Author Response Letter to Editor and Referees

Soil moisture monitoring with cosmogenic neutrons: an asset for the development and assessment of soil moisture products in the state of Brandenburg (Germany)

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EC/RC: ***Editor/referee comment***, AR: *Author Response*, ☐ Manuscript text

Dear Dr Somogyvári, dear referees,

we would like to thank both referees for the critical review. Based on the extensive and thorough comments, we fundamentally revised the manuscript. Please find below our detailed point-by-point replies. However, we would like to introduce the main improvements already at this point of the response letter (apologies for the resulting redundancies with the point-by-point replies):

- **Scope and research questions:** As repeatedly emphasized, our original intention had been to briefly introduce – in the context of an NHESS special issue on the Berlin-Brandenburg region – the new CRNS-based soil moisture monitoring network in Brandenburg to the community, and to briefly demonstrate its potential, specifically when being combined with a soil hydrological model. Following, however, the editorial decision after the first round of reviews, we expanded the manuscript to a research paper while still aiming to keep it concise and in line with the original intention. During the second round of reviews, both referees criticized that the main research question remained unclear (referee #3), or that the presented research was not comprehensive enough (referee #4).
  In order to address these concerns, we have now sharpened the aims and research questions, and extended the scope of the paper. Still, we start out from the fact that there is a new CRNS network which allows, for the first time, the possibility to obtain spatially representative root-zone soil moisture estimates across various hydrotopes typical for the state of Brandenburg. In allowing to monitor soil moisture conditions at selected locations, these observations have a value in themselves, and we have now demonstrated this by extending the analysis period and comparing the years 2024 and 2025 with regard to the conditions in spring and summer (as suggested by referee #4). More importantly, yet, these observations provide a new opportunity - a new reference - to assess the validity of soil moisture products for the Brandenburg region - let it be from modelling or remote sensing. That way, we can leverage the observational records to expand the limited temporal, vertical and horizontal coverage of the mere instrumental monitoring, i.e. to use the observational data in order to develop and assess soil moisture products for the state of Brandenburg. This was exemplified in a case study guided by three questions:

  1. How do widely used large-scale soil moisture products (such as ERA5-Land and Soil Water Index of the Copernicus Land Monitoring Service, as suggested by referee #4) capture the observed

soil moisture dynamics in comparison to a soil hydrological model that was set up on the basis of region-specific data?

2. Can the CRNS-based soil moisture estimates help to improve such products, e.g., by means of bias correction?
3. What are the implications of this evaluation for the application of such products in the management of water-related risks in the state of Brandenburg? Which products show the best prospects, depending on the application context?

- **Data paper:** In the course of the process, the possibility of a data paper was repeatedly suggested. However, the format of a data paper does not exist in NHESS, and we have repeatedly argued why a data paper would not be an adequate format for an ongoing monitoring effort. In order, however, to address this issue, we have created a persistent *data publication*, including documentation, that includes the data until September 1, 2025. It is citable, serves a similar purpose as a data paper itself, provides a useful asset to the paper, and a complement to the existing data repository that integrates the real-time observations.

- **Literature cited in the introduction:** Another important concern of referee #3 is the representativeness of the cited literature in the introduction. We apologize for this issue, the root of which lies in our original submission as a ”Brief Communication” for which the total number of references was limited to a maximum of 20. We gladly addressed the referee’s corresponding comments which were very helpful.

- **English version of the website:** We have provided an English language version of the website and the data repository (referee #3).

- **Title of the paper:** Referee #4 repeatedly argued that the title does not adequately reflect the content of the paper. We agree. The focus of the paper is not on drought monitoring, but more generally on soil moisture monitoring, and not exclusively on instrumental monitoring, but also on model-based techniques. In order to also adequately express the aforementioned changes in research questions in the title, we changed it to:

  > Soil moisture retrieval from cosmogenic neutrons: an asset for the development and assessment of soil moisture products in the state of Brandenburg (Germany)

  This new title also puts less emphasis on the network character, as raised by the referee, and more on the application of soil moisture products in the topical context of the NHESS special issue.

- **Network design and representativeness:** Referee #4 also demanded more details on the selection of monitoring locations, and their representativeness for conditions in Brandenburg. In essence, we think that our approach is quite similar to the network design approach followed by Bircher et al. (2012, as cited by the referee) in considering topography (or groundwater depth), land cover, soil type, and climate (precipitation) as well as the availability of additional monitoring infrastructure. The main difference is the number of 30 sensors in the HOBE network which allowed for a more formal approach in sampling across topography, land cover and soil type. For the CRNS network in Brandenburg, site security also played an important role due to the visibility and value of the CRNS stations. In any case, we agree that the criteria should be described more clearly, and that we should also state how well the selected sites actually represent landscape characteristics in Brandenburg. In the revised manuscript, we have hence added more details with regard to the selection criteria and the representativeness of the selected sites for the environmental conditions in Brandenburg. For that purpose, we also added a new subsection "Study area" in the "Data and methods" section in order to describe the main landscape features in Brandenburg, and their proportions in the area of the state. In the subsequent section "Monitoring network", we then expand how the choice of locations represents a large proportion of Brandenburg's landscape features. We have, however, also emphasized the fact that the ability of a network with eight (or 12) locations to representatively cover a 30,000 km large state such as Brandenburg is inherently limited, an issue that can only be resolved in the future by combining observations with models and remote sensing.

- **Split-sample model calibration/validation:** In response to referee #4, we have implemented a split-sample calibration/validation for the SWAP model (2024 data for calibration, 2025 data for validation). We also implemented a bias-correction for the competing large-scale soil moisture products and followed the same split-sampling approach as for the SWAP model.

While we are grateful for the constructive comments, we would also like to maintain that, in the process, the number and extent of comments has accumulated to a considerable level. We understand that there will always be additional and useful ideas of what could be done. But while we are open to extending the scope of the paper, we also need to make sure to constrain it to a manageable level, even if that means that not all suggestions can implemented.

