

Cosmos2026



8th International COSMOS workshop

29 September – 1st of October 2026

BOOK OF ABSTRACTS

With the patronage of



DEPARTMENT
OF AGRICULTURAL
AND FOOD SCIENCES



Supported by



ISMON – Advancing Soil Moisture Monitoring in Ireland

Caren Jarmain^{1*}, Katya Dimitrova-Petrova¹, Klara Finkele¹, Haleh Karbala Ali¹, Saji Varghese¹

(1) Met Eireann

Contact: Caren Jarmain (Caren.Jarmain@met.ie)

ABSTRACT

Soil moisture plays a fundamental role in the functioning of terrestrial and hydrological systems, yet observations of soil moisture across Ireland remain limited in both spatial and temporal coverage. Existing soil moisture deficit products available through Met Eireann provide useful broad-scale information which is used widely for operational and environmental applications, but there is an opportunity to improve their representation through increased ground-based observations. The Irish Soil Moisture Observation Network (ISMON) was initiated in 2021 to establish a coordinated network of soil moisture observations across contrasting Irish environments. This presentation provides an update on the development and early implementation of ISMON, including the network design, participating partners, current sites and measurement configurations. The network currently includes 11 cosmic-ray neutron sensing sites, combining various soil moisture and meteorological monitoring sensors across a range of soils, land uses and rainfall regimes. Beyond network deployment, we highlight early observations and ongoing research investigating soil-moisture dynamics, differences between observing approaches, and the spatial representativeness of measurements. Practical lessons from network installation and operation are also discussed, including instrumentation, communications, data management, quality control and system maintenance. The next phase will focus on strategically expanding network coverage, strengthening collaboration with

universities and students, improving automated data workflows, and using ISMON observations to support the evaluation and future development of improved spatial soil moisture products for Ireland.

The Danish national soil moisture network

Mie Andreasen¹, Majken C. Looms², Ida Seidenfaden, Jacob Kidmose¹, Karsten Høgh
Jensen², Torben Sonnenborg¹

(1) GEUS, (2) University of Copenhagen

Contact: Mie Andreasen (ma@geus.dk)

ABSTRACT

The presentation will focus on the Danish national soil moisture network, which currently consists of 15 stations. The network includes both cosmic-ray neutron and gamma-ray spectroscopy sensors. We will present examples of how the data are used at selected field stations.

Emilia-Romagna CRNS monitoring network

Cinzia Alessandrini¹, Alessandro Pirola¹, Villiam Zanni Bertelli¹, Andrea Pasquali¹

(1) Regional Agency for Environmental Protection, Hydro-Meteo-Climate Service, Emilia-Romagna, 40122 Bologna, Italy

Contact: Cinzia Alessandrini (calessandrini@arpae.it)

ABSTRACT

Soil moisture is a critical hydrological variable, playing a fundamental role in understanding water and energy fluxes between the land surface and the atmosphere. In the Emilia-Romagna region of Italy, an area characterized by intensive agriculture and increasing vulnerability to extreme hydrological events such as severe droughts and flash floods, accurate and continuous monitoring of soil water content is of paramount importance. Traditional point-scale soil moisture sensors often fail to capture the spatial variability required for regional hydro-meteorological modeling, while remote sensing products may suffer from coarse temporal or spatial resolution and limited penetration depth. To bridge this observational gap, Cosmic-Ray Neutron Sensing (CRNS) has emerged as a highly effective, non-invasive technology capable of providing continuous, intermediate-scale (hectometer footprint) area-averaged soil moisture measurements.

Recognizing the immense potential of this innovative technology, Arpaе (the Regional Agency for Prevention, Environment and Energy of Emilia-Romagna) initiated a pioneering project in early 2023 to establish the first dedicated CRNS network in the region. The project commenced with the acquisition and strategic installation of four initial neutron probes, laying the foundational infrastructure for an advanced hydro-meteorological monitoring system. The primary objective was to enhance the regional environmental monitoring capabilities,

providing robust and continuous data to support water resource management and climate change adaptation strategies at a territorial level.

Since its inception, the network has undergone significant and rapid expansion. Currently, the regional observatory comprises nine operational CRNS probes distributed across the Emilia-Romagna territory. This growth has been achieved not only through direct investment by Arpae but also through strategic partnerships and collaborations with other research institutions and stakeholders, resulting in a mixed-ownership model of the sensor fleet. This collaborative approach has allowed for a more comprehensive spatial coverage, capturing the diverse pedo-climatic conditions, varied topography, and different land uses present within the region, from the Apennine mountains to the Po River plain.

A crucial component of this expanding infrastructure is the development of a robust operational data processing chain. Arpae is currently finalizing the backend architecture required to automatically ingest, process, and perform quality control on the raw neutron count data. A key milestone of this current phase is the creation of a public-facing platform designed to disseminate this high-value data openly, ensuring that researchers, agricultural stakeholders, and the general public have unrestricted access to real-time and historical soil moisture information.

Beyond the structural implementation of the network and data publication, ongoing efforts are heavily focused on the development of practical applications derived from these soil moisture datasets. These applications are designed to directly inform decision-making processes in several critical areas, including the optimization of agricultural irrigation scheduling, the refinement of early warning systems for flood forecasting, and the continuous assessment of hydrological drought severity. By transitioning from experimental deployments to a fully operational regional network, Arpae Emilia-Romagna is setting a new standard for environmental monitoring, providing essential tools to safeguard regional water resources.

Network-wide assessment of soil water content calibration and sensitivity to biomass proxies using cosmic-ray neutron sensing in the Roaring Fork Basin, Colorado

Sophia M. Becker¹, Gwendolyn E. Davies², Trenton E. Franz¹, Tyler D. Lampard³, Todd G. Caldwell⁴

(1) University of Nebraska-Lincoln; (2) Nevada Water Science Center, United States Geological Survey; (3) Colorado Water Science Center, United States Geological Survey; (4) Division of Hydrologic Sciences, Desert Research Institute, Reno, Nevada, USA.

Contact: Sophia Becker (sophbecker16@gmail.com)

ABSTRACT

Soil water content (SWC) is a key state variable of the climate system but is often uncertain in water balance monitoring, especially in alpine environments. SWC measurements can be challenging in alpine environments due to the topography and rocky soils. In 2022, the US Geological Survey's Next Generation Water Observing System Program began research to evaluate water balance monitoring technologies, including cosmic-ray neutron sensors (CRNS). This study evaluated the uncertainty resulting from network-wide calibration of CRNS for SWC monitoring in an alpine watershed and investigated the stability of the calibration parameters across space and time, focusing on potential influence of biomass dynamics. Fifteen stations with moderated and unmoderated (bare) CRNS were deployed and made operational within the Roaring Fork Basin in west-central Colorado. The root mean squared error of the network-wide calibration using the moderated CRNS was 0.042 or 0.047 cm³ cm⁻³, depending on the calibration equation used. Relative SWC dynamics from CRNS were correlated with the in situ probes with a correlation coefficient of 0.91 or 0.87 (depending

on calibration equation). We did not find significant relationships between the calibration parameters and stationary site-specific variables. However, the calibration parameters derived from in situ probe SWC dynamics varied over time and were correlated with biomass proxies of cumulative growing degree-day, cumulative growing season index, and bare neutron counts. Future use of the CRNS network can leverage the reliable relative SWC data from network-wide calibration for watershed modeling and continue to research sensitivity of bare neutron measurements to biomass dynamics.

Non-destructive quantification of biomass water equivalent for improved cosmic-ray neutron sensor calibration

Špela Srdoč, Maja Podgornik, Rozalija Cvejić

Science research centre Koper Institute for Oliveculture; University of Ljubljana Biotechnical faculty

Contact: Špela Srdoč (spela.srdoc@zrs-kp.si)

ABSTRACT

A new SI-COSMOS network has been established in Slovenia in 2025 (Cvejić et al., 2026). One of the sites, at Marezige (45°29'54.1"N 13°47'29.5"E), is focusing the correction for the hydrogen contained in aboveground plant biomass, expressed as the biomass water equivalent (BWE), remains the least standardised and most ecosystem-specific component of the CRNS signal correction framework (Iwema et al., 2021; Köhli, 2026). Plant tissue contains substantial quantities of water, and the total hydrogen pool attributable to vegetation changes dynamically throughout the growing season as crops germinate, develop, reach peak canopy, and are harvested (Al-Mashharawi et al., 2025; Baroni and Oswald, 2015; Morris et al., 2024). If these temporal changes are not explicitly corrected, the resulting CRNS-derived SWC time series will contain systematic seasonal biases that can misrepresent actual soil moisture dynamics and compromise the use of CRNS data for irrigation scheduling or drought monitoring (Al-Mashharawi et al., 2025; Morris et al., 2024). The BWE correction is typically parameterised through a linear correction factor applied to N_0 (Morris et al., 2024). A widely adopted reference value was proposed by Baatz et al., 2025, who reported a 0.9% reduction in epithermal neutron intensity per 1 kg m^{-2} of dry above-ground biomass, but later studies showed that the magnitude of this effect varies substantially across vegetation types and ecosystems (Al-Mashharawi et al., 2025; Morris et al., 2024).

The most direct approach for considering BWE is destructive aboveground biomass sampling, followed by gravimetric determination of plant water content (Morris et al., 2024; Baatz et al., 2015). However this method is impractical for large trees, damages perennial crops and provides only snapshot measurements requiring temporal interpolation (Al-Mashharawi et al., 2025). For these reasons, non-destructive proxies have been tested, such as water pressure deficit and sap flow (Al-Mashharawi et al., 2025), normalized difference vegetation index (Wu et al., 2024) and allometric approaches combining trunk width and tree count which explained site-to-site differences in calibrated N_0 (Iwema et al., 2021). Uncorrected biomass has also been shown to cause long-term SWC overestimation in forested landscapes (Heidbüchel et al., 2016), while in annual cropping systems, crop growth substantially biases neutron counts, highlighting the need for crop-specific correction datasets (Baroni and Oswald, 2015; Franz et al., 2012; Gianessi et al., 2024; Morris et al., 2024).

Building on the finding that site-specific aboveground biomass explains differences in calibrated N_0 (Morris et al., 2024), this project proposes trunk water potential, measured continuously via microtensiometers, as a direct, dynamic calibration variable for BWE, rather than static or index-based proxy. A theoretical mathematical model was proposed to relate stem water potential to the magnitude of N_0 deviation. Based on continuous measurements, this will be tested in adjustment of BWE correction factor throughout the growing season and provide a transferable framework across heterogeneous land uses within the CRNS footprint at the study site.

