Author Response to Reviews of

Signal response of bare and moderated cosmic-ray neutron sensors to varying soil and biomass conditions

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

1. Reviewer #1

AC: *We thank reviewer #1 for investing their time in reviewing our manuscript and providing constructive suggestions for improvement. The reviewer's comments have helped to streamline our manuscript and make it clearer and more relevant for the readers of GI. In the following sections, we will reply to all comments of reviewer #1 with RC (i.e. reviewer comment) and AR (i.e. author response), respectively.*

RC: ***The authors present a timely and useful modeling study examining how bare and moderated cosmic-ray neutron detectors respond to changing soil moisture, biomass, soil chemistry, bulk density, and above-surface water conditions. A major strength of the manuscript is the move from idealized thermal/epithermal energy-window interpretations toward detector-response-function-based analysis, which makes the results more relevant to real CRNS instruments in the field. The paper also makes an important conceptual contribution by showing that bare detector signals are not equivalent to 'pure thermal neutron' behavior, but instead reflect a mixed response that still contains the legacy of the epithermal stage of neutron transport. Overall, I found the manuscript strong, well motivated, and likely to be of interest to the CRNS community. I believe it is suitable for publication after the following revisions are addressed.***

AC: *We thank reviewer #1 for their positive feedback on the strengths and scientific contribution of our manuscript. We have carefully addressed all the comments and we believe that the major strengths that the reviewer highlighted, as well as their implications, have been made more accessible to a wider GI audience.*

RC: ***Major comments***

Practical workflow / guidance for CRNS users.
As a long-time CRNS user, I would strongly appreciate a short practical workflow figure or summary box that helps readers decide when a simpler transfer-function framework is sufficient and when the more complete formulations are needed. At present, the manuscript does a very good job showing where complexity arises, but it offers less guidance on how practitioners should respond to that complexity in routine use. This would be especially helpful for newer users, for whom Eq. 6 may appear quite complex relative to the traditional appeal of CRNS as a robust and operationally simple soil-moisture method. The manuscript already demonstrates that biomass, water layers, bulk density, and detector configuration can all modify the soil-moisture response, and that the modified UTS (Eq. 6) can improve the representation of biomass effects, although its broader validation remains outside the scope of the study.
I would encourage the authors to add a brief 'recommended use cases' workflow along the following lines:
Use a simpler transfer function (e.g., Desilets-style / N0-type approach) when the site is relatively simple: low to modest biomass, limited seasonal biomass change, no persistent snow or ponded water, fairly typical mineral soils, and no expectation of strong heterogeneity or unusual absorber chemistry. In these settings, simplicity, interpretability, and operational robustness are often more valuable than adding poorly constrained correction terms. Use the UTS framework when the site is dry, when improved performance at low soil moisture is important, or when bulk density / atmospheric effects need to be handled more consistently in a physically based framework.
Use the full Eq. 6 or similarly expanded approaches with caution and only when justified by site conditions—for example, where above-ground biomass is substantial and varying, where independent biomass information is available, and where the additional model complexity is supported by the measurement objective.
Advise caution regardless of transfer function choice in settings with tall or changing vegetation, shallow water or snow layers, strong soil-chemistry contrasts, unusual bulk density structure, or configurations where bare and moderated detector behavior diverges from standard assumptions. These are precisely the

cases where the manuscript shows the response can become non-monotonic or more site-specific.
I think even a simple schematic like this would make the paper much more helpful to practitioners. It would also help balance an important tension in the paper: on one hand, the manuscript correctly highlights important limitations and complexities; on the other hand, most users still need practical guidance on when those complexities materially affect soil-moisture estimation and when simpler transfer functions remain adequate.

Suggested CRNS workflow for transfer-function choice:
Start with the study objective: routine field-scale soil moisture monitoring, or process-rich interpretation in a complex environment?
Check for major complicating factors:

- ***strong seasonal biomass change***
- ***tall vegetation interacting with detector height***
- ***snow, ponding water, or shallow surface water***
- ***unusual soil chemistry / absorbers***
- ***strong bulk density variation***

If none or only minor factors are present, a simple Desilets/N0-type calibration may be sufficient. If the site is dry or accuracy at low water content matters, favor UTS. If biomass is substantial and variable, and biomass information is available, consider Eq. 6 or another biomass-aware framework. If several complicating factors co-occur, emphasize uncertainty and site-specific calibration rather than defaulting to a more complex equation automatically.

AC: *We thank the reviewer for the constructive comment and suggestions. As a simulation-based study, our manuscript is intended to be of theoretical nature showing neutron responses under different environmental conditions and the associated signal complexities, even if the soil moisture, biomass or water layers on top of the soil are distributed uniformly throughout the model domain. Nevertheless, we fully agree that translating the specific theoretical findings of our study into recommendations for practical applications is, to a certain degree, feasible. And we agree that this will make the results more accessible to users and practitioners in the CRNS community. In the process of reviewing the manuscript, we went through the following considerations (divided by topics for easier tracking) that resulted in changes or additions to the original text.*

Practical guidance: Regarding the development of a broad practical guide, we believe that a comprehensive workflow is being provided in the 'Global COSMOS Reference' which is a CRNS community effort (https://doi.org/10.5281/zenodo.17959506) aiming at the workflow/guidance on practical CRNS applications that the reviewer suggests. This nearly finalized document is a community-developed reference for CRNS data processing, which is expected to be updated on a regular basis. Rather than providing guidelines that repeat what is available in the "Global COSMOS Reference", we have added references to this document when appropriate. We also encourage the reviewer (if not already done so) to get in touch and join the development of this community-driven CRNS reference.

