposed alternatives, like the use of neutron spectroscopy (Cirillo et al., 2021) or improvements on the use of neutron fluxes measured at the neutron monitoring station (McJannet and Desilets, 2023), should also be performed.

The sensor had also a good performance in the measurements of the total gamma radiation in comparison to a gamma ray spectrometer ($R^2 = 0.29$ at 6 h integration time). The signal also showed a negative correlation to soil moisture, as presented in other studies with the focus on specific gamma energy ranges, e.g., ^{40}K (Strati et al., 2018; Baldoncini et al., 2018). The correlation using total gamma counts is, however, weak (Pearson correlation coefficient $r = -0.18$), suggesting the need for additional studies for a better understanding of the signal response and of the footprint size for soil moisture estimation. In contrast, high peaks of total gamma radiation generated by a shower of radon in the atmosphere have been detected, allowing a clear identification of precipitation vs. irrigation events.

Overall, this tested sensor design has shown to be a valuable alternative to more traditional CRNS detectors for soil

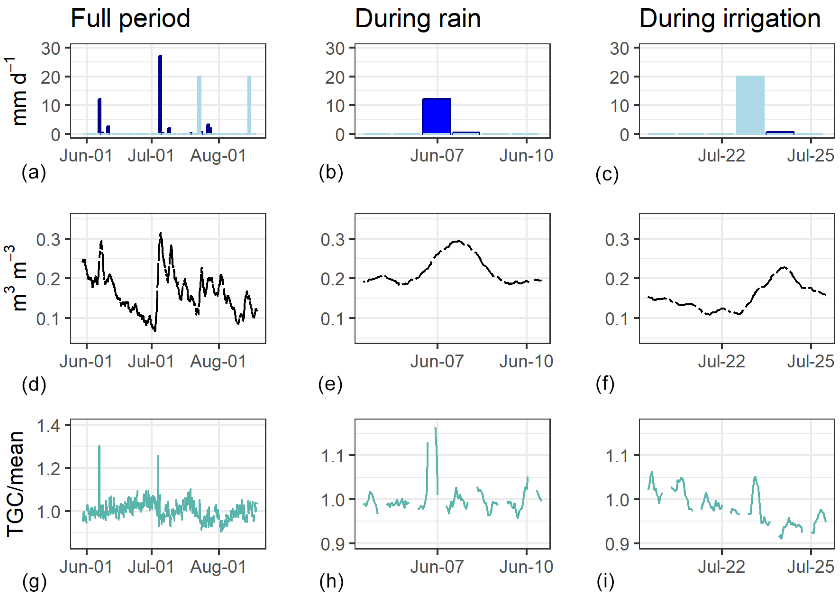

Figure 10. (a, b, c) Precipitation (blue) and irrigation (light blue) (mm d^{-1}), **(d, e, f)** volumetric soil moisture estimated by FINAPP3 (m^3 m^{-3}) and **(g, h, i)** total gamma counts (TGC) over the mean of the monitored period (year 2021).

moisture estimation. Considering that it can be built smaller than conventional neutron systems and offers the potential benefit of the additional detection of muons and total gammas, it can also pave the way for new and wider applications like space weather applications (Hands et al., 2021; Rizzo et al., 2022) and for monitoring agriculture water use (Foster et al., 2020).

Appendix A

Table A1. Results of the soil sample 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); ρ_{bd} is the soil bulk density; SOC is the soil organic carbon; and LW is the lattice water.

Site	Date (dd/mm/yyyy)	θ_a (g g^{-1})	θ_W (g g^{-1})	N_0 (cph)	ρ_{bd} (g cm^{-3})	SOC (g g^{-1})	LW (g g^{-1})
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 from the following repository: https://doi.org/10.5281/zenodo.7261534 (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 from https://doi.org/10.5281/zenodo.7156607 (Baroni, 2022b).

Author contributions. Conceptualization: GB, LS and SG. Design and implementation of field experiments and methodology: GB, LS, SG, TF, HSA, AT and GW. Original draft preparation: SG and GB. Review and editing: all co-authors. All authors have read and agreed to the published version of the paper.

Competing interests. Luca Stevanato, Matteo Polo and Marcello Lunardon are employees of FINAPP s.r.l., Montegrotto Terme, 35036 Padova, Italy. The peer-review process was guided by an independent editor, and the authors also have no other competing interests to declare.

