

Author Response to Referees

The Potsdam Soil Moisture Observatory: High-coverage reference observations at kilometer scale

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Earth Syst. Sci. Data Discuss., doi:10.5194/essd-2025-546

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

Dear referees,

we thank you again very much for the time and effort you invested in reviewing our manuscript, as well as for the helpful suggestions to improve its clarity and grammar. With this document we provide the combined answers to all five reviewer reports in a combined document. They correspond to our previous responses in the interactive discussion, now in final and partly more detailed form. However, grammar and typo correction and general reworking of text is not described explicitly, but visible in the track changes version.

Kind regards,

Lena Scheffele and Sascha Oswald (on behalf of the author team)

1. Responses to referee #1

RC: L5 – suggest “...for remote sensing algorithm validation due to its ability...”

AR: Is implemented.

RC: L15 – suggest “The data are available from: <https://doi.org/>”

AR: Changed to

The data are available at , as the doi refers to the repository.

RC: L19 – rewrite the first sentence it is very hard to get past without rereading many times. Do you mean “Soil water storage varies spatially and temporally and is critical for understanding the water cycle, fluxes between the land surface and atmosphere...”?

RC: L21 – what is an essential climate variable as defined by Bojinski? Sentence needs explanation.

RC: L25 – Fix grammar “The main challenges in soil moisture observation are...???”

AR: We rephrased the paragraph

The dynamic storage of water in soil is an important component of the terrestrial water cycle, yet it exhibits pronounced spatial and temporal variability. It regulates water and energy exchange between land surface and atmosphere and plays a key role in ecohydrological processes, agricultural productivity, forest dynamics and groundwater recharge. Due to its critical influence on weather, climate, hydrology, and ecosystem

functioning, soil moisture has been designated as one of the Essential Climate Variables (Bojinski et al., 2014). Reliable soil moisture observations are therefore needed not only for climate and ecological research, but also for applied purposes including water resources management, irrigation planning, and agricultural management, as well as flood and drought forecasting and weather prediction (Vereecken et al., 2008; Brocca et al., 2017; Moragoda et al., 2022; Levi and Bestelmeyer, 2018; Molenaar et al., 2024; Srivastava, 2017; Hövel et al., 2025; Pendergrass et al., 2020; Abioye et al., 2020; Lachenmeier et al., 2024; Szilagyi and Franz, 2020). Major challenges include the need to observe soil moisture across multiple spatial scales, the limited ability to directly capture root-zone and deeper soil water storage, and the spatial and depth mismatches between satellite observations and in-situ measurements (Oswald et al., 2024).

RC: L34 – suggest deleting “at very specific locations”

AR: We change the sentence to

These techniques provide observations with high temporal resolution but due to their small support volume (typically only a few cubic centimeters) at selected locations only (Robinson et al., 2008). Thus, due to the aforementioned heterogeneity of soil moisture, their representativeness remains limited.

RC: L52 – suggest changing to “... technology has proven to be a valuable method for intermediate...”

AR: Is implemented.

RC: L58 – suggest "Neutron counts are typically accumulated over several hours, corrected for factors such as air pressure, and then converted to volumetric water content using a custom calibration function."

AR: We changed the sentence to

Neutron counts are typically accumulated over several hours, yielding neutron count rates, that are corrected for influencing factors such as air pressure, and then converted to soil water content using a custom calibration function (Desilets et al., 2010; Zreda et al., 2012)

RC: Fig 1 – can you make the site numbers a different colour like white so they can be read

AR: They are white now.

RC: L138 – are the TDT/FDR measurements field calibrated or are factory default calibration used? This is important as factory default values can be very poor

AR: The TDT/FDR sensors were field calibrated. In the revised manuscript this section is now integrated with introduction, site description and the details regarding the TDR and FDR calibration is provided in section 3.3.

RC: L173 – the instruments sold by Quaesta are made under licence from Hydroinnova – i.e. they are the same thing. It might be a different model but it's the same technology

AR: To our knowledge, Hydroinnova supplies its systems with a Quaesta Logger as part of the complete setup. We operate different systems utilizing ³He, Li, and BF₃. Following its merger with Lab-C, Quaesta now distributes systems under its own name. As far as we are aware, all three brands — Hydroinnova, Quaesta/Lab-C, and Lab-C — use Quaesta Loggers.

RC: L185 – what correction approaches (pressure, vapour, intensity) and calibration equation have been applied to get soil moisture? NOTE – I now see this section 4 (maybe add a note that it is coming later)

AR: We restructured the manuscript and the CRNS processing and calibration is now described as a subsection

(3.1.2) in section **Stationary CRNS data (3.1)**.

RC: *L200 – A figure comparing the relative intensity of a couple of adjacent neutron sensors would be nice to see if they respond similarly*

AR: Our focus here is on demonstrating results in respect to soil moisture, not on the raw count intensity itself, also as the (dis)similarity between stations can be better interpreted on the scale of soil moisture values. Comparative neutron count data were already presented in Heistermann et al. (2023), Fig. 6 showing the similar response of sensors at the site, but also the neutron count rate levels differing by an order of magnitude between CRNS detector types. In the current paper, we refrain from repeating that insight but do provide all raw neutron counts in the data files as well as sensor sensitivities in table 2 allowing all users to do such a comparison themselves. Instead, following another reviewers suggestion you can now find another figure in the manuscript, showing the response of CRNS soil moisture for two exemplary month (**Fig. 5**).

RC: *L227 – fix reference*

AR: Done.

RC: *L453 – were not removed?*

AR: Suggestion accepted.

RC: *L499 – what does 3.6 mean?*

AR: We missed to put "refer to section". Has been corrected.

2. Responses to referee #2

RC: *The Introduction should conclude with a concise summary of the paper's structure and the data presented in this data paper.*

AR: We rephrased the end of the introduction:

In the following we will introduce the field site with the CRNS installation and supporting instrumentation, describes in detail the observations, data processing and calibration workflow, presents exemplary results illustrating key dynamics in the dataset, and highlights future applications of PoSMO as a long-term reference site for remote sensing and hydrological research.

RC: *L59: There are more papers on signal correction that could be mentioned here, e.g. Baatz et al. (2015) introduced a biomass correction for CRNS, Davies et al. (2022) tested optimal temporal filtering methods for CRNS.*

AR: We have added additional references here, however, limited to signal correction in a strict sense, not temporal or score filtering such as Davies et al. (2022) or Altdorff & Schrön (2024).

RC: *L62: Brogi et al. (2022) is not about biomass estimation using CRNS. I believe you meant Brogi et al. (2025).*

AR: Thank you. Has been corrected. And we now mention also interception and added another reference.