The Alento focal point for agro-environmental research in the Mediterranean: Cosmic-ray neutron sensing bridging long-term observations and hypothesis-driven experiments

Nunzio Romano¹, Paolo Nasta¹

(1) Department of Agricultural Sciences, Division of Agricultural, Forest and Biosystems Engineering, University of Naples Federico II, Portici (Naples), Italy.

Contact: Nunzio Romano (nunzio.romano@unina.it)

ABSTRACT

Soil moisture is a key state variable of the Critical Zone, controlling the partitioning of precipitation into infiltration, evapotranspiration, runoff, and groundwater recharge while mediating soil–plant–atmosphere interactions. Yet, its pronounced spatial variability makes representative monitoring particularly challenging. Conventional in-situ sensors provide accurate but spatially sparse profile-scale observations, whereas Cosmic-Ray Neutron Sensing (CRNS) provides non-invasive estimates of soil water content over an intermediate spatial scale of several hectares, thereby bridging the gap between point-scale measurements and catchment- or satellite-scale observations. Beyond this monitoring capability, CRNS has the potential to provide the temporal backbone for integrating complementary observations and process-oriented field experiments across spatial scales.

The Alento River Catchment (ARC), covering 411 km² in southern Italy, provides a long-term experimental platform for investigating scale-dependent soil-water dynamics under Mediterranean conditions. Since 2016, two experimental sites within the Upper Alento River Catchment have been equipped with stationary CRNS stations belonging to the COSMOS-Europe network. The sites represent contrasting land-use settings, comprising an

approximately 8 ha agricultural catchment and an approximately 18 ha forested catchment. At both sites, CRNS observations are complemented by wireless sensor networks providing soil water content and matric potential measurements at 20 locations and two soil depths (15 and 30 cm), together with continuous monitoring of meteorological variables.

The resulting long-term observations enable comparison of CRNS-derived area-wide soil moisture with spatially sparse profile-scale measurements, providing insight into the implications of their different spatial support and their ability to capture seasonal wetting and drying dynamics. Site-specific CRNS calibration relied on targeted soil sampling campaigns conducted under dry, intermediate, and wet conditions. Building upon this continuous monitoring framework, targeted campaigns involving soil hydraulic characterization, infiltration experiments, hydrogeophysical surveys, stable water isotopes, and remote sensing have been designed to test specific hypotheses concerning soil-water storage, redistribution, plant water use, and hydrological response.

The integrated observational strategy transforms the Alento observatory from a conventional monitoring network into an open-air hydrological laboratory, where continuous CRNS observations provide the temporal backbone for interpreting targeted process experiments. Integrating area-wide CRNS estimates with profile-scale sensors and process-oriented field observations offers a robust framework for testing hydrological hypotheses, improving model parameterization, and evaluating ecohydrological models under the strong seasonality and recurrent drought conditions characteristic of Mediterranean environments. Our experience demonstrates that CRNS can serve not only as an intermediate-scale monitoring technique but also as a tool to reduce the scale mismatch between observations and models in Mediterranean environments.

Keywords: cosmic-ray neutron sensing; soil moisture; Critical Zone Observatory; sensor network; Mediterranean hydrology; soil hydraulic properties; ecohydrological modelling.

Comparison of CRNS and local soil moisture measurements in two forest sites and in a vineyard in NW Italy

Stefano Ferraris, Aurora Olivero, Alessio Gentile, Davide Gisolo, Davide Canone, Giorgio Capello, Marcella Biddoccu, Marco Cauduro

DIST, CNR-STEM and CVA

Contact: Stefano Ferraris (stefano.ferraris@unito.it)

ABSTRACT

The three test sites are equipped with FINAPP CRNS probes and in the Bussoleno deciduous forest site EC-5 probes (manufactured by Meter Group) located at 10, 20, 40 cm depths, with a half-hour frequency also probes at 100, 150 and 200 cm are recording data. In the same site the CRNS system was calibrated using spatially-averaged TDR measurements during five campaigns between May 2021 and July 2022. The optimization procedure was performed on parameter of counting rate of neutrons over dry soil. The TDR probes system consists of a Campbell TDR100 and of 30 cm long stainless-steel probes, with three rods. The probes are all vertically inserted into the soil and their locations are at 1, 5, 10, 20 and 40 m from the site center along three radial axes. The Chevrere site is a coniferous forest with METER soil moisture probes at 10, 20, 40 on a slope with land slide risk, while the Cannona vineyard site is in a more gentle slope with a long time series of local soil moisture measurements. In all the three sites the data are well correlated between CRNS and local measurements, with some noise in the CRNS data, which instead have shown a better continuity of data in time.

Using CRNS to Assess Groundwater Recharge at PoSMO: Evaluating Uncertainty from Soil and Vegetation Heterogeneity

Lena Scheiffele^{1,2}, Matthias Munz², Till Francke², Sascha Oswald²

(1) Helmholtz Centre for Environmental Research – UFZ; (2) University of Potsdam, Germany

Contact: Lena Scheiffele (lena.scheiffele@ufz.de)

ABSTRACT

The Potsdam Soil Moisture Observatory (PoSMO) provides a unique, densely monitored field site for evaluating groundwater recharge (GWR) at the hectare scale. With eight continuously operating cosmic-ray neutron sensors (CRNS) complemented by point-scale soil moisture profiles, PoSMO enables robust calibration of a 1D soil hydrological model (HYDRUS-1D) using six years of high-frequency soil moisture data. The CRNS-derived effective soil hydraulic parameters (SHPs) are used to simulate vertical water fluxes below the root zone, serving as a proxy for GWR. Using inverse modeling with particle swarm optimization, we assess the impact of variability across the CRNS network and point-scale soil moisture measurements, reflecting spatial heterogeneity in soil properties, as well as uncertainty in vegetation parameterization on effective soil hydraulic parameters (SHPs) and simulated groundwater recharge rates. The calibrated models are driven by 50+ years of historical climate data to evaluate long-term recharge dynamics under these uncertainties. Results indicate that both soil moisture variability and vegetation representation significantly influence GWR estimates. Long-term annual GWR rates at PoSMO exhibit a declining trend over the past decades, even exceeding the slight reduction in annual precipitation. This study demonstrates how CRNS data enable scale-effective model calibration and provide a

foundation for quantifying GWR under real-world heterogeneity, a crucial step toward reliable field-scale recharge assessment in agricultural systems.

From Neutrons to Soil Hydrology: Informing Mechanistic Vadose Zone Models with Cosmic-Ray Sensing

Giuseppe Brunetti¹, Jirka Simunek²

(1) Università della Calabria (Italy), (2) University of California Riverside (USA)

Contact: Giuseppe Brunetti (giuseppe.brunetti@unical.it)

ABSTRACT

Cosmic-Ray Neutron Sensing (CRNS) is now well established as a reliable, non-invasive approach for monitoring field-scale soil moisture dynamics, filling the scale gap between point measurements and remote sensing. Its growing adoption has encouraged close collaboration between hydrologists and physicists, leading to coupled numerical frameworks that simulate neutron-soil interactions under transient conditions. When combined with numerical vadose zone models, CRNS observations support robust inverse estimation of soil hydraulic parameters, better quantification of surface water flux partitioning, and a marked reduction in model uncertainty. More recently, this coupling has opened new opportunities to represent dynamic, time-variable soil hydraulic behavior driven by natural processes such as soil consolidation and by management practices such as tillage, enabling a shift away from rigid, static modeling assumptions. This talk reviews recent progress and future directions at the intersection of CRNS, physics-based vadose zone modeling, and statistical inference, showing how neutron data can systematically improve our understanding and prediction of field-scale subsurface hydrology.

Burial dating of hominine fossils at the Cradle of Humankind World Heritage Site (COHWHS) in South Africa

Benedetto Giacobbe¹, Sara Rabaglia¹

(1) Istituto Nazionale di Fisica Nucleare, Sezione di Bologna

Contact: Benedetto Giacobbe (giacobbe@bo.infn.it)

ABSTRACT

The Cradle of Humankind World Heritage Site (COHWHS) in South Africa hosts one of the highest concentrations of hominin fossils globally, including *Australopithecus*, *Paranthropus*, and *Homo naledi*. These fossils are embedded within complex dolomitic cave systems whose formation history and chronology are central to reconstructing early human evolution in the region. Accurately reconstructing the exposure history of these sediments is not only a scientific objective, but also a crucial step in preserving and correctly interpreting the paleoanthropological cultural heritage preserved within the COHWHS. Cosmogenic isotope dating relies on measuring the concentration of long-lived isotopes such as ^{26}Al and ^{10}Be in SiO_2 -rich rocks, as their ratio provides an estimate of the sample's age.

Accurate burial dating requires a precise understanding of the production rates of ^{26}Al and ^{10}Be . These nuclides are produced by cosmic-ray interactions: fast neutrons inducing spallation at the surface, and fast and negative muons contributing at depth. While muon-induced production is relatively well constrained, significant uncertainties remain in the neutron-induced component due to limited experimental nuclear cross-section data. These uncertainties propagate directly into dating errors for fossil-bearing sediments.

To address this gap, we performed the first direct measurement campaign of ^{26}Al and ^{10}Be production in quartz exposed to a high-intensity neutron spectrum at the n_TOF facility at

CERN. The n_TOF source provides a white neutron spectrum closely resembling that of cosmic rays but at intensities several orders of magnitude higher, enabling statistically meaningful activation of quartz samples collected from COHWHS. Following irradiation, the resulting nuclide concentrations will be quantified via Accelerator Mass Spectrometry at CIRCE. A direct measurement of the cosmic neutron flux and spectrum to be performed at COHWHS will complete the project and will allow to measure the burial dating of the fossils and the associated uncertainties.

This contribution will present the project, the theoretical motivations for measuring the production rate and the preliminary results from the measurement campaign carried out at n_TOF.

From Field-Scale Soil Moisture Monitoring to NISAR Validation: Lessons Learned from the Norwegian CRNS Network

Zelalem Tadege Mengistu¹, Heidi A. Grønsten¹, Eivind Halvorsen¹

(1) The Norwegian Water Resources and Energy Directorate

Contact: Zelalem Tadege Mengistu (zme@nve.no)

ABSTRACT

The Cosmic-Ray Neutron Sensor (CRNS) method has become an important tool for monitoring area-averaged soil water content (SWC) at spatial scales that bridge traditional point measurements and satellite observations. Since 2016, CRNS systems have been deployed at four experimental sites in Norway representing contrasting agricultural, coastal, alpine, and snow-dominated environments. These sites provide a unique opportunity to evaluate CRNS performance under highly variable Nordic hydroclimatic conditions.

