Response to Anonymous Referee #3

We greatly appreciate your time for reviewing the manuscript. In the following letter we have provided specific responses and documentation how reviewer' comments will be addressed in the revised manuscript.

General

The authors present various calibration approaches for cosmic ray soil moisture sensing based on only 5 locations with FDR measured soil moisture. The calibration approaches vary in the choice of the specific time period within the growing period and in the treatment of penetration depth as well as in the choice and number of fitted parameters. Parameters describing the dynamics of biomass are not included in the calibration. Unfortunately, the manuscript is not well structured and is badly written – this makes it very difficult to understand and follow. I was disappointed as the title lead me to expect calibration approaches that actually accounted for the dynamics in vegetation.

RESPONSE:

- In our previous study, we installed a network with 19 locations. Mean value of 19 locations is well capture in terms of absolute values and dynamics by five selected location in current study (RMSE = 0.018 m^3 m^{-3}). Five-location mean value was verified with two campaigns with 3x121 locations. Moreover, soil properties in depth were measured and these did not vary significantly. Finally our working assumption is that five locations represent well mean soil moisture for our site conditions.
- We will improve structure of manuscript according to review and editor recommendations.
- We will present a more elaborated part about relation of attenuated neutrons (N_{att}) and vegetation. Here we will include a time-variable simple neutron correction.

Specific Comments

Abstract: It would be good to have some more details in this abstract, especially on the differences in field calibration approaches and on the different ways of soil moisture profile integration. Also, what is CRS parameter variability? What are the parameters to begin with? You do not have to become too specific, but some more basic information would be helpful. Report on the actual results from your study apart from saying that 'the calibration needs to be adapted'.
RESPONSE: Yes, we will show more details of actual results in abstract.

p. 4238, l. 9: What do you mean with ': : :was calibrated against a network of: : :'? There was no "network" there were only 5 measurement locations.
RESPONSE: Yes, this sentence will be reformulated as "calibrated against local soil moisture profiles"

p. 4238, l. 13: Better write: ‘: : :a single set of parameters that perfectly estimates: :’
RESPONSE: Yes, we will take your suggestion.

p. 4238, l. 14: Better write: ‘: : :could be understood by certain crop: : :’
RESPONSE: Yes, we will take your suggestion.

p. 4238, l. 13-15: How can the parameter variability be understood by predicting the attenuated neutrons by crop presence? These lines are unclear and need to be rephrased
RESPONSE: We will provide a detail explanation in the methodology part.

p. 4238, l. 16: Better use: ‘: : :the potential of cosmic-ray: : :’
RESPONSE: Yes, we will take your suggestion.

p. 4238, l. 17: that calibration needs to be adapted to seasonal changes in vegetation is not really a new finding in my opinion. Isn’t this a known effect due to the physics of the measurement.
RESPONSE: Yes, it is well know that fast neutrons are affected by any kind of hydrogen pool. However, this vegetation affect has not been quantified so far. We will provide a time-variable neutron correction due to vegetation cover.

p. 4238, l. 20: ‘: : :it is of great interest to several important aspects: : :’? How is something of interest to an aspect?
RESPONSE: This sentence will be changed to:

“The understanding of soil moisture variability across spatial-temporal scales is of great interest for several fields such as […]”

p. 4239, l. 13 and 18: You introduce those papers (Zreda 2008 and Desiltes 2010) twice.
RESPONSE: Yes, we will delete repetition.

p. 4240, l. 7: You should not just write subordinate clauses like: ‘: : :, meaning possible correction factors’ but explain what you mean by this. The end of this sentence does not fit to the beginning anymore.
RESPONSE: Yes, we will be clearer in our statements. This part will be rephrased as follows:

“However, there are still some open questions on this methodology that have to be evaluated such as (i) field verification of measurement volume (vertical penetration depth and horizontal footprint) in complex topographies (i.e. hill slopes); (ii) field verification of influence from other water environmental compartments (e.g. interception water, lattice water, biomass water, ponded water, etc.), (iii) calibration approach without use of complex neutron transport models; (iv) transferability of calibration parameters to other locations; etc. Especially in agricultural fields, it is important to quantify the vegetation

influence on the CRS measurements and reliability of using a single calibration curve for the entire season or other crop at next season".