RC: *L63: Here you could also cite Bogena et al. (2020).*

AR: Added.

RC: L65–67: *This sentence is unnecessary and could be removed.*

AR: Sentence has been removed. The end of this paragraph was reworked.

This can largely be attributed to the initial sparseness of sufficiently-long records, the required expertise in their conversion to soil water content and technical questions of directly using CRNS-derived root-zone soil moisture in modeling.

RC: L75: *“three such data sets“.*

AR: Was implemented.

RC: L123: *A separate “Highlights” chapter does not appear necessary. Consider integrating its content into the Introduction as part of the motivation.*

RC: L125: *This statement is difficult to understand without referring to Figure 2.*

RC: L137: *Refer to Fig. 2.*

AR: The highlights section was removed, and its content has been integrated into the introduction, the site description, and the dataset description.

RC: L157: *Methods and results are mixed in this chapter, which is inappropriate for a scientific publication. Please restructure the manuscript to clearly separate them. You may refer to Heistermann et al. (2022) as a good example, where the methods are presented first, followed by two separate chapters describing the data provided with the paper and exemplary results from the data analysis.*

AR: We thank the reviewer for this constructive comment on the manuscript structure. In the revised version, we clearly distinguish between the Methods and Results sections to ensure a more coherent and scientifically appropriate organization. The revised structure follows the example of Heistermann et al. (2022), with the methods presented first, followed by separate sections describing the datasets accompanying the paper and representative results from the data analysis.

RC: L182–185: *Since all CRNS stations are located in close proximity, it would be more appropriate to use meteorological data from the reference station for corrections of all CRNS stations. This approach ensures that corrections are applied consistently, increasing data consistency. Moreover, reference data are generally more accurate than the lower-quality sensor data used at the CRNS stations.*

AR: Our reference station (#11) is also a CRNS station equipped with the same type of sensor as the others, not a calibrated meteorological station. Using data from this single station for all corrections would not reliably represent potential spatial variations across the site, especially for air humidity. Therefore, each CRNS station was equipped with its own external sensors to account for microclimate conditions (e.g., proximity to the Wublitz water body (ID2) or location within a poplar stand (ID4)). This approach ensures that footprint-specific conditions are properly captured.

RC: L184–188: *In agricultural fields, such as those in this study, biomass changes constantly over the years, which can significantly influence CRNS signals depending on the type of vegetation (e.g., Jakobi et al., 2022). Therefore, the calibration will not implicitly account for this effect. Please discuss this aspect.*

AR: We added discussion on this in the new section **5 Exemplary views of the data set** as one of the influencing variables to improve the CRNS soil moisture estimate

Likewise, a more explicit consideration of biomass and its temporal dynamics could reduce biases and improve the robustness of CRNS soil water content estimates (Jakobi et al., 2022), and recent research suggests that combined measurements of epithermal and thermal neutron detectors may even allow biomass estimation (Brogi et al., 2025).

RC: *L208: The chapter on Bonner sphere measurements feels somewhat isolated. It is also rather long and distracts from the main focus of the paper, i.e., soil moisture data. Therefore, this chapter should be shortened and better integrated into the manuscript.*

AR: We have substantially shortened the Bonner sphere section and reorganized it by separating methods from results. This improves readability and ensures that the content is better integrated into the overall manuscript, with a clearer focus on its relevance for interpreting the CRNS-derived soil moisture data.

RC: *L399: The section on stable water isotopes in soil and groundwater appears off-topic for a paper focused on soil moisture. Given that only three campaigns may not provide sufficient accuracy to infer groundwater recharge, and the paper already covers a wide range of topics, consider removing this part.*

AR: We agree that the collected isotope data alone may not suffice to infer groundwater recharge. However, we'd like to point out that their conjunctive use with the other data sets may open additional options for seepage water-related analyses. Thus, we would like to retain this section and data despite their limitation.

RC: *L514–521: Unfortunately, this example demonstrates that the dataset's value for remote sensing validation is quite limited, as only a few grids of the RS product are actually covered by the CRNS data, with most sensors clustered within a single grid. Therefore, I suggest removing this part.*

AR: Many thanks for the comment, which helps us to clarify this point.

The Potsdam network differs from other CRNS sites (e.g., Bogena et al. (2022)) due to its uniquely high station density within a single 1-km² area.

A recent study comparing COSMOS data in Germany with 15 widely used satellite soil moisture products Schmidt et al. (2024) showed that even a 1-km satellite resolution does not resolve the spatial scale mismatch: one single CRNS footprint covers <10% of a 1-km grid cell, and individual pixels often include land-cover types outside the CRNS support area (see Fig. 7 in Schmidt et al. (2024)).

Figure 8 demonstrates that the dense configuration at PoSMO significantly improves the spatial representativeness of CRNS measurements within a 1-km pixel and thus supports more robust CRNS–remote sensing comparisons. Moreover, within this specific site we provide an actual measurement representative of the 1-km pixel, and the locations of CRNS stations in the surrounding pixels could potentially allow extending the spatial coverage to approximately 3.4 km² (see Figures 1 and 8). We therefore consider this site a valuable extension to the existing CRNS reference infrastructure.

RC: *Data archive: I downloaded some of the data (e.g., CRNS, profile, muon) to check whether the files are well documented and complete. The README file provides a good overview of the data and the units of the values. However, there is no description of the file formats. In addition, the CRNS data are split across two separate files, which is confusing. The same issue applies to the SWC profile data.*

AR: File formats are mainly txt or csv files, as described at the end of the the README file as well as in the section **Data Availability**. Details on the data and other formats provided can be found in the JSON-files containing metadata for each data-subset.

We deliberately decided to separate CRNS-counts from CRNS-soil moisture (and profile-based permittivity

records from converted soil moisture series) because we are convinced that each of the latter provides the most convenient entry point for users interested in the use of the SM-data, while the former offers more methodological improvements for re-processing the raw data. We do not expect typical use cases to use both (raw and processed data) thus we preferred to keep the respective file smaller with single variables each. In case you refer to the difference between CRNS data and the long-term observations, we acknowledge, this might be confusing. We renamed the parts of the data set and describe in the manuscript as well as the README more clearly the difference between the data. While the data set **3_01_Stationary CRNS** contains all data from the PoSMO since 2023, a subset of CRNS sensors as well as soil moisture profiles provide continuous data since 2019, which we think is valuable to present as a separate data set **3_16_long-term_soil_moisture_stations**, as a convenience for users, having consistently processed time series. We clarified this also in the respective subsection (**3.16 CRNS stations with long-term operation**).