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References

Abraham, M. T., Satyam, N., Rosi, A., Pradhan, B., and Segoni, S.: Usage of antecedent soil moisture for improving the performance of rainfall thresholds for landslide early warning, CATENA, 200, 105147, https://doi.org/10.1016/j.catena.2021.105147, 2021.

Andreasen, M., Jensen, K. H., Zreda, M., Desilets, D., Bogena, H., and Looms, M. C.: Modeling cosmic ray neutron field measurements, Water Resour. Res., 52, 6451–6471, https://doi.org/10.1002/2015WR018236, 2016.

Andreasen, M., Jensen, K. H., Desilets, D., Zreda, M., Bogena, H. R., and Looms, M. C.: Cosmic-ray neutron transport at a forest field site: the sensitivity to various environmental conditions with focus on biomass and canopy interception, Hydrol. Earth Syst. Sci., 21, 1875–1894, https://doi.org/10.5194/hess-21-1875-2017, 2017a.

Andreasen, M., Jensen, K. H., Desilets, D., Franz, T. E., Zreda, M., Bogena, H. R., and Looms, M. C.: Status and Perspectives on the Cosmic-Ray Neutron Method for Soil Moisture Estimation and Other Environmental Science Applications, Vadose Zone J., 16, https://doi.org/10.2136/vzj2017.04.0086, 2017b.

Baatz, R., Bogena, H. R., Hendricks Franssen, H.-J., Huisman, J. A., Montzka, C., and Vereecken, H.: An empirical vegetation correction for soil water content quantification using cosmic ray probes, Water Resour. Res., 51, 2030–2046, https://doi.org/10.1002/2014WR016443, 2015.

Babaeian, E., Sadeghi, M., Jones, S. B., Montzka, C., Vereecken, H., and Tuller, M.: Ground, Proximal, and Satellite Remote Sensing of Soil Moisture, Rev. Geophys., 57, 530–616, https://doi.org/10.1029/2018RG000618, 2019.

Baldoncini, M., Albéri, M., Bottardi, C., Chiarelli, E., Raptis, K. G. C., Strati, V., and Mantovani, F.: Investigating the potentialities of Monte Carlo simulation for assessing soil water content via proximal gamma-ray spectroscopy, J. Environ. Radioactiv., 192, 105–116, https://doi.org/10.1016/j.jenvrad.2018.06.001, 2018.

Barbosa, L. R., Coelho, V. H. R., Scheiffele, L. M., Baroni, G., Filho, G. M. R., Montenegro, S. M. G. L., das N. Almeida, C., and Oswald, S. E.: Dynamic groundwater recharge simulations based on cosmic-ray neutron sensing in a tropical wet experimental basin, Vadose Zone J., 20, e20145, https://doi.org/10.1002/vzj2.20145, 2021.

Baroni, G.: Data in support to the manuscript: Testing a novel sensor design to jointly measure cosmic-ray neutrons, muons and gamma rays for non-invasive soil moisture estimation by Gianessi et al., Zenodo [data set], https://doi.org/10.5281/zenodo.7261534, 2022a.

Baroni, G.: Spreadsheets for soil samples and CRNS data processing, Zenodo [code], https://doi.org/10.5281/zenodo.7156607, 2022b.

Baroni, G. and Oswald, S. E.: A scaling approach for the assessment of biomass changes and rainfall interception using cosmic-ray neutron sensing, J. Hydrol., 525, 264–276, https://doi.org/10.1016/j.jhydrol.2015.03.053, 2015.

