Response to reviewers

Anonymous Reviewer n.1

This study investigates the feasibility of soil moisture (sm) detection with cosmic-ray neutron sensors (CRNS) in the center of a squared irrigated field. The authors investigate the sm-neutron relationship and the footprint radius for various scenarios of detector shielding material, field sizes, and combinations of soil moisture conditions in the inner and the outer areas. They conclude that different thickness of HDPE material influences the footprint radius and the detector sensitivity, with HDPE 25mm + Gadolinium leading to the highest sensitivity to soil moisture changes and to the largest footprint radius. Moreover, they found that soil moisture from the outer fields substantially influences the CRNS sensitivity to the irrigated field, especially for small fields.

The study is very well written and highly relevant, being the first of its kind to study various detector thicknesses and gadolinium shields with regards to the neutron-soil moisture relationship. This will be a very important information for CRNS users and suppliers in order to significantly improve the sensor performance. Furthermore, the investigation of irrigation support is also very relevant for current and future CRNS applications. However, this study is only theoretical and limited to a very specific geometry (CRNS within a squared irrigated field). Nevertheless, it is a good step forward.

Major concerns with this study should be clarified before publication of this manuscript, particularly regarding the model assumptions, the consistency of the argumentation, and the integrity and applicability of the conclusions. Please address also the minor comments and the specific comments below.

We sincerely thank the reviewer for the appreciation of our work and for the time spent to produce a thorough and useful review. We have carefully considered all comments and observations. We provide here replies to each point with indications on the changes that were included in the new version of the manuscript or motivations for not applying further edits when this was not deemed necessary.

We hope that our work can address all the points raised by the reviewer and that this new version of the manuscript can be accepted for publication in Geoscientific Instrumentation, Methods and Data Systems.

Major concerns:

1. The authors seem to change the water content of the irrigated soil in the whole soil column (up to 160 cm depth). However, it is highly unrealistic to assume vertically homogenous wetting of the soil due to surface irrigation! Hence, I wonder how useful the results of this study are for practical applications. In the real world, surface irrigation adds moisture only to the first few centimeters of the soil, or decimeters, depending on typical depth of the roots and the hoses. This would leave a large part of the vertical footprint dry, such that the results obtained in this study might significanlty overestimate the actual sensitivity of CRNS to irrigated soil.

We thank the reviewer for this observation since, although known to the authors, this limitation was only briefly mentioned in section "4 Limitations and outlook". We agree that the wetting due to precipitation or irrigation is not homogeneous with depth. The wetting caused by irrigation would most probably start at the soil surface and reach the deeper soils within a certain amount of time depending on several variables (see below). Typically, we can expect deeper soils to have a higher SM compared to the soil surface when irrigation starts. Then, SM would increase in the soil column and peak at the top of the profile. Which would be followed by a redistribution of SM that can take up to several days/weeks.

We assumed a homogeneous SM distribution for our study because we considered that SM dynamics in soils are a rather complicated subject. The SM distribution in the soil column before, during, and after an irrigation event can depend on (among other factors):

- *Soil texture, porosity, bulk density, and presence of biopores.*
- *Previous SM conditions within the soil profile and depth of the water table.*
- *Root depth and distribution, vegetation type, and root water uptake.*
- *Agricultural management (ploughing depth and irrigation type).*

Thus, to define how the SM varies in depth in an agricultural area, it would be necessary to consider at least soil depth and texture, water table depth, ploughing depth, rooting depth, and root distribution.

Another aspect to consider is the variation of the depth of investigation of a CRNS with SM variations as well as with increasing distance from the instrument (larger below the instrument and relatively shallower at distance). Thus, the overestimation of the contribution of irrigation to the signal would be present mostly in the vicinity of the instrument. Also, during an irrigation event, the wetting of the upper soil would reduce the depth of investigation of the CRNS and thus diminish the relative contribution of deeper soils to the signal. We believe that these two factors could reduce, although not completely remove, the overestimation effect mentioned by the reviewer.

Overall, the study of the influence of vertical heterogeneity would add a further dimension to the problem that is investigated in this study and would significantly increase its complexity. As it is not feasible to include all possible scenarios into the simulation of a CRNS framework, this theoretical study presents one particular solution to one subset of problems, which we believe is already of great interest. Further research is necessary (and currently carried out by some research groups) to integrate vertical heterogeneity based, for example, on hydrological models. But this again is, in our opinion, outside the scope of this study.

This said, the observations of the reviewer are valid, and we agree that we did not discuss this specific limitation in a sufficient way in the previous version of the manuscript. In the new version of the manuscript, we will point at the limitation of a homogeneous SM distribution and at the possible overestimation effect in section "4 Limitations and outlook"

2. The authors conclude that 25 mm HDPE+Gd is the best shielding variant for CRNS detectors (L359) without studying other HDPE thicknesses together with Gd. It is indeed interesting to see gadolinium used for the first time in a sophisticated analysis of detector sensitivity to footprint and soil moisture changes. However, the authors used Gd only in

the 25 mm HDPE setup. In order to distinguish and better understand the effects of HDPE and Gd on the variables of interest, and to find the best performing detector design, it would be necessary to simulate Gd shielding also for different HDPE thickness.

We agree with the reviewer that investigating the effects of a Gadolinium based shielding on different moderator thicknesses would be interesting, at least in general terms. However, to our knowledge, such shielding is currently commercialized only with 25 mm HDPE moderators. Additionally, as shown in the following Figure 1*, a Gadolinium based shielding prevents the detection of approximately 90% of thermal neutrons. This effect differs from a HDPE moderator since the sensitivity is not shifted towards higher energies but rather cut in the thermal range. Thus, it can be expected that a 25 mm HDPE moderator with Gadolinium shielding would generally detect less neutrons than a 25 mm HDPE moderator without Gadolinium shielding.*

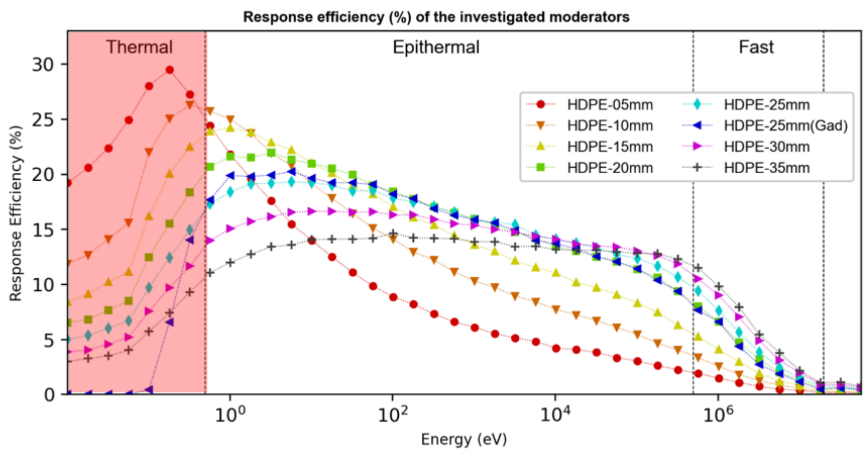

Figure 1: Response functions with the thermal neutron energy range marked with a red area.