RC: *Figure 1 only shows locations of CRNS stations (not shallow SWC and SWC profile stations).*

AR: The shallow SWC and profile sensors are all located in close proximity of the stations and would not be discernible at the map. We added this explanation to the figure caption.

RC: *Figure 5: The graph on the right is not easily readable and should be enlarged. The image on the left does not add much value.*

AR: We removed the image and enlarged the graph.

3. Responses to referee #3

RC: *The color scheme of Fig. 2 could be updated to improve the contrast among vegetation types. It is very difficult to tell them apart in the map.*

AR: The color scheme of Fig. 2 was improved. Similar vegetation classes were merged, and color contrasts were adjusted to enhance readability and improve visual differentiation among the vegetation types.

RC: *Fig. 4 - please note the interpolation method.*

AR: In response to the reviewers' feedback, the manuscript was restructured. Figure 4 was moved to the section **5 Exemplary views of the data set** and is now **Figure 5**. We added a information on how the image was created in the text

For this visualization, inverse distance weighting was applied, treating each CRNS station as a point measurement. However, due to the large horizontal footprint of CRNS, more robust interpolation approaches should account for the sensors' horizontal sensitivity, as demonstrated in Heistermann et al. (2021).

RC: *A key limitation of cosmic ray neutron sensors is that their penetration depth is approximate, but this site has the advantage of multi-depth conventional soil moisture sensors. Could a comparison graph between CRNS and conventional sensor be made - perhaps similar to Fig. 3, but showing the difference between the CRNS measurements, and the conventionally measured values interpolated to the same nominal depths? This will be very useful in giving the readers an understanding of the measurement uncertainty.*

AR: We agree, estimates of the penetration depth, together with CRNS soil moisture can provide valuable insights into the depth representativeness of the measurements. A full analysis of depth sensitivity is beyond the scope of this data paper and would be better addressed in a dedicated scientific study. Note that we disagree, that a direct comparison of CRNS and point-scale data will help readers to understand the "uncertainty" of the

measurement. Such a comparison might mislead readers to account for the point-scale measurements as the "ground-truth". We do not understand your suggestion for a comparison by using "[...] conventionally measured values interpolated to the same nominal depths". Maybe an approach like the exponential filter "aggregated over the corresponding CRNS depths"?

Nevertheless, to support interpretation, we now include in **Figure 5** an estimate of penetration depth based on point-scale soil moisture, exemplary for two months of the observation period, shown alongside the corresponding CRNS and point-scale soil moisture dynamics. We show this figure without the aim to show the uncertainty of CRNS, but rather to give space to discuss the need and approaches how to achieve a meaningful comparison between CRNS and sparse point-scale data. We also added discussion in the text on the uncertainty of estimating the penetration depth on sparse point-scale data.

The D86-estimate presented here is derived from the independently measured point-scale SWC profiles rather than from CRNS-derived SWC alone. The depth weighting procedure for point-scale data is described in detail by Schrön et al. (2017) and involves an iterative estimation of point-scale average SWC, effective sensing depth D86 and CRNS apparent soil moisture (see their section 2.3). By explicitly accounting for the shape of the SWC profile, our approach addresses an important control on CRNS-derived soil moisture estimates (Baroni et al., 2018), which is not captured when relying solely on CRNS-derived soil moisture values (cf. Appendix A in Schrön et al. (2017)). Due to small-scale heterogeneity and uncertainty in quantitative estimates from the dielectric sensors, however, the daily estimate of the integration depth based on a single soil water content profile might not be fully representative for the respective CRNS footprint. During the time frame and area covered by PoSMO, the effective integration depth estimates varied between 15 and 46 cm (on average 25 cm). This illustrates the representativeness of CRNS for root-zone soil moisture (RZSM). While the overall dynamics of the CRNS-derived SWC time-series is comparable to those of the 5 and 10 cm soil layers (Fig. 5), the CRNS measurements have a higher responsiveness to small rainfall inputs, as CRNS is also detecting with high sensitivity water content in the soil shallower than 5 cm, opposed to the point-scale sensors of the cluster. Additionally, the range of absolute values of both CRNS- and dielectric sensors for any given time suggests that there is considerable spatial heterogeneity, which calls for spatially aggregating measurement methods such as CRNS. A fair comparison between CRNS-derived and point-scale soil moisture can be achieved either by vertically "unweighting" the CRNS data, to make it comparable to a depth-averaged soil moisture profile (Scheiffele et al., 2020), or by applying depth scaling methods such as the exponential filter (Franz et al., 2020; Rasche et al., 2024), which can interpolate the different soil moisture data to the same nominal depths.

4. Responses to referee #4

RC: *The paper primarily is a comprehensive description of all data collected at the Potsdam Soil Moisture Observatory, and while reading it I felt a certain fatigue towards the end of the paper. To improve engagement of the readers, I recommend incorporating more visualizations to highlight the properties and quality of the different datasets. Additionally, including some exploratory results could make the paper more compelling.*

AR: In response to the reviewers' feedback, we largely restructured the manuscript, more clearly separating into a methods and results part, the first providing description of the measurements and data processing, the latter providing exemplary views of the data set. We tried to include your feedback and streamlined the manuscript, reducing redundancies and added additional figures, as well as some more discussion on the value of the dataset.

RC: *Section 6 discusses the validation of the Copernicus SWI product as a use case. However, while the fused ASCAT-Sentinel-1 1 km SWI product is sampled at 1 km (hence its acronym 1km SWI), its effective spatial resolution is much coarser (5–15 km; see, e.g., [DOI: 10.1016/j.jhydrol.2022.128462]). Instead, it would be more appropriate to reference e.g. the 1 km Copernicus Sentinel-1 surface soil moisture (1km SSM) product, which not only has fine sampling but also a high resolution of 1km.*

AR: We agree with the reviewer. In Figure 8, the 1 km Copernicus Sentinel-1 surface soil moisture (1km SSM) product was already shown. We correctly addressed the Copernicus SSM product in the text and in the caption.

RC: *As noted by other reviewers, the English language needs improvement, particularly in the introductory sections.*

AR: We sincerely apologize for the linguistic shortcomings. We thank the reviewer for this constructive comment and have thoroughly revised the manuscript to improve clarity, grammar, and readability, particularly in the Introduction.

RC: *In line with RC2’s feedback, the section on the Bonner sphere appears out of place and should be rewritten to fit better with the rest of the text.*

AR: We have substantially shortened the Bonner sphere section and reorganized it by separating methods from results. This improves readability and ensures that the content is better integrated into the overall manuscript, with a clearer focus on its relevance for interpreting the CRNS-derived soil moisture data.