As mentioned above, you will find point-by-point replies to all comments on the following pages.

We hope that we have, this way, addressed the referees' concerns. Thanks again for your feedback and your support of this process.

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

1. Responses to referee #3 (report #1)

RC: ***[1.1] [...] What is the main research question behind it? Does that network mainly serve as a number of reference points for drought monitoring inferred from railroad measurements? If so, why is there no analysis presented on that? Or do the authors intend to provide data on hydrologically relevant locations within Brandenburg in order to (later) feed that into a larger scale model? What role does clustering of sensors have in that context and to which extend is the scale gap discussion relevant?***

AR: In order to address the referee's comment, we have sharpened the aims and research questions, and extended the scope of the paper. Still, we start out from the fact that there is a new CRNS network which allows, for the first time, the possibility to obtain spatially representative root-zone soil moisture estimates across various hydrotopes typical for the state of Brandenburg. In allowing to monitor soil moisture conditions at selected locations, these observations have a value in themselves, and we have now demonstrated this by extending the analysis period and comparing the years 2024 and 2025 with regard to the conditions in spring and summer (as suggested by referee #4). More importantly, yet, these observation provide a new opportunity - a new reference - to assess the validity of soil moisture products for the Brandenburg region - be it from modelling or remote sensing. That way, we could leverage the observational records to expand the limited temporal, vertical and horizontal coverage of the mere instrumental monitoring, i.e. to use the observational data in order to develop and assess soil moisture products specifically for the state of Brandenburg. This will be exemplified in a case study that is guided by three questions: (1) How do widely used large-scale soil moisture products (such as ERA5-Land and the Copernicus Land Soil Water Index, as suggested by referee #4) capture the observed soil moisture dynamics in comparison to a soil hydrological model that was set up on the basis of region-specific data? (2) Can the CRNS-based soil moisture estimates help to improve such products, e.g., by means of bias correction? (3) What are the implications of this evaluation for the management of water-related risks in the state of Brandenburg? Which products show the best prospects, depending on the application context?

As to the referee's question regarding the rail-based CRNS measurements, we would like to clarify that these are not a subject of this study. In the manuscript, we mentioned the rail-based CRNS measurements for two reasons: first, because the proximity to rail-tracks was one (though rather subordinate) criterion in the selection of monitoring locations, and, second, because the rail-based CRNS measurements provide a new future perspective for spatial upscaling. We have clarified these two aspects in the revised manuscript.

The scale gap discussion was removed from the introduction.

RC: ***[1.2] The provided data seems to be available only in German (online interface). Please provide an English version.***

AR: In the course of the revision, we have developed a bilingual (English, German) version of the website. The "data" tab on the website merely provides a link to the actual data repository. Within that data repository, all metadata and readme files that are required to interpret the actual data files had already been provided in English.

RC: ***[1.3] The introduction unfortunately suffers from unrepresentative selection of literature with the focus on self-citations.***

AR: We agree. The reason for this is that in the original submission as a "Brief Communication", the number of references was limited to a maximum of 20. So we had to be very strict with citations in the introduction. As we stated in our previous response to the editor, our ambition with the revised manuscript was still to be brief and concise, which partly came at the cost of comprehensiveness. We did not intend to inappropriately advertise our own papers. Certainly, we take the referee's concern very seriously and have revised the referencing in the introduction, considering also the referee's following comments.

RC: ***[1.4] In the paragraph of soil moisture monitoring and its data sources Oswald et al. 2024, Babaeian et al. 2019 and Schmidt et al. 2024 are cited. With Babaeian et al. 2019 presenting a more fundamental overview, Oswald et al. 2024 seems to be not strongly linked to the respective claims in the text. There is no reference to point scale probes which make up the largest amount of data sources. Schmidt et al. 2024 is not representative for remote sensing. To make a more specific example: Oswald et al. 2024 is cited for the following claims: A: "soil moisture monitoring is widely acknowledged", B: "remote sensing products are limited by shallow penetration depths, low overpass frequencies, and vegetation-related uncertainties", C: "Hydrological models have the potential to overcome such limitations". A is not within the scope of Oswald et al. 2024. To the contrary, this topic is covered in literature since 50+ years. C is neither very well covered as Oswald et al. 2024 focuses on ML applications, whereas here land-surface models for example should be cited. Oswald et al. 2024 provides a short overview about remote sensing product and therefore the claim is covered but again, here the authors should focus on primary sources instead of yet again cite their own works.***

AR: Thanks for the detailed investigation. We have replaced most references to Oswald et al. (2024) with a more extended list of primary references. We also extended the citation list around Schmidt et al. (2024), while it is highly relevant in this context, being one of the first studies who comprehensively compared CRNS with multiple remote sensing products across Germany. Throughout the paper, we also sought to add references in a more differentiated way to make clear which claim they are to support.

RC: ***[1.5] In the paragraph for CRNS networks Heistermann et al. (2023), Ney et al. 2021, Zacharias et al. 2024 are cited - all publications with one of the authors or affiliated German groups. The authors mention the larger networks only in one sentence without citation "Only few countries have already established long-term CRNS monitoring networks at the national scale (e.g., the USA, UK).", even leaving out CosmOz Australia.***

AR: In the revised manuscript, we have provided a more comprehensive representation of previous efforts on long-term CRNS monitoring networks at the national scale, including CosmOz Australia.

