2021 IEEE International Workshop on Metrology for Agriculture and Forestry (MetroAgriFor) | 978-1-6654-0533-1/21/$31.00 ©2021 IEEE | DOI: 10.1109/MetroAgriFor52389.2021.9628451

Assessment of a new non-invasive soil moisture sensor based on cosmic-ray neutrons

Stefano Gianessi
Department of Agricultural and Food Sciences
University of Bologna
Bologna, Italy
stefano.gianessi2@unibo.it

Matteo Polo
FINAPP s.r.l
Padova, Italy
polo@finapptech.com

Luca Stevanato
FINAPP s.r.l
Padova, Italy
stevanato@finapptech.com

Marcello Lunardon
Department of Physics and Astronomy
University of Padova
Padova, Italy
marcello.lunardon@pd.infn.it

Hami Said Ahmed
Soil and Water Management & Crop Nutrition Laboratory
Joint FAO/IAEA Centre of Nuclear Techniques in Food and Agriculture
Vienna, Austria
H.Said-Ahmed@iaea.org

Georg Weltin
Soil and Water Management & Crop Nutrition Laboratory
Joint FAO/IAEA Centre of Nuclear Techniques in Food and Agriculture
Vienna, Austria
G.Weltin@iaea.org

Arsenio Toloza
Soil and Water Management & Crop Nutrition Laboratory
Joint FAO/IAEA Centre of Nuclear Techniques in Food and Agriculture
Vienna, Austria
a.toloza@iaea.org

Christian Budach
Institute for Environmental Science and Geography
University of Potsdam
Potsdam, Germany
cbudach@uni-potsdam.de

Peter Bíró
Institute for Environmental Science and Geography
University of Potsdam
Potsdam, Germany
pbiro@uni-potsdam.de

Till Francke
Institute for Environmental Science and Geography
University of Potsdam
Potsdam, Germany
francke@uni-potsdam.de

Maik Heistermann
Institute for Environmental Science and Geography
University of Potsdam
Potsdam, Germany
heisterm@uni-potsdam.de

Sascha E. Oswald
Institute for Environmental Science and Geography
University of Potsdam
Potsdam, Germany
sascha.oswald@uni-potsdam.de

Emil Fulajtar
Soil and Water Management & Crop Nutrition Section
Joint FAO/IAEA Centre of Nuclear Techniques in Food and Agriculture
Vienna, Austria
E.Fulajtar@iaea.org

Gerd Dercon
Soil and Water Management & Crop Nutrition Laboratory
Joint FAO/IAEA Centre of Nuclear Techniques in Food and Agriculture
Vienna, Austria
G.Dercon@iaea.org

Lee Kheng Heng
Soil and Water Management & Crop Nutrition Section
Joint FAO/IAEA Centre of Nuclear Techniques in Food and Agriculture
Vienna, Austria
L.Heng@iaea.org

Gabriele Baroni
Department of Agricultural and Food Sciences (DISTAL)
University of Bologna
Bologna, Italy
g.baroni@unibo.it

***Abstract*—In this study, the performance of a new optimized scintillator-based cosmic-ray neutron detector called CRNS-FINAPP for large-scale soil moisture estimation is presented and discussed. The assessment is based on the comparison to two commercial detectors commonly used for this application at two experimental sites and based on independent gravimetric soil moisture measurements collected at one additional irrigated cropped field. The results showed good performance of the new detector at all the experimental sites, with values well in agreement with the different benchmarks. Thus, this new detector demonstrates to be a valid alternative to existing cosmic-ray neutron devices. Considering its lower cost and the smaller dimension, it opens the path to wider use of this method in many applications.**

***Keywords*—soil moisture, cosmic-ray, neutrons, agriculture, forest**

I. Introduction

Soil moisture is a key variable for understanding the hydrological processes and for supporting sustainable management of agricultural and forest environments [1].

Several sensors have been developed to estimate this variable [2]. In most of the cases, ground measurements are performed based on invasive point-scale electrical sensors. These sensors showed good performance in several applications, but they suffer from non-representativeness due to the inherent strong spatial heterogeneity of the soil-plant system. For this reason, a key challenge is to define a

978-1-6654-0533-1/21/$31.00 ©2021 IEEE

representative position for the installation in the different applications [3]. Alternatively, several sensors could be installed but with the consequence of increased costs and possible disturbance of farming activities and operational management.