We could then expect that, by adding Gadolinium shielding to a thin moderator that has high sensitivity to thermal neutrons and low sensitivity to epithermal and fast neutrons (e.g., 5 mm HDPE), the number of detected neutrons would decrease considerably (partial removal of the red shaded area in Figure 1*). In thicker moderators, the work of Weimar et al. (2020) shows that for moderator thicknesses of 20, 22.5, 25, and 27.5 mm HDPE there are only small differences when the Gadolinium shielding is added. The authors concluded that a 22.5 m HDPE moderator with a Gadolinium thermal shielding provided the best overall performance but with only a marginal difference compared to a 25 mm HDPE moderator (as proposed by Desilets et al. (2010)) with Gadolinium shielding. It is true that thinner moderators yield slightly better signal dynamics at the cost of a small reduction of the count rate. However, such differences are marginal and, in our opinion, not significant when put in the framework on a study such as the one proposed here.*

In the end, to our knowledge, a 25 mm HDPE moderator with Gadolinium shielding is the common choice because of a) recommendations from, for example, Desilets et al. (2010) confirmed by Weimar et al. (2020) and b) production costs. Previous research has shown the influence of different moderator thicknesses, at least in a range of moderators that is relevant. We thus believe that further investigations on this topic would go out of the scope of the study and not add novel information for the reader.

Nonetheless, we carefully considered the comment of the reviewer, and we will elaborate on the choice of a 25 mm HDPE moderator with Gadolinium shielding in the material and methods section. In addition, we will better specify in the conclusion of the manuscript that Gadolinium shield variant was only studied for a 25 mm HDPE moderator as this was not often specified in the previous version of the manuscript.

3. The authors conclude that outer sm is an important factor for irrigation monitoring with CRNS by considering only one shielding option that provides the largest footprint. In section 3.4 and 3.5 the impact for inner sm changes on the neutron detector sensitivity is investigated, but only for 25 mm HDPE-Gd (mentioned in 3.4, not mentioned in 3.5). In the same study, the authors find that different shielding options have different footprint radii. So, I would expect that shielding options with lower footprint radii would lead to less impact of the outer sm. Please elaborate on this and whether different shielding options could be recommended for smaller fields than for larger fields to reduce the influence. This might change your conclusion. Also, use this opportunity to join the two otherwise separate parts of "shielding/footprint analysis" and "sm/area analysis", in order to demonstrate that a combination of those two studies in a single paper could actually lead to a greater benefit.

In the new version of the manuscript, it will be clearly stated in section 3.5 that the analysis is performed for a 25 mm HDPE moderator with Gadolinium Shielding. This was not the case in the previous version of the manuscript, and we thank the reviewer for highlighting it.

It is true that the Gadolinium shielding provided a footprint that is larger than that of the other moderators. However, it should be noted that the R86 of the 25 mm HDPE moderator with Gadolinium shielding was approximately 5 to 15 m larger than that of the other moderators (with R86 values between ~120 and ~270 m, see Fig.4 of the manuscript). Here, we noted that we did not clearly state in the previous version of the manuscript that such difference in R86 dimension is rather small and we will mention it in the new version.

Additionally, in Fig.6 of the manuscript, we show how the 25 mm HDPE with Gadolinium shielding offers a higher sensitivity compared to the other moderators. Thus, although a different moderator with a smaller R86 (e.g., 5 mm HDPE) could possibly lead to a reduced influence of the SM outside the investigated field, the moderator with the highest sensitivity (25 mm HDPE with Gadolinium shielding) would still be preferrable. Therefore, we decided to focus the second part of the results on such moderator only. In sections 3.4 and 3.5, we could have included results from all eight moderators, and we initially tried to pursue such path, but we soon realized that this resulted in an overwhelming and confusing amount of information with no real benefit for the overall message of the study.

We nonetheless think that the reviewer is raising a fair point and decided to provide additional figures in our reply to the comments. The following Figure 2 *was produced starting from Fig.9 of the original manuscript (Part-i). To this, we added similar figures obtained with data from a 25 mm HDPE moderator (Part-ii) and 5 mm HDPE moderator (Part-iii).*

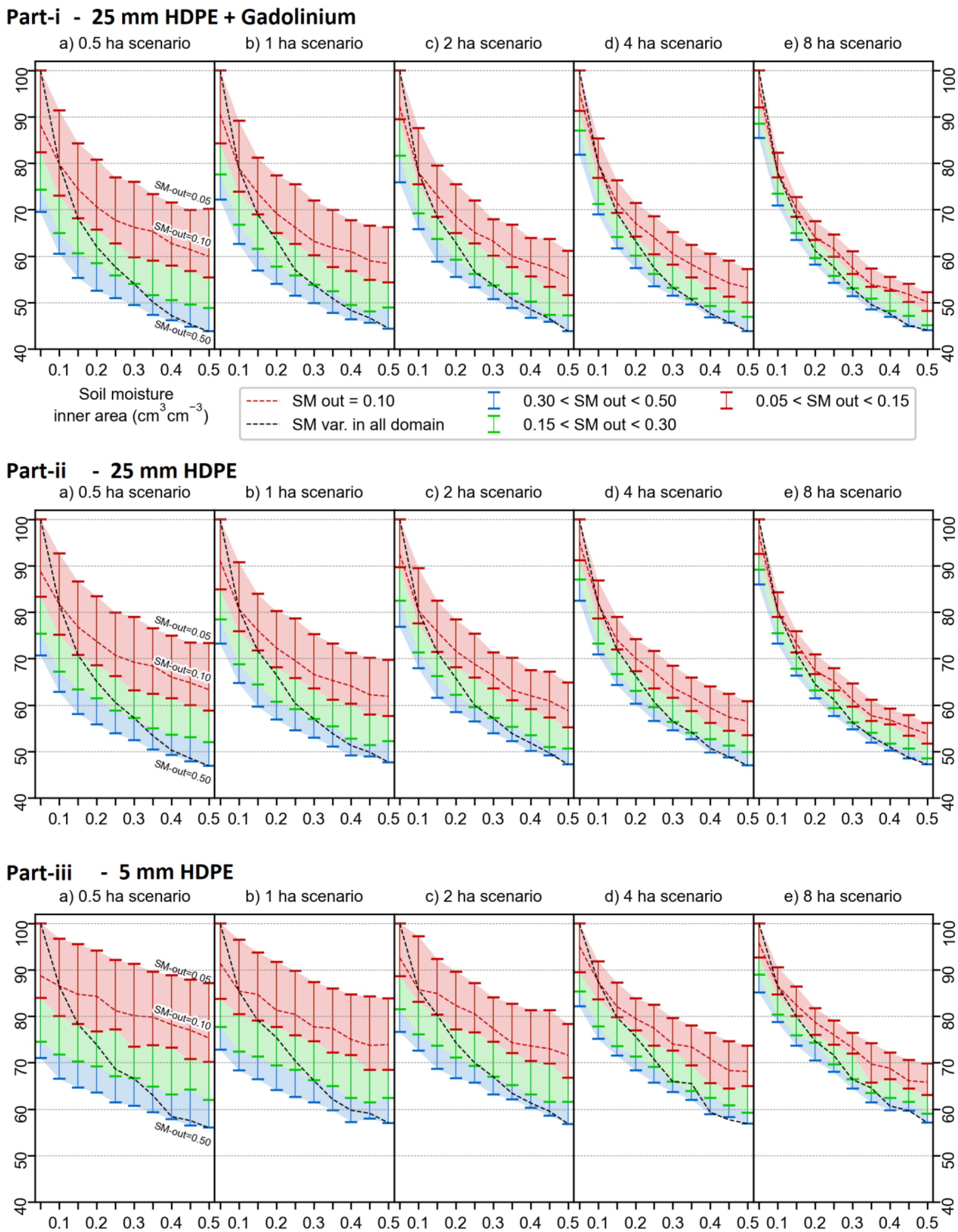

Figure 2: Part-i is a copy of Fig.9 of the manuscript (referred to a 25 mm HDPE moderator with Gadolinium shielding. Part-ii and Part-iii are figures similar to Fig.9 of the manuscript built with data from a 25 mm HDPE and 5 mm HDPE moderators respectively.