We present experiences from multi-year operation of the Norwegian CRNS stations and evaluate their performance against in situ soil moisture and snow observations. Results show that CRNS successfully captures temporal variations in SWC associated with rainfall, snow accumulation, and snowmelt processes while providing continuous measurements representative of an area with a footprint of approximately 20–150 m. The observations confirm the value of CRNS for hydrological monitoring applications including flood forecasting, drought assessment, hydrological model evaluation, and landslide hazard studies. Our experience also highlights several important challenges that remain for operational CRNS applications. These include atmospheric corrections, vegetation effects, snow cover, wetland and peatland influences, and the development of robust calibration approaches that remain valid across contrasting environmental conditions. Particular attention is given to calibration

transferability between sites and the potential benefits of multi-year and data-driven calibration approaches.

Looking forward, we discuss the role of CRNS as an independent field-scale reference for validating and improving satellite-derived soil moisture products. Planned field experiments during 2026 will investigate the integration of CRNS observations with Sentinel-1 C-band SAR and the newly available NISAR L-band SAR mission. We propose that CRNS measurements can provide an important link between ground observations and remote sensing products, supporting the development and validation of next-generation soil moisture retrieval algorithms in northern environments.

Beyond calibration, we discuss a planned extension/result of CRNS applications toward root-zone soil moisture estimation. The approach combines CRNS observations with a one-dimensional Richards equation model through data assimilation, allowing field-scale neutron measurements to constrain the simulated soil moisture profile and root-zone water storage. Such a framework could provide an important bridge between CRNS observations, hydrological models, and satellite missions such as Sentinel-1 and NISAR, while supporting improved forecasting of droughts, floods, and landslide hazards.

Keywords: Cosmic-Ray Neutron Sensor (CRNS), soil water content, root-zone soil moisture, Richards equation, data assimilation, calibration, NISAR, Sentinel-1, satellite validation, snow water equivalent, Nordic hydrology, Norway

Field-scale soil moisture and irrigation estimation with Sentinel-1 and Sentinel-2 data

Martina Natali, Sara Modanesi, Domenico De Santis, Gabrielle De Lannoy, Susan Steele-Dunne, Alessio Domeneghetti, Christian Massari

Department of Civil and Environmental Engineering, University of Perugia, Via G. Duranti, 93, Perugia (PG), 06125, Italy; Institute of Geosciences, National Research Council of Italy (CNR-GEO), Via della Madonna Alta, 126, Perugia (PG), 06128, Italy; Department of Earth and Environmental Sciences, KU Leuven, Celestijnenlaan, 200e, Leuven, 3001, Belgium; Institute of Geosciences, National Research Council of Italy (CNR-GEO), Via Cavour, 4-6, Rende (CS), 87036, Italy; Department of Geoscience and Remote Sensing, TU Delft, Stevinweg, 1, Delft, 2628 CN, The Netherlands; Department of Civil, Chemical, Environmental and Materials Engineering, University of Bologna, Viale del Risorgimento, 2, Bologna (BO), 40136, Italy

Contact: Martina Natali (martinanatali@cnr.it)

ABSTRACT

Irrigation is a significant component of the water cycle in agricultural regions such as the Po Valley, but information about how much and where irrigation is applied is scarce and uncertain. To address this, remote sensing-based products have been developed to retrieve irrigation across scales, but they are limited by spatial uncertainties and confounding factors, particularly in highly fragmented agricultural landscapes [1]. We present a novel method to estimate irrigation at the field scale by integrating Sentinel-1 C-band Synthetic Aperture Radar (SAR) backscatter data and Sentinel-2 NDVI data within a modeling framework, which involves the joint calibration of the Water Cloud Model (WCM) and a two-layer soil water balance (SWB) model based on FAO-56 to simultaneously simulate backscatter, irrigation, surface and root-zone soil moisture, and other water balance components. The model is driven by reanalysis meteorological data, and selected parameters in the WCM and SWB are calibrated exclusively using Sentinel-1 backscatter data, thus making the framework

independent of in situ ground measurements. The model is tested on 38 fields within an irrigation district in the Po Valley, Italy, during 2018, for which irrigation data are available as reference, and soil moisture estimates are compared to a COSMOS station in another irrigated field selected for validation. The model shows promising results in its capability of estimating soil moisture and retrieving irrigation quantities from the field scale to district level and can be applied on arbitrary parcels and grids without requiring any ground measurements for calibration.

References

[1] Natali, M., Modanesi, S., De Santis, D., De Lannoy, G., Steele-Dunne, S., Flammini, A., Domeneghetti, A., Massari, C., 2026. Field-scale irrigation estimation using Sentinel-1 and Sentinel-2 data within a soil water balance model coupled to the Water Cloud Model. *Remote Sensing of Environment* 346, 115639. <https://doi.org/10.1016/j.rse.2026.115639>

Soil Water Content Harmonization Across Temporal and Spatial Scales

S.Emamalizadeh^{1*}, T. Howson², R.Mazzoleni^{1**}, P. Vincent², J.G. Evans², G.Baroni¹

*(1) Department of Agricultural and Food Sciences, University of Bologna, Bologna (Italy), (2) UK Centre for Ecology and Hydrology, Wallingford, UK, *now at CNR Milano (Italy), **now at ICT International Pty Ltd, 211 Mann St, Armidale NSW 2350 Australia.*

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

ABSTRACT

Soil water content (SWC) can be estimated using a wide range of methods that provide observations at different temporal and spatial scales. Numerous studies have compared these observations to assess their consistency and evaluate measurement performance. However, differences in spatial representativeness, sensing depth, and temporal resolution are not always explicitly accounted for. This can confound the interpretation of discrepancies between methods and limit the comparability of findings across studies.

We hypothesize that explicitly harmonizing SWC observations before intercomparison is essential for meaningful calibration and validation. Drawing on the analyses presented and discussed in Emamalizadeh et al. (2026), this contribution proposes a structured workflow to support this process. The workflow emphasizes identifying differences in observation characteristics, assessing their implications for comparability, and explicitly addressing them before evaluating agreement between methods. It also highlights the importance of documenting harmonization choices and acknowledging remaining limitations. By making harmonization an explicit component of SWC intercomparison, the proposed framework aims to reduce potential misinterpretation and facilitate more transparent comparisons among analyses conducted under different conditions.

References

Emamalizadeh, Sadra, Tim Howson, Riccardo Mazzoleni, Philip Vincent, Jonathan G. Evans, and Gabriele Baroni. 'Toward a Structured Workflow to Harmonize Soil Water Content Products: A Comparative Study across Different Methods'. *Vadose Zone Journal* 25, no. 4 (2026): e70127. <https://doi.org/10.1002/vzj2.70127>.

Understanding CRNS Responses to Irrigation Through Neutron Transport Simulations: Towards Decision Support Applications

Cosimo Brogi, Felix Nieberding, Lena Scheiffle, Andre Daccache, Martin Schrön, Haojin Zhao, Heye Reemt Bogen

Agrosphere Institute (IBG-3), Forschungszentrum Jülich GmbH, 52425 Jülich, Germany; Institute of Environmental Science and Geography, University of Potsdam, Potsdam, Germany; Helmholtz Centre for Environmental Research GmbH—UFZ, Leipzig, Germany; Department of Biological and Agricultural Engineering, University of California, Davis, CA 95616, USA

Contact: Cosimo Brogi (c.brogi@fz-juelich.de)

ABSTRACT

Cosmic-ray neutron sensors (CRNS) can bridge the gap between point-scale soil moisture (SM) measurements and remote sensing products. This makes CRNS a promising tool for field-scale irrigation management, where precise and timely water input is becoming essential for food production. Observational studies have reported inconsistent CRNS responses across different irrigation methods, which are mainly due to the dynamic footprint of CRNS and the challenges of characterising heterogeneous environments. This has limited the broader adoption of CRNS and its integration into irrigation-specific decision support systems (DSS). To better understand CRNS responses under different irrigation settings, CRNS measurements and corresponding neutron transport simulations using URANOS were performed across three irrigation types in Germany and California (USA): hose reel raingun (potato, two Styx-Neutronica S1 and one Styx-Neutronica SP), central pivot (winter wheat, one Hydroinnova CRS1000), and flood irrigation (alfalfa, one Finapp3). CRNS provided consistent estimates of field-scale SM under flood and central pivot irrigation, and simulated neutron intensities matched measurements well. In hose reel raingun irrigation, responses

were weaker, particularly when irrigation occurred at greater distances from the sensor. Here, discrepancies between measured and simulated neutron intensities were attributed to the concurrent occurrence of precipitation and the relatively limited soil volume wetted by the system. Despite some limitations, the CRNS proved more effective in estimating irrigation-relevant SM than co-located profile and point-scale sensors. When testing the recent Universal Transfer Solution (UTS) against the established N0 conversion method, the N0 provided responses to irrigation that appeared stronger but reached negative soil moisture values in dry periods, while the UTS performed considerably better when SM was below 0.10 cm³ cm⁻³. This supports the use of UTS in irrigation applications. Regarding neutron transport simulations, a simplified analytical solution produced results comparable to URANOS (generally within 1-2 % difference), with potential for more rapid and cost-effective investigations. However, future applications of the analytical solution would require further development to account for vertically heterogeneous soil profiles.

In its current state, CRNS cannot be considered a precision irrigation tool. This is because a single CRNS deployed without ancillary soil information or complementary sensors cannot yet resolve spatially distributed small-scale variations in SM or irrigation patterns. It is, however, well suited for digital irrigation, where field-scale root zone SM monitoring is the key variable. Combining CRNS measurements with URANOS or other available tools will increase transferability across sites and irrigation techniques, supporting CRNS adoption in irrigation management and its eventual integration into DSS.

Finally, to demonstrate integration into DSS, a case study is presented in which CRNS-derived SM is assimilated into the enCore Community Land Model (eCLM) through an automated pipeline at the Selhausen ICOS station (Germany). The resulting 2–10-day SM forecast, meaningfully improved by the CRNS support, provides threshold-based indicators to support irrigation decisions.

Soil moisture across contrasting fields: the challenge of sensing Mediterranean agricultural mosaics with CRNS

Leticia Gaspar¹, Trenton E. Franz², María Concepción Ramos³, Borja Latorre¹, Ana Navas¹

(1) Spanish National Research Council, CSIC-EEAD, 50059 Zaragoza, Spain; (2) School of Natural Resources, University of Nebraska-Lincoln, Lincoln, NE 68583, USA; (3) Department of Chemistry, Physics and Environmental and Soil Sciences, University of Lleida-Agrotecnio CERCA Center, Av. Rovira Roure 191, 25198 Lleida, Spain;

Contact: Leticia Gaspar (lgaspar@eead.csic.es)

ABSTRACT

Cosmic ray neutron sensor (CRNS) provides non-invasive soil water content estimates over spatial scales particularly attractive for agricultural applications. However, the sensing footprint of a stationary CRNS may extend beyond individual field boundaries, integrating areas with contrasting crop types, vegetation cover and water management. This is particularly relevant in Mediterranean agricultural landscapes, where relatively small and heterogeneous fields frequently form complex mosaics of annual and perennial crops under different irrigation practices. A stationary CRNS installed in a wheat field in a semiarid Mediterranean agroecosystem in NE Spain was used to investigate the influence of the surrounding agricultural mosaic on the measured neutron signal. The monitored field is surrounded by contrasting agricultural fields, including orchards, so that the CRNS footprint extends across areas differing in crop type, vegetation structure and irrigation conditions. Selected periods representing contrasting hydrological situations were analysed, including asynchronous irrigation of the monitored and neighbouring fields and periods with more spatially homogeneous soil moisture conditions. Spatial weighting of the CRNS footprint was used to assess the potential contribution of areas located within and outside the monitored wheat field.

