Published October 3, 2019

Original Research

Core Ideas

- Cosmic-ray neutron sensing (CRNS) was used in a drip-irrigated field.
- Soil water content was estimated from CRNS.
- Neutron transport was simulated for the drip-irrigated field.
- CRNS has limitations for irrigation scheduling of drip-irrigated fields.

Can Drip Irrigation be Scheduled with Cosmic-Ray Neutron Sensing?

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Irrigation is essential for maintaining food production in water-scarce regions. The irrigation need depends on the water content of the soil, which we measured with the novel technique of cosmic-ray neutron sensing (CRNS). The potential of the CRNS technique for drip irrigation scheduling was explored in this study for the Picassent site near Valencia, Spain. To support the experimental evidence, the neutron transport simulation URANOS was used to simulate the effect of drip irrigation on the neutron counts. The overall soil water content (SWC) in the CRNS footprint was characterized with a root mean square error <0.03 cm^3/cm^3, but the experimental dataset indicated methodological limitations to detect drip water input. Both experimental data and simulation results suggest that the large-area neutron response to drip irrigation is insignificant in our specific case using a standard CRNS probe. Because of the small area of irrigated patches and short irrigation time, the limited SWC changes due to drip irrigation were not visible from the measured neutron intensity changes. Our study shows that CRNS modeling can be used to assess the suitability of the CRNS technique for certain applications. While the standard CRNS probe was not able to detect small-scale drip irrigation patterns, the method might be applicable for larger irrigated areas, in drier regions, and for longer and more intense irrigation periods. Since statistical noise is the main limitation of the CRNS measurement, the capability of the instrument could be improved in future studies by larger and more efficient neutron detectors.

Abbreviations: CRNS, cosmic-ray neutron sensing; FDR, frequency-domain reflectometry; KGE, Kling–Gupta efficiency; RMSE, root mean square error; SWC, soil water content; URANOS, Ultra Rapid Neutron-Only Simulation.

Irrigated agriculture plays a vital role in food production to support the increasing world population. Irrigation is responsible for 70% of the fresh water consumption by mankind (Vereecken et al., 2009). To save water resources and to fulfill future crop production requirements, more efficient irrigation scheduling is needed. The irrigation scheduling approach can be applied based on the difference between root-zone soil water content (SWC, cm^3/cm^3) and a target SWC that is related to the specific plant preferences (Evans et al., 1991).

Many devices can provide information about SWC, such as time domain transmissivity, frequency-domain reflectometry (FDR) (Peters et al., 2013), tensiometers (Smajstrla and Locascio, 1996), capacitance probes (Fares and Alva, 2000) and cosmic-ray neutron sensing probes (Zreda et al., 2012). The cosmic-ray neutron sensing (CRNS) probe can be used to measure SWC up to depths of 80 cm and with a footprint radius ranging from 130 to 240 m at sea level (Köhli et al., 2015). Cosmic radiation originates from extrasolar sources and penetrates the atmosphere of the Earth. This interaction creates high-energy neutrons that further collide with atoms in the air, soil, and vegetation to produce medium-energy neutrons (Zreda et al., 2012). Those neutrons can be efficiently moderated toward lower energies by collisions with hydrogen. Therefore, the intensity of medium-energy neutrons is an indication of the amount of hydrogen atoms at the land surface and its

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Received 25 May 2019.
Accepted 12 Aug. 2019.

Citation: Li, D., M. Schrön, M. Köhli, H. Bogena, J. Weimar, M.A. Jiménez Bello, X. Han, M.A. Martínez Gimeno, S. Zacharias, H. Vereecken, and H.-J. Hendricks Franssen. 2019. Can drip irrigation be scheduled with cosmic-ray neutron sensing? Vadose Zone J. 18:190053. doi:10.2136/vzj2019.05.0053

temporal variation. The medium-energy neutrons, which can be detected by the CRNS probe, travel hundreds of meters in air and tens of decimeters in the soil. Hence, the advantage of the CRNS method is its ability to determine soil water states across larger areas and deeper soil layers, noninvasively, with low maintenance, and at a smaller cost than traditional soil moisture sensors.

To properly understand the neutron signal and its dependence on the integral SWC, many attempts have been made to model the neutron response with Monte Carlo codes (Desilets et al., 2010; Zreda et al., 2012; Franz et al., 2013). In 2015, the neutron transport model URANOS (Ultra Rapid Neutron-Only Simulation) (Köhli et al., 2015, 2018) was developed to reduce the number of model assumptions and make easy-to-use neutron simulations available for the hydrological and soil science communities. Since then, the revised model results have been confirmed in many experimental studies (Heidbüchel et al., 2016; Schattan et al., 2018; Schrön et al., 2017, 2018a, 2018b; Fersch et al., 2018). The footprint is a function of air pressure, soil moisture, and air humidity and is also slightly affected by the vegetation cover (Köhli et al., 2015). For typical wet soils, the measurement depth is about 15 cm, while 86% of the measured neutrons originate from within a circle with a diameter of about 400 m (Köhli et al., 2015). In dry soils, the measurement depth can go down to 80 cm and the diameter to >500 m at sea level. The aboveground neutron density is affected by changes in the cosmic-ray intensity and by additional hydrogen sources, such as biomass and lattice water (Andreasen et al., 2017; Schreiner-McGraw et al., 2016; Baatz et al., 2015). Standard procedures are available to correct these effects.

The accuracy of CRNS retrieved SWC has been verified in many investigations (Zreda et al., 2012; Han et al., 2014; Zhu et al., 2015; Hawdon et al., 2014; Schrön et al., 2018b). Earlier work allowed improvement of the interpretation of measured neutron signals by CRNS for wet ecosystems, which showed that SWC could be estimated with an error of 0.03 cm^3/cm^3 (Bogena et al., 2013; Baatz et al., 2014). Other studies demonstrated that reliable estimates of soil moisture with standard CRNS probes under humid conditions at sea level can only be achieved for integration times $\geq$6 h (Schrön et al., 2018b).

Drip irrigation is a localized irrigation method that allows water to drip slowly to the plant roots to save water and fertilizer inputs. Drip irrigation is associated with strongly heterogeneous SWC, with relatively small irrigated wet patches and larger unirrigated dry areas. The research of Li et al. (2018) has demonstrated the possibility of drip irrigation scheduling based on FDR SWC measurements in the irrigated part. The limited number of FDR sensors and the FDR sensor's limited measurement volume (FDR footprint) has imposed considerable uncertainties regarding SWC estimates for the small wet patches, so that the estimate of the soil water deficit for the whole field is also uncertain. This in turn makes it challenging to schedule the amount of drip irrigation water needed for the plants located on the wet patches.

Because CRNS is able to estimate the soil water change for a relatively large footprint, some past research was dedicated to the use of CRNS for irrigation scheduling. Barker et al. (2017) investigated the optimal number and locations of CRNS probes for irrigation management. Han et al. (2016) tested the assimilation of synthetic neutron intensity data to improve land surface modeling with the Community Land Model and to do real-time drip irrigation scheduling. None of these studies applied CRNS data in a real-world case study for drip irrigation scheduling.

Our research question was to what extent CRNS can be used for the scheduling of drip irrigation amounts by using the measured neutron intensity as a proxy for root-zone SWC. This work aimed to test the measurement precision of CRNS in a drip-irrigated field and to evaluate whether it is sufficient to support drip irrigation management. The work relied on both field experimentation and modeling of neutron intensity. A field calibration campaign was performed for the drip-irrigated Picassent site in Spain. The neutron transfer model (URANOS) was used to model the neutron response to the drip-irrigated citrus fields and to explore the potential of the CRNS method to detect drip irrigation events.

Materials and Methods

Research Sites and Measurements

The research site is an area with drip-irrigated citrus fields located close to Picassent in Spain (39.38° N, 0.47° E), which is a semiarid region. Precipitation is concentrated in the autumn, winter, and spring, and the yearly average precipitation is 453 mm (Li et al., 2018). Citrus is one of the most productive fruit plants in the world. The growing of citrus needs abundant sunlight and adequate rainfall or irrigation. Citrus trees flower in spring; fruits develop afterward and ripen in fall or early winter. Precipitation during the main growth period of citrus fruit in summer is rare and therefore the water demand of the trees depends almost entirely on irrigation.

