Advances in Water Resources 108 (2017) 125–138

Contents lists available at ScienceDirect

Advances in Water Resources

journal homepage: www.elsevier.com/locate/advwatres

Evaluation of the soil water content using cosmic-ray neutron probe in a heterogeneous monsoon climate-dominated region

Hoang Hai Nguyen[a], Hyunglok Kim[b], Minha Choi[a,*]

[a] Environment and Remote Sensing Laboratory, Department of Water Resources, Graduate School of Water Resources, Sungkyunkwan University, Suwon, 440-746, Republic of Korea
[b] School of Earth Ocean and the Environment, University of South Carolina, Columbia, SC 29208, United States

ARTICLE INFO

Article history:
Received 14 November 2016
Revised 24 July 2017
Accepted 27 July 2017
Available online 29 July 2017

Keywords:
Cosmic-ray soil moisture
FDR soil moisture
Calibration
Validation
Temporal stability

ABSTRACT

This study was conducted to evaluate the performance of a preliminary soil moisture product estimated from the cosmic-ray neutron probe (CRNP) installed at a densely vegetated and monsoon climate area, namely the Soil Moisture - FDR and Cosmic-ray (SM-FC) site in South Korea. In this study, different calibration approaches, considering soil wetness conditions, were evaluated to select the most appropriate calibration method for deriving the best cosmic-ray soil moisture at the SM-FC site. We tested the potential application of two horizontal-vertical weighting methods, including the linear and non-linear approaches, with regard to the specific characteristics of the SM-FC site. The comparison of the two weighting approaches for *in-situ* soil moisture measurement suggested that the linear approach provided better performance compared to the non-linear in term of representing field-average soil moisture within the CRNP footprint. Our calibration results revealed that dry condition-based calibration outperformed wet condition-based calibration. The comparison of the cosmic-ray soil moisture utilizing dry condition-based calibration showed reasonable agreement with the linear weighted average soil moisture estimated from the FDR sensor network, with RMSE = 0.035 $m^3\,m^{-3}$, and bias = –0.003 $m^3\,m^{-3}$; while the worst calibration solution with the wettest conditions had RMSE and bias values of 0.077 $m^3\,m^{-3}$ and 0.063 $m^3\,m^{-3}$, respectively. The application of a biomass correction significantly improved the cosmic-ray soil moisture product at the SM-FC site, resulting in the reduction of RMSE from 0.035 to 0.013 $m^3\,m^{-3}$. A temporal stability analysis was conducted to demonstrate the feasibility of cosmic-ray soil moisture in representing soil moisture for a large heterogeneous SM-FC site. Our temporal stability analysis results indicated the representativeness of cosmic-ray soil moisture over an area with a high degree of heterogeneity, compared to single measurements from FDR stations.

1. Introduction

Soil moisture is regarded as a key variable of the water cycle, which controls the interaction between the land surface and atmosphere (Vereecken et al., 2008; Brocca et al., 2011). Characterizing the spatio-temporal variability of soil moisture improves our ability to manage meteorological and hydrological processes associated with addressing climate and natural disaster-related problems such as drought, flood, and dust outbreaks (Choi and Jacobs, 2007; Bolten et al., 2010; Jackson et al., 2010; Kim and Choi, 2015; Bell et al., 2015; Cho et al., 2017; Kim et al., 2017; Zohaib et al., 2017). Commonly, soil moisture can be estimated via various methods over different scales, consisting of ground-based measurements (e.g., gravimetric sampling, Time Domain Reflectometry and Frequency Domain Reflectometry sensors), remote sensing soil moisture retrievals from space (e.g., SMOS and SMAP sensors) or hydrological models (e.g., GLDAS and Era-Interim) (Brocca et al., 2011). However, while the *in-situ* soil moisture observations mostly provide point-scale measurements that cannot represent a heterogeneous area at larger scales; the coarse spatial resolution, long revisiting time and shallow penetration depth of microwave-based remote sensing showed the limitations in characterizing soil water content at the regional or continental scales, where the spatial variation of soil moisture content is hardly accounted for (Schmugge et al., 2002; Entekhabi et al., 2004; Wagner et al., 2008; Zreda et al., 2012). This mismatch of horizontal and vertical representativeness between those two soil moisture measurements leads to a gap at intermediate scale when validating satellite soil moisture products using ground-based datasets (Miralles et al., 2010).

* Corresponding author.
E-mail address: mhchoi@skku.edu (M. Choi).

http://dx.doi.org/10.1016/j.advwatres.2017.07.020

A promising innovation in soil moisture measurement using cosmic-ray neutrons has recently been introduced, which is expected to bridge the intermediate-scale gap in these current approaches (Zreda et al., 2008; Robinson et al., 2008). In general, the cosmic-ray neutrons on the Earth are the product of the interaction between cosmic-rays and Earth atmospheric nuclei (Hess et al., 1959). More specifically, high energy primary cosmic-rays from galactic origin, including mostly protons, collide with nitrogen and oxygen in the air to produce cascades of secondary cosmic-rays that penetrate the ground surface and interact with nuclei in soil to generate fast neutrons at 1–2 MeV (Hess et al., 1961; Zreda et al., 2008). Both theoretical calculations and actual measurements of cosmic-ray neutrons have concluded that these fast neutrons are basically moderated by hydrogen atoms and show a strong inverse correlation with hydrogen contents, which are mainly present as water (Kodama et al., 1985; Zreda et al., 2008; Zreda et al., 2011; Bogena et al., 2013). This inverse relationship suggested a feasibility to retrieve soil moisture from the conversion of low energy fast neutrons, whereas the hydrogen atoms are proportional with the soil water content.

Measured neutron fluxes using a cosmic-ray neutron probe (CRNP) are highly sensitive to the hydrogen contents within its supporting volume, which contains the horizontal footprint and effective measurement depth (Franz et al., 2013a). Initial findings pointed out that while the footprint size is a circle with a fixed radius of approximately 300 m at sea level, which is inversely proportional to atmospheric pressure and independent of soil moisture content, the measurement depth is independent of atmospheric pressure but strongly varies with different soil moisture values (Zreda et al., 2008). However, advances of Köhli et al. (2015) presented another consideration while the CRNP radius ranges from 130 to 240 m and depend on the air humidity, vegetation cover, and especially soil moisture. Since Desilets et al. (2010) initially derived a non-linear theoretical calibration function using only one calibration parameter (the N_0-method) based on neutron transport simulations, the soil water content can be converted from the measured neutron flux. To accurately quantify the neutron contributions with corresponding soil water content distributions on vertical and horizontal scales, various weighting methods have been proposed for soil moisture measured using field sampling or *in-situ* networks. Two typical weighting methods are the linear depth and distance weighting (Franz et al., 2012; Lv et al., 2014) and the non-linear depth-distance weighting approaches (Köhli et al., 2015). However, these methods require an evaluation for each individual experiment site due to the fact that different weighting methods may be preferable for different study area characteristics.

Previous studies have demonstrated the successful application of CRNP-based soil moisture retrieval all over the world. The earliest and largest cosmic-ray soil moisture network covering more than 70 distributed CRNPs – the COSMOS network, was constructed in the USA under the monitoring of the University of Arizona (Zreda et al., 2012), which also currently contributes to the International Soil Moisture Network (ISMN) system (Dorigo et al., 2011). After the first construction of the COSMOS network, Franz et al. (2012) evaluated CRNP-based soil moisture products from this network according to the field calibrations. In addition to utilizing the traditional calibration, a universal calibration function was developed in order to retrieve soil moisture content from cosmic-ray neutrons over several field areas where soil sampling is difficult to conduct and hydrogen sources can be considered separately (Franz et al., 2013a). Furthermore, Hawdon et al. (2014) also introduced the inaugural CosmOz network which employs a system of nine CRNPs across Australia. Villarreyes et al. (2011), Bogena et al. (2013), and Heidbuchel et al. (2016) generally focused on performing cosmic-ray soil moisture measurement in the low-count environments in Germany with mixed forest coverage. For the Asian region, the studies related to CRNP-derived soil moisture were carried out in China over different land cover types, e.g., heterogeneous farmland or desert steppe (Han et al., 2014; Pang et al., 2015; Zhu et al., 2015).

Regarding the Korean peninsula, there has been no research conducted in term of cosmic-ray-based soil moisture measurement by far. This suggests a need to provide an extensive analysis for a preliminary cosmic-ray soil moisture product generated at the Soil Moisture-FDR and Cosmic-ray (SM-FC) site, South Korea, expecting to enhance the motivation for further studies. Since the greater variation in the typical land cover features of South Korea with mixed forest and complex topography of mountainous areas lead to a high degree of heterogeneous soil moisture; it is necessary to apply the CRNP to limit the large number of field sampling or distributed sensor networks required for effective soil moisture monitoring. Furthermore, there have been no studies performed in a monsoon climate area where seasonal variation of precipitation is remarkable. In the current study, we aimed to investigate the performance of the CRNP over a densely forested and monsoon climate-dominated region with high soil moisture heterogeneity. As Iwema et al. (2015) highlighted, selecting appropriate wetness conditions can limit the multi-point-calibration for producing good cosmic-ray soil moisture measurement; therefore, we mainly focused on implementing calibrations based on selecting preferred soil wetness conditions. For these reasons, our specific objectives were to (1) investigate the potential application of two horizontal-vertical weighting methods, the linear (Franz et al., 2012; Lv et al., 2014) and non-linear approaches (Köhli et al., 2015), with regard to specific characteristics of the SM-FC site; (2) evaluate the performance of different calibration approaches based on selecting distinct soil wetness conditions to produce a preliminary cosmic-ray soil moisture product in a monsoon climate region of Korean peninsula; and (3) demonstrate the representativeness of our preliminary cosmic-ray soil moisture product over an area with a high degree of heterogeneity.

2. Experiment site and instrumentation

2.1. Experiment site

This study was implemented at the Soil Moisture-FDR and Cosmic-ray (SM-FC) site, a forested area belonging to the Sungkyunkwan University, Suwon, South Korea, called SM-FC site. This experiment region covers a densely vegetated area with an annual average precipitation of 1312 mm, an annual average relative humidity of nearly 70%, and an annual average air temperature of approximately 12 °C. At this site, a system including one CRNP and ten FDR stations was installed in late August 2015 (Kim et al., 2016). The detailed description data of each station's data and related information, including soil bulk density and soil texture, are summarized in Table 1. Typical soil textures of the SM-FC site have been reported as sandy loam and loamy sand soil. A location map of the CRNP and FDR sensor network at the SM-FC site is shown in Fig. 1.

2.2. Instrumentation

2.2.1. Cosmic-ray neutron probe (CRNP)

The CRNP installed at the SM-FC site (Fig. 2b) for fast neutron measurement is the CR200X model manufactured by Hydroinnova Company, LLC of Albuquerque, New Mexico, USA (www.hydroinnova.com), located at 37°17′30.7″ N and 126°57′56.7″ E (Fig. 1). This device employs a single low-density polyethylene-surrounded neutron detector filled inside with helium gas in or-

Table 1
Summary of the characteristics of CRNP and each station in the FDR soil moisture network.