p. 4240, l. 9: ': : :to other times: : :' is what you write, what you mean is ': : :to other periods of time (like seasons, moisture conditions, etc.): : :'. Please be more specific.
RESPONSE: We will delete this part, because it is already included in point (ii), see previous comment.

p. 4240, l. 16: Please be more specific. What do you mean exactly by ': : :extending knowledge of the cosmic-ray neutron sensing to different crops.'? Do you refer to the understanding of the sensitivity of the measurement here?
RESPONSE: Yes, we would like to investigate role of vegetation cover on the cosmic-ray neutron probe. So far, it has not been evaluated vegetation influence in a long-term monitoring.. Moreover, every crop may moderate differently fast neutrons because of its biomass and water content distribution in height, root density, cellulose composition, etc. This sentence will be rephrased as:

"[…] and to extend knowledge and applicability of the cosmic-ray neutron sensing to agricultural fields with continuous crop rotation".

p. 4240, l. 21-22: how did you determine that the soil is homogeneous?
RESPONSE: We will provide measurements of soil properties inside CRS footprint.

p. 4240, l. 23: You applied the method when the field was cropped with corn in order to do what? How is the other study related to this one? When you add this information you should give more details.
RESPONSE: In our previous study, we present an approach using near-surface soil moisture for calibrating the cosmic-ray sensor. This sentence will be changed to:

"At the same location, Rivera Villarreyes et al. (2011) applied the cosmic-ray neutron sensing method to measure soil moisture when the field was cropped with corn (*Zea mays*) in 2010".

p. 4241, l. 12: If you do not use the data from the bare counter you should not mention that counter in the description here.
RESPONSE: It is true that only data from the moderated counter are analyzed in this study, though the data from the bare counter was recorded also. We prefer to not suppress this information on the device itself, but will delete any further description related to the bare counter

p. 4241, l. 19: Uncertainty increases in low latitudes due to more damping of incoming neutrons on their way through the atmosphere.
RESPONSE: In text we refer to altitude, there was a mistake.

p. 4241, l. 19-22: these sentences need to be rephrased; it is not clear what you are trying to say here.
RESPONSE: Yes, we will change sentence to:

"It is well known that CRS uncertainty increase in low elevations, e.g. Bornim site with 89 m a.s.l. In those conditions, a longer integration time of neutrons (e.g. 6-12 hrs) may improve soil moisture measurements".

p. 4241, l. 23-29: why did you choose to measure soil moisture only in 5 locations? This number of measurement locations seems to be very small compared to the large footprint of the CRS method. You also have to explain your rationale of why you do not stick to the recommended grid based core sampling procedure.
RESPONSE: As we explained in response to general comment, we decreased number of measuring points down to 5 locations based on our site-specific conditions. These 5 locations represent very well absolute and dynamics of mean soil moisture from 19 locations. Position of 5 profiles was according to Zreda et al (2010) with slight modification according to texture. We will provide detail explanation about this point in revised manuscript.
Moreover, we believe that a sampling approach can not be standardized because of different field conditions such as topography, soil properties, landuse, etc.

p. 4241, l. 27-28: what were the input values for equation 1? From how many samples were they averaged and what was the variability? What was the theta you used here?
RESPONSE: Here we used data from our previous study. Values of soil moisture correspond to 5 cm depth only. The fact that top soil moisture is normally drier than values at deeper locations, it gives the driest conditions for penetration depth (maximum values). This information will be clarified in revised version.

p. 4241, l. 29: Do you mean that soil texture does not change in the first 50 cm or do you mean that the way soil texture is measured does not change? This is just an example, but also generally more precision in your formulations is necessary.
RESPONSE: Yes, we will rephrase this sentence.

