Impact of Multi-Day Field Calibration of Novel Cosmic-Ray Soil Moisture Sensors

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Abstract—**Soil moisture plays an important role in agriculture, hydrology, and land-atmosphere processes. Over the years, there has been a scale gap between traditional point-scale sensors and large-scale soil moisture products from satellite remote sensing. Recent advances suggest the use of cosmic-ray sensors (CRS) that provide integrated soil moisture at sub-kilometer scale (~300m radius and 10 to 70cm depths). The CRS works based on interactions between cosmic-ray neutrons which are attenuated by hydrogen content within its footprint (mainly soil moisture), so that more (few) neutron counting rates by the sensor corresponds to drier (wetter) soils. Site-specific calibration is required for this method, which is based on collecting soil samples within the footprint of sensors. Up until recently, it has been accepted that a single calibration day would provide enough information for accurately calibrating. However, recent modeling studies suggest that multiple calibration days can reduce CRS signal uncertainty. For this research, we test the impact of multiple-day calibration at three sites located in an organic farm in southern UK. We have analyzed all possible combinations from 3 calibration days to investigate whether uncertainties are further reduced with additional days as well which wetness combination can provide best accuracy to CRS. High uncertainties were observed when only one single soil sampling was taken. The results also indicated the benefits of at least 2-day calibrations at all sites which gives optimum soil wetness condition at approximately 0.4cm^{3}cm^{-3}.**

Keywords—Cosmic-ray soil moisture sensor; Sensor calibration days; Sensor accuracy

I. INTRODUCTION

In situ soil moisture is commonly measured with point-scale sensors [1]. However, the inherent small-scale heterogeneities of soils can reduce the accuracy and sub-kilometer monitoring with multiple sensors can be expensive and time-consuming. One the other end of spatial scale, satellite remote sensing products can estimate integrated soil moisture values over hundreds to thousands of square kilometers [1]. In addition, satellite signals can easily be interfered by other radiation sources. They also suffer from several limitations, such as shallow vertical penetration, poor coarse spatial resolution, high cost and short life span. The new monitoring technology called Cosmic-Ray Sensor (CRS) can fill the critical scale gap between point measurements and remote-sensing products [2]. As with most soil moisture sensors, the CRS needs to be calibrated for better accuracy. It is commonly accepted that a single calibration day is sufficient to provide enough soil moisture accuracy from cosmic-ray neutrons measured by the CRS. Iwema et al. [3] has applied a modelling approach to investigate the effect of multiple calibration days on the CRS signal. They found that, although a single calibration day is indeed sufficient for dry (semi-arid) sites, multiple days are needed for more humid locations such as North-western Germany and UK. The work presented here investigates these findings looking directly at the measured datasets from three sites located in Southern UK, to expand our understanding in UK humid locations beyond the work by Iwema et al. [3].

II. COSMIC-RAY SOIL MOISTURE METHOD

In atmosphere, primary cosmic-rays interact with particles to produce cascades of secondary neutrons. While these high-energy neutrons penetrate atmosphere and enter soil, they collide with nuclei in soil to trigger the release of fast neutrons. When these neutrons diffuse back to the atmosphere, they can be detected by the CRS [4]. The intensity of these neutrons detected by CRS depends strongly on hydrogen content within the footprint (mainly soil moisture), because hydrogen atoms in soil have a very high capacity to slow cosmic-ray neutrons down and thermalize them, resulting in less neutrons being emitted into air. Therefore, the intensity of the cosmic-ray neutrons detected by CRS is inversely correlated with soil moisture, as follows [5].

$$\theta(t) = \left[\frac{a_0}{\left(\frac{N_{corr}}{N_0} - a_1\right)} - a_2\right] \cdot \rho_{bd} \tag{1}$$

where, θ(t) is CRS footprint average volumetric soil moisture content (cm^{3}cm^{-3}), a0, a1 and a2 are three coefficients with fixed values at 0.0808, 0.372 and 0.115 respectively, N0 (counts per hour: cph) is the site-specific calibration parameter. ρ_{bd} (g cm^{-3}) is the soil dry bulk density. Parameter N_0 is calibrated by rearranging equation (1) (i.e., N0 in the left-hand side) and using soil moisture values obtained from soils samples collected at multiple profiles within the footprint.

