Dear Reviewer:

We greatly appreciate the your time reviewing the manuscript, and have carefully taken into consideration all of the comments. In the following letter we have provided specific responses and documentation from the revised manuscript. All coauthors have agreed to the revisions. We look forward to your response and publication in HESS.

General Comments:

As suggested by the reviewer we have modified the abstract and methods section to be more informative and comprehensive. In addition we have added a new Fig. 1 that shows an example of Eq. (1) and subsequent uncertainty bounds for different counting rates. The reviewer asked that we provide uncertainty estimates in terms of pore water content instead of cph. Given the nonlinearity in Eq. (1) it is difficult to specify pore water content uncertainty. Fig. 1 now provides a way to estimate the pore water content uncertainty from the counting rate uncertainty specified in the various fitting excercises in the manuscript. Finally we have added the influence of soil organic carbon (SOC) and its associated hydrogen to the analysis. We have treated SOC similar to lattice water as suggested by *Zreda et al.* (2012). By including SOC we have further reduced the uncertainty in the analysis with an R^2 going from 0.75 in the original work to 0.79 by including SOC in the analysis.

The following are the responses to specific comments by the reviewer (in italics). Note the line numbers and figures number are from the new revised manuscript.

Reviewer 1:

General comments:

1.The monitoring of cosmic-ray neutrons is a promising way to close the gap between point measurements and the modelling and remote sensing scale. This paper describes a new universal calibration function to be used in environments unfavourable for standard calibration by using the neutron transport code MCNPx together with observed soil chemistries and pore water distributions. Such a universal calibration function would be very useful for the application of the cosmic ray method for mobile surveys.

2. The manuscript is well written, however, I have made suggestions for improvement (see specific comments).

3. The abstract should be more informative.

We have modified the abstract and added several new sentences to be more informative about the scope of the paper.

4. The proposed method should be described in a more comprehensive and detailed way.

I also suspect that there are some inconstancies. For instance it is not clear to me, whether chemical properties are need for the application or not.

L213-219: We have now clarified that only lattice water and SOC are needed from sites in order to use the universal calibration equation. Fig. 2 shows the collapse all soil chemistries to same function, which includes SiO2, thus justifying the simple description of the soil chemistry in Eq. (4).

5. As the authors point out, subsurface biomass might lead to large uncertainties in the application of the calibration function. Therefore I would suggest including soil organic carbon content information from soil maps in order to take into account the subsurface biomass or at least to test in which way this property might influence the calibration result.

L147-149: Using our estimates of Total Carbon and soil CO2 we are able to compute soil organic C (SOC). We have included SOC in the analysis by treating it as lattice water as suggested by Zreda et al. (2012). By including SOC we have reduced the uncertainty in the analysis with an R^2 going from 0.75 in the original work to 0.79 by including SOC in the analysis.

6. The authors claim that the universal calibration function leads to accurate estimates of soil water content in the support volume of a cosmic ray probe. This conclusion should be substantiated by presenting the accuracy of the universal calibration function in terms of soil water content. For instance, given the extensive COSMOS data sets it should be possible to carry out a split-sample calibration-validation approach.

We have added a new Fig. 1 that shows an example of Eq. (1) and subsequent uncertainty bounds for different counting rates. The reviewer asked that we provide uncertainty estimates in terms of pore water content instead of cph. Given the nonlinearity in Eq. (1) it is difficult to specify pore water content uncertainty. Fig. 1 now provides a way to estimate the pore water content uncertainty from the counting rate uncertainty specified in the manuscript.

Instead of doing a split analysis we have included the 95% confidence intervals in the fitting to give the reader an idea of the uncertainty bounds. We suspect that the largest source of uncertainty is sensor to sensor, as 1 mb differences in absolute pressure can cause about 1% count rate differences. We are in the process of calibrating all sensors with a standardized neutron counter and retrofitting existing sensors with high precision pressure sensors that are less sensitive to temperature variations.

Specific comments:
P10305 L9-12: I don't agree with the statement that a COSMOS standard calibration using the gravimetric method cannot be applied to soils containing stones. It is rather a question how to account for the content of stones in deriving the volumetric water content.

L52: We have added the qualifying statement of "difficult to obtain a representative average soil moisture for sites with large cobbles or stones."

P10305 L9-12: Which additional information is needed for the application of the universal calibration function to unknown site?

L58: We added that water vapor, soil lattice water, soil organic carbon, and above ground biomass are needed to isolate soil moisture signal from the neutron intensity signal.