Transfer functions: With respect to our specific manuscript and the choice of neutron-to-soil moisture conversion functions (or transfer function), we believe that our study does not allow for a direct recommendation of *using either the UTS equation proposed by Köhli et al. (2021) or the N0-approach proposed by Desilets et al. (2010) because we did not compare the performance of the two equations in our analyses against field or simulation data. In the authors' view, drawing conclusions and giving sound recommendations on the choice of conversion function is to be addressed by future larger measurements-based studies (e.g., meta-analysis studies), which we now recommend in the conclusions in a clearer and more visible way. The same applies, in our view, to the opportunity to adjust the shape-giving parameters of the conversion functions at sites with strongly heterogeneous spatial distributions of soil moisture, biomass/ponding water and bulk density. A theoretical assessment of why this can become necessary at specific sites can be found in e.g. Schrön et al. (2023). Here, we would again like to refer to the 'Global COSMOS Reference' document described in the previous paragraph.*

UTS approach: In this study, we decided to only use the UTS approach for e.g., comparing approaches of correcting for biomass (changes) when neutron intensities observed by moderated detectors are concerned. This decision was made following findings from previous studies (Köhli et al., 2021; Rasche et al., 2024; Brogi et al., 2026), which show that the UTS outperforms the N0-approach at sites with lower soil moisture content while the performance is comparable at sites with generally higher soil moisture. We believe that the UTS has a general advantage that will eventually make it widely adopted as it can cover the entire range down to the very dry end in a single equation. Thus the choice of the UTS for our study so that results are expected to be valid and valuable in the future.

Biomass corrections: Although we cannot give recommendations on the conversion function itself, we can give recommendations on the choice of biomass correction. In our study, we found that in conjunction with the UTS (Fig. 8), the widely used linear correction approach by Baatz et al. (2015) in its original form (Eq. 5) with the slope being β *= 0.005* mm^{-1} *BWE cannot fully remove the influence of biomass on the neutron intensities observed by moderated detectors. However, our simulation results suggest that the same equation with* β *= 0.013* mm^{-1} *BWE can strongly improve the prediction of neutron intensities and in turn, the biomass correction. This simulated value of* β *is in line with findings from empirical studies (Jakobi et al., 2018, 2022; Morris et al., 2024), supporting the* β *value that we derived from our simulations. Therefore, we now clearly recommend using either the UTS or N0 neutron-to-soil moisture transfer function with Eq. 5 but with the updated* β*.*

Eq. 6 was derived as a modification of the original UTS equation because our simulation results also suggest some non-linearity and a soil moisture dependence on the neutron-biomass relationship. Therefore, we decided to integrate the biomass dependency directly into UTS which then becomes Eq. 6. Although Eq. 6 shows promising results when predicting simulation data, we believe that it is necessary to test the validity of this new approach (modified UTS) against field data. As this is beyond the scope of this modelling-based study, we now better encourage further studies to test and investigate the performance of Eq. 6.

Overall, regarding biomass correction, a specific recommendation for practical CRNS applications with respect to biomass correction was added at line 433:

Compared to no biomass correction or the original approach after Baatz et al. (2015), an improved representation of the simulated moderated neutron intensities can be achieved by using the UTS if the adjusted coefficient of 0.013 mm^{-1} BWE is used in Eq. 5 or by using the modified UTS (Eq. 6). While these results confirm findings of previous studies that an adjustment of the original β derived by Baatz et al. (2015) may be necessary, a thorough assessment of the modified UTS in Eq. 6 with integrated correction for BWE is beyond the scope of this study. Nevertheless, from a practical point of view, the findings from this study suggest that Eq. 5 with a β of 0.013 instead of 0.005 mm^{-1} BWE should be used for correcting neutron signals from moderated detectors for variations in above-ground biomass.

Additionally, a specific recommendation regarding the co-location of bare and moderated neutron detectors was added from line 232:

Furthermore, the angular distribution of neutrons, the orientation of the detector (vertical or horizontal) as well as where the additional HDPE is located are likely to have an effect on whether the bare detector counts more (due to more neutrons being slowed down by HDPE to thermal energies) or less neutrons (increased shielding). For practical applications, bare detectors should therefore be placed at sufficient distance (e.g. ≥ 30 cm) to the moderated detector or other hydrogen-rich objects such as tree stems to avoid large changes in the absolute intensity and changes of the response to e.g. soil moisture changes. If the object is much larger than the detector itself, this distance needs to be increased. The influence of co-located instruments on each other should also be kept in mind when comparing observations with results from this study, where both detector types were simulated as solitary instruments.~~Hence, while~~Despite showing the potential effect of additional moderating material close to the bare detector, the DRF approach remains a simplification and a detector-specific analysis with more detailed detector geometries is required when assessing absolute detector count rates.

RC: ***Abstract, p. 1, line 2 'researchers have hypothesize' -> 'researchers have hypothesized'.***

AC: *Will be corrected in the revised manuscript.*

RC: ***Abstract, p. 1, lines 14-15 'the simulation results shed further light on empirical findings made in previous studies, they set a baseline...'***
Consider revising to avoid the comma splice, for example:
'the simulation results shed further light on empirical findings made in previous studies, set a baseline...'
or split into two sentences.

AC: *Will be corrected according to the reviewer's suggestion.*

RC: ***Introduction, p. 3, line 86 'the simulations results' -> 'the simulation results'.***

AC: *Will be corrected in the revised manuscript.*

RC: ***Methods, p. 4, line 112 'However, In this study' -> 'However, in this study'.***

AC: *Will be corrected in the revised manuscript.*

RC: ***Methods, p. 5, lines 131–132 'A detailed description of the different homogeneous setups in given in the following sections.'***
-> 'A detailed description of the different homogeneous setups is given in the following sections.'

AC: *Will be corrected in the revised manuscript.*

RC: ***Methods, p. 5, line 132 'Fig. Fig. 1a-c' -> 'Fig. 1a–c'.***
Duplicate 'Fig.' should be removed.