As visible in Figure 2*, the use of a 25 mm HDPE moderator without Gadolinium shielding, which has an R86 that is 5-10 m smaller than the version with Gadolinium, does not show apparent reductions of the influence of the SM outside the irrigated field. However, there is a general reduction in sensitivity, as can also be seen in Fig. 6 of the manuscript. Furthermore, a 5 mm HDPE moderator, although having a footprint that is sometimes 20 m smaller than that of the 25 mm HDPE with Gadolinium variant, does not show a reduction of the effect of the outside SM. Such effect of the outside SM sometimes appears higher than in the Gadolinium case, but the most important difference is the generally lower sensitivity of the moderator without gadolinium.*

We believe that this could be connected to the fact that the detected neutron intensity of a CRNS peaks nearby the instrument and decreases with distance. Thus, a small variation in the R86 alone might not lead to meaningful differences between moderators and the instrument with higher sensitivity to SM changes should be preferred. We now realize that this concept was not fully described throughout the manuscript. It will be however better introduced in the new version of the manuscript. Also, we think that the results of Figure 2 *would be a meaningful addition to the manuscript and we will produce a new appendix to show such results.*

4. The authors suggest that sm measurements outside the irrigated area are needed to properly estimate sm inside with CRNS. But in this case, what is the added value of CRNS compared to using the suggested number of additional sensors and putting them inside from the start?

We carefully considered the comment of the reviewer and we realized that we did not offer enough information in the previous version of the manuscript. What we could suggest is the installation of a SM sensor outside the irrigated field or, alternatively, the use of a portable device. This scenario of CRNS plus a single device is different compared to the use of a sensor network within the irrigated field as a) only the CRNS would be installed in the field, b) portable or point-scale SM measurement devices are relatively inexpensive, and c) measurements of the SM outside the irrigated field could provide correction for multiple CRNS installed in fields that are located within a large area. Following the comment of the reviewer, the new version of the manuscript will mention such considerations in section 3.5, in section 4, and in the conclusions.

5. The study is limited to one specific case of field geometry: a CRNS detector in the center of a square-shaped irrigated field surrounded by a homogeneous field on all sides. Although simulations of various shielding types and square sizes are scientifically interesting, the transferability of the results to practical field geometries might be very limited. I would recommend to better communicate this limitation, at first by improving Figure 1 with a detector symbol in the center and scales in meters. Second, by providing real-world examples where this scenario could be applicable (I would rather think that radial field geometries would have been a better choice, e.g. for pivot irrigation). Third, by discussing potential deviations and uncertainties of the results if the sensor location would not be ideally centric, or if the field shape is a circle instead of a square. This would allow users to get a better idea whether the results would be still applicable to a certain degree, or whether completely new simulations would be necessary for every single deviation from the presented ideal case.

We will include the suggested changes in Fig.1 (see following Figure 3*) and, as described in detail below, we will add considerations on the selected shape of the irrigated field in section 2.4 "Simulations setup" and in section 4 "Limitations and outlook".*

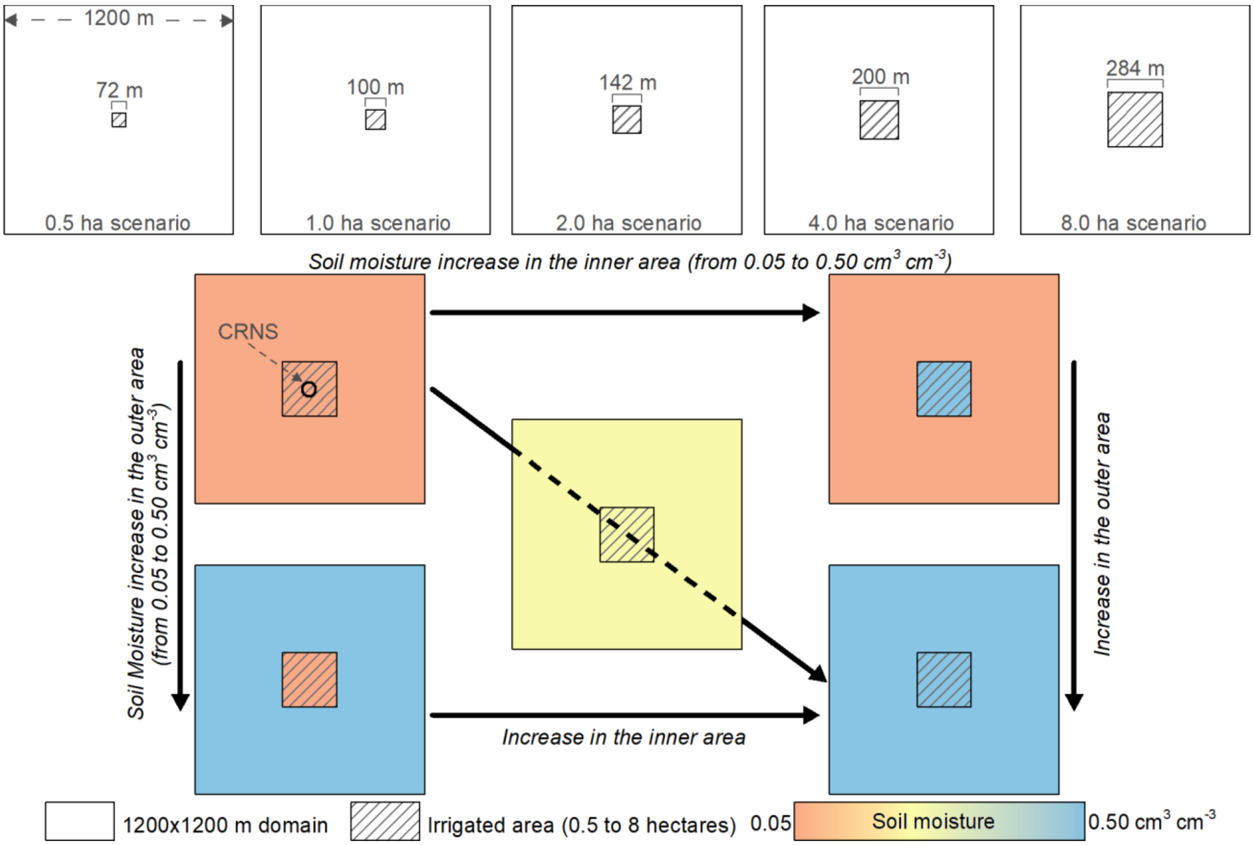

Figure 3: alternative figure that substitutes Fig.1 in the new version of the manuscript.

Reviewer n.2 also points at the shape of the irrigated field. We believe that a circular pivot irrigation field would have not been the best choice for this study. This because circular centre-pivot irrigated fields are very large and typically 400 m in radius (although 500 m are also common and larger exist). Small centre-pivot irrigated fields are not common. The large dimension of a centre-pivot irrigated field means that most of the neutrons detected by a CRNS placed in the middle of such large field (if not all detected neutrons) originate within the irrigated field. Thus, the irrigation that the CRNS would sense is comparable to a rain event, and we think this would not be as interesting as a smaller field of a few ha where the outside area plays an actual role.