RC: *Figure 3: Why is the intense precipitation event in summer 2024 (> 30 mm/d) not visible in the CRNS time series?*

AR: The CRNS-derived soil moisture time series, as shown in **Figure 4** (previously Figure 3) do show a slight response to the precipitation event, although this is not easily visible at the figure’s resolution and due to the daily aggregation of the soil moisture data. Figure 1 therefore provides a zoom-in of precipitation and CRNS soil moisture, the latter for hourly resolution.

We want to highlight that soil moisture responses are not necessarily consistent across rainfall events of similar magnitude. This is illustrated in the new **Figure 5** in the manuscript for July 2024, where a seemingly comparable event later in the month produces a much stronger response in both the CRNS and point-scale sensors. Such behavior is well documented in soil moisture dynamics and may reflect differences in antecedent soil moisture, infiltration conditions, or storm characteristics. Additionally, the precipitation data shown originate from the DWD station located some distance from PoSMO; thus, discrepancies may also arise from the localized nature of convective summer storms.

RC: *Figure 3: It would be nice to see also normalized soil moisture values to better compare the time series.*

AR: The primary aim of this paper is to provide the dataset and enable further analyses. We agree that normalized soil moisture values would facilitate comparison of the time series and acknowledge this as a valuable suggestion for future use of the dataset.

RC: *Line 227: What is an “unfolding procedure”?*

AR: The unfolding procedure involves reconstructing the neutron energy spectrum from the measured neutron count rates of the Bonner spheres through deconvolution of the measurement data. Measurements obtained with a Bonner sphere spectrometer typically provide an indirect rather than direct measurement of the neutron energy spectrum, as the recorded data represent a convolution of the response function with the true spectrum.

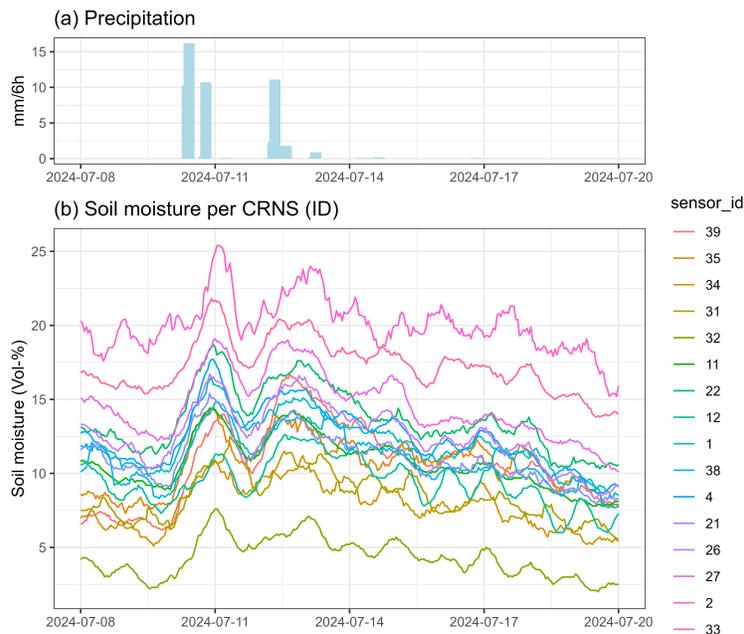


Figure 1: Short time series from July 2024 showing precipitation (a) and CRNS-derived soil moisture (b).

Deconvolution inverts this process, enabling the determination of the spectrum based on the measurements, the Bonner sphere response functions, and additional relevant experimental information. Also, what results from this is an "unfolded" neutron spectrum. However, as this is just indicating how the neutron spectrum was received, and we therefore skip the "unfolded" in the revised manuscript and just name it neutron spectrum.

RC: *Line 233: Weird to read here: “The objective of this study is twofold . . .”*

AR: We have substantially shortened the Bonner sphere section and reorganized it by separating methods from results. This part is found in the new section **5 Exemplary views of the data set** and the sentence has been rephrased accordingly. Please see the thoroughly rephrased text in section 5.3.

5. Responses to referee #5

RC: *General comments – First, the data set is very valuable and should definitely be published. Note however that I did not check the data set itself. Time and demand will show if the data can be extracted at reasonable costs.*

AR: Thank you for your positive assessment of the value of the dataset. We have invested substantial effort in ensuring that the data are accessible and well documented. In particular, we provide a detailed README describing the data structure, which has been further improved in response to comments from another reviewer.

RC: *General comments – Second, it is still too obvious that the paper was written by different authors and then compiled. What is missing here is a cleansing force that defines standards and then enforces them. Regrettably, time and effort spent on the paper are not commensurate with the effort involved in collecting*

the data. No question that homogenizing the paper is work, but it would pay off handsomely. I therefore appeal to the authors to make a further effort to improve the paper.

AR: We agree that the manuscript benefits from a more consistent style across sections. In the revised version, we thoroughly harmonized terminology, structure, and writing style throughout the manuscript. We also aligned figures, tables, and methodological descriptions to ensure a coherent presentation.

The detailed feedback from all reviewers has been very helpful in guiding these revisions, and we believe the current manuscript is now substantially more uniform and polished than the previous version.

RC: *General comments – Third, the entire observatory has obviously developed over the years into what it is today. The historical heterogeneity is evident. It is also addressed, but often in euphemistic language. I don't think that this is good. Scientists are not politicians, but peers to whom one can be honest. For example, it is obvious that the distribution of sensors is somehow historically conditioned, but overall it does not seem to follow a super master plan. No one would cluster the sensors in the eastern area and then place one sensor (no 39) so isolated in the landscape, as is the case here. As a scientist, I fully understand such constraints, but I don't want to be taken for a fool. Specifically, I would suggest dealing with the history in a separate section and then describing the structure as objectively as possible in the style of a Materials and Methods chapter, as is done quite convincingly later in the paper.*

AR: Thanks for this frank comment. We agree that we talk science not politics here and we certainly do not want readers to be misled. But, the reviewer overestimates the historical development, and instead there actually WAS a master plan though we do not claim it necessarily was super. This master plan was basis for a complete redesign and expansion of the soil moisture observations, and it was guided by the following objectives (i) Exploit the footprint sizes of the CRNS more completely than before (ii) Cover an area of about 1 km², with a denser coverage at the core and a looser coverage at the outer parts (iii) Keep some of the former CRNS (position and device) to provide long-term time series continuing former observations (iv) Enable a closer link to surface soil moisture remote sensing observations by adding shallow point scale sensors. However, the plan also had to include and adapt to a number of practical constraints which are typical for working in an agricultural used landscape, e.g. find suited positions without hindering machinery and practices within the fenced area, find suited locations outside the fenced area where the landowner agrees to having it placed and doing sampling, vandalism and theft outside and inside the fenced area. Furthermore, to implement the plan took about a year depending on additional CRNS devices becoming available, staff resources and delivery of components. We think describing this implementation process and the small adaptations needed for the master plan are much less interesting to the readers of the data paper than the final set-up at it is for almost two years now. But we now refer more clearly to these underlying objectives in the revised manuscript. Please see the more clear description in the introduction as well as the section describing study area and measurement setup.