AC: *Will be corrected in the revised manuscript.*

RC: ***Methods, p. 7, lines 148–149 'The use of a homogeneous material layers...'***
-> 'The use of homogeneous material layers...'

AC: *Will be corrected in the revised manuscript.*

RC: ***Methods / Table 2 caption, p. 7 'different amount of above-ground biomass' -> 'different amounts of above-ground biomass'.***

AC: *Will be corrected in the revised manuscript.*

RC: ***Methods, p. 8, line 155 'increments .' -> remove extra space before the period.***

AC: *Will be corrected in the revised manuscript.*

RC: ***Figure 1 caption, p. 10 'with an vertically expanding soil layer' -> 'with a vertically expanding soil layer'.***

AC: *Will be corrected in the revised manuscript.*

RC: ***Results, p. 11, lines 208–211 'In the case of a thermal neutrons...' -> 'In the case of thermal neutrons...'***
Also, 'continuos decrease' -> 'continuous decrease.'

AC: *Both will be corrected in the revised manuscript.*

RC: ***Results, p. 13, lines 243–245 'and thus, exhibits a lower signal-to-noise ratio making it less favourable...' This sentence reads awkwardly. Consider: 'and thus exhibits a lower signal-to-noise ratio, making it less favourable...'***

AC: *Will be corrected as suggested in the revised manuscript.*

RC: ***Results, p. 14, line 249 'previous studies(e.g.,' -> add missing space: 'previous studies (e.g.,'***

AC: *Will be corrected in the revised manuscript.*

RC: ***General style throughout pp. 1–15 The manuscript alternates a bit between 'bare detector,' 'bare neutron detector,' 'thermal neutrons observed with bare detectors,' and 'bare detector signal.' I would recommend tightening terminology so that 'thermal neutrons' and 'bare detector signals' are not used interchangeably, especially since one of the paper's conceptual points is that they are not strictly the same thing.***

AC: *We agree with the reviewer that the text needs consistency in this key point of the manuscript. Especially because, in the CRNS related literature, thermal and epithermal neutrons have often been used as synonyms for neutrons measured with bare and moderated detectors, respectively. In the revised manuscript, the use of thermal and epithermal neutrons was left as it was for most of the introduction chapter and in references to previous studies in which pure thermal and epithermal neutrons have been investigated by simulations.*
In the rest of the text, the terminology was streamlined. For example, by consistently using 'bare/moderated detector' in place of 'bare/moderated neutron detector', and by using 'Neutrons observed with bare/moderated detectors' instead of 'Thermal/epithermal neutrons observed with bare/moderated detectors'.

2. Reviewer #2

AC: *We thank reviewer #2 for taking the time to review our manuscript and provide suggestions for key improvement. We believe that the reviewer's comments have helped to make our manuscript clearer and more accessible to the broader CRNS community and readers of GI. In the following section we will reply to all comments of reviewer #2 with RC (reviewer comment) and AR (author response), respectively.*

RC: ***The manuscript presents a simulation-based assessment of bare and moderated CRNS detector responses under varying environmental conditions. The topic is technically relevant to the CRNS community, and the use of detector response functions is potentially useful. However, in its current form, the manuscript reads primarily as a technical sensitivity study, with limited demonstration of broader methodological or practical impact. I also have concerns regarding the justification of some modelling choices, the treatment of uncertainty, and the accessibility of the manuscript to a wider GI readership. I therefore do not recommend this manuscript for publication. However, if the Editor considers the topic suitable for GI, the authors could be invited to submit a substantially revised manuscript.***

AC: *We thank the reviewer for the critical comments and acknowledgement of the relevance of our work to the CRNS community. Following the Reviewer's comments and those of Reviewer no. 1, we have critically revised our manuscript. The revised manuscript will contain a more streamlined vocabulary and, more importantly, a set of additions to relevant parts of the discussion and to the conclusions intended to provide key points and guidance for a less specialist audience. Appropriate statements throughout the manuscript now underline the practical implications of the findings (please see author responses to specific comments below). We believe that the addition of these parts, which follow the reviewer suggestions, have further increased the relevance of this work for the broader CRNS community as well as the general readership of GI.*

RC: ***Specific comments:***

L103–105: It is not clear to me why soil moisture and absolute humidity need to be fixed here. Please expand the explanation. Is the detector not sensitive to those variables?

AC: *Generally, in setups and geometrical design of simulation scenarios for deriving detector response functions, as used in this used in this study, neutrons of defined energy levels are released separately (one energy per scenario) from a source that is directly above the neutron detector and with the same geometrical dimension of the detector surface. In typical URANOS model setups, the cutoff-rigidity rescales the energy distribution of source neutrons (how many source neutrons are released at which energy). In the special case of simulating DRF, the same number of neutrons per defined energy level were simulated for deriving the DRF. Therefore, the cutoff-rigidity is meaningless and only stated for completeness. In the DRF simulation scenarios, released source neutrons will not have meaningful interactions with the air humidity before they reach the detector because they are released directly above the detector. This results in a negligible influence of absolute humidity in the simulation of detector response functions. Similarly, most neutrons are either detected in the detector gas or pass through the detector before they scatter in the soil and away from the detector. Although a small amount of neutrons can backscatter from the soil into the detector, the effect is again expected to be negligible.*

We have now clarified these aspects as they were not explicitly mentioned in the original manuscript by adjusting line 105:

All DRF were simulated using the same default boundary conditions (soil moisture = 0.01 $\mathrm{cm^3\,cm^{-3}}$, bulk density = 1.43 $\mathrm{g\,cm^{-3}}$, cutoff rigidity = 5 GV, absolute humidity = 2.33 $\mathrm{g\,m^{-3}}$ and shielding depth = 1013 $\mathrm{g\,cm^{-2}}$) to ensure comparability between the DRF of the individual detector setups. These boundary conditions were kept constant because their variation would have negligible impacts given the fixed location of the neutron source and its short distance to the detector.