The analysis explores how spatial contrasts in soil moisture associated with irrigation and changing field conditions can affect the integrated CRNS response and its representativeness at the individual field scale. Particular attention is given to whether changes in neighbouring fields can be identified in the integrated neutron response and how their contribution varies according to their location and hydrological condition. Proximal gamma-ray spectroscopy (PGRS), characterized by a substantially smaller sensing footprint, is considered as a complementary observation scale for characterising soil moisture variability within the broader CRNS footprint.

Modern applications of Cosmic Rays Neutron Sensors to Agriculture: the experience of Finapp

Luca Stevanato¹, Stefano Gianessi¹, Gianmarco Cracco¹, Barbara Biasuzzi¹, Marcello Lunardon^{1,2} and Enrico Gazzola¹

(1) Finapp, via del Commercio 27, Montegrotto Terme, Italy; (2) Dept. of Physics and Astronomy “Galileo Galilei”, University of Padova, Padova, Italy

ABSTRACT

A reliable and representative assessment of Soil Moisture at scales relevant to farming is a critical factor to ensure sustainable growth of agriculture, but it's challenging to achieve. Cosmic Rays Neutron Sensing (CRNS) has long been considered a promising approach to address this challenge, thanks to its areal-averaged measurement with sub-daily resolution. Its widespread application has been hindered by limited, expensive technological options, but in recent years the development of innovative neutron detectors has reshaped the market and paved the way for scaling up the use of CRNS worldwide.

We will present the features of the Finapp CRNS detector, based on a lithium-doped scintillator material which makes it a handy and safe device, and the state-of-the-art of its applications to agriculture. In order to address the needs and requests of the agricultural market, we developed solutions to organically integrate the CRNS into a self-standing Decisional Support System and grant real-time data transfer even from remote areas in absence of GSM coverage.

The pillars of our DSS are an integrated management of external sensors of the like of rain gauges and flow meters, a predictive tool for the soil moisture evolution in response to

meteorological events, a dedicated user-friendly dashboard to provide clear information to the final user.

A worldwide distribution agreement with the Austrian group Bauer made the integration of the Finapp CRNS system in pivots a leading application, with the delivery scaled up to hundreds of probes per year. The cases of other irrigation techniques have been explored, including the notoriously difficult case of drip irrigation, which suffers a mismatch between the very localized irrigation and the wide-area measurement of CRNS.

The scalability of the Finapp CRNS technology and the development of dedicated operational tools is nowadays boosting the worldwide application of CRNS in Agriculture.

Integrating cosmic-ray neutron sensing with plant and atmospheric monitoring in micro-irrigated vineyards

Riccardo Mazzoleni^{1,3}; Beng Umali^{2,3}; Gabriele Baroni¹

(1) Department of Agricultural and Food Sciences (DISTAL), University of Bologna, Viale Giuseppe Fanin 42-50, 40127 Bologna, Italy; (2) University of South Australia - STEM, Adelaide, SA 5000 Australia; (3) ICT International Pty Ltd, 211 Mann St, Armidale NSW 2350 Australia.

Contact: Riccardo Mazzoleni (riccardo@ictinternational.com.au)

ABSTRACT

Water management in irrigated viticulture requires integrating soil water availability with plant hydraulic responses and atmospheric demand to distinguish soil-water limitation from atmospheric control of vine water status. Cosmic-ray neutron sensing (CRNS) provides a non-invasive, field-representative estimate of soil water content (SWC), whose relevance to irrigation management can be assessed through its relationship with vine physiology. These relationships were investigated in a commercial Syrah vineyard (*Vitis vinifera* L. cv Syrah) in Renmark, South Australia, during the summer season from November 2024 to February 2025. A CRNS sensor was installed at the centre of the monitored area to measure field-scale soil water content (SWC) across the vineyard. CRNS observations were integrated with continuous measurements of trunk sap flow (SF), stem water potential (ψ_{stem}), and atmospheric conditions, including vapour pressure deficit (VPD), in a vineyard managed under daily micro-irrigation. CRNS-derived SWC increased significantly following irrigation events ($p < 0.01$), indicating its ability to capture field-scale changes in soil water availability. Despite frequent summer VPD peaks exceeding 5 kPa, ψ_{stem} and SF maintained regular diurnal cycles and values below the stress thresholds, indicating that daily irrigation largely sustained vine water availability. CRNS-derived SWC captured the short-term increases

associated with irrigation, providing a field-scale representation of water availability across the vineyard. Multivariate analysis showed that daytime VPD, SF and ψ_{stem} formed a common hydraulic-response axis, explaining most of the observed variability, whereas CRNS-derived SWC loaded primarily on a separate axis. This separation indicates that, under non-limiting SWC, short-term vine hydraulic responses were governed mainly by atmospheric demand, while CRNS provided the broader soil-water context needed to interpret plant-level measurements. Integrating CRNS with plant and atmospheric sensors can help distinguish soil-water limitation from atmospheric control and offers a promising framework for improving irrigation assessment and adaptive water management in semi-arid vineyards.

Network-wide parameterization for estimating snow water equivalent through cosmic ray neutron sensors in the Italian Alps

Mario Gallarate^{1,2,3}, Nicola Colombo⁴, Enrico Gazzola⁵, Mauro Valt⁶, Christian Ronchi⁷, Luca Lanteri⁷, Roberto Dinale⁸, Rudi Nadalet⁸, Stefano Ferraris⁹, Alessio Gentile⁹, Davide Gisolo⁹, Michele Freppaz^{3,4}, and Fiorella Acquaotta^{1,3}

(1) Earth Sciences Department - DST, University of Turin, 10125 Torino (TO), Italy; (2) Department of Environmental Sciences, Informatics and Statistics - DAIS, Ca' Foscari University of Venice, 30172 Mestre (VE), Italy; (3) Interdepartmental Research Centre on Natural Risks in Mountain and Hilly Environments - NatRisk, 10095 Grugliasco (TO), Italy; (4) Department of Agricultural, Forest and Food Sciences - DISAFA, University of Turin, 10095 Grugliasco (TO), Italy; (5) Finapp S.p.A., 35036 Montegrotto Terme (PD), Italy; (6) Agency for Environmental Protection of Veneto - ARPAV, 32100 Belluno (BL), Italy; (7) Department of Natural and Environmental Risks, Regional Agency for Environmental Protection of Piemonte - ARPA Piemonte, 10135 Torino (TO), Italy; (8) Office for Hydrology and Dams, Autonomous Province of Bolzano, 39100 Bolzano (BZ), Italy; (9) Interuniversity Department of Regional Studies and Planning - DIST, University of Turin and Polytechnic University of Turin, 10125 Torino (TO), Italy

ABSTRACT

Seasonal snow cover plays a crucial role for mountain ecosystems and in sustaining human activities, but it's increasingly threatened by the effects of climate change, which exacerbates the need for accurate and continuous monitoring. From a hydrological point of view, snow water equivalent (SWE) is among the most relevant variables associated with snowpack. It is best assessed by in situ measurements campaigns where snow depth and bulk density values are taken through coring or snow pits, but these methods suffer of limited temporal and spatial coverage. In the last decades, sensors based on cosmic ray neutron sensing (CRNS) have been used for continuous measurement of SWE in already monitored sites, filling the gaps left by manual measurements. However, they usually relied on a site-specific parametrization of the conversion formula derived from reference measurements.

We present the derivation and application of a default parametrization of the formula to the whole network of CRNS probes for SWE in the Italian Alps, including 26 active CRNS installations at the time of the analysis and spanning an elevation range from 1422 to 2901 m a.s.l., for two consecutive snow seasons (2023-2024 and 2024-2025). The parametrization was obtained by interpolation over 35 manual SWE measurements performed at 6 sites during the first half of the first season and validated over 76 further measurements across 13 sites, showing that a reasonable accuracy can be achieved by using a shared set of parameters only. Moreover, data from unmonitored sites of the network show high correlations with monitored sites at similar elevations. These results suggest that deploying CRNS probes can be used to overcome common limitations of snow monitoring.

This abstract is part of the NODES project which has received funding from the MUR–M4C2 1.5 of PNRR funded by the European Union - NextGenerationEU (Grant agreement no. ECS00000036).

Cosmic-Ray Neutron Sensing in Mountain Regions: Where high potential for hydrological monitoring meets particular uncertainty

Paul Schattan¹, Nora Krebs² and Benjamin Fersch³

(1) Boku University Vienna (Austria), (2) University of Innsbruck (Austria); (3) Karlsruhe Institute of Technology (Germany)

Contact: Paul Schattan (paul.schattan@boku.ac.at)

ABSTRACT

Despite its crucial importance for anticipating hydrological conditions, mountain regions typically remain data sparse. This is particularly true for essential climate variables related to water storage, runoff generation and evapotranspiration. Cosmic-Ray Neutron Sensing (CRNS) has the potential to close this observational gap. This contribution gives insights into more than a decade of CRNS research in the European Alps proving that CRNS is capable of monitoring soil moisture and snow water equivalent where other technologies fail due to uneven and stony ground, high small-scale heterogeneity of soil and snow properties and harsh environmental conditions. As the neutron flux rises with altitude and soils tend to be less developed featuring high skeleton fractions and low overall water holding capacity, uncertainty related to count statistics decreases. However, specific obstacles and uncertainties appear which are less pronounced in the lowlands. In particular, calibration campaigns are more demanding in terms of both required methods and campaign planning, while topographic shielding hampers the use of universal calibration functions. Furthermore, measuring at the wet end of the spectrum when focusing on snow exposes uncertainties in calculating hydrological residuals from raw neutron counts. Using CRNS in mountain regions remains

thus an ideal test bed for both demonstrating the enormous potential of the technique and for understanding uncertainties beyond pure neutron count statistics.