p. 4242, l. 2: soil cores were extracted twice at the same locations? Once during the sunflower and once during the rye period? Explain why you think that the FDR calibration needs to be repeated for different crops. Is this due to different root densities? Or did the locations change?
RESPONSE: Soil cores were extracted in locations near the FDR profiles, but these locations were necessarily not the same (i.e. GPS accuracy of +/- 3 m). Samples were taken shortly after sowing; therefore, root density is minimal for both crops.
OK. This information will be added in revised manuscript as follows:

"The location of the FDR profiles was the same (+/- 3 m of GPS accuracy) for periods of sunflower and winter rye. During sensor installation, soil cores were extracted shortly after sowing and before FDR sensors were placed in their final location. At time of

sampling, both crops were in their initial stage with a minimal root density, therefore field conditions can be considered comparable".

p. 4242, l. 6-7: field calibration? Unclear, needs to be explained.
RESPONSE: Yes, this part will be extended as follows:

"A field soil-specific calibration from our previous study (Rivera Villarreyes et al., 2011) was used for FDR sensors. Here, volumetric soil moisture from soil cores was related linearly to the sensor output [mV] measured at the same locations, where samples were extracted".

p. 4242, l. 8-10: you took daily measurements of crop height? Please phrase this sentence more clearly. Why did you not take LAI, % of area covered and other measurements to describe vegetation biomass dynamics?
RESPONSE: Daily measurements of crop height were not taken. This sentence will be rephrased as:

"During the sunflower and winter rye periods, measurements of crop heights were taken throughout the monitoring period. Crop height was monitored always in four plants surrounding locations of each FDR profile (A–E; see Fig. 1)".

Independently, we estimated LAI from growing degree days (i.e. heat accumulation needed for plant grow) and this was linearly correlated to measurements of crop height ($r^2 > 0.9$). Therefore, as recommended by other reviewers, we will delete this information in revised manuscript. Our calibration and neutron correction procedure need length of crop growing stages only. We will present a simple approach for vegetation correction directly on neutron counts; therefore we do not other crop measures.

p. 4242, l. 16-26: this paragraph needs to be improved – the processes are not well explained and the wording is confusing.
RESPONSE: Yes, entire paragraph will be reformulated in revised manuscript.

p. 4242, l. 17: How can these neutrons be randomly distributed above ground when they penetrate the soil? This whole paragraph is unclear and should be rewritten.
RESPONSE: See above.

p. 4242, l. 19: soil nuclei?
RESPONSE: Yes, this will be explained in detail in revised manuscript.

p. 4242, l. 25: mathematical function does not seem to be the right word here
RESPONSE: Yes, we will change it to "equation".

p. 4243, l. 12: What is Ctheta? I cannot find it in equation (1).
RESPONSE: Yes, this is a typing error. We will correct in revised manuscript.

p. 4243, l. 15: "Corrections" is too vague as a heading here.
RESPONSE: It will be replaced by "Neutron corrections".

p. 4243, l. 20: it sounds as if you have set up = installed the reference station
RESPONSE: No, we did not install this. This will be changed to: "[…] the neutron monitoring station Jungfraujoch in Switzerland (www.nmdb.eu) was used as reference station".

p. 4243, l. 22: What type of relationship did you assume? A linear one? Please cite a reference here.
RESPONSE: This sentence will be changed to:
"[…] we correct neutrons in Bornim by a factor defined as the ratio of the measured neutrons in monitoring station at a given time to the historical mean".

p. 4244, l. 2: You say 'On the one hand: : :', but there is no 'on the other hand: : :' anywhere.
RESPONSE: Yes, we will correct this when it is the case.

p. 4244, l. 3: More details on this Monte Carlo simulations, please. You need to put it into a context. Also: Did you do this type of Monte Carlo calibration or are you just explaining that Desilets did it that way?
RESPONSE: These simulations were carried out and presented in Desilets et al., (2010). We will add details in text as follows:

"Cosmic-ray neutron sensing was calibrated with Monte Carlo neutron transport simulations (Desilets et al., 2010). Here, an equation was derived from the expected neutron flux for specific soil moisture conditions, assuming a fully-silica-based sandy soil and water contents from 0 m^3 m^{-3} to 0.40 m^3 m^{-3}".

p. 4244, l. 4: In the equation proposed by whom?
RESPONSE: Yes, we will rephrase as "In Desilets' equation (2010) […]".

p. 4244, l. 5: : : :and fast neutron count: : :
RESPONSE: Yes, we will take your suggestion.

p. 4244, l. 12: 'Better approaches' in regard to what? What are they supposed to do better?
RESPONSE: This sentence will be rephrased to:

"In order to explore the adequate manner for calibrating Desilets' equation (2010), we present three different procedures to calibrate the cosmic-ray probe: […]".

p. 4244, l. 15: "with respect to the parameters of Desilets" – this is unclear and needs to be rephrased
RESPONSE: This sentence will be rephrased as follows: "[…] (ii) a one-parameter calibration with factor where θ_{CRS} is calibrated by downscaling and upscaling soil moisture if Desilets' parameters (2010) would have been used, […]

p. 4244, l. 19-22: which of these two approaches did you use?
RESPONSE: This is in detail explained in revised manuscript as follows:

"The N_0-calibration approach is slightly different from the one proposed in the literature, since here N_0 value was calibrated for the entire calibration period (> 30 days, cf. 2.3.4), instead of a N_0 calculated with soil moisture data from one-day (i.e. six hours) sampling campaigns (Zreda et al. 2012 and Franz et al. 2012)".

p. 4244, l. 22-23: did you also validate your calibration? How? Using which periods? Needs to be explained.
RESPONSE: Yes, we performed a validation procedure with entire dataset (sunflower and winter rye) for each set of parameters derived from all calibration periods (D1-D6). In revised manuscript we will provide a split sampling calibration-validation procedure, as recommended by other reviewers and editor.

p. 4244, l. 23: You mean the RMSE between soil moisture derived from FDR and soil moisture derived from CRS not just the measuring devices FDR and CRS. Again, be more precise with your formulations.
RESPONSE: Yes, this sentence will be rephrased as:

"The calibration was done by minimizing the root mean square error (RMSE) between mean FDR soil moisture (5 profiles) and cosmic-ray soil moisture […]".

p. 4245, l. 13-15: seems quite arbitrary. Why not use eq. 1 with mean theta?
RESPONSE: It is not quite arbitrary. Constant penetration depth is the maximum value computed for driest conditions and also coincides with deeper FDR sensor. In the case of variable penetration depth in the scenario S2 and S4, this was compute with the mean FDR soil moisture.

p. 4245, l. 20: ': : :detected neutrons do not originate uniformly distributed in depth'. What do you mean? Please formulate in a less convoluted way.
RESPONSE: Yes, this sentence is rephrased as follows:
"The neutrons measured aboveground are not originated uniformly in depth because of vertical distribution of soil moisture in the field".

p. 4246, l. 3: ': : :which may depend on nuclear properties of the porous medium.' What are these 'nuclear properties' and what decides whether k is dependent or not?
RESPONSE: This sentence is reformulated as follows: "[…] k is a negative constant which reflects how neutrons are originated from different depth".

The neutron transport of fast neutrons trying to escape back to the atmosphere highly depends on the macroscopic neutron cross-section (strongly affected by hydrogen content at a specific time) and neutron stopping power. Additionally, we complement this explanation in text as follows:

"The value of *k* may reflect additionally some properties involved in the neutron transport such as macroscopic cross-section and stopping power".

p. 4246, l. 3-4: how did you calibrate k values from the FDR soil moisture?
RESPONSE: We will provide a better explanation in revised manuscript. Parameter k was simultaneously calibrated with the soil moisture equation (Table 1), adding it in the optimization process.

