Response to Anonymous Referee #1

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 comments

1. The universal calibration function of Franz et al. (2013) considers directly the effects of biomass and thus is a better approach to understand the biomass effects on the CRP signal. The simple approach presented in this study is of less generic nature limiting its potential for application at other test sites.

RESPONSE:
Indeed, Franz' approach (2013) takes into account vegetation water content, but with the drawback that all hydrogen pools (as well other chemical compositions) have to be known with a specific accuracy, and that these pools are treated as constant in time. In our study we observe influence of vegetation on local calibrations. In our opinion, influence of vegetation on the CRS methodology can be dealt with directly on a neutron counts correction, not only as a water mass subtraction on the final soil moisture value. As it has been already presented in the current version of manuscript, attenuated neutrons (N_{att}) represent very well variability of calibration parameter N_0, which is due to crop conditions. In the revised manuscript we will extend the discussion and present a correction approach directly on the neutron counts.

2. The difficulty of capturing area-average soil moisture at intermediate scales from point measurements was already demonstrated in many studies (e.g. Famiglietti et al., 2008). A good representiveness of in-situ measurement locations is especially important for this study, because calibration procedures are evaluated. According to recent publications on CRP calibration (e.g. Desilets et al., 2010; Franz et al., 2012; Zreda et al., 2012) vertical soil moisture distribution should be measured at 18 locations within the CRP footprint. In this study however, only five locations were used for calibration.
In addition, a comparison with measurement campaigns revealed significant deviations between both data sets by 20% and 25%. Although the authors did some statistical testing using older data, it is still questionable where these locations can adequately represent the average soil moisture within the CRP footprint.

RESPONSE:
We will add additional information to complete this issue. Our analysis was based on the outcome from 19 FDR locations from previous growing season with corn. We compare mean values of soil moisture from these 19 locations against mean values from those 5 locations presented in the manuscript. These five locations were placed approximately with a coverage according to the 18 recommended by Zreda et al 2012. Both time series of mean values with 19 and 5 FDR sensors are practically identical with a RMSE of 0.018 m^3 m^{-3}. This deviation is in the error range of the sensor, and not a natural

variability. Here, we conclude that the selected locations are representative in terms of absolute values and dynamics at the surface level. Further verification was done via two campaigns with 363 points inside the footprint. In depth, soil properties were measured and not significant differences were observed. This is in concordance with ancillary data from soil and geological maps which indicated homogenous sandy profiles at the study site.

3. **The vertical depth weighing function used in this study was calibrated jointly with the neutron calibration function. This might have introduced complicated interdependencies between the different calibration parameters.**

RESPONSE: Yes, depth weighting function was calibrated simultaneously with the soil moisture function. This procedure introduces an additional parameter to the optimization process; therefore, a direct parameter comparison is not possible. Based on this argument, current study only shows a comparison of the performance (RMSE and CRS soil moisture) of each parameter set.

4. The abstract is too short.
This will be extended in revised manuscript.

Specific comments

P4238 L9 and P4239 L25 The term “cosmic-ray probe” and its acronym “CRP” are well established (e.g. Zreda et al., 2012), so there is no need to introduce a new term which will only introduce confusion.

RESPONSE: We are consistent with terminology of other studies. For instance, below we present a compilation of different names used in other studies in last years.

We prefer to use one of the most common of these names, but one that is as appropriate as possible. The terminology “cosmic-ray probe” is misleading, since probe (or sensor) does not measure cosmic rays, i.e. high energy primary cosmic radiation or secondary cosmic rays in the atmosphere. We consider appropriate to at least make clear that the measured quantifies are neutrons. The acronym “CRP”, recommended by the reviewer, was not found in literature so far.

In the current manuscript, we have chosen “cosmic-ray sensor”, with acronym CRS, for the measuring device and “cosmic-ray neutron sensing” for the methodology, as used previously (see highlighted names in table).

Publication	**Terminology used**
Zreda, M., Desilets, D., Ferré, T.P.A. & Scott, R.L. 2008. Measuring soil moisture content non-invasively at intermediate spatial scale using cosmic-ray neutrons. *Geophysical. Research Letters*, **35,** 1-5.	cosmic-ray soil moisture probe, cosmic-ray probe, cosmic-ray neutron probe, cosmic ray sensor
Desilets, D., Zreda, M. & Ferré, T.P.A. 2010. Nature's	cosmic ray probe