Station ID	Location Latitude	Longitude	Distance r (m)	Soil texture	Soil bulk density ρ_{bd} (g/cm^3)
CRNP	37.2919 N	126.9854 E		Sandy Loams	1.51
FDR 1	37.2896 N	126.9669 E	265.2	Sandy Loams	1.51
FDR 2	37.2895 N	126.9855 E	257.9	Loamy Sands	1.63
FDR 3	37.2912 N	126.9875 E	107.4	Sandy Loams	1.51
FDR 4	37.2910 N	126.9849 E	93.0	Sandy Loams	1.51
FDR 5	37.2909 N	126.9825 E	157.4	Loamy Sands	1.63
FDR 6	37.2919 N	126.9872 E	68.1	Sandy Loams	1.51
FDR 7	37.2919 N	126.9854 E	0	Sandy Loams	1.51
FDR 8	37.2927 N	126.9870 E	113.0	Loamy Sands	1.63
FDR 9	37.2927 N	126.9854 E	94.3	Loamy Sands	1.63
FDR 10	37.2941 N	126.9869 E	251.4	Loamy Sands	1.63

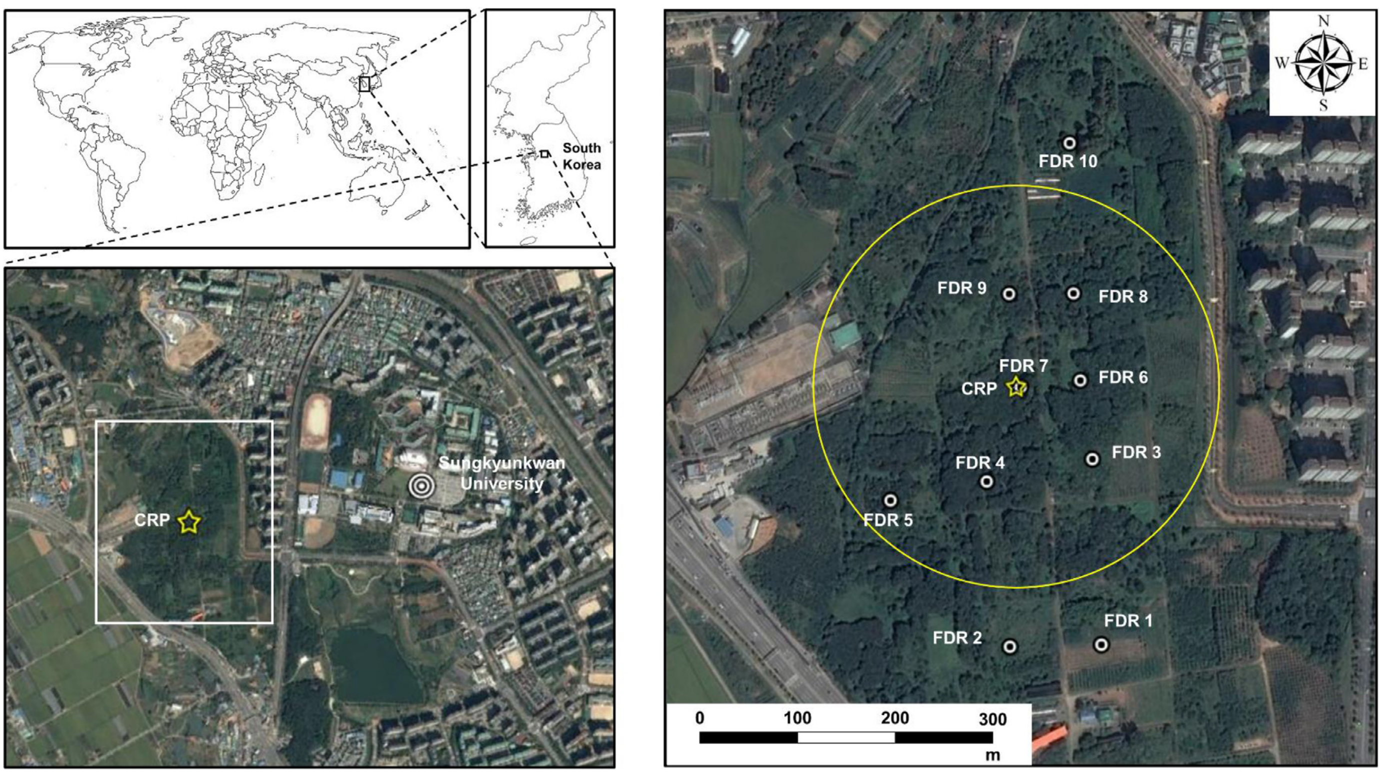

Fig. 1. Location of the CRP and FDR soil moisture network at the SM-FC site.

der to increase the sensitivity to epithermal-fast neutrons. The data logger designed by Campbell Scientific is then connected to the probe, providing fast neutron intensity measurements with additional internal temperature and relative humidity data inside the instrument at one-hour intervals.

Hourly neutron intensity measurements from September 2015 to June 2016 were utilized in this study. However, in order to avoid the snow effect during the winter period, a three-month-dataset collected from December 2015 to March 2016, was removed. To provide more accurate datasets, a similar quality control procedure as that described in Zreda et al. (2012) was applied to the raw neutron intensity measurements at the SM-FC site. Moreover, it has also been suggested that smoothing high temporal fluctuations of raw fast neutron intensity measured by CRNP using a 12-h moving average filter is necessary to reduce Poisson noise (Villarreyes et al., 2011; Bogena et al., 2013).

2.2.2. *In-situ soil moisture network*

Point-scale measurements from the SM-FC site offered the use of the Frequency Domain Reflectometry (FDR) soil moisture sensor network (Fig. 2a). The sensors employed in this research were the 5TM Soil Moisture and Temperature sensors manufactured by Decagon Devices Corporation, USA. The sensors utilizes a 70 MHz oscillator to provide water content from soil dielectric permittivity measurements using Decagon manufacturer calibration, with an accuracy of $\pm 0.03\ m^3\ m^{-3}$ (Decagon Devices, 2010). Several previous studies have reported the sufficiency of soil moisture measurements for *in-situ* networks within accuracy of $\pm 0.03\ m^3\ m^{-3}$, especially for larger scale areas (Famiglietti et al., 2008; Brocca et al., 2010; Mitelbach et al., 2011, 2012; Bircher et al., 2012).

In this experimental site, ten FDR stations were non-uniformly distributed around the CRNP, providing hourly volumetric soil moisture contents at four different depths (10, 20, 30, and 40 cm) for each station. In this study, we employed hourly soil moisture measurements at 10, 20, and 30 cm depth from the FDR stations network for a similar study period as the CRNP observations. Independent sensor testing using gravimetric soil sampling at the SM-FC site, indicated RMSE values of 0.026, 0.019, and $0.016\ m^3\ m^{-3}$ for soil moisture measurements at 10, 20, and 30 cm depth, demonstrating that the *in-situ* network can provide accu-

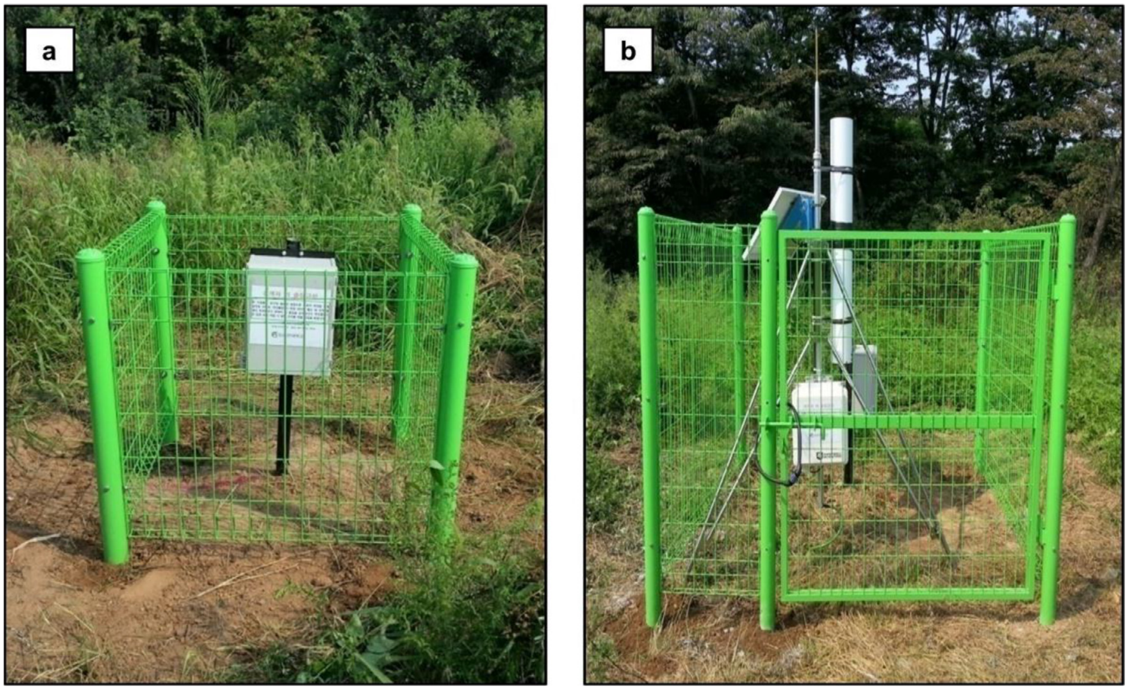

Fig. 2. (a) FDR station and (b) CRP located at the SM-FC site.

rate soil moisture products within $\pm 0.03\,m^3\,m^{-3}$. Furthermore, an automated quality control process was applied to *in-situ* measurements, as presented for the ISMN in Dorigo et al. (2012), for the FDR soil moisture network at the SM-FC site.

3. Methods

3.1. Correction for neutron intensity

The raw neutron count rate measured from the CRNP included the variations due to other environmental factors (Hawdon et al., 2014). Therefore, to exclude the impacts of environmental factors from the exact neutron signal, it is necessary to adjust for changes in air pressure, atmospheric water vapor, and incoming neutron flux. In this research, we follow the correction procedures similar to the COSMOS network as provided by Zreda et al. (2012). In particular, the atmospheric pressure correction factor (f_p) is computed as follows:

$$f_p = \exp\left[\beta\left(P - P_{ref}\right)\right] \tag{1}$$

where β is barometric pressure coefficient ($cm^2\,g^{-1}$ or $mbar^{-1}$) which can be calculated as mentioned in Desilets et al. (2006), P is atmospheric pressure at a given time of measurement, and P_{ref} is reference atmospheric pressure which can be selected as the average pressure during the study period at each specific site or sea-level pressure. For our study area, with a geomagnetic cutoff rigidity of approximately 10.5 GV (Smart and Shea, 2008), the calculated β value was $0.0071\,mbar^{-1}$ and the reference atmospheric pressure was selected as the average pressure value for the measurement period ($P_{ref} = 1015$ mbar). Additionally, the hourly atmospheric pressure dataset for the SM-FC site was collected through the Korea Meteorological Administration website (http://web.kma.go.kr/eng/). The correction factor for atmospheric water vapor fluctuations (f_{wp}) was calculated using the approach developed by Rosolem et al. (2013) as follows:

$$f_{wv} = 1 + 0.0054\left(\rho_{v0} - \rho_{v0}^{ref}\right) \tag{2}$$

where ρ_{v0} ($g\,m^{-3}$) is the near surface absolute humidity at a specific measurement time and ρ_{v0}^{ref} is the reference absolute humidity which can be calculated as the average absolute humidity over the study period for the SM-FC site ($\rho_{v0}^{ref} = 2.07\,g\,m^{-3}$). The incoming neutron intensity correction factor (f_i) is expressed as:

$$f_i = \frac{I_m}{I_{ref}} \tag{3}$$

where I_m is the measured neutron monitor intensity at a given time and I_{ref} is the baseline reference neutron monitor intensity which can be calculated as the average neutron monitor intensity over the entire study period. It is important to note that the correction for incoming neutron intensity at a location requires considering its geomagnetic cutoff rigidity (Hawdon et al., 2014). In this study, we follow the method proposed by the COSMOS network that allows data measured at the Jungfraujoch neutron monitor station to be scaled to the experiment site cutoff rigidity ($R_c = 10.5$ GV) as follows (Hawdon et al., 2014):

$$R_{c\_Scaled} = -0.075\left(R_c - R_{c\_Jung}\right) + 1 \tag{4}$$

where R_{cJung} is the cutoff rigidity at the Jungfraujoch neutron monitor station, Switzerland ($R_{cJung} = 4.49$ GV). The scaled correction factor for incoming neutron intensity (f_{i_Scaled}) can be calculated as:

$$f_{i\_Scaled} = \left(f_i - 1\right)R_{c\_Scaled} + 1 \tag{5}$$

Specifically, the time series of neutron monitor intensity at the Jungfraujoch station is collected through the website (http://www.nmdb.eu/).