p. 4246, l. 10: What do you mean by ': : :z is only available at depths of 5 cm: : :'? I thought z itself is a depth.
RESPONSE: Yes, z is a specific depth, however, the FDR profiles consist on devices at 5 cm, 20 cm and 40 cm depth. Sentence is rephrased as follow:

"The integral of Eq. (3) was linearly interpolated from values at 5 cm, 20 cm and 40 cm depth".

p. 4247, l. 17- p. 4248, l. 18: these paragraphs are a mix of results and methods – please restructure and move the methodological aspects to the methods section
RESPONSE: Yes, we will reorganize this section and move some information to the methodology part.

p. 4247, l. 25: when were these campaigns carried out? How was soil moisture measured?
RESPONSE: Please see response to comment P 4247 L 24-26 of review # 2.

p. 4248, l. 3-4: did you just use the 5 near surface values for the determination of the mean?
RESPONSE: Yes, we compared 121x3 measurements per campaign against 5 FDR locations. From our measurements of soil properties in depth and FDR profiles, we know that soil moisture variability is low in depth (at least down to CRS effective depth).

p. 4248, l. 15-18: more detail needed here
RESPONSE: Please see response to comment P 4248 L 15 of reviewer # 2. Additional, last sentence in this section will be changed to:

"The FDR calibration from our previous study provides a RMSE of about 0.04 $m^3 m^{-3}$ for soil samples taken in current study".

p. 4248, l. 19: is neutron correction the correct term here?
RESPONSE: This can be changed to "Range of corrected neutrons".

p. 4248, l. 22: decreased or decreasing? If there was a decreasing trend – why is your correction factor constant in time?
RESPONSE: These are two different things. There was a decrease of incoming cosmic neutrons in reference station during monitoring period. Here correction factor is time-variable. In the case of atmospheric water vapor, correction factor was negligible (cf. response to comment P4248 L24-25 of reviewer # 1.

Section 3.3: if I understand correctly you are applying the calibrated parameters determined from specific time periods to the entire time period of measurements and are evaluating the overall RMSE? Does this make sense? Wouldn't it be more intuitive to apply a time-variant calibration with respect to the dynamics in biomass? How do the RMSE of the calibration period compare to the RMSE of the entire period?
RESPONSE: Yes, the RMSE was computed for the entire monitoring period (sunflower + winter rye) using a specific set of calibration parameters derived for each growing stage (D1-D6), as shown in Fig 3. In revised manuscript we will present a split calibration-validation procedure.
In revised manuscript, we will also incorporate a new section presenting a simple approach of time-variable vegetation correction directly on neutron counts.

p. 4249, l. 7: this refers to eq. 1?
RESPONSE: Yes, we will refer this equation here.

p. 4249, l. 12-14: unclear, please rephrase
RESPONSE: Sentence is changed to:
"Overall, calibration approaches fitting one single parameter (f_{cal} or N_0) provide higher values of RMSE between mean FDR profile and cosmic-ray soil moisture compare to approach fitting three parameters (a_0, a_1, and a_2)".

p. 4250, l. 10: : : : with respect to your data set and study site.
RESPONSE: Sentence will be changed to: "Therefore, we conclude that four calibration scenarios do not present a statistical difference in this study".

p. 4250, l. 11: how did you apply the variable penetration depth to the time series? Is this based on eq. 1 and the mean soil moisture measured with the FDR sensors?
RESPONSE: Issue of penetration depth in Bornim was not possible to evaluate because of very homogenous soil moisture profiles measured during monitoring period. We will extend this discussion in revised manuscript.

p. 4251, l. 21 and 25 the same finding is repeated here.
RESPONSE: Yes, we will delete sentence "Moreover, we also observed […]"

p. 4251, l. 19-25. How did these calibrated N0 values compare to the measured N0 values used for the other calibrations?
RESPONSE: A new sentence will be added as follows:

"Only calibrated N_0 for period D1 is well comparable to assumed value of 1300 cph for other calibration approaches".

p.4252 l. 8-10: which figure are you referring to?
RESPONSE: We are not referring to a figure, only to table A1, as mentioned in previous sentence.