Evaluating an Empirical CRNS Calibration for Snow Water Equivalent Across Pre-Alpine and High-Alpine Sites

Benjamin Fersch¹, Nora Krebs^{2,3}, Paul Schattan^{2,3}

(1) Karlsruhe Institute of Technology, Campus Alpin, Garmisch-Partenkirchen, Germany; (2) Institute of Geography, University of Innsbruck, Innsbruck, Austria; (3) Institute of Hydrology and Water Management (HyWa), University of Natural Resources and Life Sciences, Vienna, Austria

Contact: Benjamin Fersch (benjamin.fersch@kit.edu)

ABSTRACT

Cosmic-ray neutron sensing (CRNS) offers a promising approach for spatially integrated snow water equivalent (SWE) monitoring, but transferring count–SWE relationships across contrasting alpine environments remains challenging because of site-specific environmental and geographical conditions. Above-snow CRNS stations have therefore traditionally required extensive local calibration, limiting the rapid expansion of monitoring networks.

Using extensive in-situ observations from montane sites within the TERENO Pre-Alpine Observatory, we derived empirical coefficients for converting CRNS counts to SWE. The resulting count–SWE relationship agrees well with measurements at most locations, suggesting that the need for site-specific calibration can be substantially reduced. Based on observations from the Moosbeere CRNS network, we further assess the transferability of this empirical relationship to alpine–nival environments characterized by shallow soils, steep terrain, and high SWE. We examine deviations from the empirical calibration in relation to site-specific environmental and geographical conditions. Our results demonstrate both the potential and the limitations of a generalized empirical approach for CRNS-based SWE estimation across pre-alpine and high-alpine settings.

Cosmic-ray neutron production and propagation inside snow packs characterized by multi-particle Monte Carlo simulations

Jannis Weimar¹, Paul Schattan², Rebecca Gugerli³, Benjamin Fersch⁴, Darin Desilets⁵,
Martin Schrön⁶, Markus Köhli¹, Ulrich Schmidt¹

(1) Physikalisches Institute, Heidelberg University, Germany; (2) alpS Research, Institute of Geography, University of Innsbruck, Austria; (3) Environmental Remote Sensing Laboratory, École Polytechnique Fédérale de Lausanne (EPFL), Switzerland AND Radar, Satellite and Nowcasting Division, MeteoSwiss, Locarno-Monti, Switzerland; (4) Campus Alpin, Karlsruhe Institute of Technology, Garmisch-Partenkirchen, Germany; (5) Hydroinnova LLC, Albuquerque, NM, USA; 6) Helmholtz Centre for Environmental Research GmbH – UFZ, Leipzig, Germany

Contact: Jannis Weimar (weimar@physi-uni-heidelberg.de)

ABSTRACT

Cosmic-ray neutron production and propagation characteristics inside snow packs by multi-particle Monte Carlo simulations. Cosmic-ray neutron sensors buried below a snow pack provide a passive and autonomous monitoring technique of snow water equivalent (SWE). The effective neutron flux is attenuated inside the snow volume leading to an inverse relationship between neutron intensity and the water equivalent of the snow column above the sensor. Neutrons are moderated and absorbed within the snow, while at the same time highly energetic cosmic rays produce further neutrons via spallation and evaporation processes. A comprehensive assessment of the neutron flux therefore requires multi-particle simulations which involve all relevant particle species and transient particles from incoming cosmic-ray showers which play a crucial role in neutron production.

In our study, we used the Monte Carlo toolkit MCNP6 and validated its high-energy evaporation and spallation models against a measured data set of a neutron intensity profile in water. Based on that we fitted analytical functions to a large variety of simulation setups that

describe the neutron intensity as a function of SWE and the moisture content of the soil below the sensor. Moreover, single-particle tracking revealed that the radial footprint is within a few meters for detectors placed below thick snow layers. In the case of shallow snow, however, the diffusive, long-range neutron flux in the atmosphere could reach the buried sensor, thereby increasing the influence of distant areas.

In general, the study aims at a holistic understanding of neutron propagation in snow and in the adjacent soil and air volumes in order to improve SWE monitoring by buried cosmic-ray neutron sensors.

From metrology labs to the field: Validating Cosmic-Ray Neutron Sensors (CRNS) within the SoMMet framework

M. Ángeles Millán-Callado¹, Roberto Méndez Villafañe², Buthaina A. S. Adam¹, Pavol Blahušiak³, Augusto Di Chicco¹, Mirco Dietz¹, Markus Köhli^{4,5}, Benjamin Lutz¹, Marcel Reginatto¹, Jaroslav Šolc⁶, Zdenek Vykydal⁶, Jannis Weimar^{4,5}, and Miroslav Zboril¹

(1) Physikalisch-Technische Bundesanstalt (PTB), Bundesallee 100, 38116 Braunschweig, Germany; (2) Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (CIEMAT), Avda. Complutense 40, 28040 Madrid, Spain; (3) Slovak Institute of Metrology (SMU), Karloveská 63, 842 55 Bratislava, Slovakia; (4) Physikalisches Institut, Heidelberg University, Im Neuenheimer Feld 226, 69120 Heidelberg, Germany; (5) StyX Neutronica GmbH, Cecil-Taylor-Ring 12-18, 68309 Mannheim, Germany; (6) Czech Metrology Institute (CMI), Okružní 31, 63800 Brno, Czech Republic

Contact: María de los Ángeles Millán Callado (angeles.millan-callado@ptb.de)

ABSTRACT

Cosmic-ray neutron sensing (CRNS) monitoring provides critical soil moisture data at intermediate scales, serving as a link between local point-scale sensors and satellite large-scale remote sensing products. The growing deployment of commercial CRNS instruments in regional and global monitoring networks emphasizes the need for traceable calibration standards to ensure dataset comparability and reliability. Accurate site-specific environmental corrections, including those for vegetation, atmospheric humidity, and spatial heterogeneity, depend on a precise characterization of each probe's intrinsic neutron response function.

As part of the EURAMET SoMMet* project, a laboratory-based characterization was carried out for four state-of-the-art and widely used commercial CRNS systems: Hydroinnova CRS1000 (3He), Hydroinnova CRS2000/B (10BF3), StyX Neutronica System S1 (10B-lined), and Finapp Model 3 (scintillator-based). These instruments were systematically investigated using SI-traceable neutron reference fields at PTB (Germany), CIEMAT (Spain),

CMI (Czech Republic), and SMU (Slovakia). Radionuclide sources (^{252}Cf , moderated ^{252}Cf , and $^{241}\text{Am-Be}$) were used to derive global scaling factors, anchoring MCNP transport models to real device performance and accounting for manufacturing tolerances and incomplete descriptions of the geometry. The resulting tuned models were independently validated against traceable monoenergetic fields ranging from 24 keV to 5 MeV at the PTB Ion Accelerator Facility (PIAF), yielding a 6-12% agreement over all reference geometries.

To evaluate the impact on networks deployed in the field, the validated digital twins of the CRNS probes were incorporated into virtual environmental reference fields developed using URANOS, covering a range of soil volumetric moisture content from 1% to 50%. The simulated detector responses showed close agreement with the Universal Transport Solution (UTS) and were parameterized using a two-parameter inverse power-law model.

These results provide the first laboratory-based, SI-traceable benchmark data for commercial CRNS probes, establishing a metrological foundation needed for harmonizing field-scale soil moisture observations.

The project 21GRD08 SoMMet has received funding from the European Partnership on Metrology, co-financed from the European Union's Horizon Europe Research and Innovation Programme and by the Participating States.

Current developments in environmental Bonner sphere measurement

Jonas Marach¹, Marcel Reginatto¹, Miroslav Zboril¹, Mario Albert², Jannis Weimar³,
Markus Köhli⁴, Peter Grosse⁵

(1) Physikalisch Technische Bundesanstalt; (2) German Meteorological Service (Deutscher Wetterdienst, DWD), Department Observing Networks and Data, Hamburg, Germany; (3) StyX Neutronica GmbH; (4) Heidelberg University, Physikalisches Institut, Germany; (5) University of Potsdam, Institut für Umweltwissenschaften und Geographie, Wasser- und Stofftransport in Landschaften, Potsdam OT Golm, Germany;

Contact: Jonas Marach (jonas.marach@ptb.de)

ABSTRACT

During the European research project SoMMet (Soil Moisture Metrology) the Physikalisch Technische Bundesanstalt (PTB) developed the NEMUS-UMW, an extended range Bonner sphere spectrometer (ERBSS) designed for continuous, automated neutron spectrometry under outdoor conditions. For the last year the ERBSS collected continuous at two sites in Germany.

The BSS NEMUS-UMW uses 11 proportional counters to detect the neutron component of secondary cosmic radiation. By varying the sizes (3" to 10" in diameter) of the polyethylene moderating spheres surrounding the counters, and by using copper or lead shells in the larger spheres, the system covers an energy range from 10^{-9} MeV to 10^3 MeV. Using the known response functions of the individual spheres, the neutron energy spectrum can be unfolded. The system was calibrated in the PTB neutron reference fields and is therefore capable of determining outdoor neutron spectra and radiation levels in absolute units of neutron fluence rate.

During SoMMet, the BSS NEMUS-UMW was deployed at the test field site ATB Marquardt (Potsdam, Germany). In collaboration with the University of Potsdam and Heidelberg

University, surrounding field and soil parameters were monitored, and the measured neutron-spectrum time series was used to benchmark URANOS-based neutron simulations.

In April 2026, NEMUS-UMW was installed in Braunschweig (Lower-Saxony, Germany) in collaboration with the German weather service (DWD) to accompany their CRNS measurements. This presentation introduces the NEMUS-UMW setup, the data analysis and simulation done for the Marquardt site, and the comparison with CNRS observations in Braunschweig.

A tool for community-driven standardization of CRNS sensor sensitivities

Till Francke¹

(1) University of Potsdam (Germany)

Contact: Till Francke (francke@uni-potsdam.de)

ABSTRACT

The CRNS offers a non-invasive solution to measuring soil moisture, but its widespread adoption is hindered by the need for site-specific calibration due to variable hydrogen pools, neutron flux levels, and sensor sensitivity. Especially the latter is important for transferrable applicability. Previous efforts, like pairing sensors for calibration, address sensitivity estimation but can disrupt continuous measurement and fail to account comprehensively for error propagation across sensor networks. We introduce a framework for collecting and sharing sensor pairing data, estimating relative sensitivities and associated uncertainties across varied sensor networks, identifying issues in pairing networks, and providing publicly accessible scripts for these analyses. This approach aims to improve the interpretation of heterogeneous CRNS datasets and facilitate broader sensor calibration across different groups.