RC: ***L106–108: My understanding is that, due to lower costs, the BF3 tubes from Hydroinnova, such as the CRS1000/B, tend to be more popular for deployment, especially at larger volume or in developing countries with financial constraints. Why not base the results on the CRS1000/B design? Would the CRS1000 design not further limit the potential reach of this study?***

AC: *We agree with the reviewer that it would be interesting to know how transferable the results from this study, which utilizes the dimensions and detector gas of a CRS1000 detector, are to other types, sizes and geometries of neutron detectors.*

However, we would like to stress that although the commercially available CRS1000 model contains a moderated and bare detector tube placed together in the field enclosure, we have decided to individually simulate these tubes as solitary rather than co-located instruments. As such, the majority of our simulation results are comparable with other detector setups like the CRS1000/B where the bare and moderated detector tube have a larger inter-distance compared to that of the CRS1000 (a distance that can be potentially increased by placing the tubes in different custom-made positions). The co-location analyses which are presented and discussed in chapter 3.1 and Fig. 3 are meant to test and show the influence of the moderated detector tube in direct vicinity of the bare detector tube. This is now better described from line 110 onwards:

The CRS1000 detector system is usually composed of a bare and a moderated detector with a 25 mm HDPE shield which is considered the standard moderated detector in the context of CRNS. However, in this study, the bare and moderated detector were simulated as solitary instruments and not in a co-located setup ~~to obtain more generalized results. In addition,~~ This allows for more generalized results that can be valid for similar instruments like the CRS1000/B, in which the distance between the two detectors can potentially be modified. Nonetheless, a simplified comparison of bare detector response functions illustrating the influence of the co-located placement of a HDPE shielding of a moderated detector in 10 cm distance (same as the CRS1000) will also be presented.

We understand the second part of the reviewer's comment to refer to transferability of the detector response functions simulated for the CRS1000 type to other detector types. It is indeed correct that different neutron detector types have different detector response functions which is a result of their geometry, reactive detector gas or working principle (e.g., scintillator devices or gaseous proportional detectors) (e.g., Köhli et al., 2018; Weimar et al., 2020). However, the overall shapes of the DRF of the typical detector types are very similar and differences between the individual detector response functions is much smaller than the difference between using a detector response function and using an energy window to evaluate the results from neutron transport simulations. We have added the following statement from line 237 to better convey this message:

... , the DRF approach remains a simplification and a detector-specific analysis with more detailed detector geometries is required when assessing absolute detector count rates. Nevertheless, the described findings underline the importance of using a detector response function to evaluate neutron transport simulations for an improved comparison between neutron transport simulations and observed neutron data if other approaches such as the cadmium difference method used in Andreasen et al. (2016, 2020, 2023) are not suitable. Although it can be expected that some differences in the DRF will stem from the varying working principles, designs and geometries of different detectors, this is a smaller difference compared to the difference between using a DRF or an energy window when evaluating results from neutron transport simulations.

RC: ***L112–113: How would that choice affect our understanding of actual co-located setups in situ? It would seem more appropriate to model what is effectively 'seen' in the field.***

AC: *Similar to the previous comment, we decided to simulate solitary detectors to derive more generalized and transferable results. It is true that, in addition to solitary detectors, we also simulated how the co-located detector setup would influence the results for the standard simulation setup without biomass, water layers or varying soil chemistry. However, this was only intended to show that some influence can be expected by sensor co-location. We believe that focussing on the co-located setup of the CRS1000 for the entire study (or on another fixed setup from another detector type) would strongly limit its transferability to other detector types (existing or future ones) where bare and moderated detector tubes are installed either as solitary instruments or in larger and potentially variable distance to each other. We believe that this choice is in line with the previous reviewer comment about the increasing use of the CRS1000/B and other detector models.*

We nonetheless agree that these aspects should be discussed more clearly in the text, and we made respective changes to the text by following also comments of reviewer #1:

Furthermore, the angular distribution of neutrons, the orientation of the detector (vertical or horizontal) as well as where the additional HDPE is located are likely to have an effect on whether the bare detector counts more (due to more neutrons being slowed down by HDPE to thermal energies) or less neutrons (increased shielding). For practical applications, bare detectors should therefore be placed at sufficient distance (e.g. ≥ 30 cm) to the moderated detector or other hydrogen-rich objects such as tree stems to avoid large changes in the absolute intensity and changes of the response to e.g. soil moisture changes. If the object is much larger than the detector itself, this distance needs to be increased. The influence of co-located instruments on each other should also be kept in mind when comparing observations with results from this study, where both detector types were simulated as solitary instruments.~~Hence, while~~Despite showing the potential effect of additional moderating material close to the bare detector, the DRF approach remains a simplification and a detector-specific analysis with more detailed detector geometries is required when assessing absolute detector count rates.

RC: ***L144–145: Why is the detector simulated in URANOS like a detector, while plants are simulated as a 'gas layer'? Have the authors tested the impacts of this simplification on the overall results? They earlier mention the potential for biomass estimation using a bare detector, so it seems appropriate to mimic the actual site conditions as accurately as possible in order to evaluate such potential.***