Drip irrigation is being used to irrigate these citrus tree fields, with two pipelines (1-m distance) and 10 emitters for each tree. The emitters in the study area are mostly integrated pressure compensating type, with a common flow rate of 4 L/h. All the emitters are surface placed every meter without mulch cover. The trees are separated by 5 m from each other, both along the planted lines and between these lines (see also descriptions in Li et al., 2018). The meteorological observatory of the Instituto Valenciano de Investigaciones Agrarias provides meteorological data and is located 2868 m from the CRNS probe (http://riegos.ivia.es/). During most irrigation periods, drip irrigation was applied five or six times per week. From October onward, depending on the weather and fruit maturation process, the irrigation frequency was reduced and finally stopped. Due to the drip irrigation, the soil water status of the land surface is very heterogeneous. The field can be divided into wet patches (irrigated parts) and dry patches (the rest of the field). The areal contribution of the drip-irrigated part to the whole area is small, and thus the SWC identification poses a challenge to the integral CRNS method.

As shown in Fig. 1, we have installed a CRNS probe in the dry patch between two drip lines (CRS1000, HydroInnova) and various FDR probes at the test site. The FDR probes (factory-calibrated ENVIROSCAN water content profile probe, Campbell Scientific) were installed in six irrigation plots within the footprint of the CRNS probe, measuring SWC at four depths (10, 30, 50, and 70 cm). Within a distance of 200 m from the CRNS probe, four FDR probes were installed to measure SWC in the unirrigated part of the area, and nine FDR probes were installed in the irrigated part of the area.

Field Sampling for Cosmic-Ray Neutron Sensing Calibration in Picassent

The CRNS probe needs to be calibrated with soil samples during a field campaign while neutron intensity is simultaneously measured by the CRNS probe. According to the new findings by Köhli et al. (2015) and Schrön et al. (2017), the area within a radius of <50 m from the CRNS probe has about the same contribution to the neutron signal as the remaining area beyond 50 m. In accordance with suggestions by Schrön et al. (2017), sampling radii for this study were chosen as 11, 50, and 110 m, with six sampling locations evenly distributed around each circle. At each location, the soil was sampled in six layers separated by 5 cm between the 0- and 30-cm depth.

Samples were taken using a soil corer of 30-cm length and 5-cm diameter (HUMAX, Martin Burch) on 1 June 2015. Half of the samples were taken in the wet and irrigated area (the green dots in Fig. 1) and the other half in the dry, unirrigated area (red dots in Fig. 1). Each 30-cm-long soil core was frozen and cut in 5-cm intervals to obtain six layers for each sampling location. All 108 samples were dried in an oven for >36 h until the sample weight became stable. These samples have been averaged to get footprint SWC taking into account their distance to the CRNS probe by using a weighting function that corresponds to neutron transport theory (see below).

Six soil samples (10 g) containing material from all six layers were also analyzed in the laboratory for contents of lattice water and soil organic material. The laboratory analysis gave the organic and the inorganic C content and the H_2 content (by using a heat conductivity detector) and N content. The analyzed H_2 content

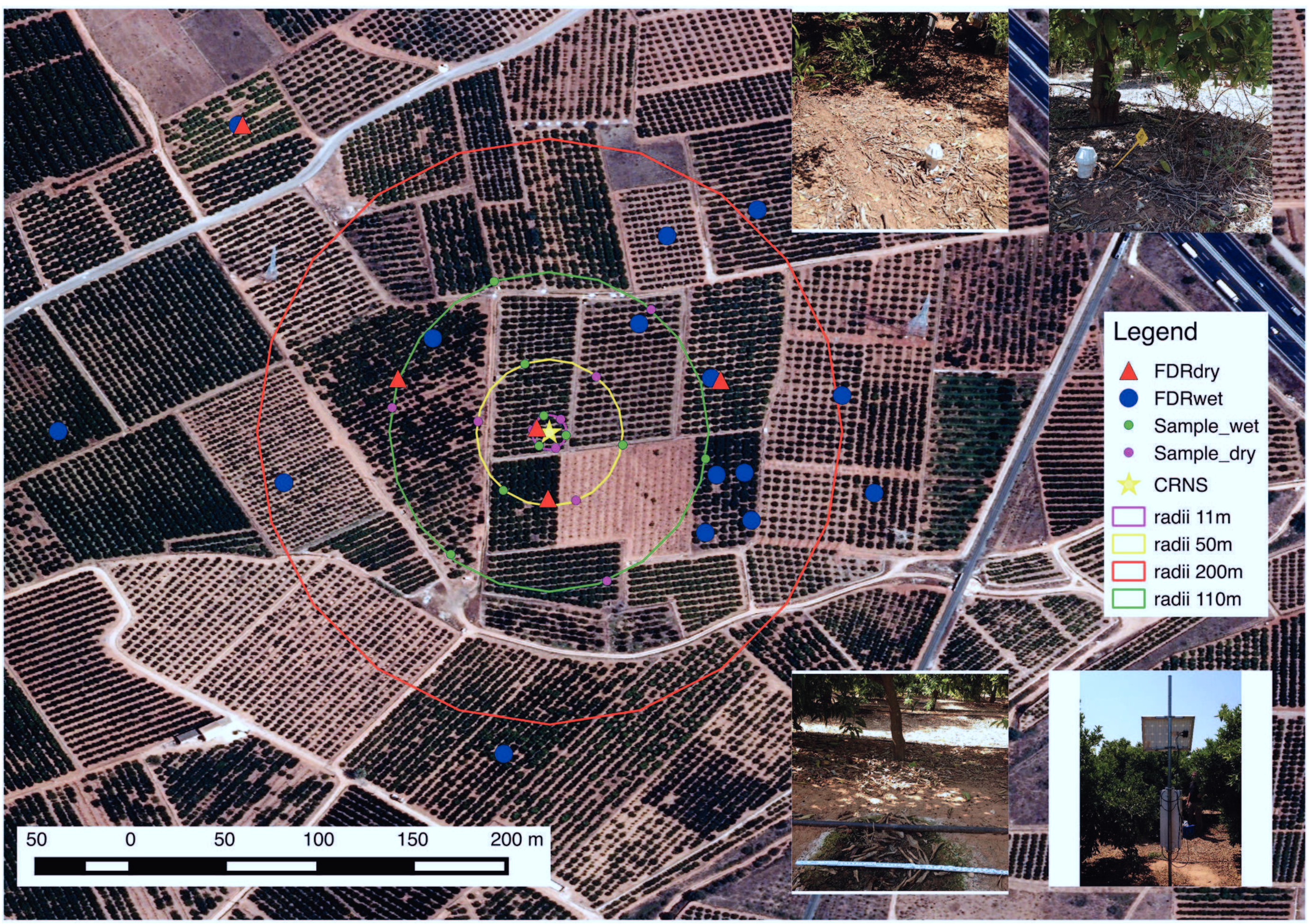

Fig. 1. The distribution of frequency-domain reflectometry (FDR) probes (for irrigated and unirrigated areas), 18 soil samples for the cosmic-ray neutron sensing (CRNS) calibration, and location of the CRNS probe in the Picassent field, Spain. The radii of the circles are 11, 50, 110, and 200 m. The small photographs show the installation of the FDR probes in unirrigated (upper left) and irrigated (upper right) areas, as well as the shape of the irrigated patch (lower left) and the installation position of the CRNS probe (lower right).

was converted to water equivalents by multiplying by a ratio value of 9 (H_2/H_2O = 1:9). From the analyzed H_2 content, all the weight of the lattice and organic water was calculated and converted to volumetric content using the average soil bulk density value. The average volumetric lattice water and organic water content were found to be 0.04 cm^3/cm^3 in total.

Footprint Soil Water Content from Soil Sampling and Frequency-Domain Reflectometry Sensor Network

To obtain a SWC time series from the CRNS probe, the FDR SWC measurements need to be vertically and horizontally averaged using the weighting function from Schrön et al. (2017). The footprint SWC from gravimetric sampling was derived to do the calibration. Meanwhile the FDR sensors were also area averaged to get the footprint SWC, which was used as verification data.