RC: *General comments – Further sugarcoating concerns the CRNS measurement method itself. Sure, the sensors cover a larger area, but firstly, as far as I know, the depth is unclear and also depends on the measured variable itself, and secondly, the signal is further distorted by vegetation, as is very shortly described in the paper further on. I would like to see a few more candid words about the possibilities and limitations of the measurement method. This would also broaden the audience, as not every possible user is familiar with the CRNS methodology.*

AR: We see the intention to improve the manuscript but strongly disagree with the conception here. The uncertainties the reviewer mentions do influence the method and should be and are acknowledged, but they do not limit the general ability of CRNS to provide soil moisture measurements over a uniquely large horizontal and vertical footprint. While the reviewer correctly identify two factors that contribute to CRNS uncertainty, neither of them undermines the fundamental capability of the method. In other words, there is no sugar

coating needed as the sugar is inside!

The integration depth of CRNS is **not** unclear, as it can be calculated, whereas this is not always done for other non-invasive methods. And it does vary with soil moisture, but not to an extent that would cause the sensor to represent fundamentally different depth ranges over time. In response to another reviewer's request, we now present in **Figure 5** the calculated integration depth and its temporal variability exemplary for two summer months of the measurement period, alongside soil water content from CRNS and point-scale sensors. We also expanded the discussion to include information on the temporal variation of integration depth over the full observation period, as well as aspects regarding its calculation and associated uncertainties.

Regarding the influence of biomass, we agree that vegetation may affect the CRNS signal. However, compared to the hydrogen pool in soil water, the hydrogen contained in vegetation water and plant tissue is relatively small, some exception being forest. While biomass does contribute to overall uncertainty, it primarily is shifting the background and has been demonstrated to be of minor relevance relative to other uncertainty sources (Baroni et al., 2018). In our experience, crop growth or even crop harvest often is not clearly noticeable in individual CRNS time series and typically only becomes detectable when very high count rates are achieved, for example by pooling several sensors Jakobi et al. (2018).

That said, for roving CRNS applications (Dong et al., 2014) and when comparing forested and non-forested areas (Heistermann et al., 2024) the influence of vegetation should indeed be taken into account. Both is not the case here, but we have added discussion of these methodological limitations to support readers less familiar with CRNS.

And our candid view is that the issue of somewhat varying integration depth and minor influence of grassland and crop or bush vegetation should not be overstressed and not be an excuse not to accept the challenge of testing other results and products against the data sets presented here (including CRNS).

RC: *line 11 – define (spell out) SWC*

AR: We defined the abbreviation a few lines above and prefer to keep SWC, as this abbreviation is used frequently throughout the manuscript.

RC: *19 – why "but"?*

RC: *22 – better "but also to applications such as"*

RC: *35 – observe data? Sounds wrong to me. Variables are observed, the data are next step, they are gathered, collected... area-representative*

RC: *37 – better "soil tillage"*

AR: Thanks for these four suggestions. We have rephrased this paragraph:

The dynamic storage of water in soil is an important component of the terrestrial water cycle, yet it exhibits pronounced spatial and temporal variability. It regulates water and energy exchange between land surface and atmosphere and plays a key role in ecohydrological processes, agricultural productivity, forest dynamics and groundwater recharge. Due to its critical influence on weather, climate, hydrology, and ecosystem functioning, soil moisture has been designated as one of the Essential Climate Variables (Bojinski et al., 2014). Reliable soil moisture observations are therefore needed not only for climate and ecological research, but also for applied purposes including water resources management, irrigation planning, and agricultural management, as well as flood and drought forecasting and weather prediction (Vereecken et al., 2008; Brocca et al., 2017; Moragoda et al., 2022; Levi and Bestelmeyer, 2018; Molenaar et al., 2024; Srivastava, 2017; Hövel

et al., 2025; Pendergrass et al., 2020; Abioye et al., 2020; Lachenmeier et al., 2024; Szilagyi and Franz, 2020). Major challenges include the need to observe soil moisture across multiple spatial scales, the limited ability to directly capture root-zone and deeper soil water storage, and the spatial and depth mismatches between satellite observations and in-situ measurements (Oswald et al., 2024). Accurate measurements for spatial scales beyond the point scale remain challenging, as small-scale variation due to heterogeneity in precipitation, soil properties, vegetation, and other influences question the applicability of point-scale sensors to achieve good spatial and temporal coverage beyond the spot measurement (Peng et al., 2021). Point-scale observations range from campaign-based manual soil sampling to long-term observations using dielectric permittivity-based methods (time-domain reflectometry, frequency-domain reflectometry, capacitance-based sensors) or suction-based methods. These techniques provide observations with high temporal resolution but due to their small support volume (typically only a few cubic centimeters) at selected locations only (Robinson et al., 2008). Thus, due to the aforementioned heterogeneity of soil moisture, their representativeness remains limited. When deployed as networks, these sensors enable representative observations of volumetric soil moisture content, in the following called soil water content (SWC) at the field scale (Bogena et al., 2022; Rosenbaum et al., 2012). However, installing and operating sensor networks is resource-intensive and may interfere with agricultural management practices, especially tillage, and thus are limited in areas where soil-moisture observations could be particularly informative.

RC: 39 – I would rather call it "assessment", although the difference to measurement is gradual. This becomes obvious later in line 48 (depends heavily)

AR: Thank you for the suggestion, we implemented it.

RC: 75 – This is not well elaborated and therefore confusing: On the one hand, the authors stress that it is great that CRNS is an integrating measurement method, on the other hand they advertise the possibility to measure heterogeneity. It is clear that this is scale-dependent but this could be presented more clearly. And the authors should also not withhold that the support volume of CRNS is state-dependent, that it integrates not only the SWC, but also the water content of canopies (see General comments). It is better to address these issues frankly than to keep them to yourself.

AR: We apologize for the confusion we might have caused. To clarify: the idea for the previous cluster at this site Heistermann et al. (2021) was to create the strongly overlapping footprints and use inversion techniques to assess sub-footprint heterogeneity. We now describe this more clearly in the manuscript:

The latter cluster was the only one explicitly aiming for long-term operation (i.e. beyond one year) and was intentionally configured at unusually high density to exploit the strongly overlapping CRNS footprints, together with inversion techniques, to resolve sub-footprint heterogeneity.