P10307 L7: How much will the radius of the hemisphere depend on air humidity and would this lead to additional uncertainties in the application of the universal calibration function?

L 131-134: Added that support radius can change by up to 10% between dry air and fully saturated air as computed by MCNPx simulations and reported in Rosolem (2012). We note that we do not consider small changes in radius here.

P10307 L22: I would suggest to wait until Rosalem et al. is accepted before citing it.

L 124: The paper is in the final stages or revisions. Franz (2012b) summarizes equations but full details are provided in Rosolem (2012) manuscript so we have elected to leave it in the manuscript.

P10307 L22: I didn't found this equation in Zreda et al., 2012

L 124: Correct, we added the Franz (2012b) reference, which summarizes the water vapor correction equations.

P10308 L15: You should not mix explanations together details of the company doing the measurements.

L149-155: We added the following sentences for clarification. See text below.

"For this work, measurements of lattice water, total soil carbon, and CO_2 measurements were made on a ~100 gm composite sample collected at the study site and analyzed at Actlabs Inc. of Ontario, Canada. The 100 gm composite sample was made by collecting ~1 gm of soil from 108 individual samples at 18 locations with the footprint (samples collected at 6 depths, 0-5, 5-10, 10-15, 15-20, 20-25, 25-30 cm, and 18 horizontal locations, bearings of 0^o, 60^o, 120^o, 180^o, 240^o, 300^o, and radii of 25, 75, and 200 m)."

P10308 L15: Please briefly explain how you derived the average chemical properties within the support volume (e.g. chemical analysis, averaging procedure etc.)

L149-155: We added the following sentences for clarification. See text below.

"For this work, measurements of lattice water, total soil carbon, and CO_2 measurements were made on a ~100 gm composite sample collected at the study site and analyzed at Actlabs Inc. of Ontario, Canada. The 100 gm composite sample was made by collecting ~1 gm of soil from 108 individual samples at 18 locations with the footprint (samples collected at 6 depths, 0-5, 5-10, 10-15, 15-20, 20-25, 25-30 cm, and 18 horizontal locations, bearings of 0^o, 60^o, 120^o, 180^o, 240^o, 300^o, and radii of 25, 75, and 200 m)."

P10308 L21: What about the COSMOS sites that are covered by other vegetation types than forest?

L 168 The USFS map is estimate of total above ground biomass for the continental USA, not only for forested areas.

P10308 L24: I am a bit confused: On the one hand you are using detailed chemical information within the support volume, but here you are stating that you assume pure quartz.

L213-219: We have now clarified that only lattice water and SOC are needed from sites in order to use the universal calibration equation. Fig. 2 shows the collapse all soil chemistries to same function, which includes SiO_2, thus justifying the simple description of the soil chemistry in Eq. (4). See text below.

"Most notably, the results in Fig. 2 illustrate that all 49 observed soil chemistries collapse to the SiO_2 case when using *hmf*, where we can account for the hydrogen in the lattice water and soil organic carbon. This result justifies the use of Eq. (4) and its simple representation of soil chemistry consisting of only SiO_2, lattice water, and organic carbon. With respect to future work using stationary or mobile cosmic-ray neutron probes, we recommend site-specific estimates of lattice water and soil organic carbon for most accurate results."

P10309 L2-4: This section should be reformulated in way that shows the difference between Hi and Ai in a simpler way.

L174-181: We have expanded Eq. (4) and added a description of each of the components. See text below.

$$hmf = \frac{\sum H_i}{\sum A_i} = \frac{H_\tau + H_{SOC} + H_\theta + H_{AGB}}{NO + SiO_2 + H_2O_\tau + H_2O_{SOC} + H_2O_\theta + C_6H_{10}O_5 + H_2O_{AGB}} \qquad (4)$$

where H_i is the sum of hydrogen moles from lattice water H_τ, soil organic carbon lattice water equivalent H_{SOC}, pore water H_θ, and vegetation H_{AGB} inside the support volume, and A_i is the sum of all moles from air NO, soil SiO_2, lattice water H_2O_τ, soil organic carbon lattice water equivalent H_2O_{SOC}, pore water H_2O_θ, and above ground biomass

$C_6H_{10}O_5 + H_2O_{AGB}$ inside the support volume.

P10309 L12: Why is the range chosen to be 10-100 eV? Mostly cosmic-ray neutrons produced by the evaporation process show an energy range between 0.1 and 10MeV. To my knowledge the Hydroinnova CRS1000 probe used in this study uses a Cd-shield to exclude neutrons with energies < 1 eV, not < 10 eV. Furthermore, there is, again to my knowledge, no clear evidence that the CRS1000 neutron counter is not sensible to cosmic-ray neutrons >100 eV.