Our research site is composed of unirrigated fields, which are typically drier, and areas that exhibit a heterogeneous soil moisture pattern due to drip irrigation. To account for this heterogeneous soil moisture pattern, we introduced the fraction of the area that is irrigated, Fr_{wet}, and calculated the weighted SWC for the wet part, θ_{wet}, and dry part, θ_{dry}, separately. Assuming that Fr_{wet} is the same across the whole CRNS footprint, the SWC for the footprint θ_{total} can then be obtained as

$$\theta_{total} = \theta_{wet} Fr_{wet} + \theta_{dry}\left(1 - Fr_{wet}\right) \qquad [1]$$

The measurements to determine the extent of the wet fraction were made before the soil sampling campaign. For each tree, there are two drip lines separated by 1 m in space. The drip points along the drip line are separated by 1-m distance. Since the row distance and tree distance are 5 m, each tree occupies an area of 5 by 5 m, within which there are 10 emitters. The average diameter (*D*) defines the wetted area for each drip point. The fraction of the total drip-irrigated area (Fr_{wet}) is given then by

$$Fr_{wet} = 10\frac{\pi(0.5D)^2}{5\times 5} \qquad [2]$$

The weighting method proposed by Schrön et al. (2017) was used to obtain a weighted average soil moisture value from the point samples and FDR sensors. The vertical weight, W_d, for different soil layers at depth d can be calculated with the following empirical function (Schrön et al., 2017; Köhli et al., 2015):

$$W_d(r,\theta) \propto \exp\left[\frac{-2d}{D_{86}(r,\theta)}\right] \qquad [3]$$

where the effective measurement depth, D_{86}, can be calculated from the distance to the CRNS probe (r) and the soil water content θ. Then the weighted average soil water content $\langle\theta_k\rangle$ from all the measurements (1–k) can be obtained by the weighting function (Köhli et al., 2015):

$$\langle\theta_k\rangle = \frac{\sum_k W_k \theta_k}{\sum_k W_k} \qquad [4]$$

An iterative approach was used to calculate the vertical weight of each layer, which means that the initial vertical SWC was set equal to the average for all six soil samples taken by the HUMAX soil corer, and in case of FDR, to the average of the first two soil layers (10- and 30-cm depths). The representative depth of each soil sample was considered as the middle of this segment (e.g., 2.5 cm is the representative depth for the first segment).

The horizontal weights for each of the soil sampling points or FDR probes depend on the distance between the FDR probes and the CRNS probe as well as the air humidity and soil water status in the footprint (Schrön et al., 2017). The average across all the profile soil samples or FDR measurements using Eq. [1] was taken as the initial SWC for the footprint, and then the horizontal weights along with Eq. [4] were used to get the new SWC for the footprint in an iterative fashion.

Soil Water Content Estimation from Cosmic-Ray Neutron Sensing Probe

The data used in the analysis were hourly neutron intensities measured by the CRNS probe from 1 June 2015 to 31 Dec. 2016 in Picassent. Besides neutron intensity, the CRNS probe also records time, temperature, relative humidity, and air pressure, which is used for data quality control and data preprocessing. Epithermal neutron count data have to be corrected for external influencing factors that are not related to SWC. Neutron intensity data are normalized to a reference air pressure (Zreda et al., 2012). In our case, it is the air pressure on the calibration day (1 June 2015).

The variation in the incoming neutron flux also needs to be corrected using the concurrent and reference high-energy neutron count rate during the research period (Zreda et al., 2012), which were provided by the Jungfraujoch neutron monitor station of the University of Bern (3-NM64, http://cosray.unibe.ch). The reference high-energy neutron count rate is the averaged value during the calibration day. The effect of atmospheric water vapor on epithermal neutron intensity was then corrected using the method described by Rosolem et al. (2013); the reference absolute humidity value was set equal to the average value on the calibration day.

The so-called N_0 method was developed by Desilets et al. (2010) to estimate soil water content θ_v in the CRNS footprint as a function of the neutron count rate N_{pih} through a simple calibration function:

$$\theta_v = \left(a_0\rho_{bd}\right)\left(\frac{N_{pih}}{N_0} - a_1\right)^{-1} - \left(a_2\rho_{bd}\right) - \theta_{lat} - \theta_{org} \qquad [5]$$

where N_0 is the neutron intensity over dry soil at a specific test site and needs to be calibrated once; a_0 = 0.0808, a_1 = 0.372, and a_2 = 0.115 are constant fitting parameters; ρ_{bd} is the soil bulk density (g/cm^3) averaged from all the soil samples taken on the calibration day (1.3 g/cm^3), calculated with an iterative method along with the weighting of SWC for each layer; θ_{lat} is the volumetric lattice water (cm^3/cm^3); and θ_{org} is the soil organic water equivalent (cm^3/cm^3). To calibrate the N_0 parameter, a single field calibration campaign was conducted as described above.

Modeling of the Neutron Response to Drip Irrigation

The neutron response was simulated with URANOS (Version 0.99rho) for the drip-irrigated field in Picassent to test the effect of drip irrigation on the neutron intensity at the CRNS location. The URANOS model simulates neutron interactions in a Monte Carlo framework and was originally developed for applications in nuclear physics (Köhli et al., 2018). Recently it has been used to model the interactions of cosmic-ray neutrons with air, soil, and vegetation to understand neutron intensity as measured by a CRNS probe (Köhli et al., 2015).

URANOS was applied here on the SWC pattern caused by drip irrigation with a model resolution of 0.5 m. As shown in Fig. 2, a typically irrigated domain of size 500 by 500 m around the CRNS probe was divided into wet and dry grids as a simplified scenario, with wet grids of 1-m width interrupted by every 0.5 m (to mimic the irrigated wet patches) and larger dry patches of 4-m width between trees. The CRNS probe is located in the dry grid within the wet stripe.

The domain was further divided into two vertical layers; the bottom layer was 0.5-m-thick soil and the upper layer was vegetation with air in the canopy space. The canopy was described as blocks with 4-m diameter and 2-m thickness, while the stem height was 1 m. The biomass density in the upper layer was 10 kg/m^2 and the air humidity was 1.4 g/m^3, which were typical values for the study domain and based on measurements.

The URANOS model used two main scenarios for the unirrigated area: an SWC value of 0.14 cm^3/cm^3 and 0.05 cm^3/cm^3 for the unirrigated part (with the 0.04 cm^3/cm^3 lattice water and organic C taken into consideration). Meanwhile the SWC values ranged between 0.10 and 0.45 cm^3/cm^3 for the irrigated part, with steps of 0.05 cm^3/cm^3. Given this model setup, we analyzed the spatial distribution of neutron density and observed intensity with regard to changing water content in the irrigated patches. The latter scenario was to test whether CRNS results differ under more arid conditions.

Statistical Analysis

The two time series (from 1 June 2015 to 31 Dec. 2016 for Picassent) of footprint SWC, calculated from neutron intensity data and derived from FDR probes, were compared by the root mean square error (RMSE), Pearson correlation coefficient (ρ), and Kling–Gupta efficiency (KGE) (Gupta et al., 2009):

$$\mathrm{RMSE}=\sqrt{\frac{\sum_{t=1}^{n}\left(X_{1,t}-X_{2,t}\right)^2}{n}} \qquad [6]$$

$$\rho\left(X_1,X_2\right)=\frac{\mathrm{cov}\left(X_1,X_2\right)}{\sigma_{X_1}\sigma_{X_1}} \qquad [7]$$

$$\mathrm{KGE}=1-\left\{\left[\rho\left(X_1,X_2\right)-1\right]^2+\left(\frac{\sigma_{X_1}}{\sigma_{X_1}}-1\right)^2+\left(\frac{\mu_{X_1}}{\mu_{X_1}}-1\right)^2\right\}^{0.5} \qquad [8]$$

where X_1 is the SWC estimated from neutron intensity measured by the CRNS probe, X_2 is the average SWC in the CRNS footprint calculated from the FDR probes, n is the number of time steps with measurements and t is the time step, cov(X_1,X_2) is the covariance between X_1 and X_2, and μ and σ represent the means and standard deviations of X_1 and X_2. In the ideal case, the best fit between X_1 and X_2 would reach RMSE = 0, ρ = 1, and KGE = 1.

The daily maximum variation of FDR SWC was calculated on drip irrigation days to demonstrate the effect of irrigation on SWC measured by FDR sensors:

$$\mathrm{DEF}=\max\left\{\max\left(X_\mathrm{d}\right)-\min\left(X_\mathrm{d}\right)\right\} \qquad [9]$$

where max(X_d) and min(X_d) are the maximum and minimum daily SWC averaged across all FDR sensors in the footprint; the average was calculated every 10 min.