RC: ***[1.6] The section about CRNS does not cite the relevant literature - neither does Andreasen et al. 2017 explain the method, nor is Schrön et al. 2017 representative for the footprint. Likewise, Altdorff et al. 2023 is neither the first nor the most relevant publication for roving. To conclude, the introduction is, for a research paper, fragmentary, unrepresentative and too much narrowed down to the publications of the researchers themselves.***

AR: Due to the limitation of citations in the earlier brief communication format, we used Andreasen et al. (2017) as a general reference where readers could find references therein which explain the CRNS method in more detail, for instance. However, we agree that in the current format the reference is not sufficient, and added further citations from Zreda et al. (2008, 2012). We disagree, though, that Schrön et al. (2017) is not representative for the footprint: the vertical and horizontal weighting functions described there are still the state-of-the-art and de-facto community standard. However, we agree that providing just one number (here 10 ha) with regard to the footprint size does not sufficiently account for the strong dependency on soil water content. In the revised version, we have changed the specification from area (ha) to radius (m) which ranges from 130–240 m based on Köhli et al. (2015) and then Schrön et al. (2017). With regard to Altdorff et al. (2023), we fully agree that this reference is not comprehensive and representative for CRNS roving, but similar to the argumentation above, one of the most recent studies which addressed CRNS roving and provide references therein to earlier work. In the course of the revision of the introduction, we have added a brief introduction to CRNS roving to motivate the location of the CRNS sites near rail networks, and we added more representative but also recent citations to support that argument (e.g., Franz et al., 2015; McJannet et al., 2017; Schrön et al., 2021; Handwerker et al., 2025)

RC: ***[1.7] l41: "So far, however, CRNS has mainly been used in experimental contexts" - what does experimental (short-term) contexts mean? If ignoring other literature about CRNS networks, the reader might come to the conclusion that probes would be installed on a short term basis, but as a matter of fact a large number of the probes are used in long-term monitoring contexts, so that claim seems to be not very well supported.***

AR: We agree, and have deleted that sentence.

RC: ***[1.8] l47: "The first attempt in Germany to systematically apply CRNS technology at the federal state level was initiated in 2024". The authors previously cited Ney which is definitely an application of "CRNS technology at the federal state level prior to the authors' initiative.***

AR: In the previous sentence of the manuscript, we explained that the ADAPTER network to which Ney et al. (2021) refer does not aim at the entire federal state of North Rhine-Westphalia, and that it only covers cropland sites. That is why we, despite the (as of now) still limited number of sensors and the lack of coverage in southern Brandenburg, consider the effort in Brandenburg to be different. Then again, we do not intend to unnecessarily insist on the uniqueness of the Brandenburg network, as our main point is its relevance in the Brandenburg context (which is also the context of the special issue in NHESS to which this manuscript was submitted). Therefore, we changed the sentence to

> For the federal state of Brandenburg, a consortium of research institutions and state agencies was formed in 2024 in order to implement and maintain a CRNS-based soil moisture monitoring network, designed to represent typical combinations of land use, soil and groundwater conditions in the state.

RC: ***[1.9] l77: "Such a station includes a neutron detector, logger and telemetry, solar power supply, and sensors for barometric pressure, temperature, and humidity, as well as conventional point-scale sensors of soil moisture in various measurement depths as an additional reference" - please name sensor type and manufacturer.***

AR: We have added manufacturer and sensor type for the conventional point-scale sensors of soil moisture, and also added the manufacturers of the different CRNS systems in the caption of Tab. 1.

RC: ***[1.10] l85: "Sensor footprint that are homogeneous with regard to these attributes are preferable with regard to the interpretation of the CRNS signal." - this statement seems to conflict with the approach to collocate sensor with (considerably dry) train lines. Altdorff et al. 2023 shows in Fig. 1 a sensor in a distance of approximately 1 m to trainlines, which would make the sensor potentially susceptible to the road effect. How distant are these sensors to the rail infrastructure and in which way did the authors account for that?***

AR: Thank you for this comment which is quite to the point. First of all, we would like to emphasize that the CRNS sensor shown in Fig. 1 of Altdorff et al. (2023) is located in a different federal state and is not part of the Brandenburg monitoring network. For those locations in the Brandenburg network which are close to railroads, we still had to face a trade-off between proximity to the railroad and homogeneity of the CRNS footprint (as we stated in the paper, homogeneity was *preferable*, but not an exclusive criterion). In order to limit the (rail-)road effect on the CRNS signal, we kept a distance of 10 meters to the rail tracks for the CRNS stations in Golm (GOL) and Paulinenaue (PAU). For the sensor in Marquardt (MQ), the distance is larger than 100 meters. So while for GOL and PAU, there might still be some minor effect of the trainlines on the neutron signal, we estimate that the overall contribution to the signal is less than 5 percent. Future analysis will however keep an eye on these influences and will acknowledge them in signal interpretation and potential specific corrections.

RC: ***[1.11] Table 1: "Land use from OpenStreetMap contributors (2024)" - why do the authors cite the (relatively vague) OSM maps. Did they not characterize the sites themselves in terms of land use and soil texture? That seems to be a minor red flag.***

AR: We did characterise the land use ourselves, and the reference to OSM in the table is in fact redundant and was removed. Yet, we have to disagree with regard to the "vagueness" of the OSM maps. These are usually very precise, at least for Brandenburg, and a fully valid source of local scale land use mapping. We also have contributed to the OSM-data wherever this was not the case.

RC: ***[1.12] l111: "The sensitivity of the neutron detector relative to a known reference" - in what way is that procedure a 'general calibration'. If each sensor still has its own normalization factor this procedure seems to be not different than as has been done at other sites.***

AR: We would like to refer to Heistermann et al. (2024) for the details. The main point is, however, that this "normalisation factor" is not obtained by means of calibrating an N_0 value (or other kind of normalisation factor) on observed soil moisture data, but by independently measuring the sensitivity of the detector via collocating it with another detector. That way, we independently quantify the effect of detector sensitivity. The idea of the "general calibration" is hence not to ignore the local effects on the CRNS signal (other than soil moisture), but to quantify them independently and not rely a local calibration based on local soil moisture observations (since these are inherently uncertain due a number of reasons).

RC: ***[1.13] l114: "The spatial variation of incoming cosmic radiation was accounted for by using the PARMA model (Sato, 2015)" - what does that mean? Did the authors conduct an own analysis and how do they map the high-altitude site JUNG to their data?***

AR: Again, we would like to refer to Heistermann et al. (2024) for a detailed explanation. The main point, though, is that we account for the temporal variation of the incoming neutron signal by using the observations at Jungfraujoch (JUNG), while we account for the *spatial* variation of the neutron signal by means of the PARMA model (Sato, 2015).