Relatively small fields as those investigated in this study are most often rectangular and not circular. It is true that the rectangular shape can vary greatly and elongated rectangular shapes are common, but the inclusion of elongated shapes in this study would lead to a much more complex manuscript and would go beyond the scope of the manuscript. Since the manuscript is already long and complex in the current form, we believe that the reader would have strong difficulties in navigating through additional shapes of the irrigated area. Nonetheless, it could be expected that such elongated shapes would be more challenging for the CRNS compared to a *squared shape. We agree with the reviewer that the selection of the shape is an important topic, and we will include additional considerations in section 4 "Limitations and outlook". We also think that future research, especially in real-case scenarios, should investigate these aspects and we will mention this in the revised manuscript.*

Furthermore, we tested the simulation of a circular and rectangular (142x70 m) irrigated fields of 1 ha area and compare the results with those of a squared 1 ha irrigated field. The results are shown in Figure 4 *in a similar way as they are shown in Fig.8 of the manuscript. In general, differences between the squared, circular, and rectangular shaper are rather small, at least in this simulation setup. Compared to the squared shape, there might be sometimes a small tendency towards higher relative changes in detected neutrons for a circular shape and a tendency towards lower relative changes when a rectangular shape is used. However, results are too similar to draw meaningful conclusions. A clearer picture could possibly be obtained if these two additional scenarios are simulated for the entire soil moisture range of 0.05 to 0.50 cm3 cm-3 and for the five investigated areas of the irrigated field. However, this would increase the number of simulations by +200%, which is not feasible due to time and computational constraints and goes beyond the scope of the manuscript. Thus, we decided not to add simulations of different field shapes to the manuscript.*

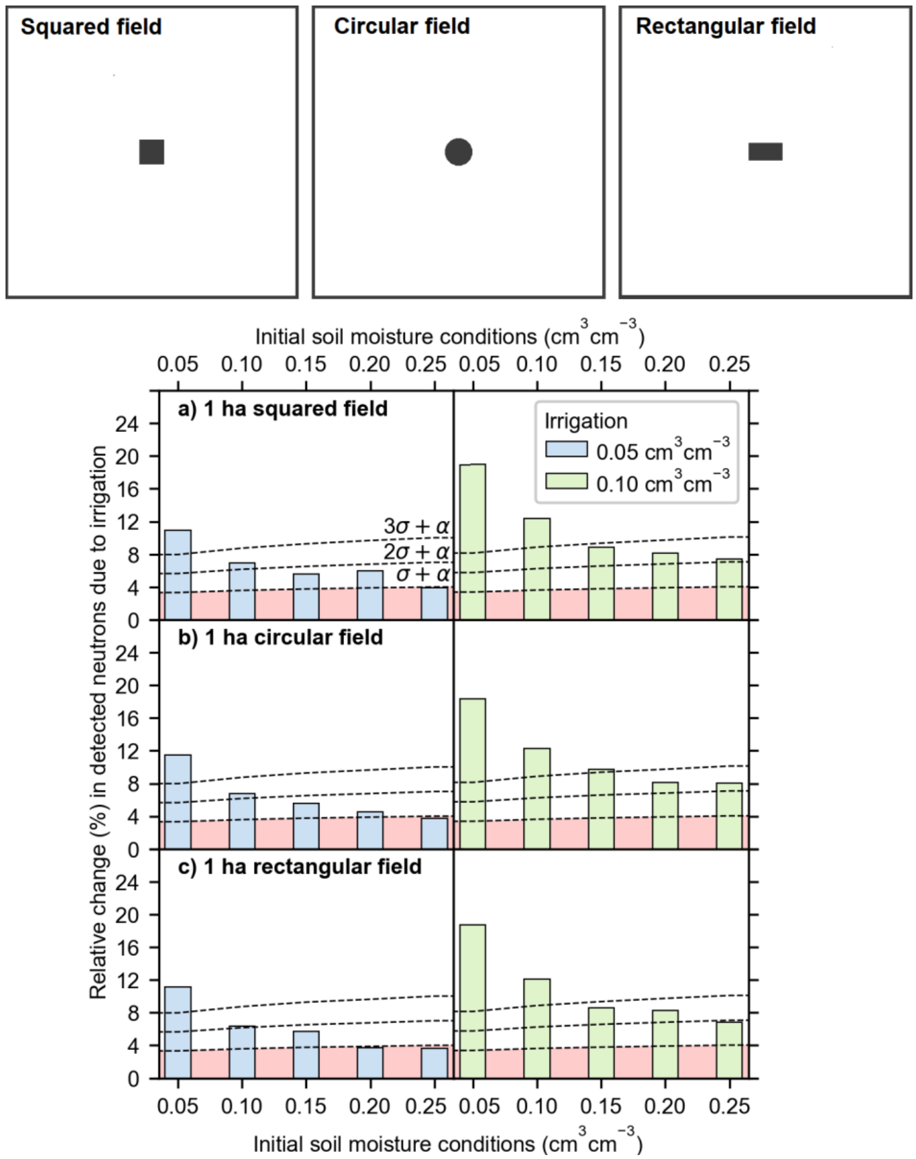

Figure 4: CRNS chance of detecting irrigation events of 0.05 and 0.10 cm3 cm-3 (blue and green bars respectively) in a) squared, b) circular, and c) rectangular irrigated field of 1 ha. The bars show the relative change in detected neutrons induced by the irrigation event while the dashed lines show the prescribed detection thresholds. The red area below the σ+α threshold indicates uncertain detection.

Regarding the positioning of the CRNS, we think that the assumption that the instrument is positioned in the centre of an irrigated field is a common practice. CRNS are sometimes not positioned in the centre of a field, for example when multiple CRNS are placed in different areas of a single field. But we believe that the discussion and investigation of device placement that are not in the centre of a given field (or its vicinities) as well as the placement of multiple devices goes beyond the scope of this study. Regarding the need for new simulations prior to CRNS installation, we suggest in the original version of the manuscript (section 4 "Limitations and outlook" and conclusions) that neutron transport simulations could be useful to assess costs and benefits before CRNS installation as well as to quantify the partitioning of neutron origins in real case scenarios. We thus do not believe that these simulations are currently exhaustive, and we think that we did not suggest their exhaustivity in the manuscript. We will however strengthen the discussion of these *limitations in section "4 Limitations and Outlook" and point at possible future research and studies in this regard.*

Minor comments

1. The authors mention that sm change outside can be larger than sm change from irrigation inside. However, it is not clear in which scenarios it is actually realistic to assume that sm changes "only" outside. Most of the time, precipitation occurs within CRNS footprints rather homogeneously. So the only cases I could image of sm changing outside (and not inside) is that these fields are also irrigated, and with a completely different schedule. You could communicate more openly that this is a special case, and only in this case the sm-outside issue becomes relevant.

We agree with the reviewer, and we understand now that we created some degree of confusion in certain instances. The new version of the manuscript clarifies this aspect at the beginning of paragraph 3.5 where we now mention the irrigation of only the neighbouring fields.

2. The authors seem to assume that only neutrons that originated from the inner area carry its sm signal (L211). However, Köhli et al. 2015 mentioned a few intermediate interactions of neutrons from longer distances with the soil on their way to the detector. In this context, it seems that neutrons from outer regions could carry signals from the inner regions, too. In this case the authors are encouraged to reconsider their assumption.

We now understand that we presented this assumption in a rather simplified way. In the new version of the manuscript, we clarify that the neutrons that originate within the irrigated area carry a large portion of the information of interest. In our opinion, this does not change the general message that a large percentage of detected neutrons that originate outside the irrigated field is a challenge in irrigation monitoring with CRNS.

In the new version of the manuscript, we will extend section 2.6 which will read "Here, it was assumed that the neutrons that originate within the inner irrigated field carry the bulk of the information of interest. Although neutrons that originate outside the irrigated field can have occasional within-field interactions before reaching the CRNS (Köhli et al. 2015), these were considered of secondary importance for the scope of this study". Similarly, section 3.1 will read: "This percentage represents the detected neutrons that originate within an irrigated field and thus carry the bulk of the information of interest in case of irrigation applications".