AC: *We thank the reviewer for raising this point. The reason for implementing vegetation as a 'gas layer' is* *threefold. First of all, our study is intended to show generalized results. Tailoring the vegetation geometry to specific study sites, vegetation types or biomes would counteract this aim. For example, in case of a forest, this would not only require the selection of a tree geometry itself but also where the individual tree stems are positioned around the virtual neutron detector, if any understory vegetation is present, what the shape of the tree crown is like. We don't think that randomly defining these parameters with the intention of deriving generalized results is useful. Secondly, using e.g., individual trees of different shapes and sizes in a simulation set-up would require the simulation to be conducted with a small virtual detector rather than a large detector layer in order to achieve acceptable statistics in the Monte-Carlo simulations. This drastically increases the computational effort in addition to the effort of setting up the model domain. Hence, implementing detailed vegetation geometries in neutron transport simulations can be useful when aiming for a better understanding of neutron signals and their dynamics at specific and individual study sites but not when generalized responses are of interest. Lastly, Andreasen et al. (2017) found that simple vegetation layer matched their epithermal neutron measurements best which is another reason why we chose this design. Nevertheless, Andreasen et al. (2017) also found a more complex vegetation design to better represent observed thermal neutron intensities. We therefore agree that some additional statement mentioning this limitation should be made.*

We added the following statement from line 412:

> It should be noted here that vegetation is implemented as a homogeneous plant gas layer, which poses a further limitation. In fact, Andreasen et al. (2017) showed that different vegetation implementations in a neutron transport models caused different neutron responses: specifically, a homogeneous vegetation layer well represented epithermal neutron observations while more complex vegetation structures best fit thermal neutron observations. ~~Hence, additional research on the joint influences of biomass, vegetation height and soil moisture on bare detector signals is required to further explore their usability in biomass estimation and monitoring.~~Hence, additional research on the joint influences of biomass, vegetation height and geometries as well as soil moisture on bare detector signals, rather than thermal neutron intensities, is required to further explore their usability in biomass estimation and monitoring.

RC: ***Section 2.2.3: How did the authors consider the fact that snow density is different from liquid water density? It appears that the proposed scenarios are based on liquid water layers only.***

AC: *Using water layers to simulate the influence of snow on neutron intensities is a common simplification which has also been used in previous studies investigating responses of low-energy neutrons to changes in snow cover (Brall et al., 2021). Similar to layers of vegetation, the main influence can be expected to arise from the height of the snow layer when the top of the snow layer approaches and exceeds the height of the detector. Based on neutron transport simulations, Weimar (2022) did not find a large effect for epithermal neutrons but some effect for thermal neutrons when the water layer approaches the neutron detector and the effective height of the detector decreases. Therefore, our results are only valid for thin layers of water of 10 cm on the soil surface, which correspond to 30 cm of snow considering a snow density of 0.3 g cm^{-3}. Given the findings in Weimar (2022), this is especially important for the bare detector. To underline this further, we will add the following statement from line 444:*

~~In contrast, moderated detector intensities always decreased with snow height. The simulation scenarios in this study representing above-surface water as a liquid water layer support these observations.~~In contrast, intensities measured with moderated detectors always decreased with snow height. The simulation scenarios in this study representing all above-surface water as a liquid water layer support these observations. Although this has been done in previous studies (e.g., Brall et al., 2021), representing snow as a water layer remains a simplification which does not account for the lower density of snow. For example, similar to layers of biomass, snow layers with heights approaching or exceeding the height of the detector are likely to lead to a different response despite containing the same amount of a water layer with lower height. Therefore, the results of the simulations conducted in the scope of this study are only valid for snow layers of heights up to approx. 30 cm (at a snow density of 0.3 g cm^{-3}).

RC: ***Section 3.2.2: The authors have not clearly explained why this transfer function is needed, only that it was lacking for bare detectors. What is the intended usage of this equation? Are users expected to switch from moderated to bare detectors?***

AC: *We will make clarifications in the text with respect to this point. Bare neutron intensities have been used in several empirical studies for estimating biomass and snow. Due to the low sensitivity to soil moisture compared to other variables, most of these studies assumed that bare detectors are insensitive to soil moisture variations. Thus, characterising the response to soil moisture through a transfer function similar to those available for neutrons from moderated detectors is, in our view, a prerequisite for further and more detailed research on the potential of bare detectors for environmental monitoring. This is what we wanted to convey in our text. We do not suggest that soil moisture should be estimated from neutron signals measured with bare detectors. Nonetheless, we have improved the text to clarify, for specialists and non-specialists alike, the envisioned use of this transfer function by adding the following statement to line 301:*

While different transfer functions to derive soil moisture from moderated detector signals have been introduced in the last 15 years (Desilets et al., 2010; Franz et al., 2013; Köhli et al., 2021), a transfer function for the bare detector is currently lacking, largely because of the decreased response to soil moisture changes and because the higher complexity and variability of the bare detector response to changes in soil moisture hampers the development of a generalised transfer function. However, mathematically characterising the response of bare detector signals to changes in soil moisture is a prerequisite for a future exploration of potential applications of bare detectors for environmental monitoring, e.g. for estimating uncertainties of biomass products from bare detector signals which originate from underlying soil moisture dependencies.

RC: ***Results section: In general, I found several statements to lack a follow-up implications sentence to help the general reader understand the contribution of this paper. The manuscript appears to have been written primarily for CRNS detector specialists. Even hydrologists, agricultural scientists, and many non-specialist CRNS users may struggle to follow this manuscript.***

AC: *The reviewer raises a good point here and we will now add statements on the practical implications of specific findings in the results and discussion chapters (see also responses to reviewer #1)*

RC: ***Figure 7, right-column panels: It seems that the region where there is large variability in the signal, between approximately 1 and 10 BWE, is also where fewer simulated cases were carried out in the study. Would it improve the results to simulate this range with more points?***

AC: *We fully agree that our study shows that future and more detailed simulation-based assessments of bare detector intensities are necessary, especially in this range of biomass amounts. Such future study could then also include another dedicated simulation experiment on how simulation results differ between site-specific spatial distributions and vegetation characteristics and the strongly simplified uniform plant gas as suggested in a previous comment. More data points in this region would certainly be interesting but remain outside the scope of this manuscript which is intended to give a broad and generalised overview based on the more than 400 simulation scenarios conducted which cover a wide range of environmental conditions.*