L187-194: We have added a new reference, Desilets (2011), which is a publically available report describing the physics of the detector. The moderated or fast detector has a median energy detection level of 10 eV but measures a range of energies as you suggest. In addition simulations over 1 to 10^5 eV indicate minimal differences in the sensitivity to pore water content. See text below.

"At 1 to 2 m above the surface the fast neutron flux, *N* (energy range 10-100 eV), is tallied; it corresponds to approximately the same energy neutrons that are measured by the cosmic-ray neutron detector moderated or "fast" channel [*Desilets*, 2011]. *Desilets* [2011] notes that the moderated channel measures a range of neutron energies with the median value near 10 eV, where detection frequencies drop off as 1/e for higher energy neutrons. We note that MCNPx simulations of neutron flux of each binned energy level between 1 and 10^5 eV indicate nearly identical response functions to soil moisture changes, thus justifying the use of the energy range used here.".

P10309 L15: From a soil science perspective I would recommend to use the term "soil water content" instead of "pore water value"

We have decided to keep the term "pore water content" in order to distinguish it from lattice water, which is also in the soil and may cause unnecessary confusion.

P10309 L15: Why were all simulations normalized to a pure water case? I assume that the production rate of pure water is lower compared to a porous medium and thus the simulated neutron intensity might be less comparable.

L 203-205: We use this factor because it will be constant for all soil chemistries as opposed to the dry soil case or N_0 used in Desilets et al. (2010) where sites may have the same pore water value but differ in hydrogen content due to differences in lattice water and soil organic carbon.

P10310 L1: Please explain how Ns can be specified

L 210-212: This parameter may be sensor dependent, but can be easily specified by measurements over a large water body (> ~500 m on all sides and deeper than 1 m) and following the standard correction factors in *Zreda et al.* [2012].

P10310 L5: Please explain in which way you have coupled HYDRUS-1D with MCNPx

L 223: We now state that we used 1-D solutions as input in the MCNPx modeling. Therefore it is a forward approach.

P10310 L11: The RMSE should be expressed in count/h, as it is also done later in the text. In addition, I would suggest expressing the error also in terms of (equivalent) soil water content.

L 232-235: RMSE is now expressed in cph. Given the nonlinearity in equation 1, it is more appropriate to express uncertainty in cph instead of pore water content as it varies over different count rates. We note that Figure 1 can now be used to estimate the equivalent uncertainty in terms of water content for one specified N_0 value. See text below.

“We note that all uncertainties are expressed in terms of cph given the nonlinearity in converting cph to pore water content (Eq. 1). However, Fig. 1 may be used to estimate the equivalent uncertainty in terms of pore water content for different count rates and uncertainties.”

P10310 L14: How is this reflected in Tab. 1

L 231-232: It is reflected in the RMSE for the different soil textures with the largest uncertainty for sandy soils. We now state this in the text.

P10310 L17-18: Table S1 presents more than 5 data sets. To which of them are you referring to.

L 240: Added COSMOS Site Number 11 to specify.

P10310 L23: see comment P10310 L11

L 232-235: RMSE is now expressed in cph. Given the nonlinearity in equation 1, it is more appropriate to express uncertainty in cph instead of pore water content as it varies over different count rates. We note that Figure 1 can now be used to estimate the equivalent uncertainty in terms of water content for one specified N_0 value. See text below.

“We note that all uncertainties are expressed in terms of cph given the nonlinearity in converting cph to pore water content (Eq. 1). However, Fig. 1 may be used to estimate the equivalent uncertainty in terms of pore water content for different count rates and uncertainties.”

P10311 L4: Better: “The problem is less pronounced for the calibration data sets in *which the volumetric soil water content was determined using the gravimetric method."*

L251-253: We changed the sentence as advised.

P10311 L7: "shows that"

L257: Changed to shows that.

P10311 L7: Instead of "accurately" you should use "reasonable".

L257: Changed to reasonable.

*P10311 L6-13: I suppose that a decrease in soil moisture variation will reduce R**2**, whereas a decrease in the variation of the other influences should lead to an increase of R**2**. For the potential user of the universal calibration function it would be interesting to know, in which way the influencing factors will affect the quality of the sensor calibration.*

Soil moisture uncertainty will dominate the overall uncertainty in the relationship as it is the largest pool of hydrogen at 1 to 4 cm of water in the top 30 cm of soil. Water vapor, lattice water, SOC and biomass varies on the order of mm's. Given the simplicity of equations 2 to 5 a full sensitivity analysis could easily be performed but was deemed not necessary for this work. Figure 6 is a basic sensitivity analysis of lattice water and *AGB* and gives the reader a sense of the affects on neutron counts due to those factors.