3. Minimum soil moisture used in this study is 0.05 m^3/m^3, while irrigation might be particularly interesting in extremely arid regions, where sm below 0.05 can exist. Given the very steep neutrons-sm function, there is a potentially significant performance increase of CRNS for dry soils. Can you add ~0.03 m^3/m^3 to your analysis?

We carefully considered the possibility to add 0.03 m^3/m^3 to our simulations. But we finally concluded that this would not add important information or change the message and conclusions of the manuscript. Although it is true that soils can theoretically have a SM content below 0.05 m^3/m^3 (e.g., residual soil moisture), we believe this value is very unlikely in agricultural fields (if not impossible in irrigated fields). Regarding the area that surrounds an irrigated field, we again *believe that a SM of 0.05 m³/m³ is already a rather low value. A lower value could be found in the top 1-2 cm of soil, but then higher SM would be commonly found below such shallow depth. Thus, we believe that a homogeneous value of 0.05% in the soil column is already a sufficiently low SM value for the scope of this study.*

Regarding the results that we could expect by including a SM of 0.03 cm^3 cm^{-3}, (see, for example, Fig.8 of the manuscript) an irrigation event that leads to a final SM of 0.08 cm^3 cm^{-3} (plus 0.05 cm^3 cm^{-3} as done for the other SM cases) would be easily sensed by the CRNS since the SM variation 0.05 to 0.10 cm^3 cm^{-3} is already sensed. Same can be said for a 0.10 cm^3 cm^{-3} SM variation (from 0.03 to 0.13 cm^3 cm^{-3}). At the same time, we do not think that it is necessary to investigate a SM increase from 0.03 cm^3 cm^{-3} to 0.05 cm^3 cm^{-3} as this does not seem relevant in irrigation.

4. Nomograms for the presentation of the results are very hard to read (e.g. Fig 3). I can understand the authors idea to put both, the inner and the outer sm on the two axes, but it took me several minutes starring at the plot to understand what they are showing. And now that I understand it, I still find it hard to read out what fraction of neutrons comes from the inner or the outer part for a given soil moisture condition. Especially since both relative neutrons are not adding up to 100% (due to direct neutrons?). So, I would strongly suggest to reconsider these graphs, focusing on the main message, which probably is: "How do neutrons from inner and outer areas compare?". If two variables need to be compared, try to show them in the same plot. And since they add up to a total neutron count (or to 100% inlcuding direct neutrons), the usage of stacked barplots might be good choice. One advantage of a N-over-SM plot would also be that the curves could be easily compared with the conventional N(SM) functions to show how this function changes for different irrigation pattern. Just like in Figure 9. Consider replacing Fig 3 with Fig 9 or at least refering to it.

We understand now that the readability of Fig.3 can be improved. We also agree with the reviewer that clear indication on the presence of non-albedo neutrons in the calculation should have been included in the description of the figure.

For the new version of the manuscript, we first attempted to create a figure based on stacked bar plots as this was one of the possible suggestions from the reviewer. The result can be seen in the following Figure 5. *Although some details of the figure could be improved, we think that this illustration method does not allow to clearly show many simulation results. Although the difference between the 0.5 and the 8 ha cases is crystal clear (left and right column respectively), the differences in neutron origin between the 100 simulations for a 0.5 ha field is hardly readable. Same goes for the 8 ha simulations.*

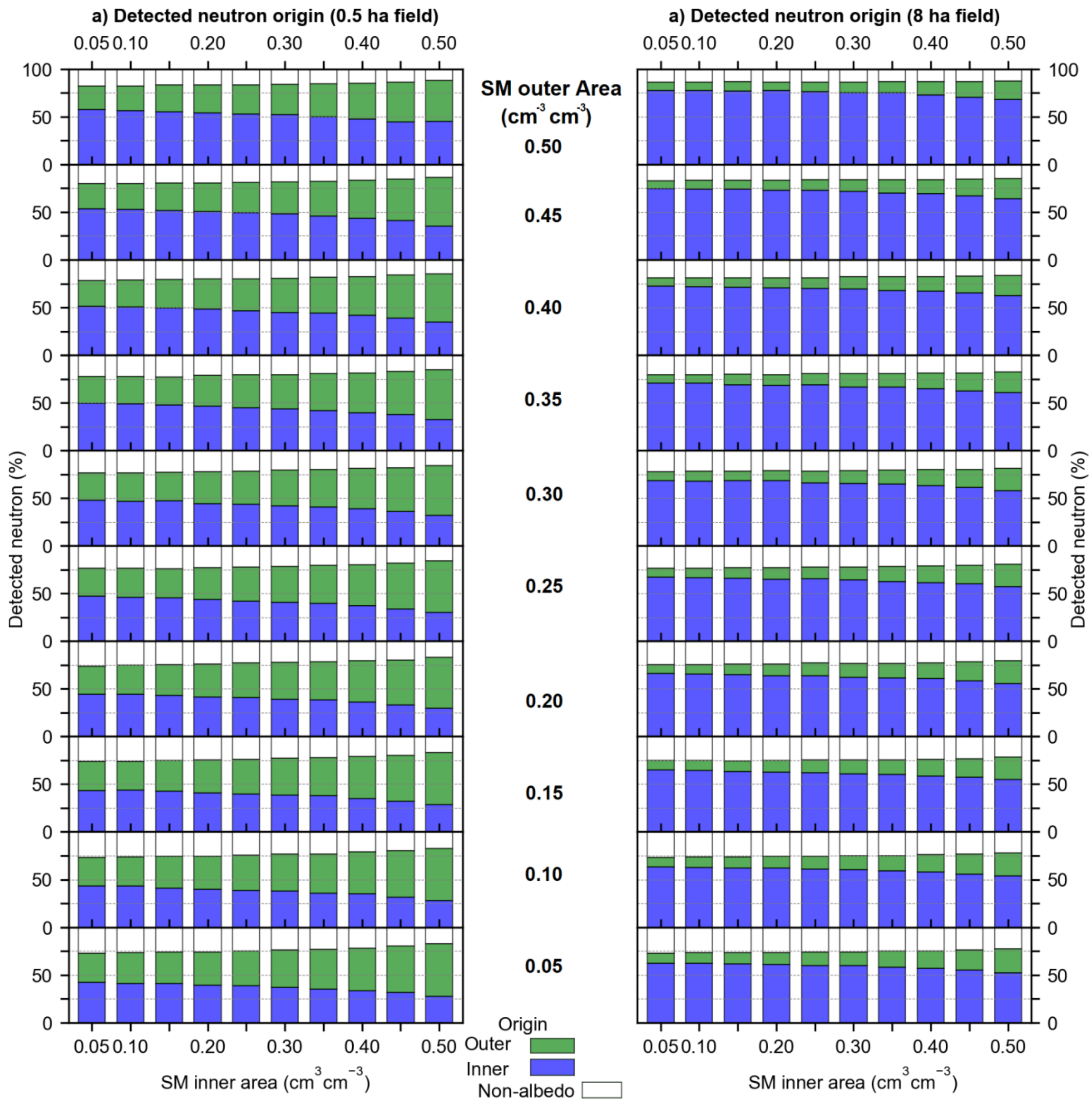

Figure 5: Alternative to Fig03 of the original manuscript using stacked bar plots. Not selected.

Nonetheless, we still agree with the reviewer comment on Fig.3 and tried an alternative illustration for Fig.3 of the manuscript. We followed the suggestion of using Fig.9 style and the result is the following Figure 6.