RC: ***L398–413: There is no discussion about how the plant 'gas layer' simplification could have driven these differences against empirical estimates. Could the authors discuss this?***

AC: *See author response to the reviewer's previous comment on the use of plant gases in the neutron transport model.*

RC: ***L433–435: How could uncertainty in the non-linear equation hinder this improvement? The non-linear equation adds significant complexity compared with the linear approach developed by Baatz. It is not clear to me that this added complexity significantly changes the response to BWE sufficiently to justify abandoning the linear approach. This needs to be further investigated. Are the data points in Figure 8b significantly different from those in Figures 8c or 8d?***

AC: *We have carefully reviewed our text to ensure that we do not appear to suggest to abandon the linear approach developed by Baatz et al. (2015), as this is not what we intended to convey. What we want to convey is that the linear approach should use a different* β *than the original value of 0.005 proposed by Baatz et al. (2015). This is shown in Fig. 8c where the linear approach after Baatz et al. (2015) using Eq. 5 is implemented with the new value of* β *instead of the original value of 0.005. This new adjusted value of 0.013 was derived from the simulations conducted in this study and is in line with empirical studies largely showing* β*-values in a similar range (e.g., Jakobi et al., 2018, 2022; Morris et al., 2024).*

Fig. 8d shows the results when the modified UTS (Eq. 6) is used which is indeed non-linear. We've developed this approach since the simulation results suggested a non-linearity in the neutron-biomass relationship as well as an influence of soil moisture on this relationship. Fig. 8d highlights that this approach can work similarly well as the linear approach (Eq. 5) once the adjusted β *of 0.013 is included in the original approach. Since we haven't tested and evaluated the performance of Eq. 6 against field data, we cannot recommend this equation for immediate and broad application. Thus, in the manuscript, we only illustrated the potential of this new approach while recommending that it is tested in future studies, which we believe is a justified consideration.*

Following the reviewer's comment, we double checked whether the $> 60\%$ *reduction in RMSE between the data points in Fig. 8b and 8c/8d, which is accompanied by an increase in R2 from 0.89 to 0.99, leads to a significant difference. We have now performed a paired Wilcoxon rank sum test between the absolute errors of simulated and predicted data points shown in Fig. 8b and 8c, and we can confirm that the mean absolute error in Fig. 8c and 8d is significantly lower. The mean absolute difference between simulated and predicted values using the UTS with the original approach after Baatz (Eq. 5,* β *= 0.005) is 0.103 (Fig. 8b) while it is 0.029 for the adjusted Baatz approach (Eq. 5,* β *= 0.013). The difference is significant with a p-value of* $2.325 \cdot 10^{-15}$*. Similarly, the mean absolute difference between simulated and predicted values using the UTS with the original approach after Baatz (Eq. 5,* β *= 0.005) is 0.103 (Fig. 8b) while it is also 0.029 for modified UTS (Eq. 6). This difference is also highly significant with a p-value of* $2.915 \cdot 10^{-15}$*. We have now added this interesting detail to the caption of Fig. 8 which now reads as follows:*

> Comparison between the different approaches to predict simulated neutron intensities from the scenarios with biomass water equivalents (BWE) in Tab. **??** using the UTS in its original form without accounting for BWE, with accounting for BWE using the inverted BWE correction after Baatz et al. (2015), the adjusted Baatz approach ($\beta = 0.013$) and the modification of the UTS which are both based on the neutron transport simulations of this study. At the significance level of $\alpha = 5\%$, the mean absolute difference between simulated and predicted values of both adjusted methods (Fig. 8c and 8d) is significantly lower than the original approach shown in Fig. 8b.

RC: ***L480–482: Knowing that the neutron counts observed by the sensor follow a Poisson distribution, with mean = N and standard deviation = sqrt(N), and generally assuming that a considerable number of neutrons will have interacted with the soil moisture 'source', this would reduce the overall 'leftover count/signal' to be attributed to other processes. Lower effective counts mean higher overall uncertainty. Yet here, and in similar papers trying to assess the nature of CRNS measurements of other quantities simultaneously, the manuscript does not adequately account for the uncertainty propagated to these other 'observed' processes if the soil moisture signal is removed from the overall signal. The authors should address this.***

AC: *The specific lines the reviewer is referring to in this comment concern the neutron ratio, a variable which has been used in several empirical studies to derive biomass and snow information by utilizing the ratio of the signal of the moderated and bare detector. Some of these empirical studies showed promising results but others did not. Our analyses give a potential reason why past studies found contrasting results when using the neutron ratio, which is that the neutron ratio is still heavily affected by soil moisture changes. The conclusions we draw are a) care needs to be taken when utilizing the neutron ratio and b) soil moisture dependence needs to considered when further research on the neutron ratio and its potential is conducted. The original manuscript already states this from line 496:*

> The dependence of N_r on soil moisture, BWE and snow water equivalents (or water layers on top of the soil) reduces the practical applicability of N_r for estimating BWE or snow water equivalents. Nevertheless, the knowledge of these dependencies gained from simulations presented in this study may facilitate an improved analysis of the potential and limitations of N_r for future CRNS studies.

We are neither showing nor recommending to disentangle the neutron signal of either the bare or the moderated detector (or the neutron ratio) in order to simultaneously derive biomass and soil moisture from one signal at the same time. In contrast, we show that this is unlikely to be possible and that if accurate soil moisture measurements are desired, biomass information is required and needs to be corrected for. Vice versa, we show that if biomass information is the target variable, soil moisture needs to be known. The bare detector signal can be more responsive to biomass than soil moisture changes under some circumstances as shown in Fig. 7, however, the underlying effect of soil moisture remains and needs to be considered. Since we are not attempting to disentangle these signals, propagating uncertainties of measuring different quantities with the same signal is beyond the scope of this study. Nonetheless, if some future study attempts to investigate the potential of disentangling a single neutron signal (e.g., from the moderated detector) into different quantities, we agree that in such future study, an uncertainty analysis would need to be performed.