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

Bogena, H. R., Schrön, M., Jakobi, J., Ney, P., Zacharias, S., Andreasen, M., Baatz, R., Boorman, D., Duygu, M. B., Eguibar-Galán, M. A., Fersch, B., Franke, T., Geris, J., González Sanchis, M., Kerr, Y., Korf, T., Mengistu, Z., Mialon, A., Nasta, P., Nitychoruk, J., Pisinaras, V., Rasche, D., Rosolem, R., Said, H., Schattan, P., Zreda, M., Achleitner, S., Albentosa-Hernández, E., Akyürek, Z., Blume, T., del Campo, A., Canone, D., Dimitrova-Petrova, K., Evans, J. G., Ferraris, S., Frances, F., Gisolo, D., Güntner, A., Herrmann, F., Iwema, J., Jensen, K. H., Kunstmann, H., Lidón, A., Looms, M. C., Oswald, S., Panagopoulos, A., Patil, A., Power, D., Rebmann, C., Romano, N., Scheiffele, L., Seneviratne, S., Weltin, G., and Vereecken, H.: COSMOS-Europe: a European network of cosmic-ray neutron soil moisture sensors, Earth Syst. Sci. Data, 14, 1125–1151, https://doi.org/10.5194/essd-14-1125-2022, 2022.

Boo, J., Hammig, M. D., and Jeong, M.: Compact lightweight imager of both gamma rays and neutrons based on a pixelated stilbene scintillator coupled to a silicon photomultiplier array, Sci. Rep., 11, 3826, https://doi.org/10.1038/s41598-021-83530-4, 2021.

Bronstert, A., Creutzfeldt, B., Graeff, T., Hajnsek, I., Heistermann, M., Itzerott, S., Jagdhuber, T., Kneis, D., Lück, E., Reusser, D., and Zehe, E.: Potentials and constraints of different types of soil moisture observations for flood simulations in headwater catchments, Nat. Hazards, https://doi.org/10.1007/s11069-011-9874-9, 2011.

Cester, D., Lunardon, M., Moretto, S., Nebbia, G., Pino, F., Sajo-Bohus, L., Stevanato, L., Bonesso, I., and Turato, F.: A novel detector assembly for detecting thermal neutrons, fast neutrons and gamma rays, Nucl. Instrum. Methods, 830, 191–196, https://doi.org/10.1016/j.nima.2016.05.079, 2016.

Cirillo, A., Meucci, R., Caresana, M., and Caresana, M.: An innovative neutron spectrometer for soil moisture measurements, Eur. Phys. J. Plus, 136, 985, https://doi.org/10.1140/epjp/s13360-021-01976-x, 2021.

Cooper, H. M., Bennett, E., Blake, J., Blyth, E., Boorman, D., Cooper, E., Evans, J., Fry, M., Jenkins, A., Morrison, R., Rylett, D., Stanley, S., Szczykulska, M., Trill, E., Antoniou, V., Askquith-Ellis, A., Ball, L., Brooks, M., Clarke, M. A., Cowan, N., Cumming, A., Farrand, P., Hitt, O., Lord, W., Scarlett, P., Swain, O., Thornton, J., Warwick, A., and Winterbourn, B.: COSMOS-UK: national soil moisture and hydrometeorology data for environmental science research, Earth Syst. Sci. Data, 13, 1737–1757, https://doi.org/10.5194/essd-13-1737-2021, 2021.

Coopersmith, E. J., Cosh, M. H., and Daughtry, C. S. T.: Field-scale moisture estimates using COSMOS sensors: A validation study with temporary networks and Leaf-Area-Indices, J. Hydrol., 519, 637–643, https://doi.org/10.1016/j.jhydrol.2014.07.060, 2014.

Corradini, C.: Soil moisture in the development of hydrological processes and its determination at different spatial scales, J. Hydrol., 516, 1–5, https://doi.org/10.1016/j.jhydrol.2014.02.051, 2014.

de Mendonça, R. R. S., Braga, C. R., Echer, E., Dal Lago, A., Munakata, K., Kuwabara, T., Kozai, M., Kato, C., Rockenbach, M., Schuch, N. J., Al Jassar, H. K., Sharma, M. M., Tokumaru, M., Duldig, M. L., Humble, J. E., Evenson, P., and Sabbah, I.: The temperature effect in secondary cosmic rays (muons) observed at the ground: analysis of the global muon detector network data, Astrophys. J., 830, 88, https://doi.org/10.3847/0004-637X/830/2/88, 2016.

Desilets, D., Zreda, M., and Ferré, T. P. A.: Nature's neutron probe: Land surface hydrology at an elusive scale with cosmic rays, Water Resour. Res., 46, https://doi.org/10.1029/2009WR008726, 2010.