Refined and Revised: CRNS Footprint and Intensity Relation

Markus Köhli¹

(1) Helmholtz Centre For Environmental Physics - UFZ, Leipzig

Contact: Markus Köhli (markus.koehli@ufz.de)

ABSTRACT

How detailed can we know the environmental water content and to what precision is it possible to rely on Cosmic-ray Neutron Sensing (CRNS)? Accurate soil moisture measurements are key in hydrological observations and subsequent applications as it can greatly improve our understanding of soil processes. Although several measurement methods exist on multiple scales, the harmonization turns out to be challenging. Despite the growing significance of CRNS in hydrological sciences this lack of precision often marginalized the topologically complex assessment of soil moisture. In addition, there is an urgent need for real-time, high-quality, temporally and spatially consistent data on soil moisture. The strength of CRNS for soil moisture monitoring is its representative footprint of several hectares and half a meter in depth, which aligns well with irrigation planning and monitoring applications. In the recent years the understanding of neutron transport by Monte Carlo simulations led to major advancements in precision. Investigating the above-ground neutron flux by URANOS simulation campaigns revealed an even more detailed understanding of different contributions to the signal under heterogeneous conditions around the sensor. This refines - or hence revises - the previous methodology based on homogeneous topologies. This contribution provides an overview of the methodological and instrumental advances in CRNS achieved within the second 3-years period of the research group CosmicSense and the SoMMet project with the updated and potentially final description of footprint, detector response and intensity relation.

Incoming Flux Correction for Cosmic Ray Neutron Sensing

Lasse Hertle, Fraser Baird, Julia Boike, Peter Dietrich, Enrico Gazzola, Bernd Heber, Nora Krebs, Nicholas Larsen, David McJannet, Ombretta Pinazza, Daniel Rasche, Francesco Riggi, Paul Schattan, Ulrich Schmidt, Michael Walter, Pauli Väisänen, Gary Womack, Steffen Zacharias, Martin Schrön

Contact: Martin Schrön (martin.schroen@ufz.de)

ABSTRACT

The incoming flux of cosmic rays serves as the source of neutrons measured in Cosmic Ray Neutron Sensing (CRNS). Since the flux is determined by solar and geomagnetic conditions, CRNS products are highly sensitive to the long-term solar cycle, to short-term solar events, and to the geomagnetic location on Earth. We will discuss three approaches to correct for this changing source signal: (i) external measurements by neutron monitors, (ii) measurements using CRNS on water bodies, or (iii) muon detectors co-located with CRNS.

The neutron monitor network is sparse in comparison to the CRNS network. Consequently, the reference signal for CRNS correction must be localised to the CRNS site, requiring scaling based on differences in cut-off rigidity and atmospheric depth. We tested multiple scaling approaches and developed a sophisticated method considering the impact of differing geomagnetic and local conditions. In contrast, whilst co-located muon detectors do not require spatial rescaling, they observe a distinct component of the atmospheric cascade. We examined the difference between the muon and neutron cascades using observations of a solar event in the arctic environment of Svalbard. These suggest that a muon-based correction requires scaling to account for differences in cascade components, which in turn demands an understanding of each detector's sensitivity to the primary cosmic ray spectrum. During the maximum of Solar Cycle 25, a latitude survey was undertaken aboard the German Research

Vessel Polarstern, utilising a mini neutron monitor, two CRNS detectors of differing design, and a muon telescope, from which we characterised the sensitivities of the different detectors to the primary cosmic ray spectrum, examining the difference between muons and neutrons, and between neutrons over water of differing energies.

Improving the Incoming Neutron Flux Correction: a COSMOS-UK Case Study

Jonathan Evans¹, Magdalena Szczykulska¹, Tim Howson¹ and the COSMOS-UK Team¹

(1) UK Centre for Ecology & Hydrology

Contact: Jonathan Evans (jge@ceh.ac.uk)

ABSTRACT

Cosmic-ray neutron sensors (CRNSs) have been deployed in the UK soil moisture observation network (COSMOS-UK) for over eleven years. Amongst other neutron count corrections, the incoming flux of neutrons must be corrected, as it varies over the eleven-year solar cycle. Here we analyse the CRNS response to incoming neutron flux changes, as recorded by Neutron Monitors (NMs). We calculate the correction parameter referred to as ‘tau’ using published models and compare these with a correction parameter (gamma) estimated from the local CRNS response. Since the local CRNS response is also influenced by soil moisture, steps are taken to reduce the impact of soil moisture variations, and the uncertainty in gamma is investigated. Results show that in general gamma estimates are significantly higher than the calculated tau values, and their application can better reduce unrealistic and NM-correlated residual trends in soil moisture time series, compared with applying tau values. The dependency of gamma on cut-off rigidity (R_c) is explored, with the potential to model gamma over the UK range of R_c and to provide evidence to improve tau models.

Spatial Variability of the Barometric Coefficient in Cosmic-Ray Neutron Sensing: Implications for Improved Soil Moisture Estimation

Patrick Davies¹, Roland Baatz², Paul Schattan³, Emmanuel Quansah¹, Leonard K.

Amekudzi¹ and Heye R. Bogen⁴

(1) Department of Meteorology and Climate Science, KNUST, Kumasi, Ghana.; 2) CDM Smith SE, Berlin, Germany; (3) Institute of Hydrology and Water Management (HyWa), BOKU University, Vienna, Austria; (4) Agrosphere Institute (IBG-3), Forschungszentrum Jülich GmbH, Jülich, Germany;

Contact: Heye Bogen (h.bogen@fz-juelich.de)

ABSTRACT

Cosmic-ray neutron sensing (CRNS) has become an established technique for monitoring field-scale soil moisture, but accurate correction for atmospheric pressure remains essential for reliable observations. This correction depends on the barometric coefficient (β), which is commonly assumed to be constant or estimated using analytical approaches that neglect local environmental conditions.

In this study, we present the most comprehensive assessment of β variability across terrestrial CRNS and neutron monitor (NM) networks to date: Barometric coefficients were estimated for 71 CRNS stations across Europe and the United States and 47 neutron monitor stations worldwide using two empirical methods and an analytical approach. The resulting estimates were compared with respect to their spatial variability, agreement among methods, and relationships with environmental controls. Principal component analysis was used to identify the dominant factors governing β variability.

The empirical methods revealed substantially larger spatial variability than the analytical approach, while remaining physically consistent with published values. All methods produced

similar spatial ranking of sites, but empirical estimates captured local and sensor-specific conditions that are neglected by analytical formulations. Altitude and atmospheric humidity explained most of the observed variability, whereas geomagnetic cut-off rigidity represented a secondary but significant control. A sensitivity analysis demonstrated that realistic variations in β can introduce systematic soil moisture biases of up to $\pm 0.02 \text{ m}^3 \text{ m}^{-3}$, comparable to the target accuracy of CRNS observations. We propose that site-specific β estimation should be considered to improve pressure correction and enhance the accuracy of operational CRNS networks.

Balancing Signal Purity and Count Support in Mobile CRNS Applications

Daniel Altdorff¹

(1) UFZ Leipzig - Helmholtz Centre for Environmental Research GmbH

Contact: Daniel Altdorff (daniel.altдорff@ufz.de)

ABSTRACT

Railborne cosmic-ray neutron sensing (Rail-CRNS) offers a promising route towards repeated soil water content (SWC) observations along large transport corridors, but its processing requirements differ from those of stationary or conventional roving CRNS. During train operation, neutron counts are integrated over segments rather than representing discrete point measurements. Along these segments, rapidly changing infrastructure and surface conditions, such as bridges, tunnels, roads, buildings, water bodies, vegetation, and land-use transitions, may affect the neutron signal and bias its SWC conversion (in both directions). At the same time, few observations may be stretched over long track sections, creating an additional challenge for statistically robust SWC products.

Here, we outline a context-aware processing strategy designed to address this balance between signal quality, spatial representativeness, and limited count support. Clear hard exclusions, such as bridges and tunnels, are removed prior to aggregation. Remaining measurements are evaluated using a contextual screening score derived from spatial features within a predefined CRNS footprint around the track. The score quantifies the weighted fraction of the footprint affected by potentially disturbing features, with stronger weighting for features closer to the sensor, and is used as an indicator of signal purity: low score values indicate high purity, whereas high values indicate stronger contextual influence and lower purity.

A central element of the framework is the aggregation of screened data into stable, non-overlapping geozones. These geozones represent track sections with broadly comparable land-use and infrastructure context and prevent temporal moving averages from smoothing signals across spatial boundaries. To ensure sufficient counting statistics, a geozone-based SWC estimate requires at least six valid 10-s observations, corresponding to a minimum one-minute count integral. If this support cannot be reached after filtering, the respective geozone remains without an SWC value for that day.

This strategy deliberately reduces data volume through hard exclusions, score-based filtering, and the geozone support criterion. In an example long-distance processing day (~350km), only about 58% of data remained in the final geozone product. While this reduces spatial coverage, it provides fewer but more robust SWC products with explicit spatial and statistical support. Initial processing indicates that simple moving averages might appear visually plausible but may obscure its pure data quality.

Currently, the Rail-CRNS geozone products are being compared with mHM-based soil moisture (e.g. the UFZ Drought Monitor), and satellite products, while accounting for differences in spatial support, sensing volume, and aggregation scale. These comparisons are intended to assess spatio-temporal consistency. In the longer term however, Rail-CRNS observations may serve as explicit measurement support for established soil moisture products.

Neptoon: an extensible processing framework for cosmic-ray neutron sensors, from operational monitoring to methodological research

Louis Trinkle, Markus Köhli, Daniel Power, Till Francke, Rafael Rosolem, Fredo Erxleben,
Steffen Zacharias, Martin Schrön

Contact: Louis Trinkle (louis-ferdinand.trinkle@ufz.de)

ABSTRACT

Cosmic Ray Neutron Sensing (CRNS) has become an important technique for monitoring root-zone soil moisture at the hectare scale, closing the gap between point measurements and coarse remote-sensing products. However, converting raw neutron counts into reliable soil moisture estimates still requires advanced knowledge of cosmic-ray physics. As CRNS is adopted across observatories, agricultural services, and research networks, the absence of shared and transparent processing tools increasingly limits comparability between sites. We present neptoon, an open-source Python framework designed to support both operational processing and methodological development within a unified, reproducible workflow. Building on experience from earlier CRNS tools, neptoon provides a modular architecture that covers the full processing chain - from atmospheric pressure, humidity, and incoming-intensity corrections, through N0 calibration and quality assessment, to the estimation of soil moisture from corrected neutron counts. Established correction and quality-assessment methods are implemented through a composable interface, and new approaches can be integrated and evaluated within the same framework without requiring separate codebases. This structure allows specific user requirements to be tested, compared, and shared more efficiently across sites. Neptoon is designed to be usable across the community: a graphical interface supports easy accessibility, a configuration-driven workflow enables reproducible

operational processing, and a fully scriptable Python API serves method developers. By combining standardisation with extensibility, neptoon provides a shared foundation for harmonising CRNS data processing while supporting the uptake of new scientific developments. Further development focuses on extending support for mobile roving applications, multi-site processing and integration with meteorological data services. The framework is openly developed at codebase.helmholtz.cloud/cosmos/neptoon, with documentation and examples available at neptoon.org.

