Author Response to Reviews of

A dense network of cosmic-ray neutron sensors for soil moisture observation in a pre-alpine headwater catchment in Germany

Benjamin Fersch et al.

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

Dear Referees,

we would like to thank you very much for your positive comments and constructive suggestions to our manuscript. In this document, we would like to provide our responses to the comments of each of the referees in one single document and to outline the corresponding changes to the manuscript. We hope that our response together with the revision of the manuscript sufficiently addresses the referees' concerns.

Kind regards,

Benjamin Fersch

on behalf of the author team

1. Referee #1

1.1. Title

A dense network of cosmic-ray neutron sensors for soil moisture observation in a pre-alpine headwater catchment in Germany

RC: *I am not sure if the title of the paper is a good representation of the content as there is just as much data on meteorology and alternative soil moisture information as there is on CRNS measurements. Not sure how best to capture the breadth of observations but perhaps a title along the lines of the following might be better...*

"A dense network of cosmic-ray neutron sensors for soil moisture observation in a pre-alpine headwater catchment in Germany including supplementary meteorological and hydrological observations"

or

"A dense network of cosmic-ray neutron sensors and supplementary measurements for soil moisture observation in a pre-alpine headwater catchment in Germany"

AR: *We thank the referee for the suggestion. We would like to propose the following changed title: "A dense*

network of cosmic-ray neutron sensors for soil moisture observation in a highly instrumented pre-alpine headwater catchment in Germany".

1.2. Availability of a soil moisture product

RC: *The datasets are well organised with suitable metadata and data structures used throughout. I would like to have seen a version of the CRNS static data with an estimate of soil moisture data using a predefined approach. I realise techniques are evolving and the key focus is on CRNS processing options, but this would provide an off-the-shelf option for some users who just want some measure of soil moisture for analysis (i.e. hydrological model, satellite cal/val). This may increase data utilisation. As it stands the raw counts and all of the data required for corrections and processing are provided, but users with little experience in the CRNS field may be a little reluctant to process the data themselves.*

AR: *We certainly understand the referee's concern that the presented data would not be helpful for users with little experience. Yet, the referee pointed out himself that the retrieval of a soil moisture product from neutron count rates is still evolving and not trivial. The aim of this data publication is to provide a data set to the research community that can be used for soil moisture estimation at varying levels of complexity. Adding any preliminary or "first-order" soil moisture product as part of the published data set would not be a valuable service to the community. Providing an in-depth analysis, on the other hand, is certainly beyond the scope of this publication. Instead, we are currently working on an extensive study that explores options for soil moisture estimation at the level of individual probes, but, more importantly, on the consistent interpolation of soil moisture across the study area. As part of that ongoing study, we also aim at providing a soil moisture product which will then be adequately documented and validated as part of the corresponding publication.*

1.3. Line 8

RC: *Change 'that network' to 'this network'*

AR: *Will be changed.*

1.4. Line 10

RC: *change to '...allow users to...'*

AR: *Will be changed.*

1.5. Line 19

RC: *change to '...EU-DAT and is split into two subsets...'*

AR: *Will be changed to: "EUDAT Collaborative Data Infrastructure (EUDAT), and is split into two subsets:"*

1.6. Line 19

RC: *1st hyperlink includes first part of reference and does not work*

AR: *We are sorry that the hyperlink did not appear to work for the referee. We double-checked it with different pdf reader formats and it worked as expected. We would like to ask the reviewer to double check the link as well, and we hope for a final solution of the issue during the process of typesetting.*

1.7.   Line 29

RC: *maybe spell out TDR and TDR first time through*

AR: *We assume the referee meant "FDR and TDR". We will spell out both at first time use.*

1.8.   Line 31

RC: *do you mean support volume*

AR: *Correct. We will change "support" to "support volume".*

1.9.   Line 36

RC: *add'are' between 'and' and 'thus*

AR: *Will be added.*

1.10.   Line 39

RC: *It might be less clunky to just say they have poor temporal resolution.*

AR: *We thank the referee, but we would prefer to keep the sentence as it is since such datasets do not actually have a temporal "resolution", but could just be snapshots at arbitrary points in time.*

1.11.   Line 44

RC: *Not sure describing the footprint as exponentially shaped is a good description. The footprint declines radially with distance from the CRNS – its more bell shaped or declines exponentially with distance from the CRNS.*

AR: *Thank you for pointing this out, we have indeed described the shape inappropriately. The shape is actually very complex and not easy to describe in short. Since those details are not relevant here, we think that the provided reference is sufficient and we will remove the term "exponentially-shaped" from the text.*

1.12.   Line 48

RC: *'...presented the first...'*

AR: *Will be changed.*

1.13.   Line 58

RC: *change to "...monitoring exists and these use various gases..."*

AR: *Will be changed.*

1.14.   Line 87

RC: *suggest deleting after the :*

AR: *We understand the suggestion. Yet, we prefer to keep the two items after the column as it helps guiding the reader through what follows next. We propose to replace the colon with "such as".*