Domínguez-Niño, J. M., Oliver-Manera, J., Arbat, G., Girona, J., and Casadesús, J.: Analysis of the Variability in Soil Moisture Measurements by Capacitance Sensors in a Drip-Irrigated Orchard, Sensors, 20, 5100, https://doi.org/10.3390/s20185100, 2020.

Dorman, L. I.: Cosmic Rays in the Earth's Atmosphere and Underground, Springer Netherlands, Dordrecht, https://doi.org/10.1007/978-1-4020-2113-8, 2004.

Evans, J. G., Ward, H. C., Blake, J. R., Hewitt, E. J., Morrison, R., Fry, M., Ball, L. A., Doughty, L. C., Libre, J. W., Hitt, O. E., Rylett, D., Ellis, R. J., Warwick, A. C., Brooks, M., Parkes, M. A., Wright, G. M. H., Singer, A. C., Boorman, D. B., and Jenkins, A.: Soil water content in southern England derived from a cosmic-ray soil moisture observing system – COSMOS-UK, Hydrol. Proc., 30, 4987–4999, https://doi.org/10.1002/hyp.10929, 2016.

Fersch, B., Francke, T., Heistermann, M., Schrön, M., Döpper, V., Jakobi, J., Baroni, G., Blume, T., Bogena, H., Budach, C., Gränzig, T., Förster, M., Güntner, A., Hendricks Franssen, H.-J., Kasner, M., Köhli, M., Kleinschmit, B., Kunstmann, H., Patil, A., Rasche, D., Scheiffele, L., Schmidt, U., Szulc-Seyfried, S., Weimar, J., Zacharias, S., Zreda, M., Heber, B., Kiese, R., Mares, V., Mollenhauer, H., Völksch, I., and Oswald, S.: A dense network of cosmic-ray neutron sensors for soil moisture observation in a highly instrumented pre-Alpine headwater catchment in Germany, Earth Syst. Sci. Data, 12, 2289–2309, https://doi.org/10.5194/essd-12-2289-2020, 2020.

Flynn, K. D., Wyatt, B. M., and McInnes, K. J.: Novel Cosmic Ray Neutron Sensor Accurately Captures Field-Scale Soil Moisture Trends under Heterogeneous Soil Textures, Water, 13, 3038, https://doi.org/10.3390/w13213038, 2021.

Ford, K., Harris, J. R., Shives, R., Carson, J., and Buckle, J.: Remote Predictive Mapping 2. Gamma-Ray Spectrometry: A Tool for Mapping Canada's North, Geoscience Canada, https://journals.lib.unb.ca/index.php/GC/article/view/11270 (last access: 14 January 2024), 2008.

Foster, T., Mieno, T., and Brozović, N.: Satellite-Based Monitoring of Irrigation Water Use: Assessing Measurement Errors and Their Implications for Agricultural Water Management Policy, Water Resour. Res., 56, e2020WR028378, https://doi.org/10.1029/2020WR028378, 2020.

Franz, T. E., Zreda, M., Rosolem, R., and Ferre, T. P. A.: Field Validation of a Cosmic-Ray Neutron Sensor Using a Distributed Sensor Network, Vadose Zone J., 11, vzj2012.0046, https://doi.org/10.2136/vzj2012.0046, 2012.

Franz, T. E., Wang, T., Avery, W., Finkenbiner, C., and Brocca, L.: Combined analysis of soil moisture measurements from roving and fixed cosmic ray neutron probes for multiscale real-time monitoring, Geophys. Res. Lett., 42, 3389–3396, https://doi.org/10.1002/2015GL063963, 2015.

Franz, T. E., Wahbi, A., Zhang, J., Vreugdenhil, M., Heng, L., Dercon, G., Strauss, P., Brocca, L., and Wagner, W.: Practical Data Products From Cosmic-Ray Neutron Sensing for Hydrological Applications, Front. Water, 2, https://doi.org/10.3389/frwa.2020.00009, 2020.

Gianessi, S., Polo, M., Stevanato, L., Lunardon, M., Ahmed, H. S., Weltin, G., Toloza, A., Budach, C., Bíró, P., Francke, T., Heistermann, M., Oswald, S. E., Fulajtar, E., Dercon, G., Heng, L. K., and Baroni, G.: Assessment of a new non-invasive soil moisture sensor based on cosmic-ray neutrons, in: 2021 IEEE International Workshop on Metrology for Agriculture and Forestry (MetroAgriFor), 2021 IEEE International Workshop on Metrology for Agriculture and Forestry (MetroAgriFor), 290–294, https://doi.org/10.1109/MetroAgriFor52389.2021.9628451, 2021.