neutron probe: Land surface hydrology at an elusive scale with cosmic rays. *Water Resour. Res.*, **46,** W11505.	
Rivera Villarreyes, C.A., Baroni, G. & Oswald, S.E. 2011. Integral quantification of seasonal soil moisture changes in farmland by cosmic-ray neutrons. *Hydrology and Earth System Sciences*, **15,** 3843-3859.	cosmic-ray sensor (CRS), ground albedo neutron sensing (GANS)
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 Journal*, **11**.	cosmic-ray neutron sensor, cosmic-ray soil moisture sensor, cosmic-ray sensor
Franz, T.E., Zreda, M., Ferre, T.P.A., Rosolem, R., Zweck, C., Stillman, S., Zeng, X. & Shuttleworth, W.J. 2012. Measurement depth of the cosmic ray soil moisture probe affected by hydrogen from various sources. *Water Resour. Res.*, **48,** W08515.	cosmic ray soil moisture probe, cosmic ray soil moisture neutron probes, cosmic ray probes, cosmic ray sensor
Zreda, M., Shuttleworth, W.J., Zeng, X., Zweck, C., Desilets, D., Franz, T., Rosolem, R. & Ferre, T.P.A. 2012. COSMOS: The COsmic-ray Soil Moisture Observing System. *Hydrol. Earth Syst. Sci.*, **16,** 4079-4099.	cosmic-ray soil moisture probe, cosmic-ray probe, COSMOS probe
Franz, T.E., Zreda, M., Rosolem, R. & Ferre, T.P.A. 2013. A universal calibration function for determination of soil moisture with cosmic-ray neutrons. *Hydrol. Earth Syst. Sci. Discuss.*, **17,** 453-460.	cosmic-ray probe, cosmic-ray soil moisture probe, cosmic-ray neutron probe
Shuttleworth, J., Rosolem, R., Zreda, M. & Franz, T. 2013. The COsmic-ray Soil Moisture Interaction Code (COSMIC) for use in data assimilation. *Hydrol. Earth Syst. Sci. Discuss.*, **10,** 1097-1125.	COSMOS probe
Desilets, D. & Zreda, M. 2013. Footprint diameter for a cosmic-ray soil moisture probe: Theory and monte carlo simulations. *Water Resources Research*, accepted.	cosmic-ray probe, cosmic-ray soil moisture probe
Rosolem, R., W. J. Shuttleworth, M. Zreda, T. E. Franz, X. Zeng, and S. A. Kurc. 2013. The Effect of Atmospheric Water Vapor on Neutron Count in the Cosmic-ray Soil Moisture Observing System. Journal of Hydrometeorology. In press.	cosmic-ray probe or cosmic-ray soil moisture probe, cosmic-ray soil moisture sensor, cosmic-ray sensor
Chrisman, B. & Zreda, M. 2013. Quantifying mesoscale soil moisture with the cosmic-ray rover. Hydrol. Earth Syst. Sci. Discuss., 10, 7127-7160.	COSMOS probe, cosmic-ray probe

P4240 L6 Explain "bounded water"

RESPONSE: This term will be changed to "lattice water".

P4240 L21-22 You are not providing detailed soil properties, so how do you know that the soil is homogeneous?
RESPONSE: We will provide detail information of soil properties in the methodology section.

P4241 L19 "increases" instead of "decreases"
RESPONSE: Yes, we will change this term.

P4241 L24 "soil water content" instead of "texture" (otherwise the sentence does not make any sense)
RESPONSE: This sentence will be rephrased as "Moreover, measurements of soil texture did not vary significantly in the first 50 cm top soil (cf. section 3.1), suggesting no need of placing FDR sensors in a specific depth".

P4242 L25 ": : :function to convert fast neutrons into soil moisture: : :"
RESPONSE: Yes, we will change this sentence according to reviewer recommendations.

P4243 L1 the term "ca." is rather unusual in English publications. Better use terms like "approximately" or "about"
RESPONSE: Yes, we will change this term throughout entire manuscript.

P4243 L8 The more advanced equation including soil organic matter of Franz et al. 2013 should be used here.
RESPONSE: Yes, we will include this term in equation.

P4243 L12 delete "C"
RESPONSE: Yes, we will delete this.

P4243 L20 ": : :was used as: : :"
RESPONSE: Yes, we will change this.

P4244 L2 Delete "On the one hand,.."
RESPONSE: Yes, we will delete this.

P4244 L3 You should mention here that all calibration approaches used in this study are based on the function developed by Desilets et al. (2010).
RESPONSE: Yes, all calibration approaches follow Desilets' equation (2010). We will include this information in revised manuscript.

P4244 L13-19 All equations are variations from a function developed by Desilets et al. (2010). Please reformulate this section accordingly.
RESPONSE: OK. See above.

P4246 L11-12 Explain in more detail.
RESPONSE: Yes, we will explain more here. The definite integral in Eq. (3) was approximated by linear interpolation between the measurement depths.