RC: ***[1.14] l122: "we followed the weighting procedure outlined by Schrön et al. (2017)" - did the authors use the sampling scheme as well or the footprint function?***

AR: We used Schrön et al. (2017) in order to obtain the vertical and horizontal weights, but not for the sampling scheme. We revised the manuscript to clarify this.

RC: ***[1.15] l211: "At this point, we should reiterate that the focus of this paper is to introduce the new soil moisture monitoring network in Brandenburg" - the introduction of a monitoring network by itself is not a research goal. The authors claimed to try to focus on providing a substantial contribution, not an outlook based on preliminary findings.***

AR: We have removed the statement, also in the light of the newly formulated research questions. We agree that the introduction of a monitoring network is not a research goal in itself.

Still, we consider the monitoring effort itself as highly relevant to the audience of the NHESS special issue, i.e. to the research community that is concerned with topics such as drought monitoring, hydrological modelling, water resources management and climate change adaptation in the Berlin-Brandenburg region.

RC: ***[1.16] l214: "we maintain that the model is able to reproduce the observed soil moisture dynamics in the upper 30–50 cm of the soil"- The authors previously mentioned that the sites are only capable of measuring the soil water content to a depth of 30 cm. Explain this statement.***

AR: We apologize, but we could not find such a statement in the previous version of the manuscript, although the typical penetration depth of CRNS measurements is in fact often referred to as 30 cm for average conditions. As shown in Fig. 2 (original and revised), the penetration depth depends much on the soil moisture, and varies roughly between 25 and 60 cm. Please also note that the corresponding paragraph does no longer exist in the same form in the revised manuscript, yet we have clarified in the text that the penetration depth varies in time.

RC: ***[1.17] Fig. 2: much too small, please enlarge.***

AR: For the revised figure, we have used a figure layout with four rows and two columns in order to allow for a larger representation of the figure subpanels.

RC: ***[1.18] l311: "ware" -> "were"***

AR: Was changed to "will" in the revised version.

RC: ***[1.19] in the conclusions section ”User-oriented monitoring products” - many research questions are presented which are not covered in the manuscript.***

AR: We would like to emphasize that the section is entitled ”Conclusions and outlook”, exactly because we would like to use the opportunity to outline prospective lines of research and applications. We think that this is a common and well-accepted scope for such a section. However, we think that with the revised version of the manuscript, the points that are addressed in the outlook now align much better with the subject of the paper.

RC: ***[1.20] Additionally, with only a German data interface most of the potential users face a language barrier.***

AR: As pointed out above, we have also provided an English version of the website, and also of the required files in the data repository.

RC: ***[1.21] l350: "In any case, (...)" - that is a rather colloquial statement and potentially does not contribute in a meaningful way.***

AR: We have removed ”In any case” from the statement.

RC: ***[1.22] While the contributions statement suggests MH, TF, DA, AB, AM, and SO were the core researchers, the other co-authors may have had minor roles, potentially indicating ’gift’ or ’coercive’ authorships.***

AR: The authorships are neither ”gift” nor ”coercive” authorships. Yet, we agree that the contributions should be documented in more detail, and have revised the manuscript accordingly. We followed the CRediT contributor roles taxonomy (link), as also recommended by NHESS guidelines for manuscript composition.

2. Responses to referee #4 (report #2)

RC: ***[2.1] The paper is interesting as it presents a soil moisture network based on CRNS. The data will be valuable for multiple research applications, and thus it is of interest to publish this manuscript. Looking at the previous reviews I agree it is too much for a Brief communication, but for a research paper it is not innovative or comprehensive enough. It is more suitable as a data paper. For a research paper, the manuscript needs significant improvements before publication.***

AR: We understand the concern, and have increased our efforts to strengthen the research component of the manuscript (see also comment [1.1].

We would also like to comment on the idea of a data paper. This idea had already been suggested in the first round of review. We think that this paper is not and should not be a data paper for mainly two reasons: first, a data paper typically refers to a snapshot of data, even more typically after the ”end” of a process of data collection (a campaign, a project, ...) that yielded a substantial amount of data. Here, however, our original and still valid motivation is to point the community to an ongoing activity in order to involve researchers and users as early as possible. Technically speaking, we do not want to refer to a closed dataset, but to a continuous data collection effort, and to a network that is still evolving. Second, NHESS does not provide the format of a data paper, while we are (and were, from the very beginning) convinced that this paper fits very well into the context of the NHESS special issue ”Current and future water-related risks in the Berlin–Brandenburg region”.

As a solution, we would like to suggest a compromise: we have published the dataset in its state on September 1, 2025, in a dedicated data publication portal that supports the FAIR principles, including an adequate documentation and a persistent DOI (10.23728/b2share.dfde74f4be294bd7b927f67988365f8e). We have added this data publication as an ”asset” to this paper, and we refer to it in the revised manuscript. That way, we have linked the paper to a published dataset, while the scope of the paper is still beyond that of a data paper. At the same time, we maintain the website and data portal to allow for an ongoing provision and presentation of data with short latency.

We hope that this solution meets the demands expressed by the referee.

RC: ***[2.2] In general, the title points towards a drought monitoring network which is installed in Brandenburg. My expectation is then, that there is a detailed description of the network set-up, how locations were chosen, a thorough validation of the network and with a focus on its ability to monitor drought. However, this is not sufficiently represented in the manuscript. The selection of locations is not satisfactorily described, the validation and quality assurance is lacking (a validation based on one observation per station is not sufficient), and there is no mention of drought monitoring. This needs to be improved in the manuscript before this can be published as an introduction to a new monitoring network in the form of a research paper.***

AR: This comment raises quite a variety of issues, and we will try to address them one by one.