RC: ***Conclusions: This section is heavily written for readers with high expertise in CRNS and perhaps particle transport physics. It seems to target a very specialised and niche audience. If I am simply a typical***

CRNS user, it is unclear what I gain from this study. For example: should I replace my CRS1000/B with a CRS1000? What happens if I only have the moderated tube? Which conditions are more or less recommended for deploying both tubes from a CRS1000? How do I simultaneously utilise the signal from both moderated and bare tubes if their footprints are different?

AC: *Following the reviewer comment, we will reorganize the conclusions so that they are more clearly presented to the readers. In general: 1) The original version of the manuscript does not include a statement suggesting to prefer one detector model over another and this was kept as is. Such considerations are, in our view, beyond the scope of the manuscript. 2) Almost all the presented simulation results consider the use of solitary moderated and bare tubes (single tube detectors) to give more transferable results. Only the design of the detector tubes themselves follow the CRS1000 model (size, detector gas, etc.) and the CRS1000 tube serves as one example of neutron detectors. Using a solitary detector tube from a different model such as the CRS1000/B would only lead to minor differences and hence, taking the CRS1000 tube design as an example, the derived findings remain transferable to other detector tube designs. Also, only Fig. 3 shows in one example what would happen if a bare detector is installed close to the HDPE shielding of a moderated detector, which is done to provide a short but insightful example. 3) While not addressed in details to maintain conciseness, we will now add a statement on the distance in which a bare and moderated tube should be installed to reduce the effect from one on the other. 4) The footprints of moderated and bare detectors are indeed different, which would need to be considered when utilizing both signals. For example, if one would want to use the neutron ratio (ratio of bare and moderated detector signal) the footprint of the ratio would be some average of the two footprints. This indeed further complicates such applications.*

Despite these considerations, we agree with the reviewer that more and clearer practical implications are necessary in the conclusion section. Therefore, we have added a table to the conclusion chapter which lists the specific findings of our manuscript that have direct implications for the practical use and application of the CRNS technique (see below). We believe that this has made the manuscript and its conclusion section more on point and more relevant to CRNS experts and developers as well as general CRNS practitioners.

We will modify the conclusion chapter in the following way (The abstract will be modified accordingly):

~~This study provides the first generalised comparison of the response of bare and moderated low-energy neutron detector signals to changes in soil moisture under a broad range of environmental conditions. Thermal neutrons observed with bare (unmoderated) neutron detectors respond differently to epithermal neutrons observed with moderated neutron detectors. Furthermore, the simulated response of both, bare and moderated neutron detectors, differs between neutron transport simulations being evaluated with defined energy thresholds (energy windows) or detector response functions which mimic the sensitivity of real neutron detectors. This study showed the benefit of using detector response functions for enhancing the comparability between simulation results and observations. However, it should be noted that the main results of this study were derived for solitary bare and moderated detectors, while many operational CRNS stations use co-located detector setups. As shown in Section 3.1, co-location with HDPE shielding can shift the bare detector response function and increase absolute count rates which means that the quantitative transfer of the presented results to specific co-located detector configurations may require additional site- and setup-specific assessments.~~

This study provides the first generalised comparison of the complex response of bare and moderated low-energy neutron detector signals to changes in soil moisture under a broad range of environmental conditions. Based on our results, we conclude that a paradigm shift is necessary on how we interpret these two types of neutron signals. Moderated and bare detector signals can no longer be treated as being independent from single environmental variables nor be used for independently estimating soil moisture, biomass or snow water equivalents since we revealed that neutron signals respond to different hydrogen pools in a complex, sometimes counter-intuitive manner.
Neutrons observed with bare (unmoderated) detectors respond differently to the environment compared to neutrons observed with moderated detectors. Furthermore, the simulated response of both, bare and moderated detectors, is sensitive to the choice of energy thresholds (energy windows) and detector response function used in the model to mimic the sensitivity of real neutron detectors. This study showed the benefit of using detector response functions for enhancing the comparability between simulation results and observations. However, it should be noted that the main results of this study were derived for solitary bare and moderated detectors, while many operational CRNS stations use co-located detector setups. As shown in Section 3.1, co-location with HDPE shielding can shift the bare detector response function and increase absolute count rates which means that the quantitative transfer of the presented results to specific co-located detector configurations may require additional site- and setup-specific assessments.

and:

This leads to the conclusion that estimating changes and monitoring BWE or snow water equivalents with bare detectors is most effective within the thermalisation radius. Beyond such distance, changes in these environmental variables will likely have a minor and different effect on bare detector count rates which may well prevent their estimation. It should be noted that these conclusions are not limited to neutron signals observed with bare detectors which also contain fractions of higher-energy neutrons, but affects detected thermal neutrons in general.

Despite using simplified simulation setups, the results in this study are generally in line with empirical findings from observation data and support the theoretical concepts derived in previous studies concerning the response and potential applications of bare and moderated detectors. While the limited comparability of these generalised simulations with complex and heterogeneous real-world conditions is apparent, this study is of value for better understanding and interpreting observed neutron signals at specific real-world observation sites with key implications for practical applications being summarised in Tab. 4. Finally, the presented results and findings may serve as a starting point for the design of site-specific simulation studies as well as generalised but more detailed neutron transport simulations to investigate neutron signal responses to changes in biomass and snow water equivalents, their geometry, and spatio-temporal distribution around the neutron detector.

The new table which is added to the conclusion chapter as Tab. 4:

Table 1: Summary of key findings and recommendations.