Finally, the corrected neutron flux (N_{corr}) can be computed based on the equation:

$$N_{corr} = N_{raw}.\left(\frac{f_p.f_{wv}}{f_{i\_Scaled}}\right) \tag{6}$$

in which N_{raw} is the original neutron flux measured from the CRNP. The time series of corrected neutron intensity retrieved at the SM-FC site was then derived to the time series of reliable soil moisture product.

3.2. Calibration of the CRNP

To convert fast neutron intensity to volumetric soil moisture content, Desilets et al. (2010) proposed a shape-defining function based on the Monte Carlo N-Particle eXtended Transport Code (MCNPX) (Pelowitz, 2005), which is defined as follows:

$$\theta = \left(\frac{a_0}{\frac{N_{corr}}{N_0} - a_1} - a_2 \right) \rho_{bd} \tag{7}$$

where θ ($m^3 m^{-3}$) is volumetric soil moisture content, N_{corr} is corrected neutron intensity (counts per hour, cph), N_0 is neutron intensity over dry soil under the same conditions (cph), and ρ_{bd} ($g\,cm^{-3}$) is average soil bulk density. The three fitting parameters a_0, a_1, and a_2 are simulated for the generic silica soil by MCNPX, with the value of $a_0 = 0.0808$, $a_1 = 0.372$, and $a_2 = 0.115$. In this study, we averaged soil bulk density values of FDR stations within the CRNP footprint to obtain an average soil bulk density for the SM-FC site ($\rho_{bd} = 1.56\,g\,cm^{-3}$).

Preferred choices of wetness conditions for sampling days can improve calibration solutions and reduce the required number of calibration points (Iwema et al., 2015). Generally, in the current research, we aim to conduct an inter-comparison of calibration approaches for different levels of weighted average soil water contents to investigate how cosmic-ray soil moisture products varied with different soil wetness conditions. Furthermore, we also aim to identify the appropriate wetness conditions for generating a better cosmic-ray soil moisture product at the SM-FC site. The cumulative density function (CDF) applied to weighted average soil moisture was employed as an indicator of the soil wetness condition levels. More specifically, we split the CDF of weighted-average soil moisture content retrieved from the FDR sensor network into four groups at 25% intervals. The driest and wettest conditions belongs to the 0–25% and 75–100% groups, respectively. We randomly chose a typical calibration day for each single wetness condition level according to the corresponding weighted average soil moisture. For the driest conditions (0–25%), the selected calibration day should meet the criterion that no rainfall events took place within at least two or three days prior to calibration.

3.3. Weighted-average soil moisture of the in-situ soil moisture network

In-situ soil moisture measurements at the FDR stations used for calibration and validation the cosmic-ray-derived soil moisture required accurate quantification of soil moisture within the CRNP footprint. However, not every approach shows good performance at different experimental sites due to site-specific characteristics. Therefore, in the current research, we evaluated the performance of two soil moisture weighting approaches to determine the best approach to represent soil moisture within the CRNP footprint given by the specific features of our study area. Since the recent findings in Köhli et al. (2015) indicated little contribution of neutrons at distances greater than 200 m and the highest contributions recorded within 10 m of the sensor, we applied both weighting methods for the FDR stations located within the CRNP footprint radius of 200 m.

The first approach employed linear depth and distance weighting functions, proposed by Franz et al., 2012. The estimation of effective measurement depth (z^*) was:

$$z^* = \frac{0.058}{\theta_{CRNP} + 0.0829} \tag{8}$$

The vertical weighting factor, w(z), was calculated as follows:

$$w(z) = \begin{cases} \alpha(z)\left[1 - \frac{z}{z^*}\right] & 0 \le z \le z^* \\ 0 & z > z^* \end{cases} \tag{9}$$

where z is the depth at a given soil moisture measurement, α_z is defined as:

$$\alpha_z = \frac{2}{z^*} \tag{10}$$

The horizontal weighting factor, w(r), was computed as:

$$w(r) = \begin{cases} \alpha_r\left(1 - \frac{r}{R}\right) & 0 \le r \le R \\ 0 & r > R \end{cases} \tag{11}$$

where r is the distance from CRNP to each *in-situ* soil moisture station (Table 1), α_r is a constant, which is defined as (Lv et al., 2014):

$$\alpha_r = \frac{2}{R} \tag{12}$$

where R is the footprint radius of the CRNP (R = 200 m).

We adopted the second approach following the non-linear soil moisture weighting with respect to the measurement depth and horizontal footprint, which was introduced in Köhli et al. (2015). The effective measurement depth was then computed as:

$$z^* = \rho_{bd}^{-1}\left[8.32 + 0.14\left(0.97 + e^{\frac{-r}{100}}\right)\frac{26.42 + \theta}{0.057 + \theta}\right] \tag{13}$$

The non-linear depth weighting factor for a given depth of FDR soil moisture observation was defined as:

$$w(z) = e^{\frac{-2z}{z^*}} \tag{14}$$

The non-linear distance weighting factor was calculated according to:

$$w(r) = \begin{cases} F_1 e^{-F_2 r} + F_3 e^{-F_4 r} & 0.5\,m < r \le 50\,m \\ F_5 e^{-F_6 r} + F_7 e^{-F_8 r} & 50\,m < r < 600\,m \end{cases} \tag{15}$$

where z and r are defined as the depth and distance of a given FDR soil moisture measurement. The detailed computation of the remaining parameters has been fully described in Köhli et al. (2015).

Generally, considering the FDR soil moisture measurement at depth j, the final weighted average soil moisture of the FDR sensor network ($\theta_{weighted}$) for both approaches was calculated as follows:

$$\langle\theta_j\rangle = \frac{\sum \theta_j . w(z)}{\sum w(z)} \tag{16}$$

$$\theta_{weighted} = \frac{\sum \langle\theta_j\rangle . w(r)}{\sum w(r)} \tag{17}$$

3.4. Validation of cosmic-ray soil moisture with weighted average soil moisture

To evaluate the performance of each calibration solution, the soil moisture time series estimated from the CRNP using different calibrations were compared with the time series of the two corresponding weighted average soil moisture products derived from the FDR sensor network. We utilized two metrics including the root mean square error (RMSE) and bias as indicators for this evaluation, considering the criteria that better calibration campaign would generate lower RMSE and bias values.

3.5. Biomass correction for cosmic-ray soil moisture

The neutron intensity measured by the CRNP is highly sensitive to all the hydrogen pools present within the CRNP footprint, in addition to soil water content. Therefore, identifying all the hydrogen sources may contribute to producing a better cosmic-ray soil moisture product. However, while several hydrogen sources are nearly static (e.g., lattice water, soil organic matter) and implicitly or explicitly accounted for calibration (Franz et al., 2013a), other hydrogen sources are time-varying (e.g., biomass water, rainfall interception) and challenging to qualify (Baroni and Oswald, 2015). More specifically, in the case of the densely forested SM-FC site, the hydrogen contribution primarily comes from biomass water. Therefore, an effective vegetation correction approach is required to isolate the biomass-based hydrogen signal from that of the soil moisture-based hydrogen content. Several vegetation correction methods were introduced in previous studies (Villarreyes et al., 2011; Franz et al., 2013c; Hawdon et al., 2014; Baatz et al., 2015) based on empirical measurements. Since the CRNP senses the water in and on vegetation that the sensor network cannot sense; therefore, the difference between soil moisture obtained from CRNP and sensor network can be regarded as representative of the biomass water content. In this study, due to the unavailability of direct measurements, we applied the vegetation correction following the method proposed by Baroni and Oswald (2015), since they observed that biomass water equivalent (BWE) can be estimated based on the relationship between the CRNP effective depth and difference in soil water content retrieved between CRNP and FDR sensors network. In particular, the correction process can be implemented as follow. First, the calibration was conducted without considering biomass water content, and the effective depth can be computed based on Eq. (8). The CRNP-estimated soil water content then included the true soil moisture estimated from the sensor network and biomass water content, which can be expressed as:

$$\theta_{CRNP} = \theta_{FDR} + \theta_{bio} \tag{18}$$

where θ_{FDR} is the in-situ soil moisture measurement estimated from the FDR network using the weighting method, θ_{bio} represents the biomass water content within CRNP footprint. The BWE (mm) can be then defined as:

$$BWE = \theta_{bio}.z^{*}.10 = (\theta_{CRNP} - \theta_{FDR}).z^{*}.10 \tag{19}$$

It is important to note that the new hydrogen sources present in the support volume can lead to a decrease of the penetration depth z*. Consequently, the effective penetration depth was modified considering the presence of a hydrogen contribution to biomass water content as follows:

$$z^{*} = \frac{5.8 - \frac{BWE}{10}}{\theta_{CRNP} + 0.0829} \tag{20}$$

The correction process was calculated iteratively until the difference between two successive z* values was less than 0.1 cm.

3.6. Stability analysis of soil moisture derived from the CRNP and FDR network

In order to evaluate the robustness of the CRNP-based soil moisture in representing the field soil moisture of a highly heterogeneous study site, a temporal stability analysis introduced by Vachaud et al. (1985), was applied to the FDR sensors and CRNP network at the SM-FC site, assuming that the field mean soil moisture can be represented by a single soil moisture observation which is selected as a time stable location within the network. In particular, this method employed the analysis of relative differences ($\mathrm{RD_{ij}}$), which can be expressed as:

$$RD_{ij} = \frac{\theta_{ij} - \overline{\theta_j}}{\overline{\theta_j}} \tag{21}$$

where θ_{ij} is denoted as the soil moisture measured at location i (i = 1,…,N) and time j (j = 1,…,M). The mean of each sampling time j (θ_{j}) is calculated as:

$$\overline{\theta_j} = \frac{1}{N}\sum_{i=1}^{N}\theta_{ij} \tag{22}$$

The mean ($\mathrm{MRD_i}$) and standard deviation ($\mathrm{SDRD_i}$) of the relative differences for each location i are computed as:

$$MRD_i = \frac{1}{M}\sum_{j=1}^{M} RD_{ij} \tag{23}$$

$$SDRD_i = \sqrt{\frac{1}{M-1}\sum_{j=1}^{M}(RD_{ij} - MRD_i)^2} \tag{24}$$

The index of temporal stability (ITS) or root-mean-square error ($\mathrm{RMSE_i}$) of the relative differences, which includes both $\mathrm{MRD_i}$ and $\mathrm{SDRD_i}$ is given by (Jacobs et al., 2004):

$$ITS = RMSE_i = \sqrt{MRD_i^{\,2} + SDRD_i^{\,2}} \tag{25}$$

The selection of a representative location for field average soil moisture within the CRNP footprint was conducted based on considering which soil moisture station provided the lowest ITS value during the study period. In this research, we carried out a temporal stability analysis for the CRNP-based soil moisture product derived from a better calibration solution with applying the biomass correction associated with the depth-weighted soil moisture at single observations of FDR stations within the CRNP footprint obtained using the outperforming weighting approach. The dataset on the calibration day was excluded from the temporal stability analysis.