In addition, the normalized standard deviation (N_SD) of CRNS neutron intensity was calculated to determine the CRNS measurement error. The hourly neutron intensity N and its uncertainty σ have a relation as described by Bogena et al. (2013) and Schrön et al. (2018b): σ is the standard deviation of N using

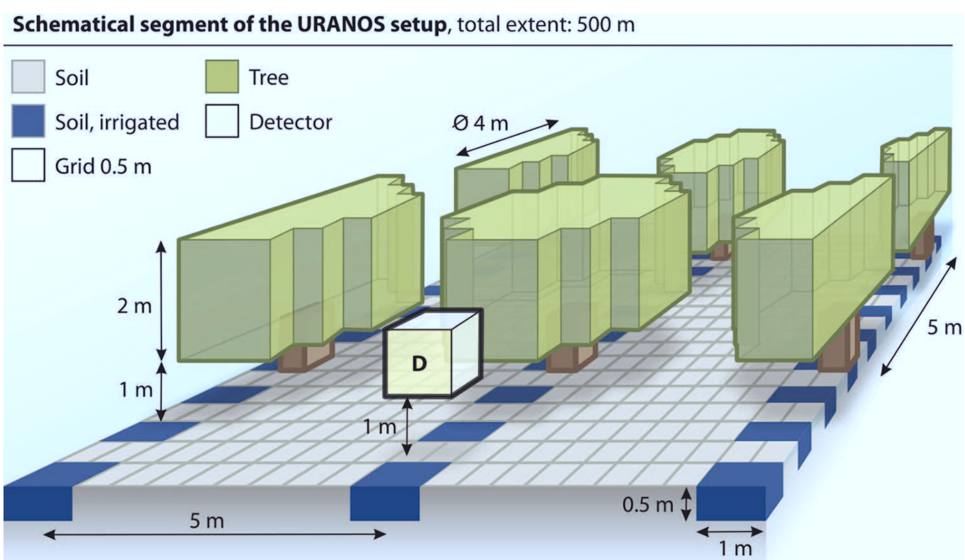

Fig. 2. Neutron transfer model settings for the typical condition in Picassent: the blue grids correspond to the irrigated patches and gray grids correspond to the unirrigated area; the green layer on the top is the simplified representation of the citrus vegetation cover including canopy and stem; the yellow cube symbolizes the cosmic-ray neutron sensing detector.

Gaussian statistics, and N_{SD} is the hourly normalized standard deviation of the neutron count rate:

$$\sigma(N)=\sqrt{N} \quad [10]$$

$$N_{SD}=\frac{\sigma(N)}{N}=\frac{1}{\sqrt{N}} \quad [11]$$

Also, a statistical analysis was performed to analyze the linear correlation between measured SWC and neutron intensity. The Pearson correlation coefficients were calculated for each month of 2016 to explore under what conditions the SWC showed a stronger correlation with the CRNS measurements.

Results and Discussion

Soil Water Measurements from Field Sampling and Frequency-Domain Reflectometry Sensors

Area-Averaged Sampling and Frequency-Domain Reflectometry Soil Water Content

Table 1 shows that a typical wet patch created by drip irrigation has an average diameter (D) of 0.50 m. Given the measured dimensions of a typical wet patch, the overall Fr_{wet} within the larger field is around 8%. The wet fraction of 8% was used for CRNS calibration using data from the soil sampling campaign in June 2015.

Table 1. Measurements of diameters of drip irrigated patches (and their average) in June 2015 in the close vicinity of the installed CRNS probe.

	Patch 1	Patch 1	Patch 3	Patch 4	Avg.
	cm				
Diameter	50	49	46	54	50

The vertically and horizontally weighted SWC values for the irrigated and unirrigated parts are shown in Fig. 3, which demonstrates the effect of drip irrigation and precipitation on the SWC as measured by FDR sensors. For averaging SWC horizontally, the relative proportions of the wet and dry fractions within the CRNS footprint are needed. Figure 3 shows the influence of the relative proportion of the irrigated, wet fraction (Fr_{wet}) on the spatial average of the FDR SWC measurements. If the fraction of the wet, irrigated part of the CRNS footprint were larger, the apparent average SWC of the CRNS footprint would also increase. The temporal evolution of SWC for the CRNS footprint coincides with the SWC for the unirrigated dry part and is strongly related to precipitation events. Due to the failure of FDR data

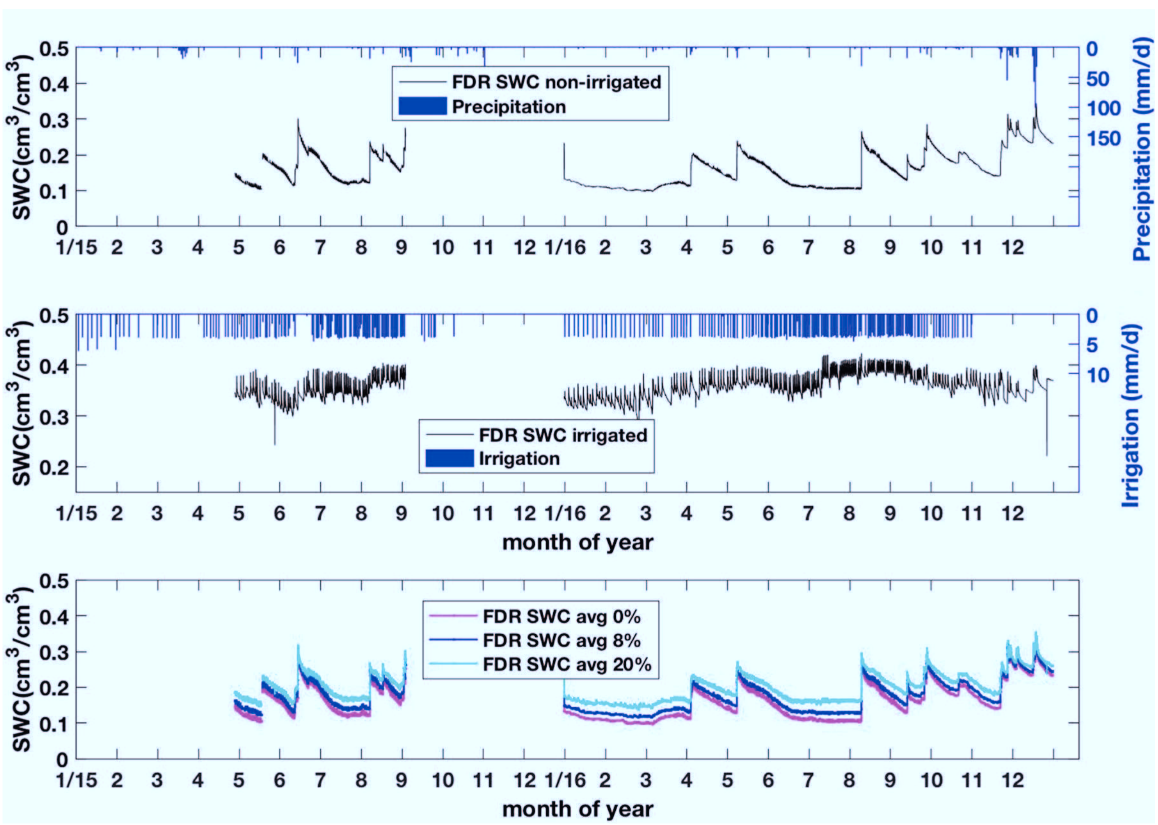

Fig. 3. Area-averaged soil water content (SWC) of frequency-domain reflectometry (FDR) sensors installed in the unirrigated part (upper) and irrigated part (middle) for 2015 and 2016, together with precipitation and irrigation depths (cubic water amount divided by field area) of the field where cosmic-ray neutron sensing (CRNS) was installed. The lower graph shows the averaged FDR SWC in the CRNS footprint as a function of different values for the wet (drip-irrigated) fraction within the footprint.

from September to December in 2015, there was a data gap for this period.

Figure 4 demonstrates that the measured gravimetric SWC for the dry, unirrigated part is lower than the SWC measured by FDR probes. It suggests the existence of a systematic bias between the gravimetric SWC measurements and the FDR data. This can be related to the sampling volume because the gravimetric SWC for the upper 10 cm was determined by two sections of sampling profiles. For the unirrigated part, the soil of the upper 5 cm is much drier than the soil at the 5- to 10-cm depth based on the soil sampling results, so that the FDR-based footprint SWC (the shallowest layer measured at the 10-cm depth) is higher than the gravimetric SWC determined throughout the upper 10 cm. The biases found were constant so that a correction of −0.05 cm^3/cm^3 was added to the FDR-derived footprint SWC time series for the unirrigated part and 0.01 cm^3/cm^3 for the irrigated part.