p.4252 l. 11-12: why did you decide to use only the calibration results of D3?
RESPONSE: The D3 provided the best calibration results. In revised manuscript we will also include in figure the worst-case scenario with period D1 and N0 calibration.

p.4252 l. 20: I do not see an advantage in using anomalies in Figure 5 – please explain how we get additional information from the lowest plot compared to the middle plot.
RESPONSE: As suggested from other reviewer, we will delete this information and modify Fig. 5 in revised version.

p.4254 l. 2-9: paragraph is unclear, please rephrase
RESPONSE: Yes, we will rephrase this paragraph as follows:

"Thus, the relation between fast neutrons and soil moisture is not unique throughout the crop season. This behavior is shown in Fig. 6 with a scatter plot between soil moisture and relative neutrons. The relation between fast neutrons and soil moisture is affected by the natural scattering of neutrons and changes of biomass water along the season. However, calibration curve (D3) also fitted well datasets for the mid-season (D5) and late season (D6) of winter rye. In periods D5 and D6, fast neutrons may be similarly moderated than in period D3. This is because two crops present its maximum yield, maximum height, maximum water content, etc."

p.4254 l. 3: what are relative neutrons?
RESPONSE: Now additional information is provided: "This behavior […] relative neutrons (N/N_0)".

p.4254 l. 13-14: why use the mean difference instead of the RMSE of D1 and D3 and compare both of these to crop height?
RESPONSE: In revised manuscript we will elaborate the discussion of vegetation influence based on neutron counts. This figure will be deleted.

p.4254 l. 18-20: unclear – needs to be explained in the methods section and results need to be shown
RESPONSE: Yes, we will explain it in detail.

p.4254 l. 23- p.4255 l. 4: this should be explained in the methods section
RESPONSE: Here we will provide the equation and better explanation in methodology section.

p.4255 l. 5-6: to compare neutrons vs neutrons? Unclear, please rephrase.
RESPONSE: We will provide a better explanation in methodology section. In revised manuscript we will show vegetation correction based on attenuated neutrons.

p.4256 l. 20: etc.? please elaborate
RESPONSE: This sentence is complemented as follows:

"It is worth mentioning that FDR sensor locations and its field conditions were not necessarily the same in both monitoring periods due to positioning accuracy, crop cover, and root density differences between sunflower and winter rye."

p.4257l. 5-17: these 4 take home messages are all badly phrased and thus hardly understandable
RESPONSE: We will rephrase the take home messages based on (i) results of calibration approaches, (ii) pros and contra of calibration approaches, (iii) new section regarding to vegetation correction based on attenuated neutrons, and (iv) uncertainty of CRS soil moisture if vegetation corrections are not taken.

Table A1: please clarify if you are calculating the RMSE indeed for the entire period or separately for sunflower and rye. If you are calculating it for the entire period – why do you change the procedure for the data in Figure 3?
RESPONSE: Based on reviewer suggestions, we will present here also a split calibration-validation.

Figure 3: legend for the colors is missing
RESPONSE: Colors will be deleted from graph.

Figure 5: why is the CRS overestimating soil moisture in the second half of June 2011? Axis labels are too small. In what way is the calculation of the anomalies helpful in this case?
RESPONSE: Graph will be modified according to comments of reviewers. As we discussed along the manuscript, a single set of calibration parameters (even with minimum RMSE) can not perfectly fit entire monitoring period (sunflower + winter rye) due to crop effect.

Figure 6: what calibration is used here?
RESPONSE: Here we used final calibration approach (cf. section 3.3). This will be specified better in figure caption.

Figure 7: in the methods you were talking about daily measurements of crop height – in this plot the measurement intervals are longer – why?
RESPONSE: Yes, we will clarify this point. We do not have daily measurements.

Technical Corrections

RESPONSE: Authors agreed all technical corrections of reviewer. We will pay more attention in grammar and sentence structure in revised manuscript. Moreover, revised manuscript will undergo expert English proof-reading by the HESS editorial office.