- **Title**: We agree that the previous title did not sufficiently reflect the content of the paper. Specifically, the focus of the paper is not exclusively on drought monitoring, but more generally on soil moisture monitoring, and not only on instrumental monitoring, but also on model-based techniques (and now also remote sensing products). In order to also adequately express the aforementioned changes in research questions in the title, we changed it to: ”Soil moisture monitoring with cosmogenic neutrons: an asset for the development and assessment of soil moisture products in the state of Brandenburg (Germany)” This new title also puts less emphasis on the network character, as also raised by the referee, and more on the applicability of soil moisture products in the topical context of the NHESS special issue.
- **Network design and selection of locations**: As pointed out in the previous item, we revised the title to remove the emphasis on ”drought monitoring network” in order to avoid raising false expectations with regard to the aspects of ”network” and ”drought”. Regarding the choice of monitoring locations, we think that our approach is quite similar to the network design approach followed by Bircher et al. (2012, as cited by the referee) in considering topography (or groundwater depth), land cover, soil type, and climate (precipitation) as well as the availability of additional monitoring infrastructure. The main difference is the number of 30 sensors in the HOBE network which allowed for a more formal approach in sampling across topography, land cover and soil type. For the CRNS network in Brandenburg, site security also played an important role due to the visibility and value of the CRNS stations. In any case, we agree that the criteria should be described more clearly, and that we should also state how well the selected sites actually represent landscape characteristics in Brandenburg. In the revised manuscript, we have hence added more details with regard to the selection criteria and the representativeness of the selected sites for the environmental conditions in Brandenburg. For that purpose, we also added a new subsection ”Study area” in the ”Data and methods” section in order to describe the main landscape features in Brandenburg, and their proportions in the area of the state. In the subsequent section ”Monitoring network”, we then expand how the choice of locations represents a large proportion of Brandenburg’s landscape features. We have, however, also emphasized the fact that the ability of a network with eight (or 12) locations to representatively cover a 30,000 km large state such as Brandenburg is inherently limited, an issue that can only be resolved in the future by combining observations with models and remote sensing.
- **Validation and quality assurance**: The referee stated that ”the validation and quality assurance is

lacking (a validation based on one observation per station is not sufficient)". We assume that the comment refers to the validation of the CRNS-based soil moisture retrieval, and we disagree with that notion. The general calibration approach that was used in our study to estimate soil moisture from neutron counts, as documented by Heistermann et al. (2024), is based on a large sample of 75 sites across Europe (including Brandenburg). While we think that it is interesting to compare our CRNS-based estimates to the references from the sampling campaigns, it is not common procedure in the CRNS literature to carry out such a validation. Given the number of sites, we think that our study is in fact exemplary in providing an independent assessment of the soil moisture estimation at all, while other studies often use the groundtruthing data only for calibration, and not for validation. In response the the referee's comment, we have, however, discussed in more detail the uncertainties that result from the limited number of independent reference measurements.

- **Drought monitoring**: As pointed out above, we have removed the emphasis on drought monitoring from the title of the manuscript which we hope addresses the issues raised in this comment. However, in the new section "Implications for the management of water-related risks in Brandenburg", we discuss aspects related to drought monitoring and drought risk management, too.

RC: ***[2.3] I realize that the network is only operational since spring 2024, but currently this gives you one year of data. In addition, the current situation in Brandenburg is pressing with a drought warning and high alert levels (European Drought Observatory), whereas spring 2024 was more humid. So my suggestion is to extend the analysis period to include a full year of data including the last months to also observe the onset of drought conditions in Brandenburg in 2025. One option is for example to calculate a drought indicator based on soil parameters, i.e. the Soil Water Deficit Index, which allows you to also showcase the drought monitoring capabilities.***

AR: We thank the referee for this comment, and appreciate the suggestion of the "Soil Moisture Deficit Index" (SMDI, as published by Narasimhan and Srinivasan, 2005). Yet, it illustrates the challenge that we face with the relatively short (approx. one year) observational time series of our CRNS-based soil moisture (as also pointed out by the referee): the SMDI requires long-term soil moisture statistics (minimum, median, maximum) which can only be obtained by model-based extrapolation in time - as already demonstrated in the previous manuscript version. Hence it cannot be applied to the observational series.

Yet, we agree with the referee that it makes sense to extend the analysis period to include spring and summer of 2025, as these in fact contrast well with the conditions in 2024. Given the changes in the title and the scope of the paper, though, we focused on soil moisture instead of drought indices. In the revised section 3.1, we now briefly discuss the differences between 2024 and 2025 with regard to the presence of very dry conditions.

RC: ***[2.4] Furthermore, there are many applications of soil moisture data such as reconstruction of water fluxes and enhancing information along the vertical dimension, but these are all described very minimal without proper evaluation of the results. In addition, they are all based on the modeled soil moisture and not CRNS soil moisture. The paper seems to have a hard time balancing between the CRNS data and the model, and the current content of the paper does not reflect the title of the paper.***

AR: We agree that it was challenging to find an adequate balance between the presentation and analysis of observations and model results. This is because, on the one hand, the observations represent a means in itself, as they provide direct and independent information on the soil moisture status across the federal state of Brandenburg. On the other hand, the use of a soil hydrological model unlocks a variety of additional applications, namely by extending the scope of analysis in space and time (see comment [2.3]), and from soil moisture to vertical water fluxes. This kind of extended view requires a validated model, and the observations are one component for such a validation. So yes, it is difficult to find a balance between the adequate introduction of the observational network, and the demonstration of its combination with a model. The latter remains, in the context of this manuscript, admittedly superficial. Still, we are convinced that this demonstration is an integral component in providing a more comprehensive perspective on this effort. We have revised the paper accordingly to make this even clearer, revised the research question (see comment [1.1]), and also adjusted the title accordingly (see [2.1]).

RC: ***[2.5] line 47 - 50: Adjust this, because this statement is not entirely true, CRNS data is available in the International Soil Moisture Network and also available through other sources.***

AR: We are not sure if the referee in fact refers to ll. 47 to 50 of the manuscript under revision. We assume the reference is rather to the preceding lines about other CRNS network efforts. Also in response to the comments of referee #3, we have revised this section to adequately account for CRNS networks established previously, including CRNS data available through the International Soil Moisture Network.