Whereas the PoSMO cluster acts at larger scale and addresses heterogeneities of SWC on the landscape scale (1 km²). Regarding the critique about the state-dependent support volume of CRNS, again, the reviewer is not wrong, but the implications are less dramatic than suspected by the reviewer. Essentially, also the horizontal footprint can be calculated with established formulas, which can be relevant for a future dedicated mapping product based on CRNS, but it is not affecting the data set and not the objective to represent root-zone soil moisture at the km scale. Regarding that biomass is contributing to the signal as a background, this is clear from CRNS literature since more than a decade, nothing to withheld; and please see our answer to the first general comment of the reviewer.

RC: 81 – Past and perfect tense ("was" and "has aimed") do not go together well

RC: 82 – better "particularly high density"

RC: *Around 85 – Better describe what it is and why it was established, not how it developed. Short and concise, and important things first would be best. The history of PoSMO follows in section 2 anyway and that's where it belongs.*

AR: Thank you for your suggestions. The paragraph has been rephrased

The Potsdam Soil Moisture Observatory (PoSMO) replaces the former high-density cluster at the ATB site and was established to provide spatially representative reference data for validating high-resolution satellite soil moisture products and for capturing hydrological extremes. Its design was guided by the following objectives (i) to exploit the footprint sizes of the CRNS more completely than before; (ii) to cover an area of about 1 km², with a denser coverage at the core and a looser coverage at the outer parts; (iii) to keep some of the former CRNS stations (position and device) to provide long-term time series continuing former observations, as valuable e.g. for satellite remote sensing comparison; and (iv) to enable a closer link to surface soil moisture remote sensing observations by adding shallow point scale sensors.

RC: *108 – Better "Crops grown include"*

RC: *109 – no hyphen necessary*

RC: *111 – Top soil? which soil depth? add "sand content" and "by mass" (If correct) between the brackets*

RC: *112 – by mass?*

AR: The sentences have been rephrased according to these four suggestions.

The ATB site, as the most densely instrumented western area of PoSMO, is located at 40 m a.s.l. on a gentle hillslope sloping towards the lake in the west and characterized by diverse experimental agricultural plots (Fig. 2). Crops grown include cereals, maize, alfalfa, sunflower, rape seed, the site also features meadows, a variety of orchards (cherry, apple, chestnut) and a poplar short-rotation plantation. With exception of a few irrigated orchards and occasional local irrigation (on potatoes, maize and spring wheat), the site is predominantly rainfed. The observatory is situated on predominantly periglacial deposits with sandy to loamy topsoil (0 to 50 cm depth) and soil texture ranging from 68–91% sand, 8–27% silt, 0.6–4.4% clay, and organic matter contents between 0.4–17.3% (by mass).

RC: *113 – "average temperature" is enough, or what is the added meaning of "annual" here?*

AR: We think "mean annual air temperature" is a standard climatological notation, as used for example in the IPCC report. We suggest to rephrase the "average annual" to "mean annual" for both precipitation and temperature to stay close to these notations.

RC: *114 – "ground surface" two ... were installed in 2019" is enough. "continue to provide data" goes without saying.*

RC: *116 – better "provide"*

RC: *120 – environment*

AR: Thank you for these comments, we implemented the suggested changes.

RC: *121 – this is a meaningless sentence (Its setting enhances...), I would delete it. If not, it should be moved to the Conclusions.*

AR: Sentence was removed.

RC: 123 – It would be better to replace the section 2.2 by a discussion of the strengths and weaknesses and to move it to the end of the text, after the data and related measurement methods have been presented. Rather like a Conclusion section, e.g. under the title "Conclusion and Highlights".

AR: Thank you for this constructive suggestion. In line with your comment and consistent with feedback from the other reviewers, we have revised the manuscript structure. We removed Section 2.2 and integrated its content into the introduction and site description. Relevant details now appear only in the measurement and data description sections to avoid redundancy.

RC: Figure 1 caption – I do not agree at all. It is an unfounded claim that the measured SWC represent the field plots as indicated. In particular, if different crops are grown on the plots. And is there any explanation why the footprints of the CRNS are so different? And why they coincide with the agricultural plots? It is also not clear what the numbers mean. And it is unclear what the meaning of shallow SWC and SWC profile is.

AR: We apologize for the misunderstanding caused by our caption. To clarify: **The purple area is not meant to represent CRNS footprints.** It instead delineates the general extent of mixed agricultural land use with broadly similar land use and soil types. This area was chosen because it approximates the scale at which satellite products would treat the landscape (i.e., after excluding forest and settlement areas). An approximate depiction of footprints is only provided for the dense western cluster in Figure 2. Numbers in the figure refer to the names/IDs of the CRNS stations, a station consists of a CRNS sensor, a dielectric soil moisture profile sensor and additional more shallow dielectric soil moisture sensors. We revised the caption to make this explicit

Locations of CRNS stations at the Potsdam Soil Moisture Observatory (PoSMO). Numbers refer to the station IDs, a station consisting of a CRNS device and point-scale shallow and profile soil moisture sensors installed in close proximity. The purple area indicates the extent of predominantly agricultural land with broadly similar land use and soil types, representing land-use unit that PoSMO aims to characterize and provide reference data at landscape scale and that is consistent with the spatial aggregation of satellite soil-moisture products (forest and settlement areas excluded). Background image from Google Earth (retrieved in September 2023 (Gorelick et al., 2017), Maxar Technologies).

RC: 126 – The CRNS sensors were placed, not the locations

AR: Thank you for pointing this out. The section was be integrated into other sections and the sentence deleted.

RC: 128 – The land use is all but similar as you state yourself above. And in the following line you even mention grassland, which is a very different land use. This is the first time that "soil type" is mentioned, but no soil type is specified - your statement lacks trustworthyness. Better be more specific. You could build up trust by providing a soil map in Supporting Materials.

AR: Please see our detailed answer to your comment on the caption of Figure 1. This section has been integrated into the other sections, and this specific bullet point into the site description, integrating your feedback.

RC: 136 – this is redundant

RC: 150 – on 17 February

AR: Section 2.2 has been integrated into other sections, thus the sentences you refer to are reworked and we reduced redundancies throughout the manuscript.

RC: Section 2.2 as a whole – The authors should remove the promotional tone, including the promotional headline, and instead describe precisely what was measured, when, at what frequency, at what resolution, and

using what methods. The whole section is not well written. I think you should either stress the highlights or give details in Material and Methods style. The mixture is really unsatisfying. See recommendation in the General comment.