III. METHODOLOGY

The data were collected from three sites located at the Sheepdrove Organic Farm on the West Berkshire Downs in South England. This region has an average precipitation about 815.1mm yr^{-1}, and the mean daily minimum and maximum temperatures are 5.4 °C and 14.0 °C, respectively. The three sites represent different physical characteristic in land use and soil types, as showed in Fig. 1 and summarised in Table 1. Soil samples were collected at each site for three times in different months: July/2015, November/2015 and February/2016, respectively; to represent various meteorological conditions and vegetation growth stages. Samples were subsequently

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taken to the laboratory and oven dried at 105°C for 24 to 48 hours allowing volumetric water content (θ) and dry bulk density (ρ_{bd}) to be calculated. Calibration parameter N_0 for different combinations (i.e., using day 1, day 2, day 3, days 1 and 2, days 1 and 3, days 2 and 3, and finally all three days) on of the three calibration days were then obtained with soil sample information. For each combination, an N_0 parameter is obtained, resulting in different versions of Equation 1 to be tested against independently measured soil moisture from soil samples. The differences between the estimated soil moisture from Equation (1) and observed values are compared mean bias (Bias) and root mean squared deviation (RMSD) metrics.

Figure 1: Land cover and CRNS of the three sites, namely Pounds 2b (left), Melville Woods (center), W2/W3 (right).

Table 1: Characteristic of the three sites

Site	Latitude	Longitude	Land cover	Soil type
Pound 2B	51.515°N	1.458°W	Grasslands and croplands	Brown clay
Melvilles Woodland	51.523°N	1.486°W	Mixed forest	Grey loam
W2W3	51.529°N	1.468°W	Grasslands and croplands	Grey loam

IV. RESULTS

As shown in Fig. 2, yellow, green and purple columns represented Bias and RMSD values of using a single, two or three calibration days, respectively. RMSD values of the first calibration day were relatively high suggesting that a single calibration can introduce additional uncertainty due to different stages of vegetation cover and soil wetness not fully representative of site average conditions. Melvilles Woodland had relatively larger values because of its relatively high vegetation content compared to the other two sites. Vegetation can be regarded as providing an additional hydrogen source due to biomass which can be taken care separately with laborious measurements. Here, we are investigating whether multiple calibration days can indirectly reduce such impacts. Overall, results from Figure 2 suggest that a 1-day calibration strategy does not effectively reduce all uncertainties in the CRS signal, suggesting that errors can be further reduced with two to three additional calibration days. This corroborates the modelling results obtained by Iwema et a. [3], especially at humid sites similar to the ones investigated in this study. W2/W3 had higher RMSD values on the third calibration day. Due to rain-fall and wind, samplings from 75 to 200m away the CRNS were not taken on the third day. Overall, yellow columns (single day) were relatively higher than green (2-day) and purple (3-day) ones, which demonstrated that using the 1-day strategy is not always sufficient to reach an accurate result, and the 2-day strategy is more efficient.

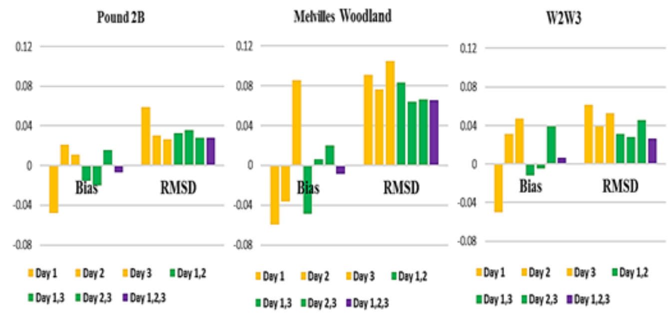

Figure 2: Histogram of Bias and RMSD (both in $cm^3\ cm^{-3}$) for different combinations of calibration days.

Additionally, we investigated whether the average soil wetness conditions from multiple combinations of calibration days have any influence on the quality of calibration. Given the limited number of calibrations undertaken at each site (i.e., a total of three per site), we assume the calibration using all three days to be our reference point for comparison. With the three-day calibration, we expect the calibration to reduce and indirectly account for any remaining uncertainties (obviously, the more calibration points the lower the expected error, but each calibration day can take 3 to 7 hours of time per site).

We analyzed the results for both RMSD and Bias, but for simplicity, we show only the results for Bias in Fig. 3. It is important to remember that with Bias, computed values can be either positive and negative and that the aim is to reduced it to zero. Our results clearly indicate a strong linear relationship between Bias and soil wetness. In addition, we also notice the benefit of multiple calibration as the 3-day reference calibration strategy is shown to be very close to the zero bias value for all three sites, followed by 2-day calibration points (with exception of a single 1-day calibration which performs slightly better). Linear regression is computed for all sites to determined optimum soil wetness condition for sampling. The optimum soil wetness condition at Pounds 2B, Melville Woodland, and W2W3 were 0.39, 0.39, and 0.35 $cm^3\ cm^{-3}$, respectively. Also interestingly, the coefficient of determination computed for each site show the lowest values at the Melville Woodland (R^2 = 0.80) , followed by the grassland/cropland Pounds 2B site (R^2 = 0.92), and the highest value calculated at the grassland W2W3 site (R^2 = 0.97). The increase in R^2 shows some correlation to vegetation cover, so that sites with less vegetation cover (and possibly with low seasonality in growth), e.g., grasslands, show better performance when calibrated for multiple days.