1.15.   Line 88

RC: *needs rewording - does not make sense as is*

 AR: *Thank you, we propose to change the sentence to: "The term 'Roving CRNS' stands for the utilization of mobile CRNS sensors to increase the spatial extent of soil moisture measurements. It has been recognized ..."*

1.16.   Line 96

RC: *change 'of' to 'in'*

 AR: *Will be changed.*

1.17.   Line 130

RC: *change 'had' to 'have'*

 AR: *Will be changed.*

1.18.   Line 149

RC: *delete 'however'*

 AR: *Will be deleted.*

1.19.   Line 156

RC: *By backbone do you mean existing long-term datasets? If so suggest changing.*

 AR: *We will change "backbone" to "long-term".*

1.20.   Line 160

RC: *change 'could identify' to 'identified'*

 AR: *Will be changed.*

1.21.   Line 170

RC: *insert 'this was' between 'and' and 'followed'*

 AR: *Will be added.*

1.22.   Line 213

RC: *Do you mean back ground?*

 AR: *We will remove the term "backbone".*

1.23.   Figure 2

RC: *Figure 2 is not referenced in the text.*

AR: *We propose to change the text as follows: "Tab. 2 gives an overview of all stationary CRNS sensors that were used during the campaign. Fig. 2 illustrates the proportions of the different sensor models."*

1.24. Fig3 caption

RC: *Use "Note: y-axis scaling differs between plots"*

AR: *Will be changed.*

1.25. Line 361 Line 362

RC: *inverted commas wrong*

AR: *Will be corrected.*

1.26. Line 374

RC: *Needs to be reworded for clarity. What is being constrained? Models?*

AR: *We suggest to replace "but also allows to better constrain" by "it also informs about".*

1.27. Line 386

RC: *change to "A large number of manual soil moisture measurements were carried out from June 25 to 26, 2019 and these were useful for increasing the spatial coverage of the continuously-recorded soil moisture data, enabling the calibration of the moisture sensors and obtaining basic soil properties (bulk density, residual water content, organic matter content, texture).*

AR: *Will be adopted.*

1.28. Line 475

RC: *change 'is' to 'was*

AR: *Will be changed.*

1.29. Line 493

RC: *'on top of'*

AR: *Will be changed.*

1.30. Line 567

RC: *remove 'yet' and 'already'*

AR: *Will be removed.*

1.31. Line 578

RC: *delete 'already'*

AR: *Will be deleted.*

1.32. Line 600

RC: *change to "...allow users to..."*

AR: *Will be changed.*

2. Reviewer #2

2.1. Introduction

RC: *I think the context chosen by the authors to justify the choice of area is slightly incomplete (or maybe slightly misleading). Reading the relevant sections of the manuscript, it gives the impression that this choice was because typical applications of cosmic-ray sensors are either done for single (isolated) sites or for large-scale continental/national networks, which consequently misses this overlapping aspect of multiple measurements at the same 1 sq-km (grid) area (note that the area represents a tiny fraction of the 55 sq-km Rott catchment). The nature of single sites of large networks is continuous monitoring capability whereas here the data describes a short-term summer campaign (from late-April to early-July). There is nothing majorly wrong with the text but given that this is short campaign, framing the paper more towards the importance of short-term intensive campaigns would, in my opinion, make the paper present better the motivation for this dataset. Authors can cite similar work done for other products such as SMOSMANIA and SMAPEx campaigns, for example. In addition, an area of 1 sq-km is probably related to very small catchments, and the context would probably be better linked to understanding spatial heterogeneity for high-resolution soil moisture applications. I am surprised to see the authors failed to cite seminal work by Roger Grayson, Andrew Western, and Gunther Bloschl in the 1990s that tackle this high-resolution measurement problem with very interesting and impactful results to the hydrological community.*

AR: *We thank the referee for this thoughtful comment. Yet, we tend to disagree with the view that the prime feature of the presented campaign was its short-term character – in comparison to long-term national scale networks. At least we interpret the following comment accordingly: "[...] given that this is a short campaign, framing the paper more towards the importance of short-term intensive campaigns would, in my opinion, make the paper present better the motivation for this dataset." In our view, however, the prime feature of this campaign was the high spatial density of CRNS sensors in a study area characterised by large heterogeneity of land use, soil, and soil moisture. That spatial density is motivated, on the one hand, by the aim to cover root zone soil moisture dynamics at the small catchment scale, and, on the other hand, by the aim to represent the spatial variability of soil moisture at that scale, and to use the overlap of CRNS footprints for that purpose. As soon as you place CRNS probes so far from each other that their footprints do not overlap anymore, the retrieval of spatial patterns is "reduced" to the problem of spatial interpolation. However, as the footprints overlap, there is the potential to extract additional spatial information from the fact that the same area is covered by different probes (similar to the idea of a geophysical inversion). We have tried to explain these aspects in ll. 121–125 of the original manuscript.*

So while we appreciate the comment, we think that the short-term character of this campaign is not its prime feature nor its motivation. The duration was rather constrained by resources. However, we have already started to establish a dense network of 12 CRNS sensors near Potsdam that is designed at least for a medium-term operation (i.e. several years).