To overcome these limitations, in the last decades, several geophysical non-invasive methods for soil moisture estimation have emerged [4]. Among them, cosmic-ray neutron sensing (CRNS) has shown to be a valuable method for estimating soil moisture non-invasively at the intermediate scale of hectares and a temporal resolution of hours [5]. This method relies on the inverse correlation between natural neutrons generated by cosmic-ray fluxes and the amount of hydrogen at the land surface. Since most of the hydrogen is present as soil moisture, it is shown that a neutron detector installed above-ground is a reliable method for non-invasive soil moisture estimation [6], [7]. In addition, since neutrons are capable to move over long distances in the air and penetrate some decimeters into the soil, the signal detected represents a footprint of several hectares and a relevant fraction of the soil moisture at the root zone [8]–[10].

This method has been now used by many research groups all around the world [11]. Most of the sensors currently employed are based on the proportional gas tubes (helium 3 or boron trifluoride). While they have a high sensitivity to neutrons, they are relatively expensive. For this reason, the development of alternative detectors is now under investigation by many research institutions and commercial companies [12]–[14].

In this contribution, we show the tests conducted on a new CRNS detector based on scintillators called FINAPP (https://www.finapptech.com/en). This is a relatively low-cost and compacted detector for measuring thermal neutrons. The probe is equipped with a few centimeters of polyethylene, a material enriched with hydrogen that acts as a moderator slowing down the epithermal/fast neutrons more sensitive to soil moisture [9]. Further details of the assembled detector can be found in Stevanato et al. [15], [16]. A prototype was initially assessed showing good performance with the advantage of measuring not only neutrons but also other particles like muons and gamma-ray fluxes [15]. This prototype has been further optimized for accounting for temperature drift and energy consumption [16]. In this study, this new detector is further assessed by comparing the signal to the measured neutron intensities detected by commercial CRNS sensors commonly employed for soil moisture applications based on data collected at one experimental site in Vienna (Austria) and in Potsdam (Germany). Moreover, the detector is assessed based on independent soil moisture data collected at one irrigated cropped field close to Padova (Italy).

II. Comparison between Neutron Detectors

A. Test sites and detectors

The tests are conducted at two experimental sites (Fig. 1). The first site is located close to Marquardt (Potsdam, Germany). The second one is close to Vienna (Austria). In both cases, the sensors are installed at a grass strip surrounded by cropped fields.

In both sites, a new scintillator-based CRNS-FINAPP detector has been installed in April 2021. At Marquardt site, two additional CRNS sensors are available for comparison. The first sensor is a helium-3 proportional gas tube called CRS1000 made by Hydroinnova (https://hydroinnova.com/main.html). This is currently the most and widely adopted detector for CRNS applications. The second detector is a recently new developed sensor based on two boron trifluoride proportional gas tubes produced by LabC (http://lab-c.co/products/). This sensor showed a high sensitivity for neutron detection and promising applications for estimating soil moisture at sub-hourly time resolution [17]. At Vienna experimental site, the same CRNS-FINAPP sensor is compared with a boron trifluoride proportional gas tube also produced by Hydroinnova (version, CRS2000).

Fig. 1. Experimental sites showing the CRNS sensors (top) at Marquardt site, and (bottom) at Vienna site.

All the sensors are installed at a height of around 1.5 m above the ground and at less than few meters distance from each other. Considering the large footprint of the signal detected, this horizontal difference is considered negligible for the comparison. All the sensors are equipped with a solar panel and with GSM data-transmission for supporting long-term and real-time observations.

For the comparison of the time series, the Kling-Gupta efficiency metric (*KGE*) is used:

$$KGE = 1 - \sqrt{(\beta - 1)^2 + (\gamma - 1)^2 + (\rho - 1)^2} \quad (1)$$

with

$$\beta = \frac{\mu_A}{\mu_B} \quad (2)$$

$$\gamma = \frac{\sigma_A \, \mu_B}{\mu_A \, \sigma_B} \quad (3)$$

$$\rho = \frac{(A - \mu_A)(B - \mu_B)}{\sigma_A \sigma_B} \quad (4)$$

with A and B the two time series to be compared. μ and σ are the mean and standard deviation, respectively, ρ is the linear correlation coefficient, β represents the bias ratio and γ the relative variability. Values close to one indicate perfect matches between the two variables.