RC: ***[2.6] line 94: Are these stations already installed now? Otherwise I would change this to summer.***

AR: The referee is correct (we assume the reference is to l. 81 of the manuscript version under revision), and, indeed, touches a sore spot: the new locations are fixed and the corresponding CRNS stations are purchased and ready to be deployed - except that the remote data transfer is not yet fully functional. This is the first time that we experience such a persistent issue: for more than four months now, our technicians, together with the manufacturer, are trying to resolve it, and, in fact, there has been considerable progress in the past weeks. Yet, we will only deploy the stations in the new monitoring locations when remote data transfer has been robust over a test period of four weeks from our test field site near Potsdam. Given that the recent firmware fixes are successful, the sensor deployment is, of now, planned for November 2025. Updates will be provided via the news page of our website (`https://cosmic-sense.github.io/brandenburg/en/aktuelles/`). In the revised manuscript, we have changed the information across the various occurrences in the paper to a designated instrumentation date in November 2025.

RC: ***[2.7] The Data and Methods section is missing quite some information, and this should be added to the manuscript. Some methods are mentioned but not explained. In detail the following points should be added to increase the quality of the manuscript: What has been the method for selecting the sites? A representative network is important, as is written in the introduction, but there is no description on how the sites were chosen based on land cover, terrain and soil characteristics. Looking at the maps in Fig. 1 it seems that the south of Brandenburg is not represented, which also includes some areas with a low groundwater table. When planning a network usually one takes an approach to make sure you cover all typical landscapes (or hydrotopes as Bircher et al did for the HOBE network).***

AR: This comment refers to the issue of network design and selection of locations. We hence kindly refer to our response to comment [2.2].

RC: ***[2.8] In addition, please provide an overview how the locations and characteristics of the stations (table 1) correspond to the characteristics of Brandenburg, are you really covering everything? This is especially important for drought monitoring, which is one of the main purposes of this network. In addition, if in the future the ministries or other institutions are going to use this network for drought monitoring, or if this even is going to be used for agricultural applications (i.e. drought impact analysis, insurance purposes) the representativeness of the network is crucial.***

AR: Again, this comment raises the issue of network design and the resulting representativeness, so please also refer to our response to comment [2.2]. Based on the referee's suggestion, we have added more details with regard to the representativeness of the selected sites for the environmental conditions in Brandenburg. For that purpose, we also added a new subsection "Study area" in the "Data and methods" section in order to describe the main landscape features in Brandenburg, and their proportions in the area of the state. In the subsequent section ”Monitoring network”, we then expand how the choice of locations represents a large proportion of Brandenburg’s landscape features.

Yet, we would like to emphasize that we do not and did not claim ”to cover everything”. In fact, we had already emphasized the limited ability of a network with eight (or 12) locations to representatively cover a 30,000 km large state such as Brandenburg, an issue that can only be resolved in the future by combining observations with models and remote sensing. While we have included this issue in the research questions of the revised manuscript (see response to 1.1), it remains a major challenge for prospective research, as also outlined in the section on conclusions and outlook.

RC: ***[2.9] Also, I suggest to add the stations that are/will be installed in spring 2025 for completeness to table 1.***

AR: We have added the stations to Tab. 1, including a row header to indicate the dedicated date of installation (November 2025, please also see out response to comment [2.6]).

RC: ***[2.10] line 120: How were the four soil sampling locations within the CRNS footprint chosen? How do they represent the footprint characteristics?***

AR: The sampling locations were chosen randomly within the near range of the footprint (i.e. within a radius of 20 m), given that this near range exerts the strongest impact on the signal. Certainly, the limited number of samples for bulk density is one source of uncertainty. We have discussed the resulting uncertainties in more detail in section 3.1 of the revised manuscript.

RC: ***[2.11] In line 79 it is mentioned that there are conventional point-scale sensors of soil moisture installed at the site. But in line 129-130 you mention that "To evaluate the CRNS-based soil moisture estimates (θ_{CRNS}), reference observations within each CRNS footprint were obtained from the aforementioned soil sampling campaigns". From the results it seems only the sampling is used for validation. But why did you not also use the point-scale sensors for validation. Of course, spatial representativeness can be a point of concern, but a validation on a single sampling date is also not representative or a proper validation. I suggest to add also a validation over time, i.e. with the point-scale soil moisture sensor data.***

AR: It is correct that we only use the soil moisture observations from the sampling campaign to obtain reference estimates which we then use to assess the CRNS-based soil moisture estimates. Having more additional sampling campaigns in order to obtain more reference values was not feasible based on the available resources. However, we would like to emphasize once more that our soil moisture estimation follows the ”general calibration” procedure as documented by Heistermann et al. (2024) which is based and evaluated on a large sample of 75 sites across Europe. We have pointed this out more clearly in the revised manuscript (section 2.3). Still, we think that it is, in fact, good practice to compare our CRNS-based estimates to the references from the sampling campaigns, as we did, and it is not common to carry out such a comparison with independent measurements in CRNS applications (see also our response to comment [2.2]).

Regarding the installed point-scale sensors, these do only constitute one single profile with measurement depths at 5, 10, 20 and 30 cm. Using such a single profile as a validation reference would be pointless, given that it is exactly the lack of representativeness of such point-scale sensor which we aim to overcome by using the CRNS technology. Neither an agreement nor a disagreement of our CRNS-based estimates with a single profile would be conclusive with regard to the validity of the CRNS-based time series. This is why we prefer not to implement this suggestion.

RC: ***[2.12] Line 135, please write out the method you used to get the weighted reference soil moisture, not just the publication. And also, which method and metrics did you use to then validate your CRNS soil***

moisture?

AR: We have revised the manuscript in order to explain the weighting procedure in more detail, and to state which metrics have been used for the evaluation: the error (difference between θ_{CRNS} and θ_{REF}) at each location, and the mean error (ME) and the root mean squared error (RMSE) across all eight monitoring locations.