Frequency-Domain Reflectometry Response to Drip Irrigation

Figure 5 shows the hourly SWC averaged across all FDR sensors measured in the irrigated wet part. There is a daily cycle

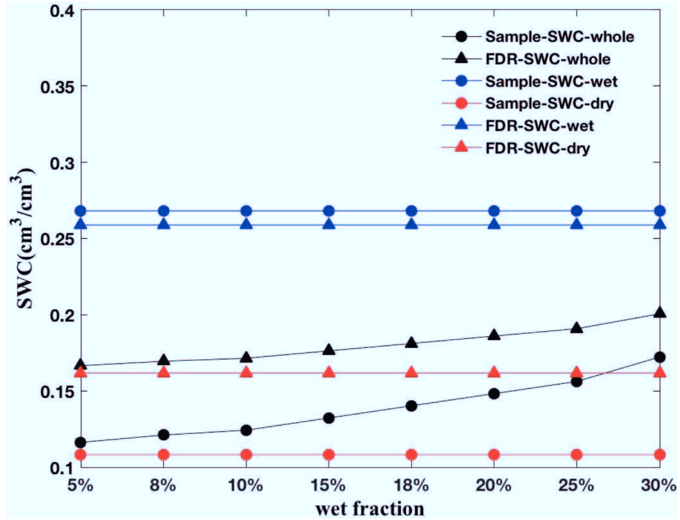

Fig. 4. The footprint soil water content (SWC, black line) at the cosmic-ray neutron sensing calibration day in Picassent, calculated from both the soil sampling campaign and the installed frequency-domain reflectometry (FDR) sensors. The averaged SWC for the irrigated part (blue) and unirrigated part (red), from both the soil sampling and corresponding FDR data are also shown. The wet fraction on the *x* axis is the drip-irrigated percentage in the CRNS footprint.

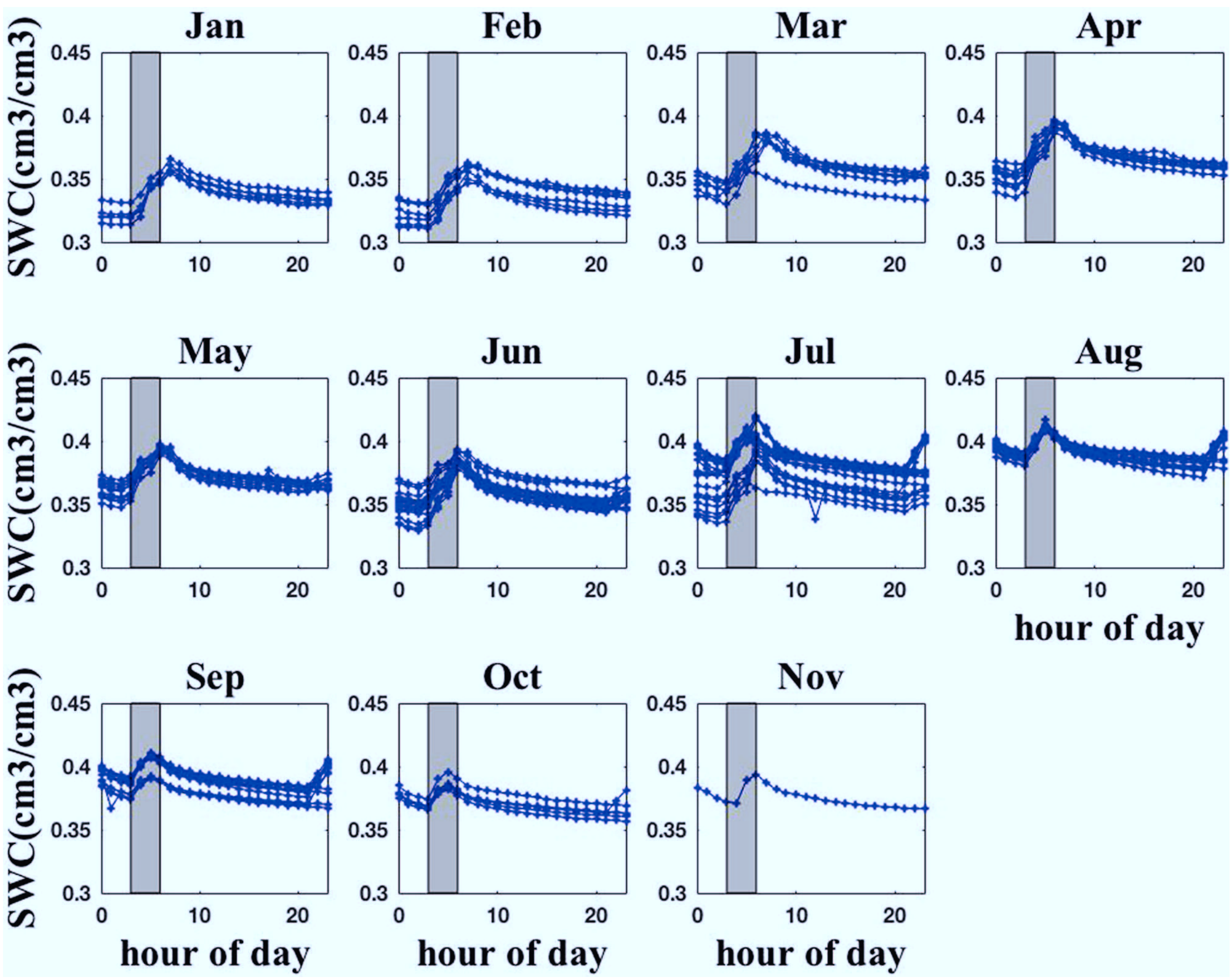

Fig. 5. Hourly records of area-averaged soil water content (SWC) measured by frequency-domain reflectometry sensors installed in the irrigated wet part for all irrigation days and for different months (2016). The shadow area highlights the irrigation period (starts at 3 AM and lasts 1–2 h).

Table 2. The daily maximum variation range (DEF) of frequency-domain reflectometry soil water content (SWC) measured in the drip-irrigated area during irrigation days, then averaged for each month,

	Jan.	Feb.	Mar.	Apr.	May.	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
	cm^3/cm^3											
DEF(SWC)	0.043	0.042	0.048	0.054	0.041	0.052	0.055	0.045	0.034	0.027	0.027	NA†

† NA, no data.

of SWC on irrigation days for each month in 2016. The SWC increased rapidly when irrigation started late at night but dropped to lower values close to pre-irrigation afterward, with a daily maximum variation <0.05 cm^3/cm^3, as shown in Table 2.

Soil Water Content Inversion from Cosmic-Ray Neutron Sensing for Drip-Irrigated Field

Neutron Intensity Measured by Cosmic-Ray Neutron Sensing

The measured hourly and 12-hourly averaged neutron intensity data from June 2015 to December 2016 in Picassent were corrected for fluctuations in air pressure, variations in incoming neutron intensity, and variations in water vapor pressure of the air. Figure 6 shows the temporal evolution of the corrected neutron intensity and also illustrates that neutron intensity and precipitation are inversely correlated. Major rainfall events are associated with a rapid drop in the neutron count rate.

Relation between Cosmic-Ray Neutron Sensing Data and Footprint Soil Water Content

Figure 7 shows the correlation between the footprint SWC calculated from FDR measurements (assuming a wet [irrigated] fraction of 8%) and measured neutron intensity. Measured neutron intensity was averaged across a 24-h interval. The results show weaker correlation coefficients between SWC and neutron count intensity (larger than −0.5) in February, March, June, and July, when SWC is generally lower than in other months. The possible reason is that the effect of irrigation on neutron intensity is neutralized by strong evaporation during summer days, resulting in limited SWC fluctuations with time. The months with stronger (more negative) correlation exhibit days with higher SWC and therefore more variation in SWC, which is related to higher precipitation amounts in those months (Fig. 6). This also indicates that the calibration curve will be better determined if data are available from days with more different SWC values, as suggested in previous research (Iwema et al., 2015).