B. *Results*

The results are presented in Fig. 2 spanning the period May 2021 to July 2021. Specifically, pressure corrected neutron intensities (5) are compared. The sensors showed different sensitivity with averages over the period of around 850, 1800, 1200 and 8500 neutron counts per hour (cph) for CRS1000, CRS2000, FINAPP and LabC, respectively. For this reason, the neutron intensities are also scaled to their long-term averages for comparison.

The results show very good correlation between the detected neutrons. KGE calculated over the period between data measured by FINAPP and the other sensors is above 0.9 at both sites. For these reasons, the results confirm that the new FINAPP detector is a valid alternative to existing cosmic-ray neutron devices that can be used in many applications for soil moisture estimation.

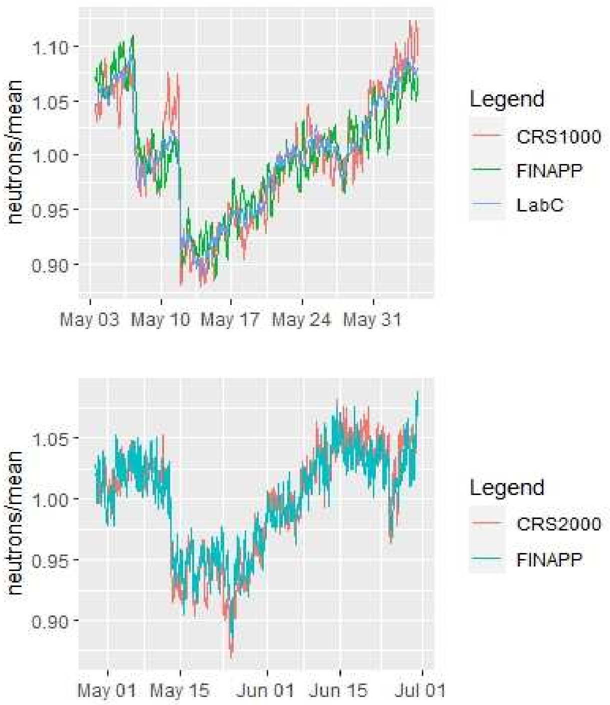

Fig. 2. Comparison between pressure corrected epithermal neutron counts measured by the different detectors. The neutron counts are scaled by their long term mean for comparison.

III. Assessment of Soil Moisture Estimation

A. *From neutron counts to soil moisture*

The measured neutron count rates N are corrected for air pressure, incoming variability and air vapor following standard methods [5]:

$$f_p = N_{raw} \cdot exp\left(\beta\left(\langle p \rangle - p_{ref}\right)\right) \quad (5)$$

$$f_i = \frac{I_{ref}}{I} \quad (6)$$

$$f_v = \left(1 - \alpha\left(\langle h \rangle - h_{ref}\right)\right) \quad (7)$$

$$N_c = N \cdot f_p \cdot f_i \cdot f_v \quad (8)$$

where, h is the absolute humidity in g·m^{-3}, I the incoming flux of galactic cosmic-ray, $\beta = 0.0066$, $\alpha = 0.0054$, and h_{ref}, p_{ref} are the mean value of air humidity and pressure during the measuring period, respectively. I_{ref} is the average value of the incoming fluctuation over a long period and depends on the efficiency of the station used for correction. Data of the incoming fluctuations can be downloaded from the following web-page: https://www.nmdb.eu/nest/. For the specific case study, data from Jungfraujoch station (Switzerland) are used for the correction as commonly adopted in many applications.

Finally, corrected neutrons N_c are transformed to volumetric soil moisture θ based on Desilets equation [18]:

$$\theta(N_c) = \left(\frac{0.0808}{\frac{N_c}{N_0} - 0.372} - 0.115 - \theta_{offset}\right) \cdot \frac{\rho_{bd}}{\rho_w} \quad (9)$$

where ρ_{bd} and ρ_w are respectively the soil bulk density (kg·m^{-3}) and water density (kg·m^{-3}), θ_{offset} is the gravimetric water equivalent of additional hydrogen pools (e.g., lattice water, soil organic carbon), and N_0 is the counting rate over dry soil. The value N_0 could be calibrated based on independent soil sampling campaigns as suggested in different studies [7], [8], [19].

