Author Response to Reviews of

Improving Calibration and Validation of Cosmic-Ray Neutron Sensors in the Light of Spatial Sensitivity – Theory and Evidence

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RC: ***Reviewer Comment***, AR: *Author Response*, ☐ Manuscript text

Dear Prof. Dr. Bob Su,

we are greatful to the reviewers for the consistent evaluation of our revision as being of "excellent" quality, and for highlighting few technical corrections. Please find below our response to the suggestions, highlighting the changes that we did to improve readability of the manuscript.

1. Reviewer #2

1.1. Figure 1 caption

RC: ***Do you want to say the conventional approach "overestimate" the weight for the shallow layer, when compared to the revised approach? and the 'Equal" underestimate the weight (vs. "revised") for shallow layer, while overestimate for the deeper layer?***

AR: *The wording depends on the perspective (absolute or relative), but we agree that given the data in the figure, the word "overestimate" is more appropriate here:*

> **Figure 1.** (a) A comparison between the *revised* and the *conventional* penetration depths, $D(\theta, r, \varrho_{\text{bulk}} = 1.4\,\text{g/m}^3)$ and $D^{\text{conv}}(\theta)$, respectively. On average, both approaches follow an almost similar shape, however the conventional formulation is independent of distance r and soil bulk density ϱ_{bulk}. (b) Normalized vertical weighting functions (eqs. 3 and 4) based on 12 sample points. The conventional, linear approach ~~underestimates~~ overestimates the relative contribution from shallow water when compared to the revised, exponential function, and neglects contributions from depths beyond $D^{\text{conv}} \equiv z^*$ ($= 23\,\text{cm}$ in this example).

1.2. Page 10 Line 13

RC: ***What does ϑ stand for? Areal contribution?***

AR: *This is a standard symbol for the solid angle in polar coordinates, we added a short explanation:*

> Let $\Omega(r, \vartheta)$ ~~[m^3]~~(in m^3) be the spatial domain of the footprint volume in polar coodinates ~~,~~ (radius r, solid angle ϑ), Ω_P ~~[m^2]~~(in m^2) the horizontal representative area of the profile P, and Ω_L ~~[m]~~(in m) the representative soil horizon of the measurement at layer L.

1.3. Page 15 Line 21

RC: ***"unique"***

AR: *Both meanings are similar, but we agree to replace "single" by "unique":*

> Fig. 5 demonstrates how the *equal* (red) and *conventional* (orange) weighting of the three calibration datasets deviate significantly from the ~~single~~ unique theoretical relation $N(\theta)$.

1.4. Page 17 Line 11

RC: ***delete "the"***

AR: *Thank you, we deleted "the".*

> In the intensive monitoring site *Schäfertal* a CRNS probe is located in the center of a small area that is covered by ~~the~~ a soil moisture monitoring network.

1.5. Page 16 Lines 13–15 and Figure 6 caption:

RC: ***This is a bit contradicting. Please see my comments for Figure 6.***

According to Figure 6, the July neutron counts are always higher than May, either using conventional or revised. Please clarify with your statement on "unrealistic reduction of hydrogen pools" during July and after harvest. And, from the figure, you can see Oct is actually getting the lower neutron counts than May. In that case, do you want to say following: July's N > May's N is contradicting the "increasing N represent decreasing water equivalent" Nevertheless, as i mentioned, for both conventional and revised, July's N > May's N. How to explained?

AR: *The way we described the observations was correct. However, if the figure is not properly understood, it could induce an apparent contradiction. We admit that our point was hard to understand and that the figure does not clearly transport this specific messsage, as the "reduced biomass effect" was considered a side note. We changed the caption of Figure 6 and refered to the text for details:*

> **Figure 6.** Recalibration of the CRNS sensor in an agricultural maize field (Braunschweig, Germany). Sizes of the circles indicate the corresponding uncertainty range of the measurement, while every such measurement corresponds to a calibration curve $\theta(N, N_0)$. The *conventional* weighting approach is not able to provide a unique theoretical line through the three calibration days~~and further predicts unrealistic reduction of hydrogen pools during maximum plant height~~. Furthermore, for a given neutron observation the difference between estimated moisture (~~July~~lines) and ~~after harvest~~ actual soil moisture (~~Oct~~ellipses) indicates unrealistic biomass dynamics throughout the study period (see explanations in the text). The revised approach converges the datasets to confirm the accepted neutron theory almost in a single calibration curve within uncertainties (size of ellipses).

AR: *We rewrote the text to describe the effect in a more clearer way:*

Insights from the British grassland have also been confirmed with calibration datasets from an agricultural site near *Braunschweig*. During the agricultural season in 2014, Scheiffele 2015 used the *COSMOS standard sampling scheme* for three calibration campaigns ~~during the agricultural season 2014~~ in May (~~no crop~~very small crop, mediocre soil moisture), July (maximum water content in biomass, dry soil), and October (~~after harvest).~~ biomass residues after harvest, mediocre soil moisture). The general behavior of the soil moisture dynamics could be reproduced well (Fig. 6), independent of the campaign used for calibration (i.e., determination of N_0). In all three cases, the neutron counts reflect that soil has dried considerably from May to July, to levels below 10 %, followed by a period of high precipitation and irrigation that led to increased soil wetness in October. However, the performance of the sensor to reflect exact soil moisture states depends on the calibration dataset. Using the *conventional* averaging approach~~(orange), the three~~ , the corresponding calibration curves in Fig. 6 ~~indicate that similar soil moisture conditions correspond to increasing neutron counts from May to~~ (orange lines) indicate a non-unique relationship between neutrons and soil moisture throughout the study period. I.e., hydrogen pools other than soil moisture may have changed, where biomass is the most likely candidate. For example, following the calibration curve from May (solid orange line), the neutron counts detected in July and October ~~. Since an increase of N always responds to a decrease of water equivalent, this observation could be interpreted as a reduction of biomass during the period of growing maize. This is opposed to observations by Franz et al. (2013) and Baroni and Oswald (2015) who confirmed that the water contained in crop biomass and below-ground residues typically adds to the apparent soil water equivalent~~would correspond to lower soil water content than actually measured in the field (ellipses), i.e., these neutron observations were higher than expected. This mismatch could be misinterpreted as a reduced amount of biomass in July and October, because decreasing biomass water equivalent usually corresponds to increasing neutron counts (Franz et al. 2013, Baroni and Oswald 2015). However, the maize was seeded in May, reached maximum height in July, and left residues after harvest in October. Therefore, such a conclusion drawn from the conventionally weighted calibration data would be unrealistic.

The data weighted with the *revised* ~~functions~~ approach (blue in Fig. 6) demonstrates that the ~~lines infered from the calibration points~~ calibration curves converge much closer to a ~~single~~ unique theoretical line (Desilets et al. 2010). ~~Although~~ Their deviation is insignificant given the observational uncertainty of the neutron counter. Although, this approach almost removes the unrealistic effect of ~~reduced hydrogen pools~~a seemingly reducing biomass water equivalent, the assumption of a ~~single~~ unique calibration paramter N_0 ~~must be considered to be illegitimate due to significant~~ still does not reflect the expected biomass dynamics in the investigated period. ~~The remaining deviation of the three calibration curves still indicates a small water reduction effect, however its magnitude is insignificant given the observational uncertainty of the neutron counter.~~ It remains an open ~~questions~~ question whether a revision of the parameters of eq. 1 would better catch the local dynamics and would further contribute to the interpretation of the signal. Nevertheless, the example shows that the revised weighting strategy contributes to a more realistic interpretation of the water availability from CRNS measurements, which is especially important when used in conjunction with irrigation management.