Gosse, J. C. and Phillips, F. M.: Terrestrial in situ cosmogenic nuclides: theory and application, Quaternary Sci. Rev., 20, 1475–1560, https://doi.org/10.1016/S0277-3791(00)00171-2, 2001.

Haghighi, E., Short Gianotti, D. J., Akbar, R., Salvucci, G. D., and Entekhabi, D.: Soil and Atmospheric Controls on the Land Surface Energy Balance: A Generalized Framework for Distinguishing Moisture-Limited and Energy-Limited Evaporation Regimes, Water Resour. Res., 54, 1831–1851, https://doi.org/10.1002/2017WR021729, 2018.

Hands, A. D. P., Baird, F., Ryden, K. A., Dyer, C. S., Lei, F., Evans, J. G., Wallbank, J. R., Szczykulska, M., Rylett, D., Rosolem, R., Fowler, S., Power, D., and Henley, E. M.: Detecting Ground Level Enhancements Using Soil Moisture Sensor Networks, Space Weather, 19, e2021SW002800, https://doi.org/10.1029/2021SW002800, 2021.

Hawdon, A., McJannet, D., and Wallace, J.: Calibration and correction procedures for cosmic-ray neutron soil moisture probes located across Australia, Water Resour. Res., 50, 5029–5043, https://doi.org/10.1002/2013WR015138, 2014.

Heidbüchel, I., Güntner, A., and Blume, T.: Use of cosmic-ray neutron sensors for soil moisture monitoring in forests, Hydrol. Earth Syst. Sci., 20, 1269–1288, https://doi.org/10.5194/hess-20-1269-2016, 2016.

Heistermann, M., Francke, T., Scheiffele, L., Dimitrova Petrova, K., Budach, C., Schrön, M., Trost, B., Rasche, D., Güntner, A., Döpper, V., Förster, M., Köhli, M., Angermann, L., Antonoglou, N., Zude-Sasse, M., and Oswald, S. E.: Three years of soil moisture observations by a dense cosmic-ray neutron sensing cluster at an agricultural research site in north-east Germany, Earth Syst. Sci. Data, 15, 3243–3262, https://doi.org/10.5194/essd-15-3243-2023, 2023.

Hendrick, L. D. and Edge, R. D.: Cosmic-Ray Neutrons near the Earth, Phys. Rev., 145, 1023–1025, https://doi.org/10.1103/PhysRev.145.1023, 1966.

Iwema, J., Rosolem, R., Baatz, R., Wagener, T., and Bogena, H. R.: Investigating temporal field sampling strategies for site-specific calibration of three soil moisture–neutron intensity parameterisation methods, Hydrol. Earth Syst. Sci., 19, 3203–3216, https://doi.org/10.5194/hess-19-3203-2015, 2015.

Jakobi, J., Huisman, J. A., Vereecken, H., Diekkrüger, B., and Bogena, H. R.: Cosmic Ray Neutron Sensing for Simultaneous Soil Water Content and Biomass Quantification in Drought Conditions, Water Resour. Res., 54, 7383–7402, https://doi.org/10.1029/2018WR022692, 2018.

Jakobi, J. C., Huisman, J. A., Schrön, M., Fiedler, J. E., Brogi, C., Vereecken, H., and Bogena, H. R.: Error estimation for soil moisture measurements with cosmic ray neutron sensing and implications for rover surveys, Front. Water, 2, 10, https://doi.org/10.3389/frwa.2020.00010, 2020.

Jeong, J., Lee, S., and Choi, M.: Correction efficiency and error characteristics for cosmic-ray soil moisture on mountainous terrain, J. Hydrol., 601, 126657, https://doi.org/10.1016/j.jhydrol.2021.126657, 2021.

Kodama, M., Nakai, K., Kawasaki, S., and Wada, M.: An application of cosmic-ray neutron measurements to the determination of the snow-water equivalent, J. Hydrol., 41, 85–92, https://doi.org/10.1016/0022-1694(79)90107-0, 1979.