B. *Agricultural field test and soil moisture observations*

A FINAPP sensor has also been installed at an irrigated cropped field at Ceregnano, close to Padova (Italy) in March 2021 (Fig. 3). The system has been further integrated with air temperature and humidity sensors for retrieving local and representative data for the atmospheric correction (7).

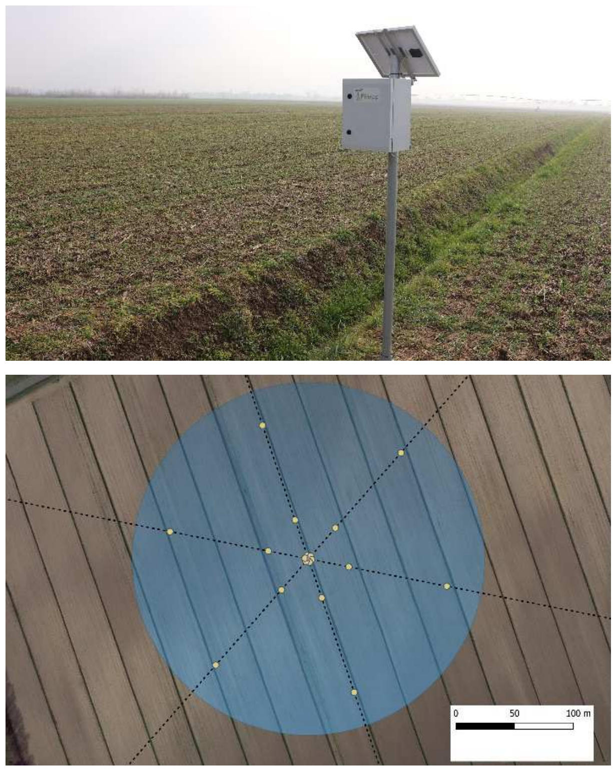

Fig. 3. Ceregnano experimental site, with (above) CRNS-FINAPP and (bottom) soil sampling locations and CRNS footprint (150 m radius).

Two soil sampling campaigns have been conducted on March 10th 2021 and on May 31st 2021, respectively. The data collected during the first campaign has been used for the calibration of the parameter N_0 in (9). The data collected during the second campaign are used for the assessment. In each campaign, undisturbed soil samples have been collected at four depths (0-5 cm, 10-15 cm, 20-25 cm and 30-35 cm) and at 18 locations as shown in figure 3. These locations are selected to address the spatial sensitivity of the detected signal and they represent the current standard for the calibration process [8]. Soil water content of each soil sample has been measured based on the gravimetric method (i.e., oven dry soil at 105° Celsius for 24/48 hours to a constant soil weight). A composite sample is also analyzed for the assessment of soil texture, soil organic carbon *SOC* and lattice water *LW*. These last two parameters have been calculated by loss-on-ignition method at 400 ˚C and 1000 ˚C, respectively [20]. These two values are summed up to the soil moisture (θ_{offset}) in (9).

C. Results

Analyses performed on the soil samples are shown in Table I. The analyses indicate a silt loam soil with a high value of soil organic carbon as typically detected in the region. Average volumetric soil moisture at the two soil campaigns is comparable with values around 0.22 [m^3 m^{-3}] and relatively high spatial variability (standard deviation up to 0.04 [m^3 m^{-3}]). As previously indicated, the value obtained during the first campaign is used for the calibration of the parameter N_0 in (9). The value measured during the second campaign is considered for the assessment.

TABLE I. CEREGNANO SITE SOIL PARAMETERS

Soil analyses	
Variable	***Mean (standard deviation)***
Soil organic carbon *SOC* [g/g]	0.036
Lattice water *LW* [g/g]	0.076
Soil texture	silt loam
Average soil moisture on 10/03/2021 [m^3 m^{-3}]	0.23 (0.03)
Average soil moisture on 31/05/2021 [m^3 m^{-3}]	0.21 (0.04)
calibrated *No* based on 1st campaign [cph]	1468

Soil moisture estimated by CRNS-FINAPP is shown in Fig. 4. The results show a consistent soil moisture dynamic well in agreement with precipitation events. The comparison with soil moisture measured during the second soil sampling campaign is also in very good agreement. For these reasons, the analysis suggests that CRNS-FINAPP is a reliable method for non-invasive soil moisture estimation over large areas.