P10311 L16: Please explain in more detail why the observed hydrogen molar fraction for these cases is higher than for the liquid water case?

L 267: The sites have a large amount of above ground biomass and were relatively wet on the day of the calibration

P10312 L7: What do you mean with "small axis of variation"

L 287: Changed wording to systematic uncertainty due to not including geometry of vegetation.

P10312 L11-14: Wouldn't it possible to account for soil organic carbon content quite straightforward by using such information from soil maps.

L147-149: Yes. Using our estimates of Total Carbon and soil CO2 we are able to compute soil organic C (SOC). We have included SOC in the analysis by treating it as lattice water as suggested by Zreda et al. (2012). By including SOC we have reduced the uncertainty in the analysis with an R^2 going from 0.75 in the original work to 0.79 by including SOC in the analysis.

P10312 L21: see comment P10311 L7. In order to make such a conclusion you should *also present the accuracy of the universal calibration function in terms of (equivalent) soil water content.*

L 232-235: RMSE is now expressed in cph. Given the nonlinearity in equation 1, it is more appropriate to express uncertainty in cph instead of pore water content as it varies over different count rates. We note that Figure 1 can now be used to estimate the equivalent uncertainty in terms of water content for one specified N_0 value. See text below.

"We note that all uncertainties are expressed in terms of cph given the nonlinearity in converting cph to pore water content (Eq. 1). However, Fig. 1 may be used to estimate the equivalent uncertainty in terms of pore water content for different count rates and uncertainties."

P10312 L26: Don't you need also the chemical properties for each site for applying the universal calibration function?

No, all soil chemistries collapse to SiO2 when including lattice water and SOC.
L213-219: We have now clarified that only lattice water and SOC are needed from sites in order to use the universal calibration equation. Fig. 2 shows the collapse all soil chemistries to same function, which includes SiO2, thus justifying the simple description of the soil chemistry in Eq. (4). See text below.

"Most notably, the results in Fig. 2 illustrate that all 49 observed soil chemistries collapse to the SiO_2 case when using *hmf*, where we can account for the hydrogen in the lattice water and soil organic carbon. This result justifies the use of Eq. (4) and its simple representation of soil chemistry consisting of only SiO_2, lattice water, and organic carbon. With respect to future work using stationary or mobile cosmic-ray neutron probes, we recommend site-specific estimates of lattice water and soil organic carbon for most accurate results."

P10313 L2: I think you are referring to Table S1

L 293: Changed to Table S1.

P10313 L1-16: This section is very speculative. For instance, the use of the proposed method for mapping biomass would need the knowledge of spatial distribution of the soil moisture content in the top 70 cm, which is normally not available.

Correct, you would need either independent soil moisture measurements in the area or potentially another neutron intensity measurement at a different energy level or height from the surface. We clarified this statement stating you need measurements of the other pools (L312-313). This is something we are actively pursuing with moderate success thus far.

Given the section is title outlook we feel that these speculative statements are appropriate.

The point of the manuscript is to present a set of equations to decouple the convoluted neutron intensity measurements into the individual pools of hydrogen. We believe other smaller pools may be detectable in the neutron intensity measurements and are actively working in this area.

P10313 L4-7: This is an interesting aspect, but it doesn't fit in the outlook chapter. I would suggest presenting this aspect in an extended version in a separate chapter.

We cut sentence from manuscript.

Tables and Figures

Table 1: Why is Ns sometimes assumed?

Model uncertainty is in terms of count per count, need to assume an N_S to compare it with observations using an actually detector instead of modeled layer detector.

Fig.1a): the range of the x-axis should correspond to the min. and max. value of soil water content

Changed x axis to maximum value of 0.6 instead of 1.

Fig. 3): Is this a curve fitted to the soil moisture data from this site or is it an application of the universal calibration using ancillary data?

N_S fitted to volumetric data points than applied to independent distributed sensor network data (L 244 -247). See text below.

"Using the five volumetric sample data points we estimate an N_s value of 1037 cph using Eq. (5). Then using the independent distributed sensor network measurements we compute an RMSE of 110.1 cph and R^2 of 0.854 (Fig. 4, Table 1)."