Köhli, M., Schrön, M., Zreda, M., Schmidt, U., Dietrich, P., and Zacharias, S.: Footprint characteristics revised for field-scale soil moisture monitoring with cosmic-ray neutrons, Water Resour. Res., 51, 5772–5790, https://doi.org/10.1002/2015WR017169, 2015.

Köhli, M., Weimar, J., Schrön, M., Baatz, R., and Schmidt, U.: Soil Moisture and Air Humidity Dependence of the Above-Ground Cosmic-Ray Neutron Intensity, Front. Water, 2, 544847, https://doi.org/10.3389/frwa.2020.544847, 2021.

Lichtenberg, E., Majsztrik, J., and Saavoss, M.: Grower demand for sensor-controlled irrigation, Water Resour. Res., 51, 341–358, https://doi.org/10.1002/2014WR015807, 2015.

Maghrabi, A. and Aldosary, A. F.: The Effect of Some Meteorological Parameters on the Cosmic Ray Muons detected by KACST detector, in: Proceedings of 35th International Cosmic Ray Conference – PoS (ICRC2017), 35th International Cosmic Ray Conference, 10–20 July, 2017, Bexco, Busan, Korea, 062, https://doi.org/10.22323/1.301.0062, 2018.

McJannet, D. L. and Desilets, D.: Incoming Neutron Flux Corrections for Cosmic-ray Soil and Snow Sensors Using the Global Neutron Monitor Network, Water Resour. Res., 59, e2022WR033889, https://doi.org/10.1029/2022WR033889, 2023.

Morin, S., Lejeune, Y., Lesaffre, B., Panel, J.-M., Poncet, D., David, P., and Sudul, M.: An 18-yr long (1993–2011) snow and meteorological dataset from a mid-altitude mountain site (Col de Porte, France, 1325 m alt.) for driving and evaluating snowpack models, Earth Syst. Sci. Data, 4, 13–21, https://doi.org/10.5194/essd-4-13-2012, 2012.

Ochsner, T. E., Cosh, M. H., Cuenca, R. H., Dorigo, W. A., Draper, C. S., Hagimoto, Y., Kerr, Y. H., Njoku, E. G., Small, E. E., and Zreda, M.: State of the Art in Large-Scale Soil Moisture Monitoring, Soil Sci. Soc. Am. J., 77, 1888, https://doi.org/10.2136/sssaj2013.03.0093, 2013.

Patrignani, A., Ochsner, T. E., Montag, B., and Bellinger, S.: A Novel Lithium Foil Cosmic-Ray Neutron Detector for Measuring Field-Scale Soil Moisture, Front. Water, 3, 673185, https://doi.org/10.3389/frwa.2021.673185, 2021.

Peerani, P., Tomanin, A., Pozzi, S., Dolan, J., Miller, E., Flaska, M., Battaglieri, M., De Vita, R., Ficini, L., Ottonello, G., Ricco, G., Dermody, G., and Giles, C.: Testing on novel neutron detectors as alternative to ^{3}He for security applications, Nucl. Instrum. Methods, 696, 110–120, https://doi.org/10.1016/j.nima.2012.07.025, 2012.

Power, D., Rico-Ramirez, M. A., Desilets, S., Desilets, D., and Rosolem, R.: Cosmic-Ray neutron Sensor PYthon tool (crspy

1.2.1): an open-source tool for the processing of cosmic-ray neutron and soil moisture data, Geosci. Model Dev., 14, 7287–7307, https://doi.org/10.5194/gmd-14-7287-2021, 2021.

Rivera Villarreyes, C. A., Baroni, G., and Oswald, S. E.: Integral quantification of seasonal soil moisture changes in farmland by cosmic-ray neutrons, Hydrol. Earth Syst. Sci., 15, 3843–3859, https://doi.org/10.5194/hess-15-3843-2011, 2011.

Rizzo, A., Antonacci, G., Borra, E., Cardellini, F., Ciciani, L., Sperandio, L., and Vilardi, I.: Environmental Gamma Dose Rate Monitoring and Radon Correlations: Evidence and Potential Applications, Environments, 9, 66, https://doi.org/10.3390/environments9060066, 2022.