As the duration of the drip irrigation was normally 1 to 2 h, we also explored the relation between CRNS measurements and drip irrigation in an hourly time interval. However, the measured hourly neutron intensity did not show a clear trend related to the applied drip irrigation (see Fig. 8). The sampling fluctuations are also large, related to the short time period (hourly) for averaging neutron intensities. To determine the uncertainty of CRNS measurements, the hourly standard deviations (N_{sd}) of CRNS measurements on irrigation days are shown in Table 3.

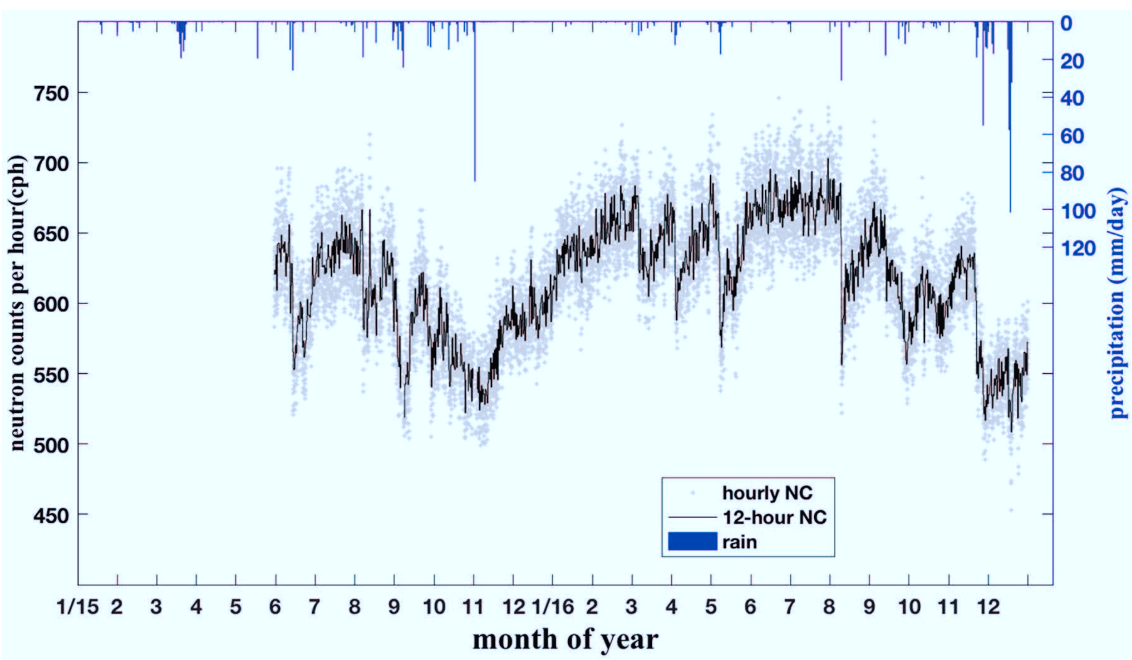

Fig. 6. The corrected neutron intensity (NC) averaged for 1- and 12-h intervals and daily precipitation amounts (meteorological data from the Instituto Valenciano de Investigaciones Agrarias) at the Picassent site in Spain from June 2015 to December 2016.

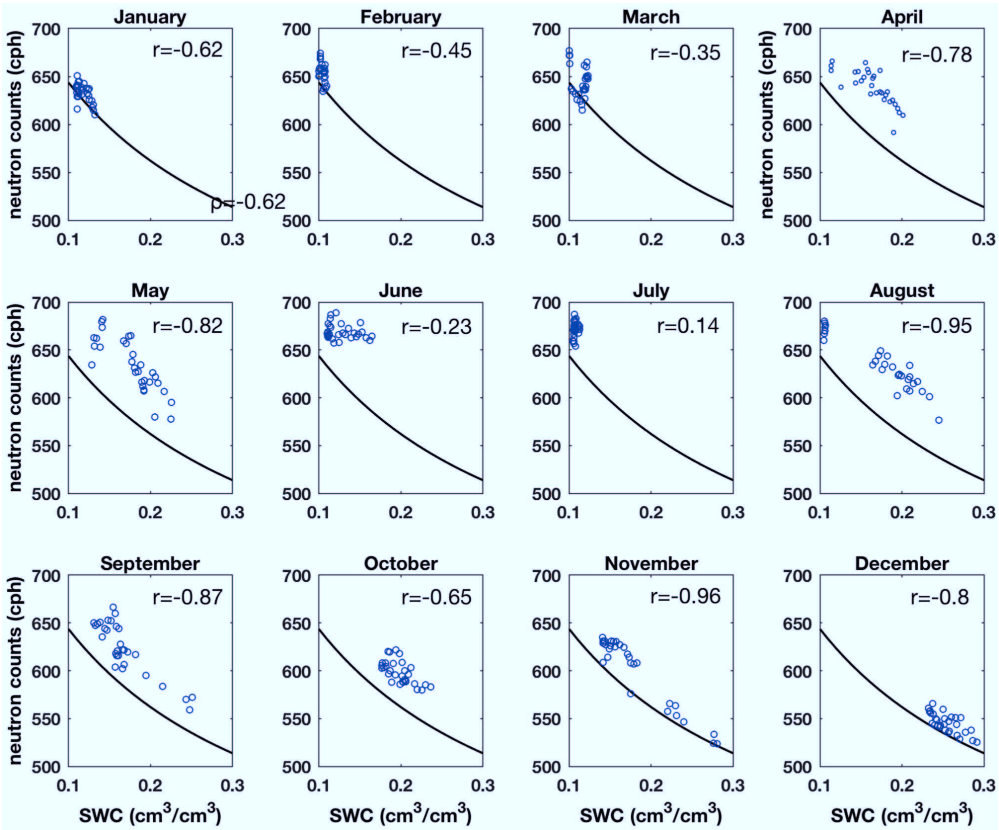

Fig. 7. Correlation between daily averaged cosmic-ray neutron sensing neutron counts (counts per hour) and footprint soil water content (SWC) for all months of 2016 with their Pearson correlation coefficients (r). The line in the background is the calibration curve.

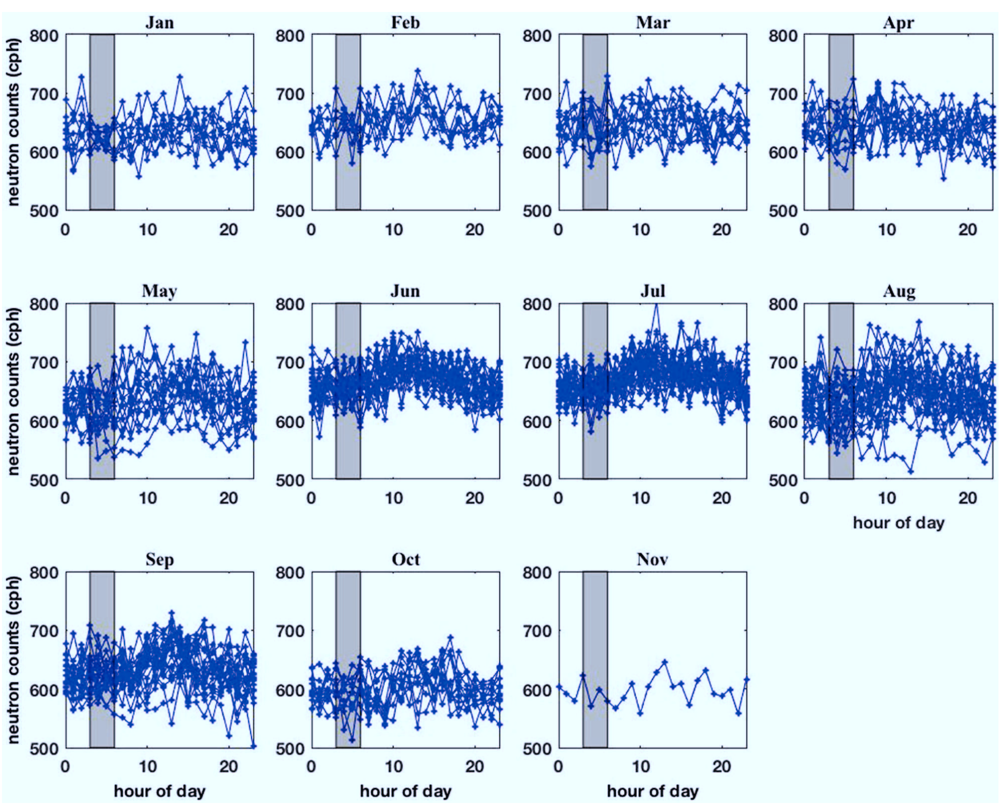

Fig. 8. Hourly neutron intensity (counts per hour) during drip irrigation days at the Picassent site from January to December 2016. Each line symbolizes the hourly variations for 1 d. The shadow area highlights the irrigation period (starts at 3 AM and lasts 1–2 h).