RC: ***[2.13] Table 2 contains many acronyms that are not explained, please write them out in full.***

AR: We assume that the referee refers to the first column with the parameter names. These parameter names are listed only to provide an exact reference to the model parameters. The meaning of these parameters is explained in the column ”meaning” which provides, in our view, sufficient information to understand the parameter’s relevance. For any further detail, we refer to the model documentation (Kroes et al., 2017), which we clarified in the revised version of the manuscript.

RC: ***[2.14] Section 2.3 what is the spatial and temporal resolution of your model?***

AR: The temporal resolution is one day. The spatial resolution (i.e. in the vertical, as it is a 1-dimensional model) is 1 cm (at 0-5 cm), 2.5 cm (at 5-15 cm), then 5 cm (at 15-50 cm), 10 cm (at 50-100 cm), 10 cm (at 100-200 cm), 20 cm (at 200-500 cm) and 50 cm below. The actual depth of the soil column depends on the depth of the groundwater surface at the corresponding location. We have added the corresponding information in the revised manuscript.

RC: ***[2.15] For the inputs to the pedotransfer function, why didn’t you use the actual soil information from the soil sampling campaign and instead did a so-called "fine-tuning"? Is soil texture (sand, silt, clay) data not available for the sites from your sampling campaign? It would be beneficial to use this instead of tweaking your model inputs with estimated sand, silt and clay values to a point to get satisfactory results. If it is not available I suggest to at least check your calibrated sand, silt and clay content with the bulk density values from your samples to see if this is comparable.***

AR: We use the texture data from the soil map (BUEK300) as input to the pedotransfer function because this information is available anywhere in Brandenburg. This is a precondition for any spatial upscaling for which we would like to provide a perspective on the basis of our analysis. We have pointed this out more clearly in the revised manuscript. We do not consider this as ”tweaking” because we keep the fractions of sand, silt and clay within the ranges specified by the soil map. Given the generally high sand content, we do not agree, either, that comparing the calibrated sand, silt and clay contents to the bulk density at the measurement locations would be helpful since bulk density will largely be influenced by soil structure, as a result from, e.g., vegetation and agricultural management practices and organic matter – aspects which, however, are beyond the scope of this study. Please also note that, following the comprehensive revision of the manuscript, we now evaluate the uncalibrated version of the model as well as a calibrated (fine-tuned sand content) model (see section 2.4.1 and 2.5 of the revised manuscript).

RC: ***[2.16] Section 3.1 gives a short overview of the soil moisture estimation and validation. First, which in situ soil moisture measurements were now used here, the stations or the samples?***

AR: As pointed out in our response to comment [2.11], we used the soil moisture obtained in the sampling campaigns. We have clarified this in the manuscript in section 2.3.

RC: ***[2.17] I suggest to also use the RMSE as a quality control metric, as this is quite common in soil moisture validation studies (i.e. Gruber et al. 2020 for satellite soil moisture retrievals).***

AR: We have replaced the MAE with the RMSE as a metric.

RC: ***[2.18] Also, I suggest to add some more references to publications that have validated CRNS sensors, to place your network in context to other CRNS networks, i.e. what were the metrics obtained for the TERENO network.***

A fair validation is only possible for sites with a number of point-scale measurements that is able to sufficiently represent the footprint area around the CRNS station, and which have not been used for the CRNS calibration. Usually, any such measurements are used for calibration, so that an independent validation is rarely conducted. Still, few studies carried out such a validation, either based on additional sampling campaigns or based on continuous sensor networks: Cooper et al. (2021) stated that "repeat calibrations using secondary samples have been conducted at two COSMOS-UK sites to explore the accuracy of the derived VWC obtained on a particular day [...]. There was below $0.03\,\mathrm{m^3\,m^{-3}}$ difference in volumetric water content". Coopersmith et al. (2014) used an in-situ network at one COSMOS station for validation and found the RMSE "well below $0.04\,\mathrm{m^3\,m^{-3}}$ [...]". Schrön et al. (2017) followed a similar approach and found RMSE values between 0.006 and $0.051\,\mathrm{m^3\,m^{-3}}$ across four CRNS sites in Germany, three of which belong to the TERENO program. Finally, Iwema et al. (2015) systematically validated the effect of the number of calibration measurements at two TERENO sites in Germany and found validation MAE values between about 0.04 and $0.07\,\mathrm{m^3\,m^{-3}}$ (depending on the number of calibration dates from one to six). We consider the validation results obtained in the context of our study quite well in line with these references, and we have added the corresponding references and results to our manuscript in the context of discussing the errors estimated for the sites in our network in Brandenburg. At the same time, we would like to emphasize that great care has to be taken when such error metrics are compared across sites or networks. Currently, there is work in progress to quantify such metrics for CRNS sites across the globe, and we appreciate the reviewers confirmation that such research would be valuable.

RC: ***[2.19] Especially, as the soil moisture values are very low at the time of sampling, your MAE and bias might be not representative (i.e. higher errors might occur with a higher variability in soil moisture).***

AR: We do not agree with the general statement that "soil moisture values are very low at the time of sampling". Given the soil conditions Brandenburg, this only applies to the locations Booßen and Kienhorst.

RC: ***[2.20] One of my major concerns is that you have calibrated your model parameters on the actual CRNS SM data. Then you use the same datasets, both CRNS and model SM to evaluate your results. This is not a proper way of doing an evaluation, as you have used the same data for calibration and validation, making these results invalid. So, either split your data in training and test (cal/val) data to asses model performance, or use another approach to obtain the model parameters.***

AR: Thanks for this comment. For the revised manuscript, we have implemented a split-sample calibration/validation for the SWAP model (2024 data for calibration, 2025 data for validation). We also implemented a bias-correction for the competing large-scale soil moisture products and followed the same split-sampling approach as for the SWAP model. Please note that the overall presentation of results is now fundamentally different since the validation metrics for both the uncalibrated and the calibrated SWAP model are now presented in section 3.2 together with the metrics for the large-scale soil moisture products (without and with bias correction).

