Interactive Discussion: Author Response to Referee #3

Spatio-temporal soil moisture retrieval at the catchment-scale using a dense network of cosmic-ray neutron sensors

Maik Heistermann et al.
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RC: ***Reviewer Comment***, AR: *Author Response*, ☐ Manuscript text

Dear Referee,

we would like to thank you for your critical comments and constructive suggestions to our manuscript. We very much appreciate the time and effort that you have invested in your report.

Please find below our detailed responses to the issues you have raised in your report. We are confident that the manuscript will improve as a consequence to addressing your concerns.

Kind regards,
Maik Heistermann
(on behalf of the author team)

3.1. Advancement of practical applications

RC: ***This manuscript describes the first ever attempt to use multiple CRNS to estimate catchment-scale soil moisture, including temporal and spatial variations. The research conducted is of interest and importance to the research community, even if the findings are somewhat marginal in their advancement of practical application.***

AR: The campaign itself and the present analysis were designed to answer primarily theoretical and methodological questions of cosmic-ray neutron sensing, and not geared towards practical applications. We agree that it will, for the foreseeable future, not be cost-effective or practical to deploy 10-20 CRNS probes per square kilometer for routine soil moisture monitoring (see also our response to comment 3.9). And yes, the results of the present analysis, in terms of the soil moisture patterns retrieved from our CRNS network, might not appear overwhelming, as opposed to the spatial detail that could be achieved with wireless sensor networks (see also our response to comment 3.8).

As the referee pointed out correctly, this analysis is the first attempt to use the observations of such a dense network for a spatially explicit retrieval of soil moisture patterns, and it has a clear methodological focus: (1) we demonstrate a uniform homogenisation and calibration approach across multiple CRNS stations (a concept that will be relevant particularly for future CRNS observatory networks), and (2) on that basis, the potential to capture main features of spatial soil moisture variability at the scale of hectometers, continuous in time. We also introduce an entirely new approach to constrain a spatial interpolation by the dynamic CRNS footprint characteristics. What this study does *not* claim to achieve: to provide a scalable monitoring technique, to represent small-scale features of soil moisture variability, and to consistently link our observations to hydrological and soil hydraulic processes (although we briefly discuss potential explanations of temporal dynamics in section 5.3 of the original manuscript).

While this study does explicitly not claim to *achieve* these objectives, it is still *motivated* by them and works towards those goals. For example, future research should aim to combine such CRNS observations with spaceborne remote sensing data: to obtain patterns at a higher resolution via downscaling, or to upscale CRNS observations beyond such local networks in a cost-efficient way. And we should design assimilation experiments with hydrological models at various levels of physical detail in order to understand how we can consistently represent our observations and our physical expectations. We do not solve these issues in the present study, but we outline a methodological framework that should facilitate them.

We apologize if the scope of the present manuscript has not come across clear enough. In the revised version, we will attempt to clarify the scope, but also to better outline prospective research threads that will hopefully unfold a more visible impact.

3.2. Length of the manuscript

RC: ***While the paper is well-organized and written, it is excessively long and tedious to read. I understand that the authors wish to share the minutia of their novel methodology, but as written the paper is difficult to read and seems more akin to a grant proposal than a scientific manuscript.***

AR: We thank the referee for this comment. It is in line with the comments of referee #1 who also suggested to shorten the manuscript. Then again, referee #2 rather required *more* details in terms of both methodology and discussion. In summary, we agree that there is potential to make the paper more concise, and we have outlined, in reply to the very constructive suggestions of referee #1, how to achieve that goal. At the same time, we tend to insist that due to the strong methodological focus of the paper, the adequate documentation of methodological details and the discussion of their limitations should not suffer. We are confident, though, to find a balance between these two ends in the revised manuscript.

3.3. Absolute values

RC: ***I dislike the goal of the project to match the pattern rather than absolute values (stated in Line 434) and the general avoidance of quantifying differences or variability in the estimated and measured soil moisture values. I understand why the authors have chosen this approach, but I also think that the use of the absolute values of measured and estimated volumetric water content would be useful to present to the scientific community. Relative values only provide so much information.***

AR: There is maybe a misconception of the study, as it has not been "the goal of the project to match the pattern rather than absolute values", and from our perspective there is no "general avoidance of quantifying differences or variability" in the manuscript.

The reviewer refers to line 434 of our manuscript:

> [...] to eliminate the potential effect of systematic bias in the SoilNet data, [...] we target the matching of the pattern rather than the absolute values."