4. Results

4.1. Neutron intensity measurement

Fig. 3 shows the time series of the raw neutron intensity from the CRNP at the SM-FC site in comparison with the corrected neutron intensity over the study period. The raw neutron count rate ranged from 708 to 1131 cph with an average neutron intensity and standard deviation of 929 cph and 58 cph, respectively. Both the maximum and minimum raw neutron counts were recorded in the first three-month period, indicating a high variation in raw neutron intensity during this measurement time compared to the second three-month period. A similar pattern for the raw neutron intensity was repeated in the corrected neutron intensity. Particularly, the time series dataset ranged from 751 to 1083 cph with an average value of 936 cph. The corrected neutron intensity showed a lower standard deviation (48 cph) than the raw neutron intensity (58 cph).

4.2. Weighted in-situ soil moisture using two different weighting approaches

Fig. 4 provides the time series soil moisture data from the FDR sensor network within the CRNP footprint, which was estimated using the two different weighting approaches. It can be inferred from the graph that the soil moisture patterns generated from both weighting methods responded well to rainfall events in this study area. However, the weighting method employing non-linear functions yielded higher soil moisture values, associated with higher variability, compared to the linear function-based weighting approach. The mean - standard deviation values of the linear and non-linear weighting approaches were 0.193–0.036 $m^3\,m^{-3}$ and 0.237–0.042 $m^3\,m^{-3}$ (Table 2). In order to identify the significance of the difference between the standard deviations of the two current approaches, an *F*-test was adopted at significance level $\alpha = 0.05$. The results revealed that with the measured means and standard deviations of the two methods, the *F* value was 1.35, which was greater than the F_{critical} of 1.05, providing a rejection of the null hypothesis that the standard deviations

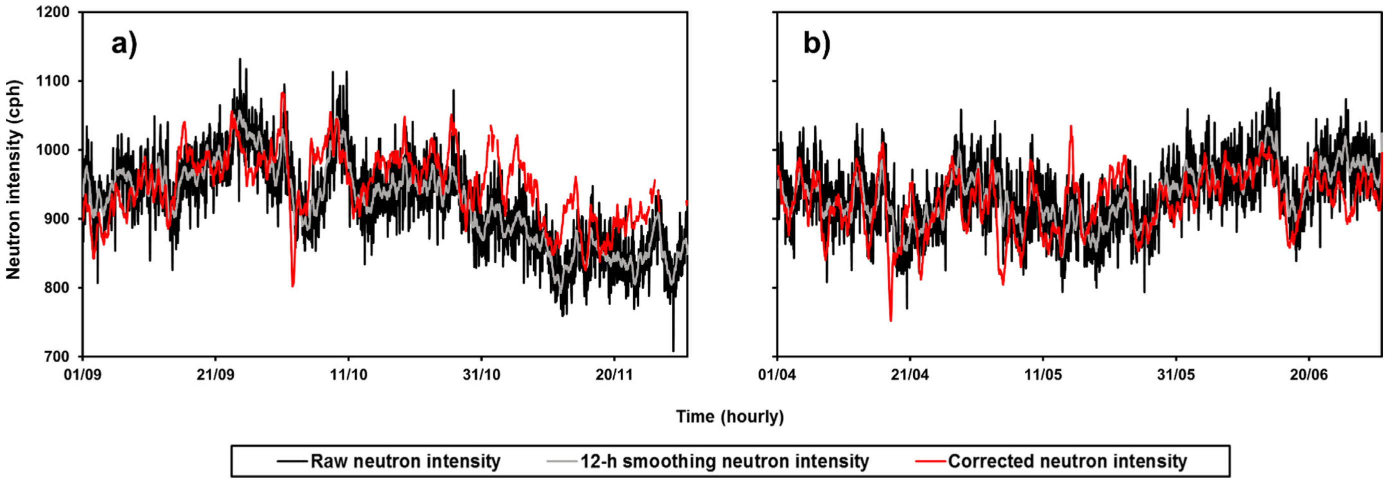

Fig. 3. The time series of raw neutron intensity (black line); 12-h moving average neutron intensity (gray line); and the corrected neutron intensity after applying 12-h moving average filter, correcting for atmospheric pressure, atmospheric water vapor, and incoming neutron intensity (red line) during the study periods in (a) 2015 and (b) 2016. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

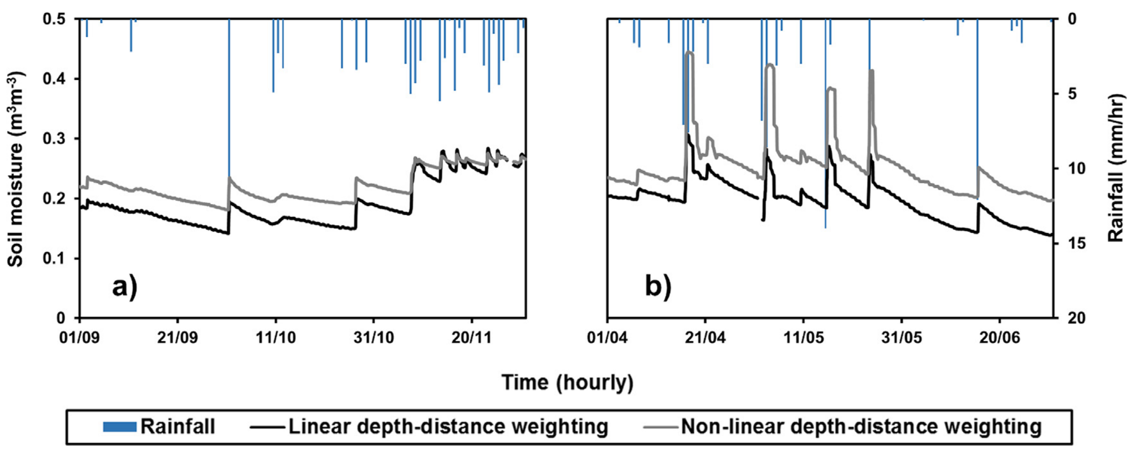

Fig. 4. Time series of weighted average soil moisture products for the FDR sensors network using the linear depth-distance weighting and non-linear depth-distance weighting methods for the study periods in (a) 2015 and (b) 2016.

Table 2
Means (μ) and standard deviations (σ) of the time series weighted average soil moisture products using linear depth-distance and non-linear depth-distance weighting approaches.

Weighting approach	$(\theta_{\mathrm{weighted}})\mu$ ($m^3\,m^{-3}$)	$(\theta_{\mathrm{weighted}})\sigma$ ($m^3\,m^{-3}$)
Linear depth-distance	0.193	0.036
Non-linear depth-distance	0.237	0.042

of the two approaches were equal. The non-linear method, therefore, derived a significantly higher variation compared to the linear approach at the 0.05 significance level.

4.3. Comparison of calibrations for different soil wetness conditions

The selection of soil wetness conditions was implemented based on the CDF of the weighted average soil moisture, which showed that the soil moisture thresholds for the driest conditions, using linear and non-linear weighting approaches, were less than $0.164\,m^3\,m^{-3}$ and $0.207\,m^3\,m^{-3}$, respectively. Those for the wettest conditions recorded were greater than $0.212\,m^3\,m^{-3}$ and $0.260\,m^3\,m^{-3}$, respectively (Fig. 5). General information for the selected calibration days at each level of 25% increment of the

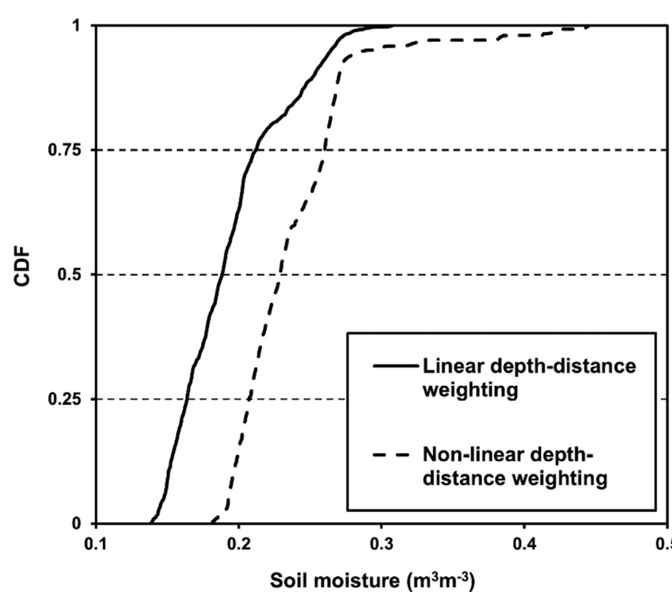

Fig. 5. The cumulative density functions (CDF) of the weighted average soil moisture products for the FDR sensor network using linear depth-distance weighting and non-linear depth-distance weighting approaches for selecting different soil wetness conditions.

Table 3
Summary of parameters used in calibration with linear depth-distance weighted and non-linear depth-distance weighted soil moisture.

Calibration	CDF levels	Day of calibration	Values in the day of calibration			
			Mean ρ_{bd} ($g\,cm^{-3}$)	Mean $\theta_{weighted}$ ($m^3\,m^{-3}$)	Mean N_{corr} (cph)	N_0 (cph)
Linear depth-distance weighting	0–25%	29/09/2015	1.56	0.145	992	1305
	25–50%	04/11/2015	1.56	0.179	977	1350
	50–75%	12/04/2016	1.56	0.203	951	1356
	75–100%	17/04/2016	1.56	0.296	896	1407
Non-linear depth-distance weighting	0–25%	29/09/2015	1.56	0.185	992	1381
	25–50%	04/11/2015	1.56	0.212	977	1408
	50–75%	12/04/2016	1.56	0.231	951	1401
	75–100%	17/04/2016	1.56	0.431	896	1549

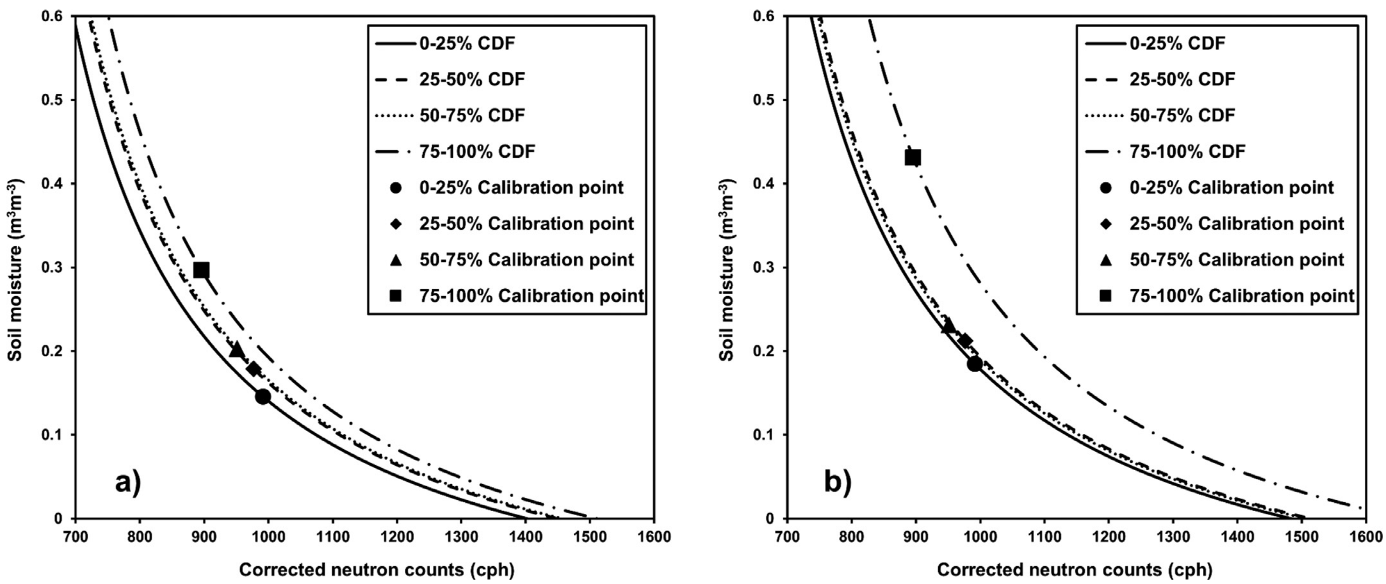

Fig. 6. Calibration curves and the points of calibration for different soil wetness conditions using the weighted average soil moisture derived from (a) linear depth-distance and (b) non-linear depth-distance weighting methods.