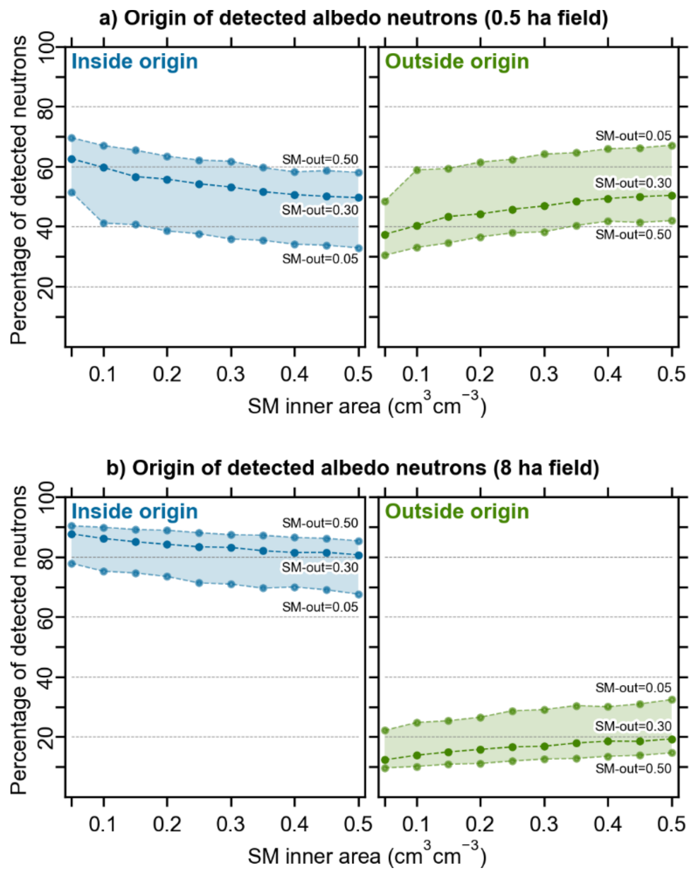

Figure 6: alternative figure that substitutes Fig.3 in the new version of the manuscript.

In this figure, we decided to not show the results of all simulations as the plotted lines would sometimes get too close to each other. Thus, we only show results for three values of SM outside the irrigated field, which we believe is sufficient. We also show only detected albedo neutrons now, and thus the percentages sum is 100%. We think that this new figure is more easily readable, and it conveys the messages that are described in the text. We thank the reviewer for his suggestions. Following this change, the text and the figure caption will be modified to fit the new Fig.3.

5. Parts of the introduction are unnecessary or not clear. There are long paragraphs about food security and irrigation in general, point-to-large scale sensors, CRNS detectors in general and their multifaceted applications from snow to regional modeling, and so forth. All this sounds like a great literature review, but it is out of scope in large parts. Instead, in the end of the introduction the very important concept of "energy dependent response function" is just mentioned, while it has never been introduced. Please consider shorteing the introduction and provide a more concise structure with a focus on the actual topic: simulation of multiple neutron detector variants in heterogeneous irrigated terrain. Unclear: the argumentation about thermal neutrons, how are they different from epithermal neutrons, and why is it necessary to exclude them? Here would be a good spot to elaborate on energy response functions. See also the 16 specific comments below.

We will shorten the first two paragraphs of the introduction to have a better focus on the topic of the manuscript. Also, we will better introduce and describe certain topics such as the difference *between thermal and epithermal neutron detection. The specific comments provided by the Reviewer will be also addressed as it is described in the followings.*

Specific comments:

- L47: I don't see how Andreasen et al. 2016 demonstrates that CRNS can close gap between point and large scales. Please double-check the reference and think about providing references related to the footprint and in comparison with actual point measurements (for example, Heistermann et al. 2021, doi:10.5194/hess-25-4807-2021)

The original reference will be substituted with the one proposed by the Reviewer.

- L49: "cosmic-ray radiation" is tautologous.

In this case, "cosmic-ray radiation" is not tautologous as it refers to radiation induced by cosmic radiation. Cosmic rays are (primarily) high-energy protons. By interaction with the atmosphere, they create showers of secondary particles which are, in case of neutrons, a different type of radiation. Therefore, the term "cosmic-ray induced neutrons" is often used instead of the shorthand versions "cosmic-ray neutrons" or the mentioned "cosmic-ray radiation". We therefore believe that no modification needs to be made in this point of the manuscript.

- L50: "The detected neutrons are generally in the thermal ... or epithermal ...". Please rephrase to avoid questions like: What means "generally"? Can a detector directly detect epithermal neutrons? Is a spectrometer involved? Can you provide a reference for the energy sensitivity?

In the introduction, we provide a simplification of the actual processes that are involved in neutron detection, both technically and physically. In Weimar et al. (2020) the principles of neutron detection for a CRNS instrument are described at length. After considering the comment of the reviewer, we decided to add a reference to Weimar et al. (2020) in this sentence. Specifically, the largest part of detected neutrons lies within the given energy ranges. More importantly, most of the details are included in the simulation and therefore do not alter the results. Other details which are not represented in the simulations are, for example, the actual geometry of the sensor. Francke et al. (2022) show however, that the differences between a simulated virtual detector and a simulated detector with its actual dimensions and materials are rather small. We believe that the text is sufficiently informative here after the addition of the abovementioned reference.

- L52: Consider adding a references that is less than 10 years old, e.g., Köhli et al. 2021, doi:10.3389/frwa.2020.544847

The reference will be added to the text.

- L56: "dry soils have a higher neutron density" - Please rephrase. Is it the soil that "has" this neuton density, or the atomic nuclei inside the silicate atoms? Or the air above the soil?

We will modify the text in: "For example, the count rate is inversely proportional to SM since dry soils result in higher environmental neutron density that allows more accurate measurements compared to wet soils".

- L49-57: The whole paragraph: you start with telling that CRNS is both, thermal and epithermal. Are all these statemens in the text (sensitivity to sm, snow, vegetation, ...) refererring to thermal, to epithermal, or both? Do they behave equally? If no, how are thermal neutrons different? If yes, why do you want to exclude them?

Following the comment of the reviewer, we will describe at the end of the paragraph that, in the specific case of soil moisture monitoring, thermal neutrons have been shown to have lower sensitivity to soil moisture than epithermal neutrons and that thermal contamination of standard probes leads to a lower signal-to-noise ratio compared to shielded detectors. We will also provide references to such statements. Such addition will be limited to soil moisture as this is the focus of our study. We believe that a wider description would further lengthen the introduction and go beyond the scope of this study.

- L60: I don't see how Schrön et al. 2017 uses multiple counter tubes to achieve higher count rates. Do you mean Schrön et al. 2018, doi:10.5194/gi-7-83-2018 ?

We will substitute the original reference with the proposed one.

- L64: "... prevent the detection of thermal neutrons" - Not clear: why should the detection of thermal neutrons be prevented? Please restructure this paragraph to explain why thermal neutrons behave differently and why they are not useful for soil moisture monitoring.

For the answer to this comment, please refer to the above comment L47-57.

- L69-70: You argue that CRNS does not need to be removed during harvest. Is the instrument of infinitesimal size? If not, what is the spatial extent of the apparature including anchoring, and how can a farmer pull around it? Please consider reporting about pros and cons of CRNS more objectively.

The previous version of the manuscript described this part in a rather simplistic way, which may be interpreted as an underestimation of CRNS cons. Indeed, the instrument is not infinitesimal and occupies a space of approximately 35x35 to 80x80 cm, depending on the instrument type, manufacturer, and installation. Our goal was to highlight how a single CRNS differs from a sensor network composed of multiple distributed nodes. In this case, the farmer needs to drive around a single sensor (generally well visible and placed in the middle of the field) instead of driving around multiple sensors that are distributed within the field. In the latter case, the complication of driving around multiple sensors generally results in the need for complete removal and reinstallation. This is not the case with a single CRNS. We will improve the text in the new version of the manuscript by including additional wording from Franz et al. (2016): "In the context of agricultural applications, a CRNS can be placed in between or out of the way of routine production practices. It consequently does not present the logistic challenges associated with directly inserted sensors, *which need to be removed and reinstalled during harvest, planting, and other management actions (Franz et al. 2016)".*

- L75: What is "rover-based"?