P4246 L15 In these studies the sensor locations were chosen in a way that an averaging will directly produce a horizontally weighed average. Therefore they cannot be compared with this study in which the sensor locations are not reflecting the decreasing sensitivity of the CRP with horizontal distance.
RESPONSE: Yes, we fix 5 locations in order to represent the mean value from 19 locations, as discussed in Major comments. Positions are similarly located to those suggested by Zreda et al (2010) and slightly modified according to soil properties.

P4247 L12-16 Please quantitative measures for the homogeneity of the spatial and vertical soil texture distribution (e.g. min-max ranges).
RESPONSE: Yes, this information will be discussed in the methodology part. A new table with information of soil properties will be also include in revised manuscript.

P4247 L17-23 A temporal soil moisture stability analysis should have been performed to select the most representative sites (e.g. Vachaud et al. 1985; Vanderlinden et al., 2012).
RESPONSE: As we discussed in second major comment, 5 selected locations represent very well absolute values and dynamics of soil moisture in 19 locations. Moreover, mean value of 5 locations is very well in agreement with sampling campaign, deviation is inside sensor error. Moreover we will acknowledge reviewer recommendation with a new paragraph in methodology:

"Based on our field conditions, the procedure applied in this study to select sensor locations is simplified compared to other studies (e.g. Martinez-Fernandez et al. 2005). For instance, a temporal stability analysis of soil moisture (Vachaud et al. 1985) should be addressed in order to identify representative locations for mean soil moisture in sites with heterogeneous field conditions, e.g. different crops inside footprint, stronger soil layering, higher ranges of soil properties, etc".

P4248 L2-10 Actually the two measurement campaigns indicate that the five in-situ soil moisture measurement locations are creating a significant soil moisture overestimation (0.011 m3/m3 and 0.035 m3/m3 or 21% and 25 %, respectively). Therefore, it is questionable where these locations can adequately represent the average soil moisture within the CRP footprint. A good representiveness of the in-situ measurement locations is especially important for this CRP calibration evaluation study.
RESPONSE: As already commented at the end of response to general point # 2, selected five locations provide mean values representative in terms of absolute values and dynamics of mean soil moisture from 19 locations. Based on site-specific conditions, network was reduced. However, approach provides a continuous observation in time not addressed in previous approaches (e.g. Zreda et al 2012).

FDR sensors were placed immediately after sowing and before harvest in the field. Number of FDR profiles is practical for agricultural purposes carried out in the field. Deviation of FDR sensors respect to campaigns is within the expected sensor error.

P4248 L24-25 Atmospheric water vapour corrections eliminate temporally varying neutron attenuation efficiency of atmospheric hydrogen. Therefore is a correction with a constant factor is without any effect.
RESPONSE: We meant that atmospheric variation of hydrogen in our field conditions revealed no need of using atmospheric water vapor corrections. We will reformulate this part in manuscript.

P4248 L27 What is the meaning of the "+/-" numbers?
RESPONSE: These numbers represent the standard deviation of counts, expressed as its square root. We will expand range of neutrons including such limits.

P4249 L2-12 This section fits better in the method chapter.
Yes, we will move this section to the methodology part. This is our working assumption for the CRS calibration.

P4249 L24- P4250 L3 This result is actually no surprise. A splitting of the data set into calibration and validation subsets would shed more light on the meaningfulness of the different calibration approaches.
RESPONSE: Based on the Physics of the CRS methodology, results are clear. However, we provide a quantification of the vegetation influence. Yes, we will provide a split sampling for calibration and validation purposes.

P4250 L5-6 Fig. 4 doesn't show any criteria showing the quality of the CRP calibrations.
Please reformulate.
RESPONSE: Yes, we will reformulate this sentence as follows: "The variability of cosmic-ray soil moisture in respect to the ground-truth for the different calibration scenarios is plotted as the error bars in Figure 4".

P4250 L13 ": : : down to: : :"
RESPONSE: Yes, we will change this term.

P4250 L20-22 This statement is in contradiction with findings of Franz et al. (2012). One reason for this outcome might also be the low number of measurement locations.
RESPONSE: This will be clarified in revised manuscript. The misunderstanding is that we observe at our site that accounting for a variable penetration depth does not matter, but that is based on the specific soil moisture profile at our site, not a general statement:
Depth-averaged soil moisture in current study was computed using a fixed depth (z = 40 cm) and variable depth (z* from Franz et al. 2012). Both mean values do not show a statistical difference. This is in agreement with similar vertical distribution of soil

properties measured in the field. We do not want to say that CRS has a constant penetration, instead this penetration become constant due to specific-site conditions.