CDF is provided in Table 3. We then compute the soil moisture from cosmic-ray neutrons using the traditional calibration of N_0-method. The obtained N_0 for different wetness conditions ranged from 1305 cph to 1407 cph for the linear weighting approach and from 1381 cph to 1549 cph for the non-linear weighting approach. We selected one calibration scheme for each soil wetness level to generate the calibration curves as shown in the Fig. 6. This results indicated that the difference between the driest and wettest curves for the calibration based on the non-linear weighting approach was larger than that of linear weighting approach (Fig. 6). Moreover, the variation in the shape of the calibration function with respect to different soil wetness conditions was also indicated, whereas the wettest conditions-based calibration curve was steeper than driest condition-based calibration curve (Fig. 6).

The validation results of the cosmic-ray soil moisture products with weighted average soil moisture indicated the values of RMSE ranged from 0.035 to 0.077 $m^3\,m^{-3}$ for linear weighting and from 0.042 to 0.151 $m^3\,m^{-3}$ for the non-linear approach (Table 4). It is important to note that for the both proposed soil moisture weighting methods, calibrations considering drier conditions outperformed those with wetter conditions, whereas lower RMSE and bias values were produced with drier conditions (Table 4). To select a good cosmic-ray soil moisture product for the SM-FC site, we set a utility standard employing the typical error of satellite soil moisture product (0.04 $m^3\,m^{-3}$, Kerr et al., 2001; Entekhabi et al., 2010), whereas the obtained RMSE from the selected calibration scheme should not be exceeded the standard. Consequently, the soil moisture product estimated from calibration considering driest conditions and linear weighting approach can only meet the standard of utility, with the lower RMSE of 0.035 $m^3\,m^{-3}$ compared to the threshold of 0.04 $m^3\,m^{-3}$. In addition, we tested the RMSE and bias obtained from a set of N_0 ranging from 1000 to 1600 cph (Fig. 7). The results showed that for our CRNP data, the optimal solutions of the calibration were achieved with the N_0 of 1310 cph when validating with linear weighting approach, which yielded an unbiased soil moisture product at the RMSE of approximately 0.035 $m^3\,m^{-3}$. The similar pattern was repeated regarding the non-linear weighting approach, but the unbiased cosmic-ray soil moisture can be estimated at N_0 value of 1380 cph and RMSE of nearly 0.040 $m^3\,m^{-3}$ (Fig. 7). For our selected calibration options, the best solutions were recorded for the group of 0–25% CDF, when the average soil moisture during the day of calibration was 0.145 and 0.185 $m^3\,m^{-3}$ for linear and non-linear weighting approaches, corresponding to the N_0 of 1305 and 1381 cph, respectively. These obtained N_0 are close to the optimal values, demonstrating the potential in producing a good cosmic-ray soil moisture product with consideration of driest conditions. In contrast, the worst solutions were achieved with calibration during the wettest day, with maximum soil moisture values observed on the calibration day (0.296 $m^3\,m^{-3}$ for linear and 0.431 $m^3\,m^{-3}$ for non-linear methods). In evaluating the two soil moisture weighting approaches, the better calibration so-

Table 4
Validation of time series soil moisture estimated from the CRNP with the corresponding *in-situ* weighted average soil moistures using linear depth-distance and non-linear depth-distance weighting methods.

Calibration	CDF levels	N_0 (cph)	RMSE (m^3m^{-3})	Bias (m^3m^{-3})
Linear depth-distance weighting	0–25%	1305	0.035	−0.003
	25–50%	1350	0.046	0.024
	50–75%	1356	0.049	0.028
	75–100%	1407	0.077	0.063
Non-linear depth-distance weighting	0–25%	1381	0.042	0.001
	25–50%	1408	0.049	0.020
	50–75%	1401	0.047	0.015
	75–100%	1549	0.151	0.136

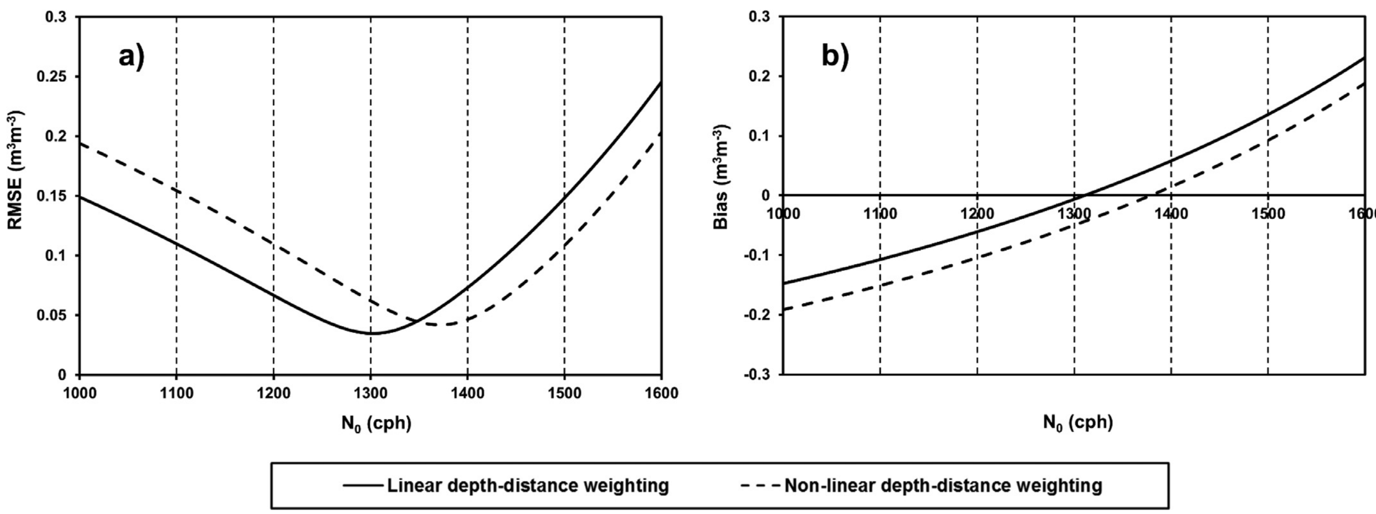

Fig. 7. a) RMSE and b) bias of the validation work of cosmic-ray soil moisture estimated from the range of N_0 with the weighted average soil moisture using linear and non-linear depth-distance weighting methods.

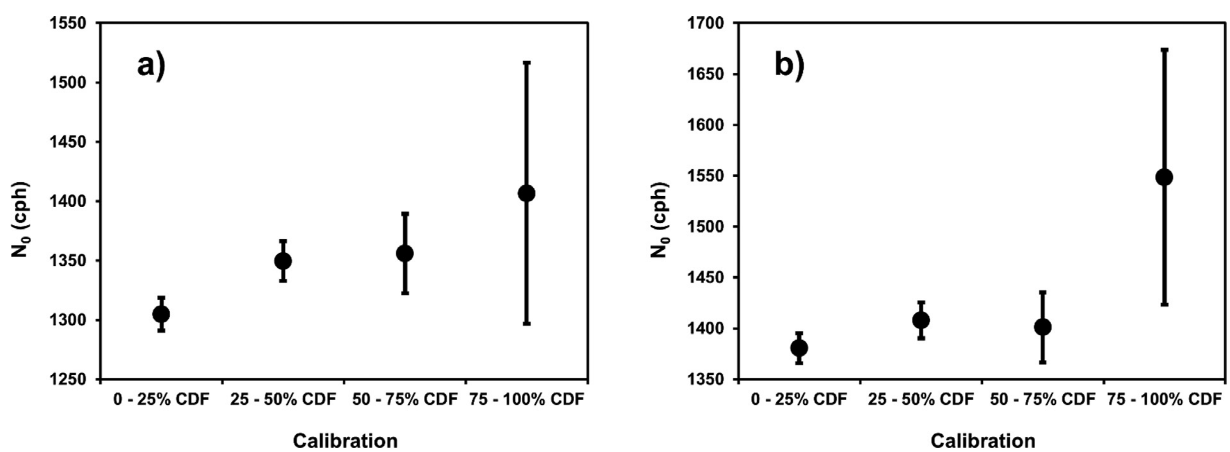

Fig. 8. Uncertainty analysis for calibrations considering different soil wetness conditions for using a) Linear and b) Non-linear depth-distance weighting approaches.

lutions tend to be obtained with the linear soil moisture weighting method (Table 4).

4.4. Uncertainty analysis

The uncertainties based on standard deviations of different N_0 for corresponding calibration solutions using the Linear and Non-linear depth-distance weighting approaches were shown in Fig. 8. In particular, we measured standard deviations in calibration datasets of the neutron intensity and soil moisture retrieved from the in-situ sensor network on the calibration days. We then propagated these uncertainties into the calibration parameter N_0 using the calibration function (Eqn. 7). As inferred from Fig. 8, with respect to the four different calibration schemes, the uncertainties in N_0 increased with increasing soil wetness conditions for both Linear and Non-linear weighting methods. Large differences in uncertainties between calibrations with driest (0–25% CDF) and wettest (75–100% CDF) conditions were captured, with standard deviations of N_0 for the driest and wettest condition-based calibrations were 1305 ± 14 and 1407 ± 110 cph when applying the Linear weighting method and 1381 ± 15 and 1549 ± 125 cph for the Non-linear weighting method, respectively. These results demon-

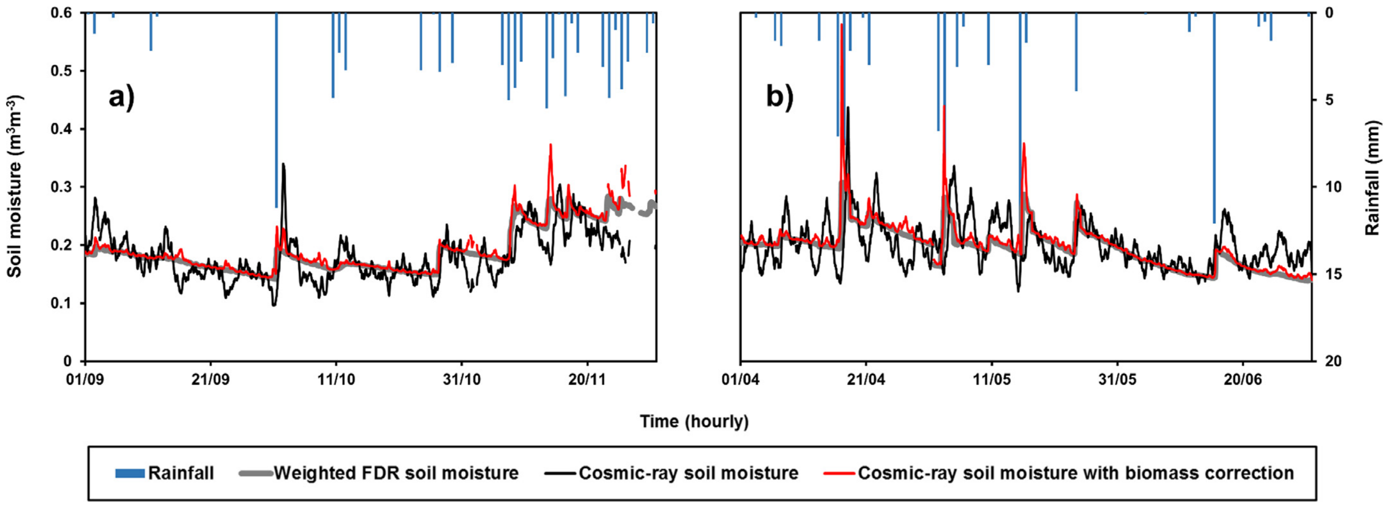

Fig. 9. Time series of hourly soil moisture estimated from CRNP with dry condition based calibration with and without applying biomass correction, and weighted average soil moisture of the FDR network using the linear depth-distance weighting approach over the study periods in (a) 2015 and (b) 2016.

strated that calibrations considering different soil wetness conditions based on the CDF curves of the weighted average soil moisture are distinguishable, especially between the driest (0–25% CDF) and wettest (75–100% CDF) conditions. Furthermore, the lowest uncertainty in N_0 for the driest condition-based calibration provided a better performance, compared to the wettest conditions, in generating cosmic-ray soil moisture product, resulting in the lowest RMSE value when calibration considering driest conditions.