This statement only applies to the comparison to the SoilNet data, and explains why we use Spearman's rank correlation coefficient as an objective measure of similarity between the soil moisture inferred from the SoilNet and the interpolation of CRNS-based soil moisture estimates: in this case, we are specifically interested in how well the spatial patterns agree, in order to evaluate which interpolation method better represents soil moisture gradients at the hectometer scale. Numerous equations exist for converting permittivity (the prime observational variable of the SoilNet) to volumetric soil moisture [Mohamed and Paleologos, 2018], and the exact shape could differ substantially, depending on underlying functions and corresponding coefficients. To eliminate the associated uncertainty and arbitrariness from our analysis, we chose to use Spearman rank correlation.

But we agree that the above formulation is ambiguous, so we suggest to change the paragraph to:

> We evaluate the similarity of the spatial soil moisture patterns obtained from the FDR-cluster and the interpolation of $\theta(N_i)$ for each day from May 20 to July 15, 2019. As a measure of similarity, we chose Spearman's rank correlation of the corresponding soil moisture grids. Using that measure, we eliminate potential effects of uncertainty in the soil moisture values obtained from the SoilNet, as the conversion from permittivity to volumetric soil moisture can be subject to systematic bias [Mohamed and Paleologos, 2018].

While we are convinced that this comparison approach is adequate in the context of this study, we would still like to address the referee's concern of a "general avoidance of quantifying differences or variability in the estimated and measured soil moisture values." To that end, we would like to adopt the referee's suggestion made in comment 3.8: *"[...] I would be more interested in a time series figure showing the mean field-scale volumetric water content for each of the three scenarios- unconstrained, constrained, and SoilNet. I suspect that the constrained and unconstrained values would be far more similar to one another than to the SoilNet values."* Certainly, the referee is correct with assuming that the two CRNS-based interpolation results (constrained, unconstrained) are far more similar to each other than each of them is to the SoilNet estimates. We think that this notion is obvious from the soil moisture maps shown in Fig. 9. Still, we would like to meet the referee's demand, and suggest to add another panel to Fig. 10 in which we show the soil moisture time series for the three scenarios for the area of the SoilNet. We interpret the term "mean field-scale volumetric water content", as suggested by the referee, as the mean over the SoilNet area.

3.4. Shallow groundwater

RC: ***Section 2: The authors mention in passing the presence of very shallow groundwater, but do not mention how this likely has significant effects on their CRNS measurements. This issue should be addressed much more thoroughly.***

AR: We agree that the interpretation of soil moisture patterns would benefit from a better knowledge of the depth to the groundwater table. Unfortunately, we rely on the references given in section 2 of the original manuscript. Spatially explicit information on depth to the groundwater table are not available, and we assume that the below-ground structure is complex and heterogeneous: the very shallow groundwater, where present, appears to result from the local accumulation of percolating water on low-permeable soil layers – a perched aquifer, if at all. As such, it would not be a laterally extended water body that feeds water to the top-soil but rather a part of the soil water balance. All this information, however, is patchy, and rather hypothetical, and does not rely on robust spatial observations of shallow groundwater. Hence, we would prefer not to excessively hypothesize about this matter in the manuscript. However, we suggest to mention, in the revised manuscript, the possibility of such local structures, but also emphasize the lack of corresponding data.

3.5. Soil texture and SOM

RC: ***Additionally, the authors should provide the textural and SOM information for samples taken near each CRNS (texture) and for each mixed sample (SOM). Providing an average catchment-scale value is not acceptable, and readers cannot be expected to read every cited paper to find this information, which could easily be incorporated into Table 2.***

AR: We agree that it would be helpful to explicitly link soil attributes to CRNS locations in order to allow for a better interpretability. A soil texture analysis was unfortunately not carried out for the soil that was sampled by cylinders near each CRNS. Based on the referee's request we have, however, computed the relative coverage of soil types as extracted from the Übersichtsbodenkarte (1:25000) of the Bayrisches Landesamt für Umwelt [Bayerisches Landesamt für Umwelt, 2014] and soil texture classes as obtained from the Bayrisches Landesamt für Digitalisierung, Breitband und Vermessung within the product Bodenschätzungsdaten [Landesamt für Digitalisierung, Breitband und Vermessung, 2018], using the horizontal weighting scheme from [Schrön et al., 2017]. The soil organic matter (SOM) content was only determined for mixed samples from the three landuse/soil classes (forest/mineral, grassland/mineral, and grassland/organic). In order to meet the referee's demand, we suggest to include the SOM content (weighted average in the footprint) as an additional attribute in Tab. 2. As for the soil texture class and type, we suggest to include the dominant soil texture class and soil type in Tab. 1 instead of Tab. 2, as the dominant land use type in the footprint is also provided in that table.