P4251 L14 ": : : was already explained: : :"
RESPONSE: Yes, we will change this in revised manuscript.

P4251 L24-26 This statement is unclear. Please give more information.
RESPONSE: We will rephrase sentence as follows: "N_0 parameters in the sunflower period presented an exponential tendency from initial to mid-season of sunflower, followed by an increase of N_0 at the late sunflower season. This tendency is similar in a daily and monthly resolution. Similar conclusions were drawn by Hornbuckle et al. (2012) for maize".

P4252 L2-4 This statement is unclear. Please reformulate.
RESPONSE: We identified that tendency of parameter variability is similar using daily or monthly computations. Therefore, a single-day calibration is sufficient with a single parameter calibration. We will reformulate this paragraph in revised manuscript.

P4252 L12-18 I don't see the benefit of introducing this statistic. It is also not used to validate the calibration approaches. Therefore I suggest omitting it.
RESPONSE: We considered the use of soil moisture anomalies for better comparison of FDR soil moisture and CRS soil moisture due to their different support volumes. Anomalies reduce the influence of different means and variances from both techniques. However, as reviewer suggested, we will omit this statistics because these elaborations for the specific case did not add particular information.

P4253 L3-5 In this study, the CRP is underestimating soil moisture over a period of more than one month. The underestimation reported by Franz et al. (2012) lasted only some days (during the infiltration of a sharp wetting front). Therefore this reference is not adequate. In fact the discrepancy might be due to the influence of the biomass on neutron count rate.
RESPONSE: OK, reference will be deleted in revised manuscript and discussion will be focused more on biomass.

P4253 L17-22 The effects of lattice water and organic matter on the neutron count rate should be quantified before make such a statement.
RESPONSE: We will provide values of lattice water and organic matter in methodology section in order to have a clear discussion. Average values of lattice water and organic matter in field are 0.012 g/g and 0.023 g/g. These values are relatively low compared to COSMOS sites (Zreda et al. 201) and they only affect penetration depth. For instance, maximum effective depth is reduced from 70 cm down to 40 cm. Moreover, since we are carrying out local calibrations and hydrogen pools from lattice water and organic matter are constant in time, there is no need to quantify them for the calibration.

P4253 L25 "make it"
RESPONSE: OK.

P4254 L4-6 A large part of the scatter is produced by the CRP measurement noise. There this statement is not appropriate.
RESPONSE: We recognized that there is a complex interaction between noise and trend added by crop. However, crop effect is more predominant than natural variability of neutrons (observed as noise). We will improve this imagine proving a moving average.

P4254 L12-15 Why are so many dates missing in Fig. 7b (Fig. 5 indicates a lower number of data gaps)?
RESPONSE: In current manuscript we provided average values. We will make the discussion of vegetation influence based on temporal variability of neutron counts in revised manuscript (see P4255 L4-11). Therefore, this figure will be deleted.

P4254 L13-15 Either results are shown or this sentence should be omitted.
RESPONSE: See above.

P4254 L29 Please provide the equation.
RESPONSE: Equation will be provided in methodology part.

P4255 L4-11 Why is No for WR much higher than for S? In order to better understand the relationship between Natt and biomass, you should also present the time series.
RESPONSE: Authors can not follow comment of reviewer in text. We will provide a new methodology part of vegetation correction based on neutron counts. Time series of attenuated neutrons will be presented in revised manuscript.

P4255 L11-13 Why should the Poisson's variability produce this discrepancy?
RESPONSE: Now we added additional explanations as follows:

"The decreased tendency of N_0 values with respect to N_{att} (Fig. 8) was expected; the higher N_0 values at the initial sunflower stage corresponded to the lower values of N_{att} and vice versa. Maximum attenuation occurred at maximum crop stage in both sunflower and winter rye, i.e. large biomass and well developed root structure. The fact that there is an offset of about 50 counts per hour for N_{att} is related to (i) crop growing within initial stage (i.e. height fluctuated from 5 cm to 30 cm), (ii) contribution of constant hydrogen pools such a lattice water, (iii) contribution of organic matter, and (iv) natural noise of neutron signal".

P4255 L20 Please only provide conclusions (a summary should be given in the abstract).
RESPONSE: Yes, this section will be shortened.

Figures

Fig. 2 The different scenarios are well described. Therefore, this figure is unnecessary.
RESPONSE: Yes, we will delete this figure.

Fig. 4 Please indicate the calibration approach used
RESPONSE: Authors can not follow comment. Name of calibration approach is plotted on the right vertical axis. This figure will be deleted in revised manuscript. Values are already presented in Appendix tables.