Evaluating Gamma-Ray Spectrometry to Extend Soil Moisture Monitoring into Ireland's Wetter Landscapes

Eve Daly¹, Caoimhe Mannion¹, Caren Jarman², Klara Finkele², Katya Dimitrova Petrova²,
Haleh Karbala Ali², Saji Vergese²

(1) Earth and Ocean Sciences, Ryan Institute, University of Galway; (2) MetEireann

Contact: Eve Daly (eve.daly@universityofgalway.ie)

ABSTRACT

Real-time soil moisture observations are essential for climate-change adaptation, reducing nutrient losses and greenhouse gas emissions from agriculture and forestry, and improving flood and drought forecasting. Soil moisture is monitored across spatial scales, from point measurements to catchment- and national-scale networks. The non-invasive cosmic-ray neutron (CRN) method can provide spatially integrated soil moisture estimates over footprints of several hundred metres, while stationary gamma-ray spectrometry (GRS) offers continuous, non-invasive monitoring at an intermediate scale of tens of metres.

In Ireland, soil moisture is measured through the Irish Soil Moisture Observation Network (ISMON), a partnership between the joint Agricultural Meteorology (AgMET) working group, Teagasc, Terrain-AI, COSMOS-UK and Met Éireann. ISMON currently comprises 11 CRN stations on mineral soils. Coverage is limited in north-western regions, where high rainfall and extensive organic-rich and peat soils create hydrological conditions poorly represented by the existing network. Expansion into these environments therefore requires monitoring approaches capable of operating reliably under persistently wet and spatially heterogeneous conditions.

CRN sensing may face limitations in highly saturated organic soils whilst integrating moisture across a relatively large footprint. This is important in heterogeneous Irish landscapes, where fields, soil types and land-cover units may be smaller than the CRN footprint. GRS could potentially provide observations at a finer spatial scale and greater sensitivity to field-scale hydrological variability, but its performance under Ireland's high-rainfall conditions and on organic-rich soils remains untested.

Here we present research where the primary objective is to evaluate the suitability, accuracy and operational performance of stationary in-situ GRS for continuous soil moisture monitoring under these conditions. A secondary objective is to determine whether integrating stationary GRS with drone-based spatial measurements can better characterise surrounding soil moisture variability and bridge the scale gap between local measurements and CRN observations. Together, these measurements will assess whether GRS can robustly complement CRN and support future ISMON expansion into Ireland's wetter landscapes.

Combining CRNS and Gamma Ray Sensing in agricultural fields

Marco Benfenati¹, Francesco Vinzio¹, Gabriele Baroni¹

(1) DISTAL, Università di Bologna, Italy

Contact: Marco Benfenati (marco.benfenati8@unibo.it)

ABSTRACT

Gamma-ray detection is increasingly emerging as a promising technology for soil moisture measurement, either as an alternative or in combination with the more established Cosmic Ray Neutron Sensing (CRNS) technology. Compared to spectrometric instruments, non-discriminating gamma-ray detectors do not allow the extraction of information from individual spectral energy windows; however, they represent a more compact and cost-effective alternative, but requiring additional post-processing considerations.

In this study, data collected from CRNS instruments paired with non-discriminating gamma-ray detectors across sites in the Emilia-Romagna region (Northern Italy) were analyzed. Hourly CRNS data were processed in accordance with established CRNS community guidelines. The hourly gamma-ray time series were subjected to peak removal to eliminate atmospheric radon-washing effects during precipitation events, followed by Seasonal-Trend Decomposition (STL) to remove diurnal variations. The resulting trend components were subsequently converted into soil moisture estimates using the equation formulated by Baldoncini et al. (2018).

The results demonstrate good agreement with the CRNS-derived time series, adequately capturing the annual trend. On a daily to hourly scale, however, an alternation between phase agreement and phase opposition in the slopes was observed. The gamma time series exhibited a strong positive correlation with air temperature and a negative correlation with relative air

humidity. A similar, even if less pronounced, correlation was also observed in neutron data corrected for atmospheric pressure, air humidity, and incoming radiation. This suggests the co-existence of both instrumental and environmental effects in gamma-ray measurements, which may partially account for the periodic trend discrepancies observed between neutron and gamma-ray data. Future developments of this study will focus on investigating potential correction routines for the gamma-ray time series and evaluating the impact of biomass.

A common biomass correction method improves soil moisture estimation from bulk and energy-resolved gamma radiation

Sonia Akter¹, Johan Alexander Huisman¹ and Heye Reemt Bogaen¹

(1) Agrosphere Institute (IBG-3), Forschungszentrum Jülich GmbH, 52428 Jülich, Germany

Contact: Sonia Akter (s.akter@fz-juelich.de)

ABSTRACT

Accurate information on soil moisture dynamics is essential for efficient water resource management and for understanding of land–atmosphere interactions under a changing climate. Continuous gamma radiation measurements from permanently installed gamma-ray sensors provide a promising non-invasive technique for observing sub-field-scale soil moisture dynamics while bridging the spatial gap between point-scale observations and remote sensing. The measurement principle relies on the inverse relationship between soil moisture and gamma radiation emitted from natural soil radionuclides. Among all the naturally occurring soil radionuclides, 40K is the most reliable source for soil moisture estimation because it emits gamma rays at 1460 keV, which are less susceptible to confounding factors (e.g., atmospheric radon, biomass). In contrast, bulk or environmental gamma radiation (EGR) is particularly attractive because measurements are already available from existing radioactivity monitoring networks (e.g., EURDEP), offering the potential for large-scale soil moisture monitoring. In our previous study, we successfully estimated soil moisture from EGR measurements. However, the accuracy of soil moisture estimates derived from EGR (7–9 vol.%) was lower than that of 40K-based (3–5 vol.%) estimates, partly because biomass—a well-known confounding factor in gamma radiation-based soil moisture estimation—has a stronger influence on EGR measurements. To investigate this in more detail, we conducted a two-year

study at an agricultural site in Selhausen, Germany, covering two growing seasons with two contrasting crops: winter wheat and sugar beet, to better understand biomass-induced variability in bulk and energy-resolved gamma radiation measurements. The experimental set up consists of co-located EGR and 40K detectors alongside an in-situ soil moisture sensor network. Using destructive above-ground biomass (AGB) measurements, we derived and tested a biomass correction coefficient (β) through a sensitivity analysis. EGR-based soil moisture estimates were considerably more sensitive to biomass correction than 40K-based estimates. Nevertheless, both approaches exhibited remarkable similar response patterns, with fresh AGB outperforming AGB water content as the correction variable. Optimal results were achieved for both crops and measurement types when a common β value of 0.01 was applied, resulting in an RMSE of <4 vol.% for EGR and <3 vol.% for 40K. These findings provide a simple and transferable biomass correction approach and demonstrate the potential of existing EGR-based radioactivity monitoring networks for large-scale, country-wide soil moisture monitoring.

Why, when and how could we be more pragmatic in applying cosmic-ray neutron sensing

Sascha Oswald¹, Sabine Attinger^{1,2}

(1) University of Potsdam (Germany), (2) UFZ Leipzig (Germany)

Contact: Sascha Oswald (sascha.oswald@uni-potsdam.de)

ABSTRACT

The CRNS method has been shown fruitful and applicable in the decade after its inauguration, but also complex when assessed in detail in experiments and simulations. And some definitions and conventions have been useful, but may not always be pragmatic anymore when combined with the full complexity. We will outline some computationally simple approaches and concepts giving pragmatic options, also for heterogeneous footprint conditions.

Integration of soil moisture measurements into the observation network of the German Meteorological Service – tests and adjustments to enable a network of operational in-situ- and Cosmic-Ray Neutron Sensing measurements

Leonhard Hufnagl¹, Mario Albert², Mathias Herbst¹, Wolfgang Kurtz¹, Jan Lenkeit²

(1) German Meteorological Service (Deutscher Wetterdienst, DWD), Center for Agrometeorological Research, Braunschweig/Oberschleißheim, Germany; (2) German Meteorological Service (Deutscher Wetterdienst, DWD), Department Observing Networks and Data, Hamburg, Germany.

Contact: Leonhard Hufnagl (Leonhard.Hufnagl@dwd.de)

ABSTRACT

For soil-state information, the German Meteorological Service (DWD) offers a soil moisture viewer based on a water balance and evaporation model that provides data for agrometeorological consultation. However, a nationwide standardized and automatized soil moisture network, further referencing the model, is lacking in Germany.

Therefore, the DWD is preparing the introduction of an automatized, nationwide soil moisture network in the internal project IsaBoM (“Integration of standardized and automatized soil moisture measurements in the DWD observation network”). In each station a complementary measuring system consisting of in-situ-sensors and Cosmic-Ray Neutron Sensing (CRNS) is planned. It is aimed to follow the guidelines of the World Meteorological Organization (WMO) towards the permanent monitoring of this essential climate variable. The project’s tasks are, amongst other aspects, testing and selecting suitable sensors and calibration procedures, setting up data analysis methods, preparing the automatic dataflow and public

data provisioning and ultimately providing solutions to integrate the soil moisture data into the existing operational models.

Here, we present the current status of the project IsaBoM, where a nationwide soil moisture network with 20 initial stations is prepared. The sites are chosen to cover all main soil properties and climate conditions throughout Germany and are selected for a minimum amount of obstructions in the surrounding area that could distort the CRNS-signal.

We show the newest results of the comparison between CRNS-sensors with different sensitivities, where we observe small differences in soil moisture, mostly during precipitation and drying out events at the project test sites Braunschweig and Weißenstephan-Dürnast (Freising).

Furthermore, we focus on the adjustment of the CRNS-calibration for the DWD's operational requirements with the aim to reduce efforts without loss of data quality. Therefore, we tested a hybrid calibration using the planned setup on an operational DWD-measuring site, where in-situ-sensors are placed near the CRNS in addition to manual soil probing and handheld TDR-Measurements.

In addition, the CRNS soil moisture estimates are compared to the in-situ profile data in close proximity. We found the changing soil moisture to be seemingly consistent in both measuring systems throughout a multi-year time series.