AR: Thank you for this comment. We would like to clarify that the intention of Section 2.2 was not promotional, but to highlight the aspects that distinguish this CRNS cluster from previous installations. However, we acknowledge that several reviewers found the tone and structure of the section unsatisfactory.

In response, we have removed Section 2.2 entirely. Its overarching context is now integrated into the introduction and site description, all technical details regarding what was measured, when, at what frequency, and with which methods are now provided exclusively in Section 3 (Observations and Methods), ensuring a clearer, more consistent, and non-redundant presentation.

RC: *Figure 2 – The graph is too small and the quality insufficient. The color coding is unreasonable. What do the numbers stand for? Circles should be explained. Unnoticed by the authors, the caption contradicts the statement of representativeness made in Figure 1.*

AR: Thank you for this feedback. We added information on the numbers (sensor names/IDs) to the caption, increased the figure, and improved the color coding. We again apologize for the misunderstanding regarding the sensor footprint, please refer to our detailed answer regarding your comment on the caption of Figure 1. The caption now reads

Overview of the Potsdam soil moisture observatory central area, showing continuously operating CRNS stations with the numbers showing their ID (a station includes a CRNS sensor; point-scale shallow and profile soil moisture sensors), as well as groundwater monitoring wells and climate stations. The approximate horizontal footprint of the CRNS sensors is given as highlighted area, with outer edges of the covered area given as dashed lines. Additionally the map shows the two ERT transects, hyperspectral camera position, Bonner sphere spectrometer location and calibration sampling points (Manual ThetaProbe profile and Split-tube profile). Background layers illustrate land use such as farmland, buildings, lake (Wublitz) and forested areas etc. are based on OpenStreetMap (OSM) with few amendments.

RC: *167 – first time that a hillslope is mentioned*

AR: Thank you for noticing, we added this information to the site description.

RC: *169 – cropped areas.*

AR: Thank you, we corrected this typo.

RC: *The table could be much more useful if extended by quantitative information about spatial coverage and the frequency of the observations. In its present form, the information is fragmented. E.g. it is not clear what SWC shallow means or what the depth and resolution of SWC profile is. On the other hand, the manual soil sampling comes with a sampling depth. The presentation is quite heterogeneous. As the table currently stands, it looks rather like a fairground-like compilation of measurements. I understand that this is indeed the case to some extent, and this is how science develops, but I would recommend improving the look and feel.*

AR: We improved the table following your suggestions. The table is also meant to provide only an overview of the data described in the following sections, we provide details on each data subset in the respective section.

RC: *199 – How can the Inverse Distance Weighting procedure be justified if CRNS provides, as you claim yourself, an integrated signal? Or were the CRNS measurements not treated as point measurements?*

AR: Thank you for this comment, and we apologize for the unclear wording. **For the purpose of visualization only**, we treated the CRNS-derived soil moisture as point measurements and applied simple inverse distance weighting. We clarified this in the manuscript and added a recommendation in the text to use more advanced interpolation methods that account for the horizontal sensitivity of CRNS, as demonstrated in Heistermann et al. (2021), when generating gridded products intended for further use.

RC: Figure 4 – What is the definition (and depth with variable land-use) of root-zone?

AR: Thank you for this comment. We acknowledge that the term root-zone is not sharply defined and can vary across different land-use types. Nevertheless, it is widely used in the CRNS literature to denote the part of the soil profile that governs the most dynamic soil–plant–atmosphere interactions. In our context, this corresponds to the upper portion of the profile where root density is typically highest—often within the upper 40 cm (Schenk and Jackson, 2002) and thus the zone that exhibits the strongest temporal variability in soil moisture and water fluxes. We added a definition in the introduction and discussion on this aspect in the text related to Figure 6 (formerly Figure 4).

RC: 217-247 – Odd citing of references What are all the details good for? Differences in detail as here give a very inhomogeneous impression.

RC: 235 – what study?

AR: This section has been thoroughly reworked and shortened. Details on the measurement setup are presented in section 3.6. Results and the figure, you will find in section 5.3 in the revised manuscript.

RC: 278 – "such as labor" - what is this supposed to mean?

AR: Thank you for noting this obvious mistake. The sentence has been rephrased

To investigate the potential impact of tillage (by disc) on temporal variation of soil bulk density, a test in a plot cropped with maize was done in 2024. Bulk density was sampled at 0, 5, 10 and 15 cm before and again shortly after harvest and tillage, with a time difference of about 2 months.

RC: 281 – different from that before "as tested by a Tukey test at alpha=0.05" is enough. But did you pair the locations as you should? With the proper pairing (nesting) you might see a significant difference.

AR: Yes, the data has been paired for the test. Note we restructured the manuscript to more clearly separate methods and results. The reworked sentence now appears in section **5.2 Examples subsurface properties**

A small case study assessed the impact of agricultural practices on temporal variation of bulk density by sampling soil before and after harvest at one of the larger agricultural fields. No significant effect was detected: bulk density did not differ significantly before and after harvest or tillage (Tukey's test, $\alpha = 0.05$). Given the absence of detectable temporal changes, all measurements were merged into a single dataset. Based on 152 soil cores, bulk density values ranged from 1.10 to 1.47, g,cm⁻³, with a mean of 1.30 g cm⁻³ and a standard deviation of 0.12 g cm⁻³.

RC: 284 – at ten This is a method given at an inappropriate location. It is not clear how the other samples (results given before) were processed. It comes much too late. Impression evoked: messy.

AR: Thank you for pointing this out, following another reviser's advice we will more clearly separate the method from the results throughout the manuscript. Details on the sampling are now clearly described in section **3.2 Campaign-based soil measurements for CRNS calibration**.

RC: 303 – give a reference for FRM, please

AR: We added a reference.

RC: 320 – explain CZglobe

AR: CZglobe refers to "Czechglobe the Czech Global Change Research Institute". We added this information in the manuscript.

RC: 364 – It is not clear what you mean by crop type. Do you mean a crop functional type? An arable crop or species (it looks like this in line 366)? Or even a cultivar? Please specify.

AR: Thank you for pointing this out. By crop type, we refer to the specific cultivated crop or species grown on each field (e.g., winter wheat, maize, alfalfa), rather than a crop functional type or cultivar. We clarified this in the revised manuscript.

To support a comprehensive comparison between remote sensing products and CRNS measurements and enable a more detailed analysis, we provide auxiliary information on crops grown (e.g., winter wheat, maize, alfalfa, sunflower) on the experimental plots and the associated harvest dates.

RC: 381 – 240 measurements in one specific year? If you decided to be so specific you should also provide the year.

AR: Yes, all 240 measurements refer to the single snow event observed during the overall observation period (2023–2025). We clarified this explicitly in the manuscript.