Saadi, M., Oudin, L., and Ribstein, P.: Beyond imperviousness: the role of antecedent wetness in runoff generation in urbanized catchments, Water Resour. Res., 56, e2020WR028060, https://doi.org/10.1029/2020WR028060, 2020.

Schattan, P., Baroni, G., Oswald, S. E., Schöber, J., Fey, C., Kormann, C., Huttenlau, M., and Achleitner, S.: Continuous monitoring of snowpack dynamics in alpine terrain by aboveground neutron sensing, Water Resour. Res., 53, 3615–3634, https://doi.org/10.1002/2016WR020234, 2017.

Schattan, P., Köhli, M., Schrön, M., Baroni, G., and Oswald, S. E.: Sensing Area-Average Snow Water Equivalent with Cosmic-Ray Neutrons: The Influence of Fractional Snow Cover, Water Resour. Res., 55, 10796–10812, https://doi.org/10.1029/2019WR025647, 2019.

Schrön, M., Köhli, M., Scheiffele, L., Iwema, J., Bogena, H. R., Lv, L., Martini, E., Baroni, G., Rosolem, R., Weimar, J., Mai, J., Cuntz, M., Rebmann, C., Oswald, S. E., Dietrich, P., Schmidt, U., and Zacharias, S.: Improving calibration and validation of cosmic-ray neutron sensors in the light of spatial sensitivity, Hydrol. Earth Syst. Sci., 21, 5009–5030, https://doi.org/10.5194/hess-21-5009-2017, 2017.

Schrön, M., Zacharias, S., Womack, G., Köhli, M., Desilets, D., Oswald, S. E., Bumberger, J., Mollenhauer, H., Kögler, S., Remmler, P., Kasner, M., Denk, A., and Dietrich, P.: Intercomparison of cosmic-ray neutron sensors and water balance monitoring in an urban environment, Geosci. Instrum. Method. Data Syst., 7, 83–99, https://doi.org/10.5194/gi-7-83-2018, 2018.

Schrön, M., Köhli, M., and Zacharias, S.: Signal contribution of distant areas to cosmic-ray neutron sensors – implications for footprint and sensitivity, Hydrol. Earth Syst. Sci., 27, 723–738, https://doi.org/10.5194/hess-27-723-2023, 2023.

Seneviratne, S. I., Corti, T., Davin, E. L., Hirschi, M., Jaeger, E. B., Lehner, I., Orlowsky, B., and Teuling, A. J.: Investigating soil moisture–climate interactions in a changing climate: A review, Earth-Sci. Rev., 99, 125–161, https://doi.org/10.1016/j.earscirev.2010.02.004, 2010.

Serafini, A., Albéri, M., Amoretti, M., Anconelli, S., Bucchi, E., Caselli, S., Chiarelli, E., Cicala, L., Colonna, T., De Cesare, M., Gentile, S., Guastaldi, E., Letterio, T., Maino, A., Mantovani, F., Montuschi, M., Penzotti, G., Raptis, K. G. C., Semenza, F., Solimando, D., and Strati, V.: Proximal Gamma-Ray Spectroscopy: An Effective Tool to Discern Rain from Irrigation, Remote Sens., 13, 4103, https://doi.org/10.3390/rs13204103, 2021.

Simpson, J. A.: The Cosmic Ray Nucleonic Component: The Invention and Scientific Uses of the Neutron Monitor – (Keynote Lecture), Space Sci. Rev., 93, 11–32, https://doi.org/10.1023/A:1026567706183, 2000.

Stevanato, L., Baroni, G., Cohen, Y., Cristiano Lino, F., Gatto, S., Lunardon, M., Marinello, F., Moretto, S., and Morselli, L.: A Novel Cosmic-Ray Neutron Sensor for Soil Moisture Estimation over Large Areas, Agriculture, 9, 202, https://doi.org/10.3390/agriculture9090202, 2019.

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

Stevanato, L., Baroni, G., Oswald, S. E., Lunardon, M., Mares, V., Marinello, F., Moretto, S., Polo, M., Sartori, P., Schattan, P., and Ruehm, W.: An Alternative Incoming Correction for Cosmic-Ray Neutron Sensing Observations Using Local Muon Measurement, Geophys. Res. Lett., 49, e2021GL095383, https://doi.org/10.1029/2021GL095383, 2022.