Based on the above argument, we would also prefer not to explicitly cite the suggested references on SMOSMANIA and SMAPEX. While SMAPEX was specifically geared towards understanding soil moisture variability inside the SMAP footprint scale (i.e. 10–30 km), SMOSMANIA is about soil moisture monitoring at 21 locations as part of the national scale meteorological observation network RADOME (Meteo France). SMOS and SMAP themselves are already referred to in the overview papers we cited in section 1.1 (Wang and Qu, 2009; Mohanty et al., 2017). Yet, we thank the referee for suggesting Blöschl and Grayson who of course cannot be cited too often. In the revised version, we will refer to "Blöschl, G., R. Grayson (2000): Spatial Observations and Interpolation. In: Blöschl, G., R. Grayson (Eds.): Spatial Patterns in Catchment Hydrology - Observations and Modelling, Cambridge University Press, pp. 17-50" in l. 30 of the original manuscript.

2.2. Figure numbering

RC: *In many instances throughout the paper, I don't understand why the manuscript jumps to figures without following a common numerical order (introduces Figures 1 previously, then refers to Figure 9 here; then refers to Fig 3 later on; Fig 2 is not referred in the text before showing up in the manuscript, etc...). This makes reading through the manuscript a bit more difficult.*

AR: *We apologize for any inconvenience, but using the Copernicus tex template, we could not influence the actual placement of the figures in the manuscript draft. We will take additional care of this issue during the copy-editing phase. As for Fig. 2, we will add the reference. Fig. 9 constitutes an exception, as it is used both for illustrating the temporal coverage and presenting example. Because the focus is on the latter, it is placed closer to this sections.*

2.3. Is the CRNS technique still "novel"?

RC: *The cosmic-ray neutron sensing technique for soil moisture application is now more than 10 years old. I'd strongly encourage the authors and the community, in general, to stop using words like "emerging", "novel", "promising", etc... to describe the technique as these statements now read a bit outdated.*

AR: *We agree with your view that the CRNS method is used for various applications and that since its broader introduction in 2010 a certain standard has emerged. On the other hand, we don't think that the technique has yet evolved as a standard for soil moisture observation per se. We will go through the text and adapt our wording while acknowledging the current spread and history of the technique.*

2.4. Lines 70-71

RC: *Perhaps the authors can include the citation to previous studies that have altered the values of the 'a' coefficients in an attempt to improve the estimated soil moisture signal from the sensor:*

Rivera Villarreyes, C. A., Baroni, G., & Oswald, S. E. (2011). Integral quantification of seasonal soil moisture changes in farmland by cosmic-ray neutrons. Hydrol. Earth Syst. Sci., 15(12), 3843–3859. https://doi.org/10.5194/hess-15-3843-2011

Iwema, J., Rosolem, R., Baatz, R., Wagener, T., and Bogena, H. R.: Investigating temporal field sampling strategies for site-specific calibration of three soil moisture–neutron intensity parameterisation methods, Hydrol. Earth Syst. Sci., 19, 3203–3216, https://doi.org/10.5194/hess-19-3203-2015, 2015.

Heidbüchel, I., Güntner, A., and Blume, T.: Use of cosmic-ray neutron sensors for soil moisture monitoring in forests, Hydrol. Earth Syst. Sci., 20, 1269–1288,https://doi.org/10.5194/hess-20-1269-2016, 2016.

AR: *Thank you for suggesting additional papers about the a_i parameters. We propose to reformulate the sentence: "The parameters a_0, a_1, and a_2 have proved to be robust in their original formulation across multiple CRNS sites (Desilets2010, Evans2016, Schroen2017, among others), while few locations apparently work better with different values (Rivera2011, Iwema2015, Heidbuchel2016).*

2.5.   Figure 6

RC: ***There is just too much information in this figure. What is the main purpose of the figure? Do the authors need to show all numbers on those maps? Do they need to show all maps?***

AR: *Figure 6 shows the tracks and patterns of the roving campaign. We will replace the IDs of the CRNS-probes with simple symbols for clarity. However, we would like to show the maps for all dates to illustrate the spatiotemporal coverage of the rover campaigns and the resulting qualitative spatial patterns of soil moisture.*

2.6.   Example application

RC: ***As an example of application, the authors could easily have identified how similar or different the measurements are (20+ sensors in a 1 sq-km area seems a bit too much for me). Perhaps they could either look at the different CDF for each measurement and determine if they theoretically come from the same or different distribution using the Kolmogorov-Smirnov test; or apply some temporal stability analysis (???)***

AR: *We thank the referee for this interesting suggestion, which we will try to incorporate in our ongoing analysis of the data. Without doubt, there are countless other analyses that could be performed with the presented data. Therefore, we are happy to provide these data to the community. However, we cannot and do not intend to present any exhaustive analysis in this paper. In accordance to the ESSD journal guidelines, we are focusing on the documentation of the dataset only. Our presented application is merely one of many examples of how this dataset could be used.*