Table 3. Hourly normalized standard deviation (N_{SD}) of neutron intensity measured on drip irrigation days (averaged for each month).

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.
	counts/h										
N_{SD}	0.040	0.039	0.039	0.039	0.040	0.039	0.039	0.040	0.040	0.041	0.041

Inversion of Cosmic-Ray Neutron Sensing Soil Water Content by Soil Sampling Calibration

The fitted calibration curve based on the N_0 method is given in Fig. 9 and can be used to estimate the SWC from the measured neutron intensity. This curve is based on neutron intensity measurements averaged across 12-h intervals. The footprint SWC calculated from the gravimetric soil sampling on 1 June 2015 was used to carry out the N_0 calibration, assuming the wet part fraction is 8%. The FDR-derived footprint SWC, for the years 2015 and 2016, were used as verification.

Figure 9 illustrates that the calibration curve fits well with the FDR-derived footprint SWC and the corresponding neutron intensity. Figure 10 shows the estimated SWC for the CRNS footprint for the years 2015 and 2016 with this method. The RMSE between CRNS SWC and FDR-derived footprint SWC is 0.025 cm^3/cm^3. The calibrated N_0 is close to 876 counts/h for a wet fraction of 8%. The Pearson correlation coefficient and KGE value between calibrated CRNS SWC and FDR-derived footprint SWC during the research period are 0.848 and 0.842, respectively. Those values are all close to 1, suggesting a good fit between the CRNS calibration results and FDR observations.

Neutron Modeling with URANOS Model

As discussed above, we found that SWC can be estimated for the CRNS footprint with a relatively small RMSE. However, drip irrigation does not cause a large increase in the SWC of the footprint, as shown above. To further explore this, the detectable neutron density was simulated with URANOS for the whole field to test the effect of drip irrigation on the neutron intensity.

The URANOS simulation result (see Fig. 11) shows the highest neutron density for tree canopies, suggesting that the canopy locally dominates the whole pattern. The reason is that the canopy acts as an additional moderator, slowing down neutrons of higher energies to detectable medium-range energies. This effect is stronger than the moderation of medium-energy neutrons down to thermal energies, to which the sensor is mostly insensitive (Köhli et al., 2018).

As shown in Fig. 12, it is evident that the neutron intensity decreases when the irrigated soil becomes wetter. However, the FDR sensors located in the wet patches show that SWC (cm^3/cm^3) increases by a maximum of 0.05 related to irrigation (see Fig. 5; Table 2). The neutron count limit that can be detected by the CRNS probe in 1 h is approximately a 4% relative intensity change, as shown in Table 3. For a wetter case (0.14 SWC for the unirrigated soil), the change of 0.05 SWC by irrigation decreases the neutron intensity by

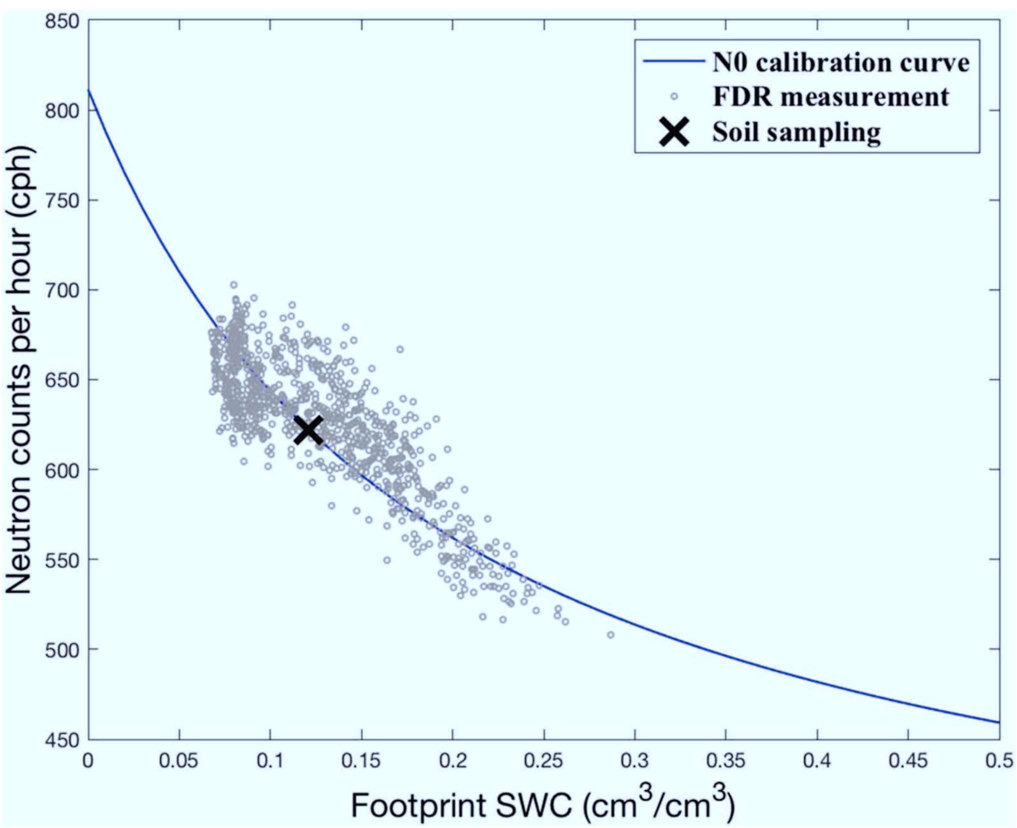

Fig. 9. The N_0 calibration curve showing the site-specific relationship between footprint soil water content (SWC) and measured neutron intensity. The cross corresponds to the gravimetric sampling campaign on the calibration day. The gray dots are the frequency-domain reflectometry (FDR) derived footprint SWC and corresponding neutron intensity.

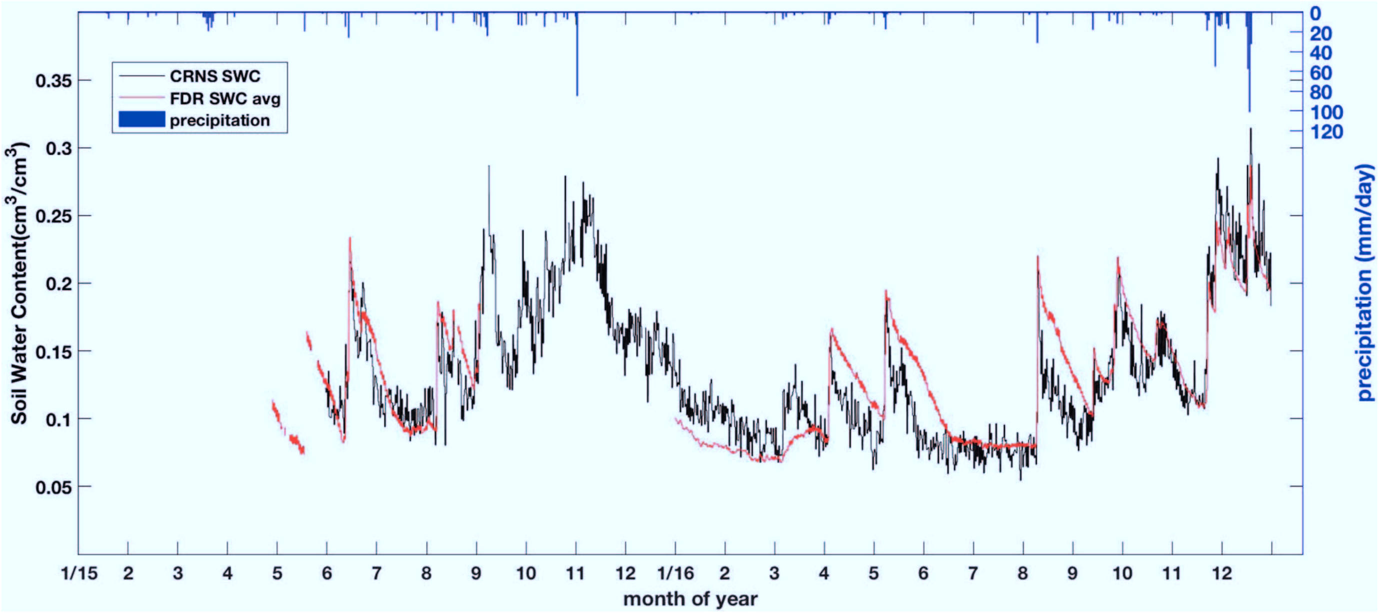

Fig. 10. Soil water content derived by the N_0 method (cosmic-ray neutron sensing soil water content, CRNS SWC) after bias correction of the frequency-domain reflectometry (FDR) sensors. Also shown are the FDR averaged footprint SWC (FDR SWC avg) and daily precipitation.