Topic	**Detector type**	**Recommendation**
Detector co-location	moderated, bare	A separation of $\geq 30\,\mathrm{cm}$ between bare and moderated tubes is sufficient to reduce co-location effects on absolute intensities and soil moisture response.
Influence of soil chemistry	moderated, bare	Even adding a thin HDPE moderator to a bare detector strongly reduces its dependence on soil chemistry by shifting its sensitivity from thermal towards higher energies.
Interaction of biomass and soil moisture	moderated, bare	Biomass alters the soil moisture response of both detectors; vegetation cover must therefore be accounted for when estimating snow water equivalents with CRNS.
Biomass correction	moderated	The linear correction by Baatz et al. (2015) is applicable with a modified coefficient of $\beta = 0.013\,\mathrm{mm}^{-1}$ of biomass water equivalent, confirming findings from e.g. Morris et al. (2024).
Sensitivity to soil moisture	bare	Bare detector sensitivity to soil moisture is smaller than that of the moderated detector (Eq. (1)-(2)) but must still be considered when deriving biomass or snow from bare signals.
Biomass & snow	bare	The effects of biomass and snow on neutrons detected by bare and moderated detectors can be opposite and may even exceed the soil moisture response of bare detectors. Additional dependency on soil moisture should be accounted for.
Footprint & depth	bare	Bare detectors have a smaller horizontal footprint but greater depth sensitivity. Influences of biomass, snow, and soil chemistry originate within $\approx 50\,\mathrm{m}$ and this zone warrants close attention in bare detector applications.
Neutron ratio N_r	ratio	The complex soil moisture dependence of N_r must be taken into account when the ratio is used for biomass or snow estimation

References

Andreasen, M., Jensen, K. H., Bogena, H., Desilets, D., Zreda, M., and Looms, M. C. (2020). Cosmic ray neutron soil moisture estimation using physically based site-specific conversion functions. *Water Resources Research*, 56(11).

Andreasen, M., Jensen, K. H., Desilets, D., Zreda, M., Bogena, H. R., and Looms, M. C. (2017). Cosmic-ray neutron transport at a forest field site: the sensitivity to various environmental conditions with focus on biomass and canopy interception. *Hydrology and Earth System Sciences*, 21(4):1875–1894.

Andreasen, M., Jensen, K. H., Zreda, M., Desilets, D., Bogena, H., and Looms, M. C. (2016). Modeling cosmic ray neutron field measurements. *Water Resources Research*, 52(8):6451–6471.

Andreasen, M., Kragh, S. J., Meyer, R., Jensen, K. H., and Looms, M. C. (2023). Mapping spatiotemporal soil moisture in highly heterogeneous agricultural landscapes using mobile dual-spectra cosmic-ray neutron sensing. *Vadose Zone Journal*.

Baatz, R., Bogena, H. R., Franssen, H.-J. H., Huisman, J. A., Montzka, C., and Vereecken, H. (2015). An empirical vegetation correction for soil water content quantification using cosmic ray probes. *Water Resources Research*, 51(4):2030–2046.

Brall, T., Mares, V., Bütikofer, R., and Rühm, W. (2021). Assessment of neutrons from secondary cosmic rays at mountain altitudes – geant4 simulations of environmental parameters including soil moisture and snow cover. *The Cryosphere*, 15(10):4769–4780.

Brogi, C., Nieberding, F., Scheiffele, L., Daccache, A., Schrön, M., and Bogena, H. R. (2026). Irrigation monitoring with cosmic-ray neutron sensors: Unraveling field experiments with neutron transport simulations. *Water Resources Research*, 62(3).

Desilets, D., Zreda, M., and Ferré, T. P. A. (2010). Nature's neutron probe: Land surface hydrology at an elusive scale with cosmic rays. *Water Resources Research*, 46(11).

Franz, T. E., Zreda, M., Rosolem, R., and Ferre, T. P. A. (2013). A universal calibration function for determination of soil moisture with cosmic-ray neutrons. *Hydrology and Earth System Sciences*, 17(2):453–460.

Jakobi, J., Huisman, J. A., Fuchs, H., Vereecken, H., and Bogena, H. R. (2022). Potential of thermal neutrons to correct cosmic-ray neutron soil moisture content measurements for dynamic biomass effects. *Water Resources Research*, 58(8).

Jakobi, J., Huisman, J. A., Vereecken, H., Diekkrüger, B., and Bogena, H. R. (2018). Cosmic Ray Neutron Sensing for simultaneous soil water content and biomass quantification in drought conditions. *Water Resources Research*, 54(10):7383–7402.

Köhli, M., Schrön, M., and Schmidt, U. (2018). Response functions for detectors in Cosmic Ray Neutron Sensing. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 902:184–189.

Köhli, M., Weimar, J., Schrön, M., Baatz, R., and Schmidt, U. (2021). Soil moisture and air humidity dependence of the above-ground cosmic-ray neutron intensity. *Frontiers in Water*, 2.

Morris, T. C., Franz, T. E., Becker, S. M., and Suyker, A. E. (2024). Effect of biomass water dynamics in cosmic-ray neutron sensor observations: A long-term analysis of maize–soybean rotation in nebraska. *Sensors*, 24(13):4094.

Rasche, D., Blume, T., and Güntner, A. (2024). Depth-extrapolation of field-scale soil moisture time series derived with Cosmic-Ray Neutron Sensing using the SMAR model. *SOIL (submitted)*.

Schrön, M., Köhli, M., and Zacharias, S. (2023). Signal contribution of distant areas to cosmic-ray neutron sensors – implications for footprint and sensitivity. *Hydrology and Earth System Sciences*, 27(3):723–738.

Weimar, J. (2022). *Advances in Cosmic-Ray Neutron Sensing by Monte Carlo simulations and neutron detector development*. Phd thesis, Heidelberg University. Thesis.

Weimar, J., Köhli, M., Budach, C., and Schmidt, U. (2020). Large-scale boron-lined neutron detection systems as a 3He alternative for Cosmic Ray Neutron Sensing. *Frontiers in Water*, 2:16.