RC: ***Further, the estimated gravimetric water content values > 1.0 g/g shown in Figure 4b are unrealistic, unless you are considering a highly organic soil. However, based on the information presented, it is impossible to determine the soil type near CRNS 21 and 23.***

AR: The referee is correct in noting that the high gravimetric soil water content values for the CRNS sensors 21 and 23 are due to the fact that the footprints of these sensors are dominated by highly organic soils. With the additions to Tab. 2 as suggested above, this should become more transparent to the reader – so we thank the referee for this suggestion.

RC: ***Table 2: In addition to including information regarding soil texture and SOM for each site, the authors should include some indication of the variability of the values shown for each site.***

AR: Quantifying the variability of soil texture and SOM in the sensor footprint is difficult due to the limited amount of data (as pointed out above): high-resolution soil mapping was, unfortunately, not part of the underlying campaign. Hence, we suggest to stick with the additional information in Tab. 2 as outlined in our response above.

RC: ***Also, bulk density values are incredibly low, less than 1 kg/L in most cases. Including the SOM content in this table would make those values look less suspect, if indeed the SOM content is extremely high. If not, the authors need to address the very low bulk density values reported.***

AR: The bulk density values shown in Tab. 2 are in fact rather low. It is important to consider, though, that these bulk density values represent the weighted average bulk density per sensor footprint, with the weights corresponding to the vertical and horizontal sensitivity as given by [Schrön et al., 2017]. The low bulk density values here are hence, partly, a result of the vertical weighting: the bulk density generally *decreases* towards the surface (as can be seen in the vertical profiles shown on the supplementary, Fig. S2), while sensor sensitivity pattern *increases* towards the surface. So while the lowest bulk density values are in fact due to organic, high porosity soils (sensors 21 and 23), the generally low bulk density values in Tab. 2 are also due to the fact that the vertical weighting emphasizes the less-dense top soil. We thank the referee for pointing out this issue as we think it would merit a brief clarification in the revised version of our manuscript.

3.6. Uncertainty of θ^{obs}

RC: ***Figure 5: How does the variability in θ_i^{obs} during Monte Carlo simulations compare to the variability observed in measured volumetric water content from thermo-gravimetric samples?***

AR: θ_i^{obs} or its variability in the Monte Carlo analysis should not be compared to the volumetric soil moisture content as obtained from the thermo-gravimetric samples. As pointed out in section 3.4.2 of the original manuscript, we only have *one* thermo-gravimetric sample close to each CRNS sensor. θ_i^{obs}, in turn, is the result of an interpolation of thermo-gravimetric samples *and* FDR-measurements, and subsequent vertically and horizontally weighted averaging. Hence, we do not see the reason for such a comparison.

RC: ***Could the authors provide mean uncertainty values for Monte Carlo $\theta(N_i)$ and θ_i^{obs}? It is difficult to estimate these values from Figure 5 alone.***

AR: We are not sure what the referee means by *"mean uncertainty values for Monte Carlo $\theta(N_i)$ and θ_i^{obs}"*. We would like to emphasize that Fig. 5 only represents the uncertainty of footprint-scale soil moisture estimates at the time of the calibration (June 25-26, 2019), based on the Monte Carlo analysis. The uncertainty is, in Fig. 5, shown as the inter-quartile range of the soil moisture estimates, as well as the range between the 5th and 95th percentile. Does the referee refer by "mean uncertainty" to the average of these percentiles over all 18 CRNS footprint represented in Fig. 5? If yes, we do not see what could be learned from such an average. As already pointed out to referee #2, the main motivation of Fig. 5 is to visually demonstrate that the disagreements that we observe in Fig. 4 can mostly be explained by the local uncertainties of $\theta(N_i)$ and θ_i^{obs}, while location 7 is clearly different. We would hence prefer not to provide average uncertainty values, if the referee agrees.

RC: ***Line 543: It would be good, again, if the authors would quantify this uncertainty.***

AR: We would like to refer to our response above: as the local uncertainty, i.e. the uncertainty of our soil moisture estimate for a specific sensor footprint, is very variable across sensor locations, we do not see the added values in providing an average value. We hope that the referee will agree.

3.7. Reference evapotranspiration

RC: ***Line 525 and Figure 6a: Reference evapotranspiration is different than potential evapotranspiration, but the terms are used interchangeably in the text. Make sure all instances are changed to "reference."***

AR: We will change all instances to "reference evapotranspiration".