not more than 1 to 3 neutrons per hour or <1% (see Fig. 12). The total SWC change from 0.14 to 0.45 modeled with URANOS corresponds to a decrease of total neutron intensity change by 4.5%, which can be visible for CRNS. For drier unirrigated soil, the total neutron intensity change is steeper, as shown in Fig. 12. The additional 0.05 SWC caused by irrigation corresponds to a 2.1% neutron intensity change. This change in the neutron intensity could be visible for more efficient CRNS detectors or with higher integration time, but in both cases a SWC change from 0.30 to 0.35 for irrigated soil cannot be resolved.

Conclusions

The drip-irrigated site near Picassent, Spain, was used for investigating how well SWC can be estimated with a CRNS

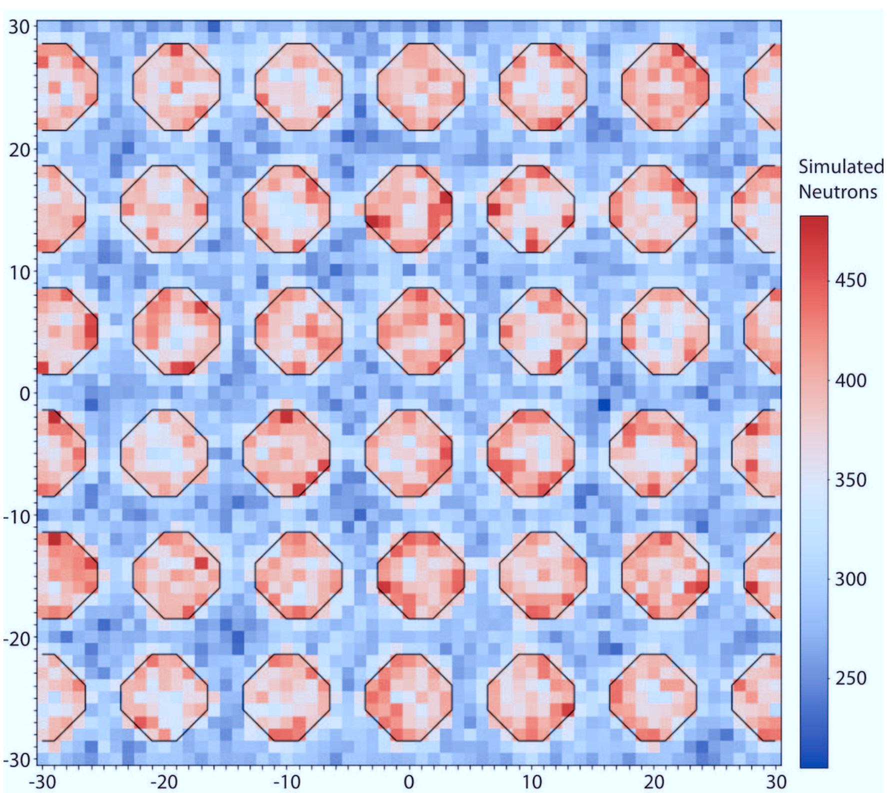

Fig. 11. Birds-eye view at a central 30- by 30-m slice of the research domain showing the modeled distribution of neutron intensity at 0.5-m resolution. Black contours indicate the location of the trees.

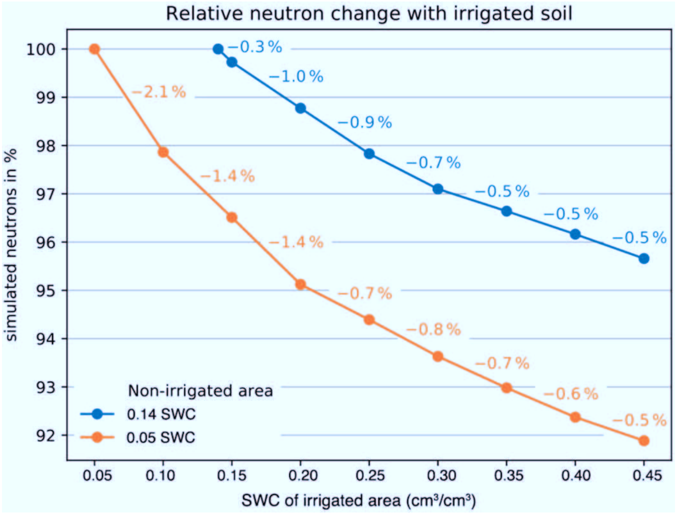

Fig. 12. Relative change in modeled neutrons as a response to drip irrigation for actual soil water content (SWC) conditions at our site (blue) and for drier conditions (orange) of the unirrigated soil.

probe and whether this can be used to reliably schedule irrigation amounts. Measurements of neutron intensity by the CRNS probe were made from June 2015 to December 2016, and SWC for the CRNS footprint was calculated for the same period. A soil sampling campaign was used to calibrate the N_0 parameter, as suggested in the CRNS literature.

The results indicate that in spite of limited calibration data, still a relatively good estimate of the CRNS footprint SWC could be obtained. Nevertheless, the soil water status of the wet, irrigated area could not be estimated precisely. Simulations by the URANOS neutron transport model confirmed that a standard CRNS probe does not allow accurate estimation of the SWC of the irrigated area at our specific site. The modeled neutron intensity changes caused by drip irrigation were lower than the statistical fluctuations of the CRNS measurement. The performance of the CRNS technique is mainly limited by the following conditions:

1. The irrigated area is only 8% of the total area. Because CRNS has an area-averaging footprint, the small patches of irrigation are hardly visible and interpretable in the neutron detector signal. We suppose that irrigation of larger areas could have a more significant influence on the CRNS signal. For example, this effect was actually observed during rain events.
2. Changes in the SWC due to irrigation are small (0.05 cm^3/cm^3) under rather wet conditions (about 0.35 cm^3/cm^3 SWC). The aboveground neutron density is much more sensitive to changes in SWC at the lower, dry end of the SWC spectrum. Hence, we suppose that the sensor would perform better in more arid regions (see also Fig. 12).
3. The irrigation is only active for a few hours. The statistical uncertainty of such a short-term neutron measurement is not sufficient to resolve changes <3%. The CRNS detector used can resolve small changes of water content only with longer integration periods of about 12 h. We suppose that larger and more sensitive detectors could be able to resolve shorter periods.

We conclude that the precise scheduling of drip irrigation is not feasible with a traditional CRNS device in our specific case, but CRNS would perform better in cases where drier soil is irrigated, during a longer time period, or with a more intense irrigation method. The sensitivity of CRNS should also be improved to get a much higher signal/noise ratio to detect small-scale drip irrigation. Non-standard CRNS probes, such as the Cosmic-ray Rover (Desilets et al., 2010; Schrön et al., 2018a) are comprised of a larger proportional counter tube and hence feature shorter integration times, allowing for higher count rates in the same time interval (Köhli et al., 2018). Multiple CRNS probes at the same field would also increase the total detected neutron intensity and decrease the statistical noise (Schrön et al., 2018b; Jakobi et al., 2018). These new instruments and measurement strategies could be further tested to observe the SWC variation caused by drip irrigation.

Acknowledgments

Dazhi Li was funded by a stipend from the government of China (CSC scholarship). The research was supported by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation), Project 414050972, Research Unit FOR 2694 “Cosmic Sense.” We are also thankful to our colleagues at the Instituto Valenciano de Investigaciones Agrarias and Universitat Politècnica de Valencia for the installation of the soil moisture sensors and for conducting field measurements.

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