Finally, we compute the deviation between different calibration strategies for one and two-day calibrations against our reference three-day calibration case for the W2W3 site, as an example (Fig. 4). The different colored-lines indicate different combinations. We observed that 2-day combinations with similar average wetness to our reference case (yellow line in Fig. 4) resulted a mean deviation of approximately 0.01 $cm^3\ cm^{-3}$ (corresponding to an average percent error on the order of 3% with respect to site-average soil wetness). On the other hand, if a single calibration day is carried out on a day not much representative of site-specific soil wetness range (e.g., red line), the deviation from our reference case is on the order of 0.05 $cm^3\ cm^{-3}$ (i.e., approximately 14% average percent error) with higher values exceeding 0.07 $cm^3\ cm^{-3}$ during the wet winter season, ultimately corresponding to percent errors on the order of 20%.

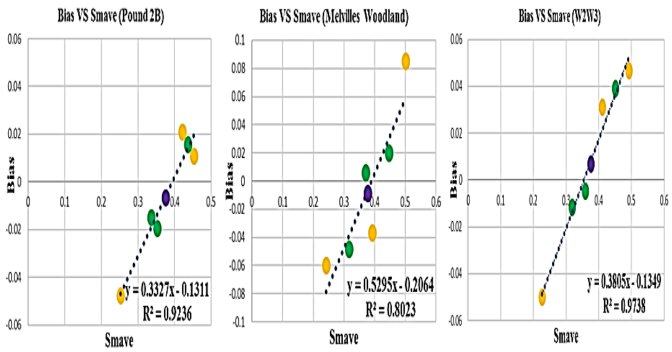

Figure 3: Mean Bias (in $cm^3\ cm^{-3}$) as a function of average soil wetness (in $cm^3\ cm^{-3}$). Yellow, green, and purple circles correspond to different calibration strategies with one-, two-, and three-day combinations, respectively. Notice, in the case of one-day calibration, site average wetness is the actual soil moisture obtained during calibration. The equation provided gives an indication of the "preferred" average soil wetness conditions for calibration.

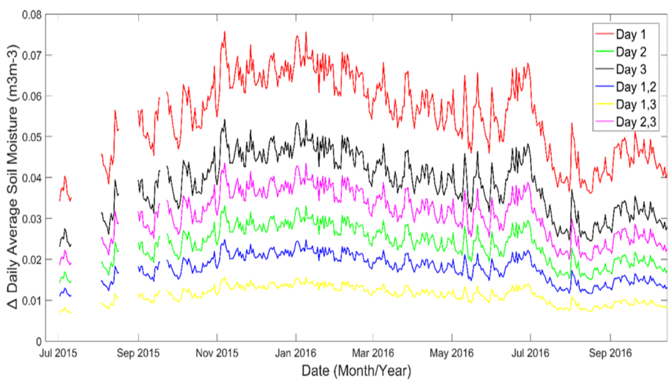

Figure 4: Differences in daily average soil moisture between the reference case (i.e., 3-day calibration) and all other combinations.

V. CONCLUSION

Recent developments in hydrologic science have highlighted the need to accurately measure soil moisture. Cosmic-Ray Sensors (CRS) provide unique opportunity for estimating soil moisture at unprecedented sub-kilometre scales. The principle of CRS is based on measuring low-energy (fast) neutrons which can be converted to soil moisture signal via site-specific calibration. Finding optimum strategies for field sampling will help researchers to obtain reliable calibration of key calibration parameter N0, consequently reducing the uncertainties in CRS signal. The performances of CRS for different combinations of the three calibration days at three UK sites have been investigated in this study. It has been found that the uncertainty in translated soil moisture data can be reduced by increasing sampling days. We found considerably improvement in estimated soil moisture by CRS when 2 or 3 field sample days are used to calibrated N0 parameter. This improvement is also found to be closely related to the average soil wetness conditions. At our three sites, we also determined the target soil wetness for near "optimum" calibration and we found that the strength of the linear relationship between calibration error and soil wetness could potentially be related to effect of aboveground biomass.

Since we only have data from three sampling days for each site, our analysis clearly indicates the impact (or disadvantage) of 1-day calibration strategy. However, we cannot make a clear conclusion on whether 2 or 3-day calibrations are sufficient at these sites (more calibration points would be needed in those cases). However, given that the common approach by CRS users is to calibrate N0 parameter with a single sampling day, our results do show key limitations with this current practice.

Overall, it is advisable to collect soil samples on more than one single calibration day possibly, representing average soil wetness conditions at specific sites. This could be achieved at sites where independent measurements of soil moisture (even if not at the same scale) are continuously recorded. Moreover, it has been found that distinct land covers and vegetation distributions can impact the estimates of soil moisture from CRS. Multiple day calibration can reduce this noise by indirectly incorporating these changes into the calibrated N0 parameter.

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