It is the use of a vehicle as a sensor platform for mobile measurements as for example presented in the cited work of Jakobi et al. (2020). As such wording is rather common in literature, we believe that no addition is needed to the text at this point.

- L77: I don't see how Dong et al. 2014 and Jakobi et al. 2020 discuss drought and flood events. Consider rephrasing.

Dong et al. (2014) and Jakobi et al. (2020) do not discuss the topic of the last noun (mentioned in Bogena et al. (2022)) but the topics mentioned in the entire sentence. We proposed the three citations together at the end of the sentence to make the reading easier. We thus believe that no additional changes are needed at this point.

- L82: "areas with different SM content can be overlooked by a single CRNS" - Please rephrase. Almost all nearby areas do influence the detector signal integratively, so "overlooked" is probably wrong wording.

We will substitute the previous text with "areas with different SM content can be underrepresented by a single CRNS".

- L87: "detection of irrigation-related SM variations might not be possible" - Are Li et al. showing that it is not "possible", or are they merely showing that the irrigation signal is within the noise level of typical CRNS detectors? If the latter, there might be chance to detect even small sm changes with better detectors? E.g., higher count rate or improved shielding? I think there is a good chance here to use Li et al. 2019 for motivating your study! Consider rephrasing.

Following this and the next comments of the reviewer, ***this paragraph will be reorganized to present the study of Li et al. (2019) in a single occurrence and better describe the general context. The new text will read:***

"*Sub-footprint heterogeneity can be reconstructed using multiple instruments, but this comes with increased costs and necessitates further assumptions regarding spatial continuity (Heistermann et al., 2021). As a result, it can be difficult to distinguish local SM variations (Francke et al., 2022), such as the difference between the SM in a small irrigated field and in its surroundings.*

Despite such limitations, Ragab et al. (2017) reported that CRNS measurements were useful for monitoring soil moisture deficit in the root-zone and Finkenbiner et al. (2019) found that information obtained from combined CRNS measurements and electrical conductivity surveys could improve water use efficiency in a field irrigated with a centre pivot system in Nebraska (USA). Also, Baroni et al. (2018) reported a clear response of CRNS to irrigation, although quantification of single irrigation events was not possible due to effects of precipitation and irrigation of nearby fields.

*In the case of drip irrigation, where the irrigated area is only a small portion of the volume sensed by the CRNS, the detection of irrigation-related SM variations can be more challenging. For example, in Li et al. (2019), it was not possible to accurately monitor drip irrigation with a standard CRNS in a citrus orchard in Spain. This was a consequence of the relatively small area wetted by drip irrigation, which resulted in a small mean SM change in the instrument footprint. However, better results could be achieved in irrigated fields with a larger wetted area, in drier regions, and for longer and more intense irrigation periods as well as by using instruments with higher count rates****".***

- L93: Again Li et al.? Consider merging the two occurances.

Please refer to the answer provided in the previous comment.

- L103-106: Three occurances of Köhli et al. 2015 within four lines with mainly identical contexts. Please consider rephrasing.

This paragraph will be reorganized: "Within this context, the aim of this study is to analyse the feasibility of CRNS-based SM monitoring in irrigated environments. To achieve this, neutron transport and detection in irrigated environments was investigated with physics-based Monte

Carlo simulations. These are widely used in CRNS studies (Andreasen et al., 2016) that are focused on, for example, the description of the footprint characteristics (Zreda et al., 2008) and the local site arrangement and instrument calibration strategies (Desilets and Zreda, 2013; Schrön et al., 2017). In this study, the Ultra Rapid Adaptable Neutron-Only Simulation (URANOS) model developed by Köhli et al. (2015) was used".

- L109: "energy dependent response function" - What is this? Please elaborate in the paragraphs above.

Here, we refer to the energy sensitivity of the detector, the so-called response function. We will specify this in the new version of the manuscript and add a reference to Köhli et al. (2021).

- L121: "measure neutrons in the thermal to fast energy regimes" - Can you be more specific or provide a reference?

We will provide reference to the work of Weimar et al. (2020) and Köhli et al. (2021).

- L124: Why is Bogena et al. 2022 a good reference for the influence of additional hydrogen pools on CRNS? Consider adding Iwema et al. 2021, doi:10.1002/hyp.14419 and Baroni et al. 2018, doi:10.1016/j.jhydrol.2018.07.053

We will substitute the original reference with those proposed by the reviewer.

- L126: "a CRNS" - Here you use CRNS as singular, but the grammar in most of your sentences suggests that CRNS is plural. Please clarify.

Due to the nature of using only the first letters to form an acronym and to the fact that CRNS is used in literature as an acronym of "cosmic-ray neutron sensor -s" and "cosmic-ray neutron sensing", often in the same manuscript, we decided to not indicate the grammatical number as this is commonly done in literature.

- L126-132: Unnecessarily detailed on how the detector, the electronics, the meteo station and the antenna work. Consider removing this part from the manuscript (which is about a theoretical, simulated detector).

We critically considered the comment of the reviewer here. One observation that we would like to stress at this point is that, although purely theoretical in nature, this is one of the first, if not the first manuscript that brings forward the topic of the feasibility of irrigation monitoring with CRNS. Such tool is relatively new in general, and examples of irrigation applications are scarce at best. As such, we expect that many readers will be not familiar with CRNS. Thus, we agree that this section can be shortened but we will not remove it completely as we believe that a short instrument description as well as the references that are provided can represent an added value for readers that are new to the CRNS topic.

- L138: "The footprint is assumed to be circular" - Schattan et al. 2019 as well as Schrön et al. 2022 showed that it can be asymmetric depending on the site heterogeneity. This could be also relevant for your study on irrigation, especially if only parts of the outer fields are irrigated. So, is this radial symmetric assumption necessary for your study?

The reviewer raises a fair point and those recent studies (among others) found that the footprint can be asymmetric. In our study as well, the rectangular shape of the field inevitably leads to minor deviations from a circular shape. This might be kept in mind, yet, as the overall study design focuses on symmetrically aligned topographical elements, such considerations are only of theoretical interest. Only in cases where there are entities of large soil moisture differences close to the sensor and heterogeneously positioned around the sensor, footprint deformations can be of interest. Also, as we stated later in the manuscript, the angular distribution is not subject of this study. We thus believe that the assumption of a circular footprint fits the scope and topic of this study and is the best choice.

Nonetheless, to provide the reader with additional information, we decided to extend this topic and include the references proposed by the reviewer. The new text will read: "Although some studies suggested an asymmetric or "amoeba-like" shaped footprint (Schattan et al. 2019; Schrön et al. 2022), most studies assume a circular footprint that depends on the Euclidean distance between the points where neutrons had first contact with the ground and the point of detection."

- Figure 1: Please indicate the detector position (e.g. with a point) and add scales (in meters) to the inner area box (hectares alone are not very easy to grasp)

As mentioned in previous comments, we will included the suggested changes in Fig.1.

- L194-197: These statements sound like results, rather than methods. Or are they already established knowledge? Then please provide references.

We will include in the text some references to previous works of Weimar et al. (2020) and Köhli et al (2018).

- L199: Consider adding Rasche et al. 2021, doi:10.5194/hess-25-6547-2021, as a reference for the discussion on thermal neutrons and their behaviour in heterogenous terrain.

We will include such reference.