IV. CONCLUSIONS

This study presents the assessment of a new soil moisture sensor based on cosmic-ray neutrons. The detector called CRNS-FINAPP is based on scintillators, and it provides a relatively lower-cost and compact alternative to current detectors currently available on the market.

The results show that the data collected at two experimental sites are in good agreement with more commonly used CRNS sensors for soil hydrological applications. The assessment conducted at an irrigated cropped field based on independent soil moisture values confirms the reliability of the method for detecting field scale soil moisture. Further analyses will be performed based on additional assessments at different experimental sites. The value of additional particles like muons and gamma-ray fluxes simultaneously detected by the sensor will be also further explored for improving incoming correction [21], [22] and detecting soil moisture at a smaller scale [23], respectively.

Overall, this study shows that current developments in sensors technology are boosting cosmic-ray neutron methods for hydrological applications, and it can open the path to a wide number of users and opportunities by increasing its robustness while lowering its costs.

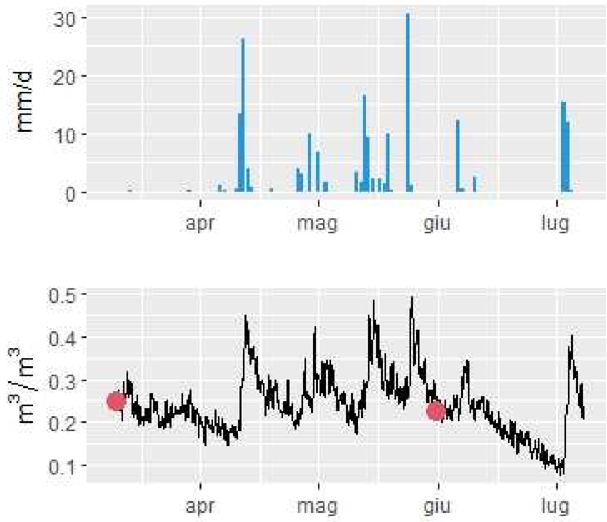

Fig. 4. Time series recorded at Ceregnano experimental site (Italy). (above) precipitation and (below) soil moisture estimated by CRNS. Red dots indicate arithmetic average soil moisture measured during the two soil sampling campaigns.

ACKNOWLEDGMENT

This study was conceived during the IAEA Coordinated Research Project (CRP) "Enhancing agricultural resilience and water security using Cosmic-Ray Neutron Sensor (D1.20.14)."

REFERENCES

[1] L. Brocca, L. Ciabatta, C. Massari, S. Camici, and A. Tarpanelli, "Soil Moisture for Hydrological Applications: Open Questions and New Opportunities," *Water*, vol. 9, no. 2, Art. no. 2, Feb. 2017, doi: 10.3390/w9020140.

[2] D. A. Robinson *et al.*, "Soil Moisture Measurement for Ecological and Hydrological Watershed-Scale Observatories: A Review," *Vadose Zone Journal*, vol. 7, no. 1, p. 358, 2008, doi: 10.2136/vzj2007.0143.

[3] J. M. Domínguez-Niño, H. R. Bogena, J. A. Huisman, B. Schilling, and J. Casadesús, "On the Accuracy of Factory-Calibrated Low-Cost Soil Water Content Sensors," *Sensors*, vol. 19, no. 14, p. 3101, Jul. 2019, doi: 10.3390/s19143101.

[4] E. Babaeian, M. Sadeghi, S. B. Jones, C. Montzka, H. Vereecken, and M. Tuller, "Ground, Proximal, and Satellite Remote Sensing of Soil Moisture," *Reviews of Geophysics*, vol. 57, no. 2, pp. 530–616, 2019, doi: https://doi.org/10.1029/2018RG000618.

[5] M. Zreda *et al.*, "COSMOS: the COsmic-ray Soil Moisture Observing System," *Hydrology and Earth System Sciences*, vol. 16, no. 11, pp. 4079–4099, Nov. 2012, doi: 10.5194/hess-16-4079-2012.

[6] C. A. Rivera Villarreyes, G. Baroni, and S. E. Oswald, "Integral quantification of seasonal soil moisture changes in farmland by cosmic-ray neutrons," *Hydrology and Earth System Sciences*, vol. 15, no. 12, pp. 3843–3859, Dec. 2011, doi: 10.5194/hess-15-3843-2011.