4.5. Time series of soil moisture retrieved from CRNP

The time series of soil moisture product estimated with the calibration considering driest condition is shown in Fig. 9, against the linear weighted average *in-situ* soil moisture. Fig. 9 illustrates that the cosmic-ray soil moisture dynamics were strongly responsive to rainfall data, especially in the case of the small rainfall events. In detail, the cosmic-ray soil moisture varied from 0.09 to 0.44 $m^3\,m^{-3}$ with average and standard deviation soil moisture value of 0.190 $m^3\,m^{-3}$ and 0.042 $m^3\,m^{-3}$, respectively. Furthermore, the time series of the cosmic-ray soil moisture product was underestimated for the first three-month period while it was overestimated for the second three-month period (Fig. 9).

To isolate the hydrogen presence from vegetation effects, a biomass correction process following the method proposed in Baroni and Oswald (2015), was applied to the cosmic-ray soil moisture estimated from the best calibration solution. The result obtained using the vegetation correction revealed a better cosmic-rays soil moisture product, as indicated by the significant decrease in RMSE from 0.035 to 0.013 $m^3\,m^{-3}$ when comparing time series of cosmic-ray soil moisture applying biomass correction and in-situ weighted soil moisture (Fig. 9). Although there was little fluctuation in the corrected cosmic-ray soil moisture, the dynamics followed the trends of time series weighted average soil moisture from FDR network, and responded well to the rainfall. Therefore, the biomass correction successfully mitigated the vegetation effects on the CRNP at the SM-FC site.

4.6. Stability analysis of cosmic-ray soil moisture

To evaluate whether soil moisture estimated from the CRNP can represent an area with a high degree of the heterogeneity at the SM-FC site, we performed a temporal stability analysis for the best CRNP-based soil moisture product and the depth-weighted

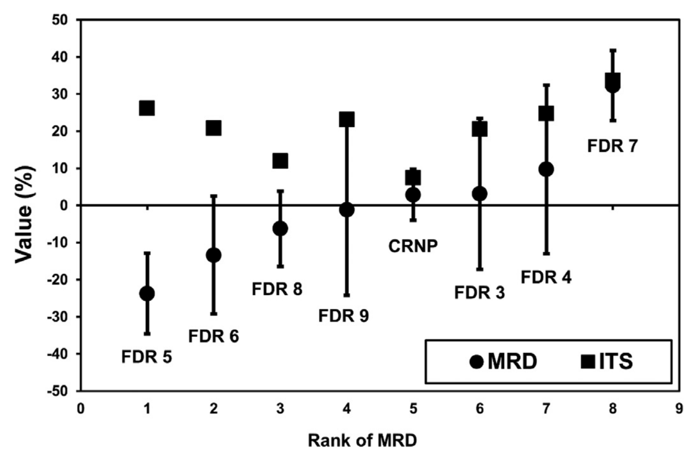

Fig. 10. Values of Mean Relative Difference (MRD) in rank and Index of Temporal Stability (ITS) for the temporal stability analysis of CRP and stations of the FDR soil moisture network.

soil moisture measurement from each station in FDR sensor network. The MRD and ITS values for all stations are shown in Fig. 10.

The results of the temporal stability analysis indicated that the MRD values ranged from −23.7% (FDR 5) to 32.3% (FDR 7), SDRD values ranged from 6.9% (CRNP) to 23.1% (FDR 9), and ITS ranged from 7.4% (CRNP) to 33.6% (FDR 7). In this study, we selected the time stable locations based on considering soil moisture stations with lowest values of ITS. In particular, two single soil moisture measurements, which provided the lowest ITS values during the study period, were the CRNP (7.4%) and FDR 8 (11.9%). In the case that cosmic-ray soil moisture is not considered, FDR 8 was selected as the representative location for field mean soil moisture estimation of the SM-FC site. Nevertheless, the lowest ITS value was provided by the cosmic-ray soil moisture when the CRNP was considered, demonstrating that the field mean soil moisture at the SM-FC site can be represented a single soil moisture observation generated from the CRNP. In addition, to evaluate the performance of the cosmic-ray soil moisture and the time stable location in estimating field average soil moisture at the SM-FC site, a comparison of soil moisture measurements at the CRNP and the FDR 8 with the field average soil moisture was implemented with regard to R and RMSE (Fig. 11). The results inferred from Fig. 11 indicated that the CRNP can provide better field mean soil moisture, resulting in higher ac-

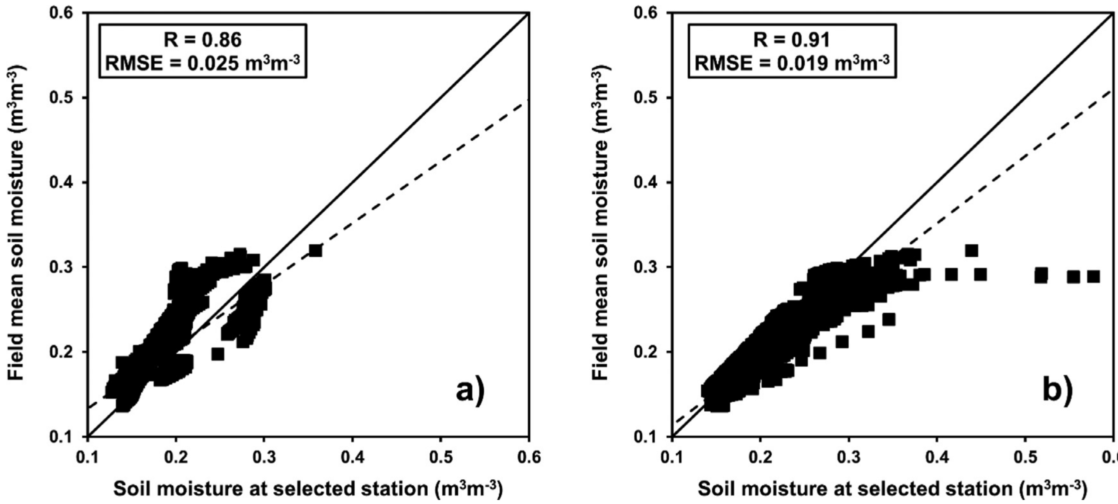

Fig. 11. Soil moisture measurements at a) Station FDR 8 and b) the CRNP versus filed mean soil moisture of the SM-FC site.

Table 5
Contribution of weight added to the corresponding measurement depth of the FDR stations within the CRNP footprint.

FDR Station	Distance r (m)	Measurement depth	Percentages of weights (%)	
			Linear weighting	Non-linear weighting
FDR 3	107.4	10 cm	94.9	68.8
		20 cm	5.1	21.1
		30 cm	0.0	10.1
FDR 4	93.0	10 cm	78.4	62.4
		20 cm	21.6	28.9
		30 cm	0.0	8.6
FDR 5	157.4	10 cm	65.8	51.9
		20 cm	23.2	26.0
		30 cm	11.0	22.1
FDR 6	68.1	10 cm	75.2	60.3
		20 cm	24.3	29.2
		30 cm	0.5	10.5
FDR 7	0	10 cm	90.6	60.2
		20 cm	9.4	30.5
		30 cm	0.0	9.3
FDR 8	113.0	10 cm	82.6	68.9
		20 cm	17.4	23.1
		30 cm	0.0	8.0
FDR 9	94.3	10 cm	90.7	74.5
		20 cm	9.3	19.5
		30 cm	0.0	6.1

curacy ($R = 0.91$, $RMSE = 0.019\,m^3\,m^{-3}$), compared to that of FDR 8 ($R = 0.86$, $RMSE = 0.025\,m^3\,m^{-3}$). These results also demonstrated that the CRNP outperformed the representative location in estimating field mean soil water content at the SM-FC site.

5. Discussion

5.1. Weighting approaches

Results from the comparison of weighted average soil moisture time series and from the calibration and validation demonstrated that a better performance was achieved with the linear weighting approach for our field site. Table 5 provides the contribution of weights added to each measurement depth at each FDR station within the CRNP footprint. As shown in Table 5, while the linear depth weighting approach did not take into account most weights in the deeper soil layers (30 cm), the non-linear depth weighting approach added much larger weights for the 30-cm soil moisture measurements, which caused higher weighted average soil water content within the footprint. It is worth noting that the neutron flux is more sensitive with the first 10 cm soil layer, so that quantifying the deeper layer in ground-based soil moisture network tends to present a mismatch on the vertical scale.

The difference between applying the linear and non-linear function can be also explained in terms of horizontal scale. The percentages of weights contributed to each FDR station as a function of distances between FDR stations and the CRNP are shown in the Fig. 12. The non-linear function produced much higher weights at FDR stations within a radius of 50 m compared to remaining stations (Fig. 12). At our field site, only the closest station, FDR 7, was located within the 50 m radius; therefore, the weighted average soil moisture employing a distance-weighting function was more likely to follow soil moisture pattern observed at station FDR 7. However, as shown in Fig. 10, station FDR 7 was the less stable location within the FDR network of the SM-FC site during the study period, especially when a high degree of soil moisture heterogeneity was present. As a result, computing the weighted average soil moisture primarily based on the single, non-stable lo-

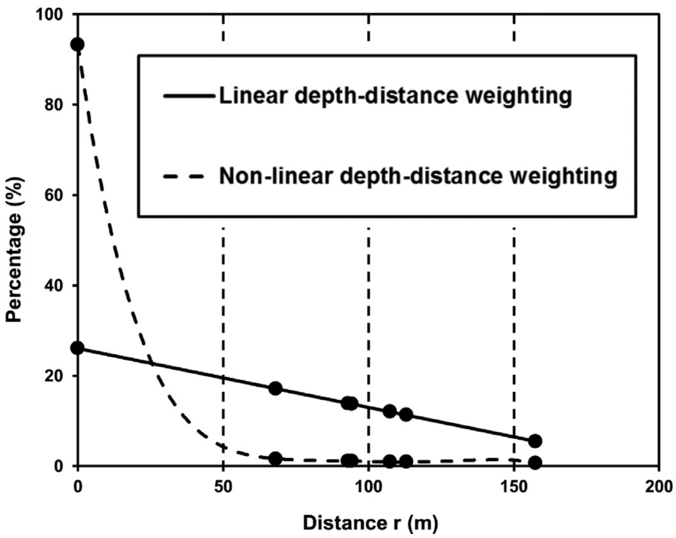

Fig. 12. The percentages of distance weights contributing to the FDR stations with respect to the corresponding distance to the CRNP for linear and non-linear soil moisture weighting approaches.

cations would not have produced a good performance. Although the linear weighting approach also considered more weights to the closest stations, the difference in their weights was not as large as in the non-linear approach (Fig. 12). This result suggested the linear weighting method was preferable for our highly heterogeneous SM-FC site.