RC: ***[2.21] And, to assess your model performance, why not use the point-scale SM measurements as independent reference?***

AR: Please refer to our response to the referee's comment [2.11].

RC: ***[2.22] In section 3.2 please add a paragraph on how your calibrated parameters compare to your soil samples. From Table 4 it can already be observed that for the station OEH your calibrated sand, silt and***

clay is at the boundary conditions. This means your model had difficulties for this site. Please check this.

AR: It is correct that the fine-tuned sand content is at the upper end of the range specified by the soil map for the station OEH which implies that the model does not fully succeed in producing the drier conditions as observed the the CRNS (overestimation of soil moisture). It is exactly why we only fine-tuned the sand content within the limits provided by the soil map. However, the reasons for the overestimation remain unknown - they could be caused by uncertainties of the soil map, the model, but also by a systematic bias of the observations. Please note that soil texture values were not obtained for all sites.

RC: ***[2.23] Also, in table 4, I assume T it Ton, but change this to C for clay, and also change U.***

AR: Thanks for pointing this out. The letters in fact represented the German abbreviations. We have changed "U" to "Si" and "T" to "C". Please note, however, that the former Tab. 4 does not exist any more in the revised manuscript because the results of the model validation (over the validation period January 1 to September 1, 2025) are now presented in the new section 3.2 in the context of the new Fig. 3. Instead, the new Tab. 3 presents the ranges of S-Si-C contents from the soil map, as well as the S-Si-C contents derived from that map for the *uncalibrated* SWAP model. For the sake of comprehensiveness, the former Tab. 4 was moved to the supplementary material.

RC: ***[2.24] In section 3.2 you describe the possible impact of vegetation dynamics on the CRNS SM. This is something that needs to be discussed more in detail. There have been studies using a dynamic vegetation parameterization in the CRNS soil moisture estimation. Especially in crop- and grasslands this might improve your estimates.***

AR: This might be a misunderstanding. In ll. 207-210 in section 3.2, we discuss the potential effect of vegetation on the SWAP model performance, not on the CRNS-based soil moisture estimation. In the corresponding lines, we had noted a discrepancy between simulated and observed soil moisture in autumn 2024, and had hypothesised that, in the model, the seasonal LAI development for grassland could be a reason for that discrepancy. Meanwhile, we could rule out this reason by testing the sensitivity of this discrepancy to the LAI in that period (not shown). Please also note that the overall discussion of the CRNS results in section 3.1 has changed, and that a detailed comparison of simulated and observed time series is not carried out any more (because we now also compare the observations to the bias-corrected large-scale products, see also comment [1.1]).

Apart from that, the referee is of course right about the effect of vegetation biomass on the CRNS-based soil moisture estimation. However, Heistermann et al. (2024) have also shown that for grassland and cropland sites, the uncertainty originating from vegetation biomass is rather low in comparison to other sources of uncertainty. This is why we assumed a constant biomass for CRNS-based soil moisture estimation in the general calibration framework. In the revised manuscript, we now briefly discuss the potential effects of vegetation biomass on the uncertainty of CRNS-based soil moisture estimates.

RC: ***[2.25] Figure 2: it may help to add the land cover type in brackets behind the station name.***

AR: We have added the land cover types in brackets. Please note that Fig. 2 has further changed subject to the revisions: it does not show the simulated time series of SWC any more, since this is now shown in the new Fig. 4, together with the time series of the bias-corrected large-scale products.

RC: ***[2.26] The section on "Increasing temporal coverage" is very minimal. I do not see how this is relevant in context with the introduction of a CRNS network for drought monitoring and what the benefit is of your model. Because what you do not show is, how reliable the SM data is for the other years. Is this better then for example satellite data or other models? Likely you do not have validation data from point-scale***

sensors, but you could compare it to e.g. ERA5-Land and CGLS Soil Water Index in a triple collocation approach to showcase the quality of your data in comparison to existing data sets. In addition, the sections on vertical integration and reconstruction of water fluxes is too minimalistic. At least make a comparison to ERA5-land. Your sites are far enough apart to allow for this.

AR: In the revised manuscript, we have introduced a new subsection 3.3 in which we discuss the results of subsections 3.1 (CRNS-based soil moisture estimation) and 3.2 (Evaluation of soil moisture products) with regard to potential implications for the management of water-related risks in Brandenburg. ”Increasing the temporal coverage” (or ”temporal upscaling”, as we term it in the revised version) is an important aspect for (drought) risk management or decision support as these typically require to put the soil moisture level at a specific point in time in context with the statistical properties over longer historical periods (typically several decades). This is exactly the motivation of the former Fig. 3 (Fig. 5 in the revised version), and we think it is worthwhile demonstrating this ability in the context of our study and also in the context of the NHESS special issue.

With the formal split-sample calibration and validation, we have validated the ability of the locally calibrated SWAP model to represent soil moisture dynamics at the monitoring locations, and it is of course the motivation of such an analysis to apply the validated model also to time periods outside the calibration/validation frame (in our examples to the period from 1993 to 2024). We have comprehensively revised the manuscript in order to make this clearer, and we hope that the referee will agree that an exemplification of such model-based temporal upscaling (or extrapolation) is worthwhile in the context of section 3.3 (although it necessarily has to remain superficial).

We also much appreciate the referee’s suggestion to compare the results of the SWAP model to other available soil moisture products such as ERA5-Land and the CGLS Soil Water Index. We implemented such an analysis as a formal benchmark experiment in which we use the CRNS-based soil moisture estimates as a reference in order to evaluate the performance of various soil moisture products from models and remote sensing. We also visually compare the soil moisture time series of the various products for 2024 and 2025 for all monitoring locations (new Fig. 4). Since this analysis shows that the SWAP model performs better than the large-scale products, we consider it justified to base the two *examples* given in section 3.3 solely on the results of the SWAP model (example 1: volumetric soil water storage for different integration depths and selected years in comparison to the period from 1993 to 2024; example 2: groundwater recharge for selected years in comparison to the period from 1993 to 2024).

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