For the third period (mid-February 2025) with depths reaching a maximum of 6 cm, a sampling campaign was conducted. We recorded the temporal progression of snow cover using a stationary wildlife camera (SECACAM HomeVista, VenTrade GmbH, Köln, Germany) capturing images. The spatial distribution and properties of the respective snow cover were mapped using UAV-based RGB imagery with a Mavic Pro (Da-Jiang Innovations Science and Technology Co., Ltd, China) from a survey flight at 100 m flight altitude. The imagery was mosaicked using Photoscan software (Agisoft LLC, St. Petersburg, Russia) and geo-referenced to 20 cm orthophotos provided by the Federal State of Brandenburg, producing an RGB image with 3 cm ground resolution. Additional manual snow sampling involved 240 measurements of snow depth using a ruler and 10 density measurements obtained either through cylinder cores or by collecting all snow from a specific area for subsequent weighing in the field.

RC: 427 – It rather impacts (or influences) water flow, otherwise we would not have to measure the unsaturated hydraulic conductivity in soil. And the boundary fluxes play also an important role (as you know, of course).

RC: 429 – Durner (1994) referred to unsaturated hydraulic conditions, I suppose. Or do you mean "tedious" or "time-consuming"? The conductivity function is difficult to measure, not K_{sat} . In line with this statement, you indeed measured K_{sat} .

AR: The introduction of this section has been rephrased

Saturated hydraulic conductivity (K_{sat}) governs water flow through soil and controls key processes such as infiltration, percolation and groundwater recharge, affecting both surface and subsurface hydrology. In unsaturated flow situations, K_{sat} is also important, as it can be used in the estimation of unsaturated hydraulic conductivity curves (Durner, 1994; Hohenbrink et al., 2023). Due to spatial variability in soils, laboratory measurements on small soil cores often fail to represent field-scale conditions, a limitation highlighted in recent studies (Weber et al., 2024). Field measurements of K_{sat} , by contrast, are considered to integrate over larger volumes, capturing effects of macropores and heterogeneities, and thus more accurately reflect the

hydraulic response of natural soils (Reynolds et al., 2000). Because PoSMO targets larger-scale soil moisture and hydrological processes, we conducted field measurements of K_{sat} to assist in the assessment of water fluxes at the site.

RC: 456 – That sounds like glossing over the fact that no one bothered to compile and standardize a common data set. I am not convinced that this is convenient for users.

AR: We are not entirely certain what the reviewer means by this comment. This data set (a subset of the CRNS stations with continuous operation since 2019) proactively addresses potential inconsistencies by offering a fully compiled and consistently processed soil moisture product so that users do not have to merge raw data from this dataset and the previous CRNS cluster dataset (Heistermann et al., 2023) themselves (nor to interpret site-specific details such as which sensors remained in place and which were relocated).

But if your concern refers to the usability of our dataset, we acknowledge that no dataset is fully plug-and-play for every application. Regarding the PoSMO data set we note the data have been carefully compiled and standardized metadata and documentation are provided (including a README file describing the data structure). While some pre-processing may still be required for specific applications, the dataset is designed to minimize the effort needed for cross-validation of high-resolution SWC products. We rephrased the section to make this more clear, please see section **3.16 CRNS stations with long-term operation**.

RC: 462 – refer

RC: 469 – rather the "weather conditions" are at stake here

RC: 472 – doubled sentence

RC: 489 – () reference missing

AR: All these were corrected in the revised manuscript.

RC: 493 – Shouldn't you give also the size of the window? If it is the window from line 500, it comes to late there.

AR: Thank you for pointing this out. We now also provide the CRNS time series calibrated with the most recent conversion function and another processing tool (Neptoon). Therefore we rephrased the paragraph accordingly.

To clarify your question: while neutron counts were not smoothed in the processing with Corny, the standard deviation is indeed calculated over a moving window internally defined within the Corny tool. Since count data follow Poisson statistics, the standard deviation of the neutron counts is computed as the square root of the observed counts.

We acknowledge that several subjective choices are involved in aggregating, correcting, and smoothing neutron counts. To ensure transparency and reproducibility, we will provide, together with an updated version of the dataset, the full configuration files used for processing the raw neutron counts in Corny and Neptoon. This will allow users to understand, reproduce, or adapt the processing without requiring excessive detail in the manuscript.

We clarified this in the manuscript, and note the section you referred to is now moved to be subsection 3.1.2, to better align with the description of CRNS measurements.

RC: 499 – "3.6.", left over?

AR: Thanks for noting, this was fixed, it is a reference to a "section".

RC: 505 – Explain N₀

AR: We explained the variable in the section dealing with CRNS data processing to derive soil moisture values (section 3.1.2).

RC: 517 – reference desirable

RC: Figure 8 – The point 39 can hardly be seen, change colouring.

AR: We changed the color of the dots.

RC: 517 – Explain what SWI means in relation to SWC, because this will play a role in the following.

AR: We added an according sentence in the revised manuscript.

The Copernicus SSM product is an index of saturation which can be converted in volumetric water content by multiplying it by the soil porosity.

RC: 519, figure 8 – 3.4 km² must be explained, also in the caption of figure 8. From figure 1 I understood that this is the total area (black line), but this does not really make sense here. Please resolve. In geography, it is good practice not to publish a map without a scale. I propose to add scales to the figures.

AR: Please see our answers to your comments regarding Figure 1 and the clarification we provide there on the CRNS footprint area. As the single pixels in the figure have a side length of 1 km, this replaces the according scale bar and the coordinates of the corners are provided in the figure. We made this more clear in the caption.

Left: Example of Copernicus Sentinel-1 relative Surface Soil Moisture (SSM), in % saturation for Northern Germany on 25 April 2024 (left). Zoom into the PoSMO area, with dots indicating an individual cluster location with CRNS, SMT100 and soil moisture profile each (right); pixel size is 1 by 1 km; the black outline marks area of similar land use and soil type, as represented by PoSMO (see Figure 1).

RC: 519, 520 – I really appreciate your extensive measuring efforts to measure, but readers will rather find that in view of their clustering the sensor positions are not really well suited for aggregation. At least not in this case.

AR: While the clustered layout does not provide spatially uniform coverage, the multi-sensor information still reduces local sampling bias and improves the representativeness of the reference data for validating satellite products. We slightly adapted the wording

The larger support volume of each CRNS together with the relatively dense distribution of CRNS within the 3.4 km² area of similar land use and soil type, enhances comparisons between remote sensing products and reference SWC data. Although the clustered layout does not provide uniform spatial coverage, the multi-sensor information helps reduce local sampling uncertainty and improves the overall representativeness of the ground observations for validation.

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