Stowell, P., Fargher, S., Steer, C., and Thompson, L. F.: Scintillating thermal neutron detectors for cosmic ray soil moisture monitoring, J. Inst., 16, P11039, https://doi.org/10.1088/1748-0221/16/11/P11039, 2021.

Strati, V., Albéri, M., Anconelli, S., Baldoncini, M., Bittelli, M., Bottardi, C., Chiarelli, E., Fabbri, B., Guidi, V., Raptis, K. G. C., Solimando, D., Tomei, F., Villani, G., and Mantovani, F.: Modelling Soil Water Content in a Tomato Field: Proximal Gamma Ray Spectroscopy and Soil–Crop System Models, Agriculture, 8, 60, https://doi.org/10.3390/agriculture8040060, 2018.

Tian, Z., Li, Z., Liu, G., Li, B., and Ren, T.: Soil Water Content Determination with Cosmic-ray Neutron Sensor: Correcting Aboveground Hydrogen Effects with Thermal/Fast Neutron Ratio, J. Hydrol., 540, 923–933, https://doi.org/10.1016/j.jhydrol.2016.07.004, 2016.

Upadhyaya, D. B., Evans, J., Muddu, S., Tomer, S. K., Al Bitar, A., Yeggina, S., S, T., Morrison, R., Fry, M., Tripathi, S. N., Mujumdar, M., Goswami, M., Ganeshi, N., Nema, M. K., Jain, S. K., Angadi, S. S., and Yenagi, B. S.: The Indian COSMOS Network (ICON): Validating L-Band Remote Sensing and Modelled Soil Moisture Data Products, Remote Sens., 13, 537, https://doi.org/10.3390/rs13030537, 2021.

van Amelrooij, E., van de Giesen, N., Plomp, J., Thijs, M., and Fico, T.: BLOSM: Boron-based large-scale observation of soil moisture: First laboratory results of a cost-efficient neutron detector, HardwareX, 12, e00342, https://doi.org/10.1016/j.ohx.2022.e00342, 2022.

van der Veeke, S., Limburg, J., Koomans, R. L., Söderström, M., de Waal, S. N., and van der Graaf, E. R.: Footprint and height corrections for UAV-borne gamma-ray spectrometry studies, J. Environ. Radioactiv., 231, 106545, https://doi.org/10.1016/j.jenvrad.2021.106545, 2021.

Vereecken, H., Huisman, J. A., Bogena, H., Vanderborght, J., Vrugt, J. A., and Hopmans, J. W.: On the value of soil moisture measurements in vadose zone hydrology: A review, Water Resour. Res., 44, https://doi.org/10.1029/2008WR006829, 2008.

Weimar, J., Köhli, M., Budach, C., and Schmidt, U.: Large-Scale Boron-Lined Neutron Detection Systems as a 3He Alternative for Cosmic Ray Neutron Sensing, Front. Water, 2, 16, https://doi.org/10.3389/frwa.2020.00016, 2020.

Zhu, X., Shao, M., Zeng, C., Jia, X., Huang, L., Zhang, Y., and Zhu, J.: Application of cosmic-ray neutron sensing to monitor soil water content in an alpine meadow ecosystem on the northern Tibetan Plateau, J. Hydrol., 536, 247–254, https://doi.org/10.1016/j.jhydrol.2016.02.038, 2016.

Zhuo, L., Dai, Q., Han, D., Chen, N., Zhao, B., and Berti, M.: Evaluation of Remotely Sensed Soil Moisture for Landslide Hazard Assessment, IEEE J. Sel. Top. Appl., 12, 162–173, https://doi.org/10.1109/JSTARS.2018.2883361, 2019.

Zreda, M., Desilets, D., Ferré, T. P. A., and Scott, R. L.: Measuring soil moisture content non-invasively at intermediate spatial scale using cosmic-ray neutrons, Geophys. Res. Lett., 35, https://doi.org/10.1029/2008GL035655, 2008.

Zreda, M., Shuttleworth, W. J., Zeng, X., Zweck, C., Desilets, D., Franz, T., and Rosolem, R.: COSMOS: the COsmic-ray Soil Moisture Observing System, Hydrol. Earth Syst. Sci., 16, 4079–4099, https://doi.org/10.5194/hess-16-4079-2012, 2012.