It is worth noticing that the footprint coverage of soil moisture monitoring network can contribute significantly to the explanation of neutron signal, resulting in the quality of cosmic-ray soil moisture products (Schrön et al., 2017). Since the in-situ soil moisture network at the SM-FC site may not fully cover the CRNP footprint due to an unavailability of appropriate soil samples obtained close to the CRNP and the detailed empirical data on vegetation height, the effectiveness of non-linear weighting approach was reduced. This led to a lower performance of the non-linear method in producing a weighted average soil moisture product at the heterogeneous forest SM-FC site, despite its promising potential.

5.2. Calibration considering soil wetness conditions

The differences in calibration results between different soil wetness conditions revealed that the shape of the N_0 calibration function is variable (Fig. 6), which led to the differences resulted in time series of volumetric soil water content. This highlighted the soil moisture spatial variability at a heterogeneous area, especially in some specific conditions (Franz et al., 2013b; Heidbuchel et al., 2016). Moreover, the evaluation of different calibration schemes demonstrated the better performance of the dry condition-based calibration in generating soil moisture products compared to the wet condition-based calibration. This was due to the fact that few hydrogen pools present during dry conditions, therefore, capturing the calibration point of the soil water content signal was associated with fewer uncertainties. Better validation results were obtained with the linear weighting method compared to the non-linear function. Because the non-linear weighted soil moisture from FDR network provided higher soil moisture values even with similar soil wetness levels, the better performance of the linear approach demonstrated that the precision of calibration results was highly depended on the soil moisture values on calibration days. These results suggest that it is feasible to generate a good cosmic-ray soil moisture product when the preferable wetness condition is selected. In terms of our experiment site, calibrations considering dry conditions are likely to produce better soil moisture products from cosmic-ray neutrons.

5.3. Time series of cosmic-ray soil moisture

The dynamics of soil moisture patterns estimated from both the FDR sensor network and the CRNP were highly responsive to rainfall data during the same study period. However, in term of small rainfall event, the cosmic-ray soil moisture showed stronger response compared to the weighted average soil moisture. These results revealed the high sensitivity of fast neutrons signal to the first centimeters of the soil surface as well as to rainfall interception compared to the FDR sensor measurement (Franz et al., 2012). Moreover, since the FDR sensors only measure soil moisture at a specific installation depth, the mismatch of vertical representativeness caused the discrepancies between cosmic-ray soil moisture and *in-situ* observation, which resulted in a higher variation of cosmic-ray soil in comparison with the weighted average soil water content from the FDR network.

The significantly strong variation in cosmic-ray soil moisture compared to the FDR weighted average soil water content is likely due to the large number of hydrogen sources present at our study area. The CRNP-based soil water content time series underestimated the weighted average soil moisture from the FDR network during the first three-month period, and overestimated in the second three-month period. There was a larger rainfall amount (273 mm in three months for the second period compared to 193 mm in three months for the first period) and the vegetation effects during the growing season were present in the second period. In particular, the biomass water and rainfall intercepted by vegetation made a confusing hydrogen signal from cosmic-ray neutrons, resulting in an increase of soil moisture content over the second period (Baroni and Oswald, 2015). These results were also strongly consistent with the finding reported in Coopersmith et al. (2014), where larger Leaf Area Index (LAI) values corresponded to overestimates of COSMOS soil water content and vice-versa. Moreover, some fluctuations in cosmic-ray soil moisture pattern which is not related to rainfall events could be related to the high variation of atmospheric pressure observed over the study area.

5.4. Evaluating the representativeness of cosmic-ray soil moisture

The better performance of soil moisture retrieved from the CRNP in a temporal stability analysis at the SM-FC site demonstrated the feasibility of cosmic-ray soil moisture in representing the field-averaged soil moisture for a heterogeneous study area. Undoubtedly, with a CRNP footprint radius of hundreds meters, the cosmic-ray neutrons showed a robustness in providing a reliable soil moisture product over a larger scale compared to a point measurement from each FDR station, despite conducting in a heterogeneous area. On the other hand, cosmic-ray neutrons sensing is a non-invasive technique and less dependent on soil type (Zreda et al., 2008); therefore, the variation in different soil textures is not usually quantified in CRNP observations compared to other *in-situ* soil moisture measurements. Furthermore, that the cosmic-ray soil moisture outperformed the time stable location represented by a single FDR station in measuring field mean soil moisture at the SM-FC site revealed that the application of biomass correction to cosmic-ray soil moisture was successfully mitigated the heterogeneity at the experiment site, which is mostly due to the dense distribution of vegetation.

6. Conclusion

In summary, this study was conducted to evaluate preliminary cosmic-ray soil moisture products in the Korean peninsula. Specifically, the basic purposes of this study were to: (1) investigate the potential application of two horizontal-vertical weighting methods, the linear and non-linear approaches, with respect to the specific characteristics of SM-FC site; (2) evaluate the performance of different calibration approaches based on selecting distinct soil wetness conditions to produce the preliminary cosmic-ray soil moisture product in the Korean peninsula; and (3) demonstrate the representativeness of our preliminary cosmic-ray soil moisture product over an area with a high degree of heterogeneity.

Regarding the comparison of the two proposed soil moisture weighting methods for the FDR sensor network, the linear weighting approach provided a better performance than the non-linear approach with respect to our study area, the SM-FC site. The results retrieved from evaluating the different calibration campaigns based on selecting different soil wetness conditions revealed that calibration considering drier conditions outperformed wetter conditions. A comparison of the cosmic-ray soil moisture utilizing dry condition-based calibration showed reasonable agreement with the linear weighted average soil moisture estimated from the FDR sensor network, with RMSEv = 0.035 $m^3 m^{-3}$, and bias = −0.003 $m^3 m^{-3}$; while the worst calibration solution at the wettest conditions indicated RMSE and bias values of 0.077 and 0.063 $m^3 m^{-3}$, respectively. The application of a biomass correction mitigated the hydrogen presence in vegetation water at the densely forested SM-FC site, significantly improving the accuracy of estimated cosmic-ray soil moisture when the RMSE reduced from 0.035 to 0.013 $m^3 m^{-3}$. Finally, the results of the temporal stability analysis demonstrated the representativeness of cosmic-ray soil moisture over an area with a high degree of the heterogeneity, compared to single measurements from FDR stations.

This is a preliminary investigation of cosmic-ray soil moisture conducted in Korean peninsula; therefore, the general calibration method was adopted. This study has several limitations such as lack of appropriate in-situ soil moisture measurements close to the CRNP and detailed vegetation data which limited the robustness of the non-linear weighting approach at the heterogeneous forest SM-FC site. However, this study may give a new insight to calibrate and validate the CRNP over existed soil moisture experiment sites. Further studies will attempt to focus on improving our soil moisture monitoring network to enhance the application of non-linear weighting method for producing a better soil moisture from cosmic-ray neutron measurements at the SM-FC site.

Acknowledgments

This research was supported by the Space Core Technology Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Science, ICT and Future Planning (NRF-2014M1A3A3A02034789), and the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIP) (NRF-2016R1A2B4008312). We would like to thank the Korea Meteorological Administration (KMA) for providing the atmospheric pressure, humidity, temperature, and rainfall datasets. We also acknowledge the Jungfraujoch neutron monitor station (JUNG), Switzerland, for kindly providing neutron monitor data.

References

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

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

Bell, J.E., Leeper, R.D., Palecki, M.A., Coopersmith, E.J., Wilson, T., Bilotta, R., Embler, S., 2015. Evaluation of the 2012 drought with a newly established national soil monitoring network. Vadose Zone J. http://dx.doi.org/10.2136/vzj2015.02.0023.

Bircher, S., Skou, N., Jensen, K.H., Walker, J.P., Rasmussen, L., 2012. A soil moisture and temperature network for SMOS validation in Western Denmark. Hydrol. Earth Syst. Sci. 16, 1445–1463. http://dx.doi.org/10.5194/hess-16-1445-2012.

Bogena, H.R., Huisman, J.A., Baatz, R., Franssen, H.J.H., Vereecken, H., 2013. Accuracy of the cosmic-ray soil water content probe in humid forest ecosystems: The worst case scenario. Water Resour. Res. 49, 5778–5791. http://dx.doi.org/10.1002/wrcr.20463.

Bolten, J.D., Crow, W.T., Zhan, X., Jackson, T.J., Reynolds, C.A., 2010. Evaluating the utility of remotely sensed soil moisture retrievals for operational agricultural drought monitoring. IEEE J. Selct. Top. Appl. Earth Observ. Remote Sens. 3 (1), 57–66. http://dx.doi.org/10.1109/JSTARS.2009.2037163.

Brocca, L., Melone, F., Moramarco, T., Morbidelli, R., 2010. Spatial-temporal variability of soil moisture and its estimation across scales. Water Resour. Res. 46 (W02516). http://dx.doi.org/10.1029/2009WR008016.

Brocca, L., Hasenauer, S., Lacava, T., Melone, F., Moramarco, T., Wagner, W., Dorigo, W., Matgen, P., Martínez-Fernández, J., Llorens, P., Latron, J., Martin, C., Bittelli, M., 2011. Soil moisture estimation through ASCAT and AMSR-E sensors: An intercomparison and validation study across Europe. Remote Sens. Environ. 115, 3390–3408. https://dx.doi.org/10.1016/j.rse.2011.08.003.

Cho, E., Su, C.H., Ryu, D., Kim, H., Choi, M., 2017. Does AMSR2 produce better soil moisture retrievals than AMSR-E over Australia? Remote Sens. Environ. 188, 95–105. http://dx.doi.org/10.1016/j.rse.2016.10.050.

Choi, M., Jacobs, J.M., 2007. Soil moisture variability of root zone profiles within SMEX02 remote sensing footprints. Adv. Water Resour. 30, 883–896. http://dx.doi.org/10.1016/j.advwatres.2006.07.007.

Coopersmith, E.J., Cosh, M.H., Daughtry, C.S., 2014. Field-scale moisture estimates using COSMOS sensors: a validation study with temporary networks and leaf-area-indices. J. Hydrol 519, 637–643. http://dx.doi.org/10.1016/j.jhydrol.2014.07.060.

Decagon Devices, 2010. 5TE water content. EC and Temperature Sensors Operator's Manual Version 6. Decagon Devices Inc., Pullman, WA, USA.

Desilets, D., Zreda, M., Prabu, T., 2006. Extended scaling factors for in situ cosmogenic nuclides: New measurements at low latitude. Earth Planet. Sci. Lett 246 (3–4), 265–276. http://dx.doi.org/10.1016/j.epsl.2006.03.051.

Desilets, D., Zreda, M., Ferre, T.P.A., 2010. Nature's neutron probe: Land surface hydrology at an elusive scale with cosmic rays. Water Resour. Res 46 (W11505). http://dx.doi.org/10.1029/2009WR008726.

Dorigo, W.A., Wagner, W., Hohensinn, R., Hahn, S., Paulik, C., Xaver, A., Gruber, A., Drusch, M., Mecklenburg, S., van Oevelen, P., Robock, A., Jackson, T., 2011. The international soil moisture network: a data hosting facility for global in situ soil moisture measurements. Hydrol. Earth Syst. Sci. 15, 1675–1698. http://dx.doi.org/10.5194/hess-15-1675-2011.

Dorigo, W.A., Xaver, A., Vreugdenhil, M., Gruber, A., Hegyiova, A., Sanchis-Dufau, A.D., Zamojski, D., Cordes, C., Wagner, W., Drusch, M., 2012. Global automated quality control of in situ soil moisture data from the international soil moisture network. Vadose Zone J. http://dx.doi.org/10.2136/vzj2012.0097.