The Brandenburg CRNS Network: From Neutron Counts to Operational Soil-Moisture Products and Soil-Water Modelling

A cooperation of the State of Brandenburg, the UFZ and the University of Potsdam - 12 stations with automated processing and public online monitoring

Jakob Terschläusen¹, Till Francke¹, Maik Heistermann¹, Sascha E. Oswald¹

(1) Institute of Environmental Science and Geography, University of Potsdam, Potsdam, Germany

Contact: Jakob Terschläusen (terschluesen@uni-potsdam.de)

ABSTRACT

We present the Brandenburg (BB) CRNS network as a cooperation between state authorities (LBGR), research organisations (UFZ) and the university, including 12 stations that have been running since 2024. The objective is to make the cosmic-ray neutron soil-moisture data operationally available through an automated, end-to-end process from raw counts to usable soil-moisture products. The raw neutron counts are converted into soil moisture readings through transparent, configuration-file-based workflows with the Python package *neptoon* and presented in an interactive online web application. The CRNS soil moisture is further used to calibrate a Soil-Water-Atmosphere-Plant (SWAP) model, which is then run to derive groundwater recharge across the monitoring sites. The long SWAP simulation time series provides a reference period, against which the current soil moisture is expressed as an easily interpretable soil water index (SWI).

MOWAX: Monitoring and Modelling Concept as a Basis for the Assessment of the Water Budget of Saxony

Felix Thomas¹, Friedrich Boeing¹, Solveig Landmark¹, Rebekka Lange¹, Daniel Altdorff¹,
Jan Bumberger¹, Andreas Marx¹, Peter Dietrich¹ and Martin Schrön¹

*(1) Helmholtz Centre for Environmental Research, Monitoring and Exploration Technologies,
Germany*

Contact: Felix Thomas (felix.thomas@ufz.de)

ABSTRACT

In the project MOWAX we present a coordinated observing and data-integration effort that deploys a dense network of area-representative Cosmic-Ray Neutron Sensing (CRNS) stations in Saxony and combines it with novel Rail-CRNS mobile sensors to deliver continuous, robust observations supporting monitoring and modelling of the regional water budget in Saxony.

The network was designed to capture dominant landscape controls on the water budget (land use, soil type, topography, climate) and follows standardized sensor placement and calibration procedures.

The majority of stationary CRNS sites are deployed and soil sampling for calibration has been done. Five german-wide operating Rail-CRNS systems are supporting the network with along-track observations that enrich spatial coverage.

Automatic processing of the data to derive soil moisture is running automatically on a daily basis for the first stations, including automated quality control (QC) routines.

The data collected so far are actively being used for calibration and validation of Saxony-wide hydrological simulations with the mesoscale Hydrologic Model (mHM), which is set up with the federal state soil map (BK-50) at a high spatial resolution of ~600 m to estimate water

budget components. The first soil moisture simulations show a high agreement with CRNS soil moisture dynamics, while simultaneously yielding good performance in discharge.

Observations and simulations automatically transfer into the UFZ timeseries management system and spatial data infrastructure. The data is presented in near-real-time dashboards to provide rapid and interactive visualization of recent data. Since the initial project setup, MOWAX has progressed towards an operational status.

At COSMOS2026 we will present network design and deployment protocols, QC workflows, information on our Rail-CRNS methodology, the data pipeline, and first assessments of how CRNS observations are improving mHM calibration and enhance informations basis regarding the water budget in Saxony.

Integrating CRNS in a flexible drought monitoring

Francesco Vinzio^{1,2}, Marco Benfenati¹, Gabriele Baroni¹, Luca Roffia²

(1) DISTAL, Università di Bologna (Italy); (2) VAIMEE s.r.l.

Contact: Francesco Vinzio (francesco.vinzio2@unibo.it)

ABSTRACT

Drought monitoring networks are increasingly widespread to support water resource management, early warning systems, and adaptive decision-making in a context of increasing climate variability. However, most operational networks remain structured around fixed sensor configurations, predefined indicators, and standardized visualization outputs, originally designed for relatively homogeneous or well-characterized contexts. This rigidity limits their ability to adapt to the heterogeneity of local hydrological, agricultural, and land-cover conditions, as well as the type of instrumentation used, and often results in outputs that are difficult for end users (farmers, water managers, and local authorities) to represent, interpret, and utilize. Cosmic ray neutron sensing (CRNS) offers a non-invasive estimate of soil moisture content at the field level, particularly suited to complement traditional point sensors within drought monitoring networks due to its spatial extension and sensitivity to moisture dynamics in the root zone. However, the integration of CRNS systems into existing operational networks, such as regional drought monitoring systems currently based on rigid sensor architectures, is rarely designed with flexibility in mind, both in terms of which sensors can be combined and how the resulting information is communicated to different types of users. This poster presents a conceptual analysis of the limitations of current rigid drought monitoring architectures and outlines the requirements for a more flexible approach to CRNS system integration.

Assessing field-scale soil moisture using cosmic-ray neutron sensing and point-scale sensors in an agricultural field in Belgium

Atina Umi Kalsum¹, Marit Hendrickx^{1,2}, Jan Vanderborght^{1,3}, Pieter Janssens^{4,5}, Jan Diels^{1,2}

(1) Department of Earth and Environmental Sciences, KU Leuven, Leuven, 3001, Belgium; (2) KU Leuven Plant Institute (LPI), KU Leuven, Leuven, 3001, Belgium; (3) Agrosphere Institute IBG-3, Forschungszentrum Jülich GmbH, Jülich, 52425, Germany; (4) Soil Service of Belgium, Leuven, 3001, Belgium; (5) Department of Biosystems, KU Leuven, Leuven, 3001, Belgium

Contact: Atina Umi Kalsum (atinaumi.kalsum@kuleuven.be)

ABSTRACT

This study evaluates soil moisture measurements in a 9.5 ha agricultural field with a silt loam soil located in Boutersem, Belgium, during the 2026 growing season. The field is approximately square, with a CRNS installed in the center, and surrounded by a homogeneous winter wheat crop. The CRNS was complemented by environmental sensors used to perform standard neutron corrections, as well as by a pluviometer. In addition, dielectric capacitance soil moisture sensors (TEROS 10, METER Group) were installed at multiple locations and depths within the CRNS footprint. Soil moisture derived from the dielectric sensors was vertically weighted to be comparable to the CRNS measurements. Field soil samples, including auger and ring samples, were collected to provide reference measurements for CRNS calibration and determine bulk density.

Soil moisture was derived from CRNS measurements using both the N0 and UTS calibration methods with soil moisture and bulk density sampling within the footprint area. The two approaches yielded similar results, indicating that both methods provide comparable estimates under the field conditions investigated. Soil moisture derived from CRNS and dielectric sensor measurements exhibited similar temporal patterns and responded consistently to

rainfall events. However, notable differences were observed during the peak growing season, likely due to vegetation effects on the CRNS signal. Hydrogen contained in the vegetation biomass and water intercepted in the canopy can influence the neutron count rate and consequently affect CRNS-derived soil moisture estimates.

Furthermore, the dielectric sensors tended to underestimate soil moisture compared with CRNS-derived soil moisture and reference soil moisture samples. After applying a calibration equation for loamy soil to the dielectric sensor measurements, the agreement between dielectric sensor- and CRNS-derived soil moisture improved substantially, with the Nash-Sutcliffe Efficiency (NSE) increasing from 0.10 to 0.66 and the RMSE decreasing from 0.051 to 0.031 m³ m⁻³. Overall, the results demonstrate that CRNS provides meaningful field-scale soil moisture information while capturing environmental influences and spatially integrated dynamics that differ from those observed in point-scale measurements.

Dynamic Harmonisation and Processing of Diverse CRNS Datasets: A Metadata-Driven Approach

Merlin Schiel, Till Francke, Jakob Terschläusen, Sascha E. Oswald

Universität Potsdam Institute of Environmental Science and Geography Subsurface Hydrology

Contact: Merlin Schiel (schiel@uni-potsdam.de)

ABSTRACT

Cosmic-Ray Neutron Sensing (CRNS) is increasingly used by both research institutions and (sub-)national environmental monitoring programs. However, as networks expand, data processing is becoming increasingly complex. Specifically, challenges can arise from diverse output structures from different sensor manufacturers, inhomogeneities due to sensor replacements or malfunctioning, and complementary auxiliary data recorded. To address this, we present a metadata-driven framework for the operational and reproducible harmonisation of diverse CRNS datasets. This approach allows for adapting to changes in sensor configurations, data structures and environmental conditions.

By using the same metadata architecture as the CRNS processing tool neptoon, this framework allows for fully automated workflows from raw, heterogeneous data into finalized soil moisture products.

On soil sampling design and CRNS calibration

Marco Benfenati¹, Francesco Vinzio¹, Gabriele Baroni¹

(1) University of Bologna (Italy)

Contact: Marco Benfenati (marco.benfenati8@unibo.it)

ABSTRACT

The use of Cosmic-Ray Neutron Sensing (CRNS) is increasing worldwide, being adopted by numerous research groups and integrated into national monitoring networks. However, the standard CRNS calibration procedure is a time- and labor-consuming requirement, representing one of the main bottlenecks to the broader diffusion of this technology. The development of optimized sampling methods and schemes is therefore a crucial and urgent objective to enhance its applicability.

This poster presents a new free-access online tool based on the Google Earth Engine cloud-computing platform for the optimization of the CRNS calibration scheme, utilizing multi-temporal analysis of suitable Sentinel-2 remote sensing indices. Once the user selects the initial parameters of the sampling scheme and the characteristics of the study area, the processing of the index can be initiated. First, a multi-temporal mean map of the index within the CRNS footprint area is calculated. Subsequently, a K-means clustering algorithm is applied either to the mean map or to one of the available Sentinel-2 images. Based on this partition, the user is finally able to move or remove sampling points and download the resulting optimized scheme. Lastly, preliminary results are presented, demonstrating how the choice of the remote sensing image analysis period and the sampling density affect both the estimation of the average soil moisture in the field and its associated uncertainty.

Development of an inversion framework for spatially resolved soil moisture estimation from cosmic ray neutron sensing data

Viola Cioffi¹, Andrea Zunino², Alessandro Ghirotto², Sebastian Uhlemann³, Giorgio Cassiani¹

(1) Department of Geosciences, University of Padua (Italy), (2) Department of Earth and Planetary Sciences, ETH Zurich (Switzerland), (3). University of Bremen (Germany)

Contacting person: Viola Cioffi (viola.cioffi@phd.unipd.it)

ABSTRACT

Cosmic Ray Neutron Sensing (CRNS) provides area-integrated estimates of soil moisture at spatial scales between point measurements and satellite observations. However, the interpretation of neutron count data is complicated by the nonlinear relationship between neutron intensity and soil moisture and by the spatially distributed sensitivity of the sensor footprint.

In this work we develop an analytical formulation of the forward problem for heterogeneous soil moisture conditions. Starting from established relationships describing neutron intensity and spatial sensitivity, we derive a discretized framework in which the contribution of each grid cell within the sensor footprint is weighted according to a spatial sensitivity function.

The resulting formulation expresses the total neutron signal as a weighted sum of contributions from individual cells and provides a convenient matrix representation that can be used for the development of inversion algorithms.