3.8. Comparison to SoilNet

RC: ***Figure 9. The results shown in this figure are underwhelming. I expected that the highly concentrated CRNS sensors would be able to provide a closer match in spatial soil moisture distribution to the SoilNet measurements. The lack of spatial agreement with SoilNet soil moisture values, even with a high concentration of CRNS that is unlikely to replicated in practice, is surprising and a bit disappointing. If the CRNS are unable to provide useful spatially explicit information, what is the benefit of using these extremely expensive sensors rather than many cheaper in-situ sensors or downscaled remote sensing data? Also, I would be more interested in a time series figure showing the mean field-scale volumetric water content for each of the three scenarios- unconstrained, constrained, and SoilNet. I suspect that the constrained and unconstrained values would be far more similar to one another than to the SoilNet values.***

AR: We have already responded to parts of this comment in our response to comments 3.1 and 3.3, so we would like to keep this response brief. We understand that the visual impression from Fig. 9 might be disappointing at first - but only if you expected to reproduce the meter-scale variability as represented by 300 invasive sensors (SoilNet, 50 profiles, 3 depths, 2 redundant measurements per depth) by 4 (inside) or 6 (near SoilNet area) non-invasive hectare-scale CRNS sensors. We hope that the referee does not misinterpret our goal as "advertising" dense CRNS networks as "the" solution (according to the comments of referee #1, we are excessively critical to our results rather than sugarcoating them). As matching meter-scale variability cannot be the goal of a study using just a few hectometer-scale CRNS stations, we would like to clarify again: Our main finding is that dense CRNS networks can help to represent soil moisture gradients at the hectometer scale, in an area of say 1 km^2, and that the inversion-style technique of constrained interpolation can add to that. In combination with auxiliary information such as remote sensing, we might even be able to add further details to such patterns - corresponding studies are underway.

Please allow a short remark regarding the mentioned proportionality, practicability, and costs: a high number of in-situ sensors such as the WSN/SoilNet can also become very expensive in terms of long-term maintenance and disruptive in terms of installation, which are clear limitations especially for intensely managed agricultural fields. In contrast, CRNS sensors require hardly any maintenance and sense soil moisture non-invasively at a larger scale, while they can be used in small networks or mobile roving campaigns. We think that these advantages could be well suited for agricultural applications as well as evaluation of remote-sensing and modeling products, where intermediate-scale soil moisture patterns are of key importance.

3.9. Costs

RC: ***Line 595: While I agree that the current application of a large number of CRNS in a small area is interesting, I do not think it is economically feasible or sustainable. The authors should at least mention the cost prohibitive nature of this study.***

AR: As already pointed out in our response to comment 3.1, we agree that such dense networks are not suited for routine soil moisture monitoring, and while we have not suggested otherwise in our manuscript, we will explicitly clarify that in the revised version.

In research environments, we hope that such dense networks can contribute to a better understanding of soil moisture variability in space and time, and that other sensor platforms, such as spaceborne remote sensing, in combination with hydrological models, could be used for a cost-efficient upscaling of these insights.

3.10. Technical corrections

RC: ***Line 301: Should read "how the availability of sampling locations affected N0 calibrations [...]***

AR: Thanks for pointing out this incomplete sentence, we changed it accordingly.

RC: ***Line 725: Should read "from August 2019"***

AR: The typo was corrected, thanks for pointing it out.

References

[Bayerisches Landesamt für Umwelt, 2014] Bayerisches Landesamt für Umwelt (2014). Übersichtsbodenkarte tk25-blatt 8132. `www.lfu.bayern.de`.

[Landesamt für Digitalisierung, Breitband und Vermessung, 2018] Landesamt für Digitalisierung, Breitband und Vermessung (2018). Bodenschätzung. https://geoservices.bayern.de/wms/v1/ogc_alkis_bosch.cgi?

[Mohamed and Paleologos, 2018] Mohamed, A.-M. O. and Paleologos, E. K. (2018). Chapter 16 - dielectric permittivity and moisture content. In Mohamed, A.-M. O. and Paleologos, E. K., editors, *Fundamentals of Geoenvironmental Engineering*, pages 581–637. Butterworth-Heinemann.

[Schrön et al., 2017] Schrön, M., Köhli, M., Scheiffele, L., Iwema, J., Bogena, H. R., Lv, L., Martini, E., Baroni, G., Rosolem, R., Weimar, J., Mai, J., Cuntz, M., Rebmann, C., Oswald, S. E., Dietrich, P., Schmidt, U., and Zacharias, S. (2017). Improving calibration and validation of cosmic-ray neutron sensors in the light of spatial sensitivity. *Hydrology and Earth System Sciences*, 21(10):5009–5030.