Entekhabi, D., Njoku, E., Houser, P., Spencer, M., Doiron, T., Smith, J., Girard, R., Belair, S., Crow, W., Jackson, T., Kerr, Y., Kimball, J., Koster, R., McDonald, K., O'Neill, P., Pultz, T., Running, S., Shi, J.C., Wood, E., van Zyl, J., 2004. The hydrosphere state (HYDROS) mission concept: an Earth system pathfinder for global mapping of soil moisture and land freeze/thaw. IEEE T. Geosci. Remote 42, 2184–2195. http://dx.doi.org/10.1109/TGRS.2004.834631.

Entekhabi, D., Njoku, E., O'Neill, P.E., Kellogg, K.H., Crow, W.T., Edelstein, W.N., Entin, J.K., Goodman, S.D., Jackson, T.J., Johnson, J., Kimball, J., Piepmeier, J.R., Koster, R.D., Martin, N., McDonald, K.C., Moghaddam, M., Moran, S., Reichle, R., Shi, J.C., Spencer, M.W., Thurman, S.W., Tsang, L., van Zyl, J., 2010. The soil moisture active passive (SMAP) mission. Proc. IEEE 98 (5), 704–716. http://dx.doi.org/10.1109/JPROC.2010.2043918.

Famiglietti, J.S., Ryu, D., Berg, A.A., Rodell, M., Jackson, T.J., 2008. Field observations of soil moisture variability across scales. Water Resour. Res. 44 (W01423). http://dx.doi.org/10.1029/2006WR005804.

Franz, T.E., Zreda, M., Rosolem, R., Ferre, T.P.A., 2012. Field validation of a cosmic-ray neutron sensor using a distributed sensor network. Vadose Zone J 11 (4). http://dx.doi.org/10.2136/vzj2012.0046.

Franz, T.E., Zreda, M., Rosolem, R., Ferre, T.P.A., 2013a. A universal calibration function for determination of soil moisture with cosmic-ray neutrons. Hydrol. Earth Syst. Sci. 17, 453–460. http://dx.doi.org/10.5194/hess-17-453-2013.

Franz, T.E., Zreda, M., Ferre, T.P.A., Rosolem, R., 2013b. An assessment of the effect of horizontal soil moisture heterogeneity on the area-average measurement of cosmic-ray neutrons. Water Resour. Res. 49, 1–9. http://dx.doi.org/10.1002/wrcr.20530.

Franz, T.E., Zreda, M., Rosolem, R., Hornbuckle, B.K., Irvin, S.L., Adams, H., Kolb, T.E., Zweck, C., Shuttleworth, W.J., 2013c. Ecosystem-scale measurements of biomass water using cosmic-ray neutrons. Geophysical Research Letters 40, 3929–3933. http://dx.doi.org/10.1002/grl.50791.

Han, X., Jin, R., Li, X., 2014. Soil moisture estimation using cosmic-ray soil moisture sensing at heterogeneous farmland. IEEE Geosci. Remote Sens. Lett. 11 (9), 1659–1663. http://dx.doi.org/10.1109/LGRS.2014.2314535.

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

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

Hess, W.N., Patterson, H.W., Wallace, R., 1959. Cosmic-ray neutron energy spectrum. Phys. Rev. 116, 445–457. https://dx.doi.org/10.1103/PhysRev.116.445.

Hess, W.N., Canfield, E.H., Lingenfelter, R.E., 1961. Cosmic-ray neutron demography. J. Geophys. Res. 66 (3), 2156–2202. http://dx.doi.org/10.1029/JZ066i003p00665.

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

Jackson, T.J., Cosh, M.H., Bindlish, R., Starks, P.J., Bosch, D.D., Seyfried, M., Goodrich, D.C., Moran, M.S., Du, J., 2010. Validation of advanced microwave scanning radiometer soil moisture products. IEEE Trans. Geosci. Remote Sens. 48 (12), 4256–4272. http://dx.doi.org/10.1109/TGRS.2010.2051035.

Jacobs, J.M., Mohanty, B.P., Hsu, E.-C., Miller, D., 2004. SMEX02: Field scale variability, time stability and similarity of soil moisture. Remote Sens. Environ. 92, 436–446. http://dx.doi.org/10.1016/j.rse.2004.02.017.

Kerr, Y.H., Waldteufel, P., Wigneron, J-P., Martinuzzi, J.-M., Font, J., Berger, M., 2001. Soil moisture retrieval from space: the Soil Moisture and Ocean Salinity (SMOS) mission. IEEE T. Geosci. Remote Sens. 39, 1729–1735. http://dx.doi.org/10.1002/2014WR015513.

Kim, H., Choi, M., 2015. Impact of soil moisture on dust outbreaks in East Asia: Using satellite and assimilation data. Geophys. Res. Lett. 42, 2789–2796. http://dx.doi.org/10.1002/2015GL063325.

Kim, H., Sunwoo, W., Kim, S., Choi, M., 2016. Construction and estimation of Soil Moisture site with FDR and Cosmic-ray (SM-FC) sensors for calibration and validation of satellite-based and cosmic-ray soil moisture products in Sungkyunkwan University, South Korea. J. Korea Water Resour. Assoc 49 (2), 133–144. http://dx.doi.org/10.3741/JKWRA.2016.49.2.133.

Kim, H., Zohaib, M., Cho, E., Kerr, Y.H., Choi, M., 2017. Development and assessment of the sand dust prediction model by utilizing microwave-based satellite soil moisture and reanalysis datasets in East Asian desert areas. Advances in Meteorology 2017, 1–13. http://dx.doi.org/10.1155/2017/1917372.

Kodama, M., Kudo, S., Kosuge, T., 1985. Application of atmospheric neutrons to soil moisture measurement. Soil Sci 140, 237–242.

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

Lv, L., Franz, T.E., Robinson, D.A., Jones, S.B., 2014. Measured and modeled soil moisture compared with cosmic-ray neutron probe estimates in a mixed forest. Vadose Zone J. 13 (12). http://dx.doi.org/10.2136/vzj2014.06.0077.

Miralles, D.G., Crow, W.T., Cosh, M.H., 2010. Estimating spatial sampling errors in coarse- scale soil moisture estimates derived from point-scale observations. J. Hydrometeor 11, 1424–1429. https://dx.doi.org/10.1175/2010JHM1285.1.

Mitelbach, H., 2011. Soil moisture monitoring for climate research: evaluation of a low-cost sensor in the framework of the Swiss Soil Moisture Experiment (SwissSMEX) campaign. J. Geophys. Res. 116 (D05111). http://dx.doi.org/10.1029/2010JD014907.

Mittelbach, H., Lehner, I., Seneviratne, S.I., 2012. Comparison of four soil moisture sensor types under field conditions in Switzerland. J. Hydrol. 430–431, 39–49. https://dx.doi.org/10.1016/j.jhydrol.2012.01.041.

Pang, Z., Cai, J., Fu, J., Song, W., Lu, Y., 2015. Adaptability analysis of cosmic-ray neutron method to monitoring soil moisture in desert steppe. Geo-Inf. Resour. Manage. Sustainable Ecosyst., Commun. Comput. Inf. Sci. 569, 816–824. http://dx.doi.org/10.1007/978-3-662-49155-3_84.

Pelowitz, D.B., 2005. MCNPX User's Manual Version 2.5.0. Los Alamos Natl. Lab., Los Alamos, N. M.

Robinson, D.A., Campbell, C.S., Hopmans, J.W., Hornbuckle, B.K., Jones, S.B., Knight, R., Ogden, F., Selker, J., Wendroth, O., 2008. Soil moisture measurement for ecological and hydrological watershed-scale observatories: a review. Vadose Zone J 7, 358–389. http://dx.doi.org/10.2136/vzj2007.0143.

Rosolem, R., Shuttleworth, W.J., Zreda, M., Franz, T.E., Zeng, X., Kurc, S.A., 2013. The effect of atmospheric water vapor on neutron count in the cosmic-ray soil moisture observing system. J. Hydrometeorol. 14 (5), 1659–1671. http://dx.doi.org/10.1175/jhm-d-12-0120.1.

Schmugge, T.J., Kustas, W.P., Ritchie, J.C., Jackson, T.J., Rango, A., 2002. Remote sensing in hydrology. Adv. Water Resour. 25, 1367–1385. https://dx.doi.org/10.1016/S0309-1708(02)00065-9.

Schrön, M., Köhli, M., Scheiffele, L., Iwema, J., Bogena, H.R., Lv, L., Martini, E., Baroni, G., Rosolem, R., Weimar, J., Mai, J., Cuntz, M., Rebmann, C., Oswald, S., Dietrich, P., Schmidt, U., Zacharias, S., 2017. Spatial sensitivity of cosmic-ray neutron sensors applied to improve calibration and validation. Earth Syst. Sci. Discuss. http://dx.doi.org/10.5194/hess-2017-148.

Smart, D.F., Shea, M.A., 2008. World grid of calculated cosmic ray vertical cutoff rigidities for Epoch 2000.0. In: 30th International Cosmic Ray Conference, 1, pp. 737–740.

Vachaud, G.A., Passerat de Silans, A., Balabanis, P., Vauclin, M., 1985. Temporal stability of spatially measured soil water probability density function. Soil Sci. Soc. Am. J. 49, 822–828. http://dx.doi.org/10.2136/sssaj1985.03615995004900040006.

Vereecken, H., Huisman, J.A., Bogena, H., Vanderborght, J., Vrugt, J.A., Hopmans, J.W., 2008. On the value of soil moisture measurements in vadose zone hydrology: a review. Water Resour. Res 44 (W00D06). http://dx.doi.org/10.1029/2008WR006829.

Villarreyes, C.A.R., Baroni, G., Oswald, S.E., 2011. Integral quantification of seasonal soil moisture changes in farmland by cosmic-ray neutrons. Hydrol. Earth Syst. Sci. Discuss. 8 (4), 6867–6906. http://dx.doi.org/10.5194/hessd-8-6867-2011.

Wagner, W., Pathe, C., Doubkova, M., Sabel, D., Bartsch, A., Hasenauer, S., Bloschl, G., Scipal, K., Fernandez, J.M., Low, A., 2008. Temporal stability of soil moisture and radar backscatter observed by the Advanced Synthetic Aperture Radar (ASAR). Sensors 8 (2), 1174–1197. http://dx.doi.org/10.3390/s80201174.

Zhu, Z., Tan, L., Gao, S., Jiao, Q., 2015. Observation on soil moisture of irrigation cropland by cosmic-ray probe. IEEE Geosci. Remote Sens. Lett. 12 (3), 472–476. http://dx.doi.org/10.1109/LGRS.2014.2346784.

Zohaib, M., Kim, H., Choi, M., 2017. Evaluating the patterns of spatiotemporal trends of root zone soil moisture in major climate regions in East Asia. J. Geophys. Res. Atmos. 122. http://dx.doi.org/10.1002/2016JD026379.

Zreda, M., Desilets, D., Ferre, T.P.A, Scott, R.L., 2008. Measuring soil moisture content non- invasively at intermediate spatial scale using cosmic-ray neutrons. Geophys. Res. Lett 35 (L21402). http://dx.doi.org/10.1029/2008GLl035655.

Zreda, M., Zeng, X., Shuttleworth, J., Zweck, C., Ferre, T., Franz, T., Rosolem, R., Desilets, D., Desilets, S., Womack, G., 2011. Cosmic-ray neutrons, an innovative method for measuring area-average soil moisture. GEWEX 21 (3), 6–11.

Zreda, M., Shuttleworth, W.J., Zeng, X., Zweck, C., Desilets, D., Franz, T., Rosolem, R., 2012. COSMOS: the cosmic-ray soil moisture observing system. Hydrol. Earth Syst. Sci. 16 (11), 4079–4099. http://dx.doi.org/10.5194/hess-16–4079-2012.