[7] T. E. Franz, M. Zreda, R. Rosolem, and T. P. A. Ferre, "Field Validation of a Cosmic-Ray Neutron Sensor Using a Distributed

Sensor Network," *Vadose Zone Journal*, vol. 11, no. 4, p. 0, 2012, doi: 10.2136/vzj2012.0046.

[8] M. Schrön *et al.*, "Improving calibration and validation of cosmic-ray neutron sensors in the light of spatial sensitivity," *Hydrol. Earth Syst. Sci.*, vol. 21, no. 10, pp. 5009–5030, Oct. 2017, doi: 10.5194/hess-21-5009-2017.

[9] M. Köhli, M. Schrön, M. Zreda, U. Schmidt, P. Dietrich, and S. Zacharias, "Footprint characteristics revised for field-scale soil moisture monitoring with cosmic-ray neutrons," *Water Resources Research*, vol. 51, no. 7, pp. 5772–5790, Jul. 2015, doi: 10.1002/2015WR017169.

[10] E. Wang *et al.*, "Making sense of cosmic-ray soil moisture measurements and eddy covariance data with regard to crop water use and field water balance," *Agricultural Water Management*, vol. 204, pp. 271–280, May 2018, doi: 10.1016/j.agwat.2018.04.017.

[11] M. Andreasen *et al.*, "Status and Perspectives on the Cosmic-Ray Neutron Method for Soil Moisture Estimation and Other Environmental Science Applications," *Vadose Zone Journal*, vol. 16, no. 8, Aug. 2017, doi: 10.2136/vzj2017.04.0086.

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

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

[14] P. Peerani *et al.*, "Testing on novel neutron detectors as alternative to 3He for security applications," *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 696, pp. 110–120, Dec. 2012, doi: 10.1016/j.nima.2012.07.025.

[15] L. Stevanato *et al.*, "A Novel Cosmic-Ray Neutron Sensor for Soil Moisture Estimation over Large Areas," *Agriculture*, vol. 9, no. 9, p. 202, Sep. 2019, doi: 10.3390/agriculture9090202.

[16] L. Stevanato, M. Polo, M. Lunardon, F. Marinello, S. Moretto, and G. Baroni, "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)*, Nov. 2020, pp. 196–200. doi: 10.1109/MetroAgriFor50201.2020.9277582.

[17] B. Fersch *et al.*, "A dense network of cosmic-ray neutron sensors for soil moisture observation in a highly instrumented pre-Alpine headwater catchment in Germany," *Earth System Science Data*, vol. 12, no. 3, pp. 2289–2309, Sep. 2020, doi: https://doi.org/10.5194/essd-12-2289-2020.

[18] D. Desilets, M. Zreda, and T. P. A. Ferré, "Nature's neutron probe: Land surface hydrology at an elusive scale with cosmic rays," *Water Resources Research*, vol. 46, no. 11, Nov. 2010, doi: 10.1029/2009WR008726.

[19] G. Baroni, L. M. Scheiffele, M. Schrön, J. Ingwersen, and S. E. Oswald, "Uncertainty, sensitivity and improvements in soil moisture estimation with cosmic-ray neutron sensing," *Journal of Hydrology*, vol. 564, pp. 873–887, Sep. 2018, doi: 10.1016/j.jhydrol.2018.07.053.

[20] L. R. Barbosa *et al.*, "Dynamic groundwater recharge simulations based on cosmic-ray neutron sensing in a tropical wet experimental basin," *Vadose zone j.*, Jun. 2021, doi: 10.1002/vzj2.20145.

[21] L. Stevanato, G. Baroni, C. Fontana, M. Lunardon, S. Moretto, and P. Schattan, "Local high-energy particles measurements for detecting primary cosmic-ray variations: application for soil moisture estimation," display, other, Mar. 2020. doi: 10.5194/egusphere-egu2020-11180.

[22] P. Stowell *et al.*, "Low Cost Neutron and Muon Detectors for Soil Moisture Monitoring," in *Proceedings of 37th International Cosmic Ray Conference — PoS(ICRC2021)*, Jul. 2021, vol. 395, p. 1318. doi: 10.22323/1.395.1318.

[23] M. Baldoncini *et al.*, "Investigating the potentialities of Monte Carlo simulation for assessing soil water content via proximal gamma-ray spectroscopy," *Journal of Environmental Radioactivity*, vol. 192, pp. 105–116, Dec. 2018, doi: 10.1016/j.jenvrad.2018.06.001.