- L201: Why "either"? Can't you use the same neutron for both, count rate calculation and footprint calcuation?

The previous manuscript version was not fully clear here. The new version will read: "Then, these weights were a) summed to obtain the number of detected neutrons and b) used in a weighted calculation of the R86".

- L214: As you have mentioned also on other places, consider adding Schrön et al. 2022, as they seem to have demonstrated exactly that.

We will include such reference.

- L215: "Here, it is assumed that having a relatively small R86 is beneficial when monitoring irrigation in small fields" - Please rephrase, what does this assumption imply?

The previous manuscript version was not fully clear here. The new version will read: "Here, the initial hypothesis is that a relatively small R86 is beneficial when monitoring irrigation in small fields as a lower contribution from the surrounding areas could be expected".

- Eq 1: Please elaborate more on where this equation comes from. It looks like you are propagating the error of N1-N2 (which is the change of neutrons upon detection), where the error of Ni is 1/sqrt(Ni)?

The reviewer correctly interprets Eq. 1. This is the result of Gaussian error propagation on ND = N1-N2, which means taking the square root of the sum of the squared derivates of ND times its error which is, due to counting statistics, the square root of the resulting number of counts in N1 or N2, respectively. We did not intend to add a long description about basic statistics and thus provided an easier reading. We believe that the original text is sufficient in this case.

- L232: The cited preprint is not a good reference here. Can you refer to a study which presents typical irrigation intervals?

We understand the point of the reviewer here as the original text was misleading. We could not find relevant information on detection uncertainty for generic CRNS in evenly irrigated small fields. Thus, we included a generic detection uncertainty for soil moisture monitoring. The new version of the manuscript will clarify this aspect and read: "In addition to σ, a value of α=1% was included in each threshold to represent a generic detection uncertainty limit for a detector that can achieve ~1000 counts per hour and aggregation times of < 12 hours that are relevant in SM monitoring (Schrön et al., 2022)".

- L248: "inimum and maximum percentages of detected neutrons" - Is this relative to all albedo neutrons, or to all detected neutrons (including non-albedo neutrons)? Please clarify.

We carefully considered the comment of the reviewer here. We will provide a clear description, and the new text will read: "For each dimension of the simulated inner area and for each moderator type, Table 2 shows the minimum and maximum percentages of detected neutrons that originate in the inner area depending on SM conditions and relative to all detected albedo neutrons".

- Figure 5: Since panel f) shows a difference rather than the actual value of R86, the colorscale should be completely different. However, it still has blue and yellow colors just like the colormap from the other panels. Please make f) more distinguishable, by choosing a more distinguishable colormap (e.g., red-white-black). Moreover, using terrain colormaps for R86 is not a good choice. Blue stands for water, but low radii have nothing to do with water. Try to use a more linear colormap (e.g., greyscales), or none.

We carefully considered the comment of the reviewer and critically examined Fig.5 of the original manuscript version. We agree that a simpler and clearer version could be produced. As low R86 can be somehow associated with wet soil conditions and large R86 with dry soil conditions, we decided to use a simpler blue-red scale for the panels a-e. Thus, green (intensity) was a good contrasting choice for panel f. We tested the use of greyscales, but it made the black contours less readable. Also, the use of no colormap resulted in a figure that was like the original version of Fig.3, which we now understand had poor readability. Thus, we believe that this new Figure 7 *is a good and readable compromise, and we will used it in the new version of the manuscript.*

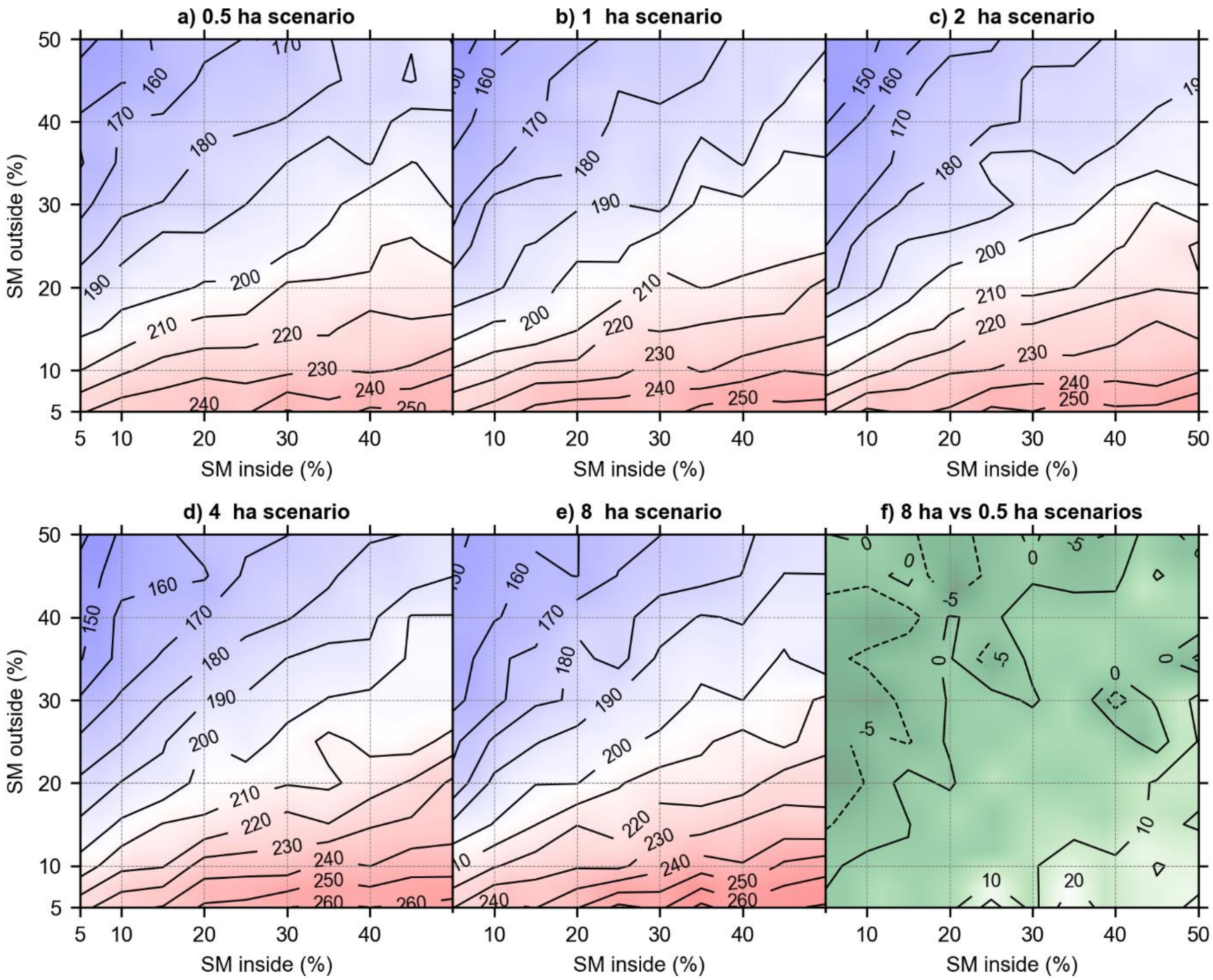

Figure 7: alternative figure that substitutes Fig.5 in the new version of the manuscript.

- Figure 6: Can you add conventional N(sm) functions for the purely homogenous case for comparison?

Following the reviewer suggestion, we will include relative change in detected neutrons for homogeneous SM variations (i.e., homogeneous area or irrigated field of infinite dimension). The result is shown in the following Figure 8*. As this new Fig.6 is more informative than the previous version, it will be added to the new version of the manuscript. The caption will be modified accordingly.*

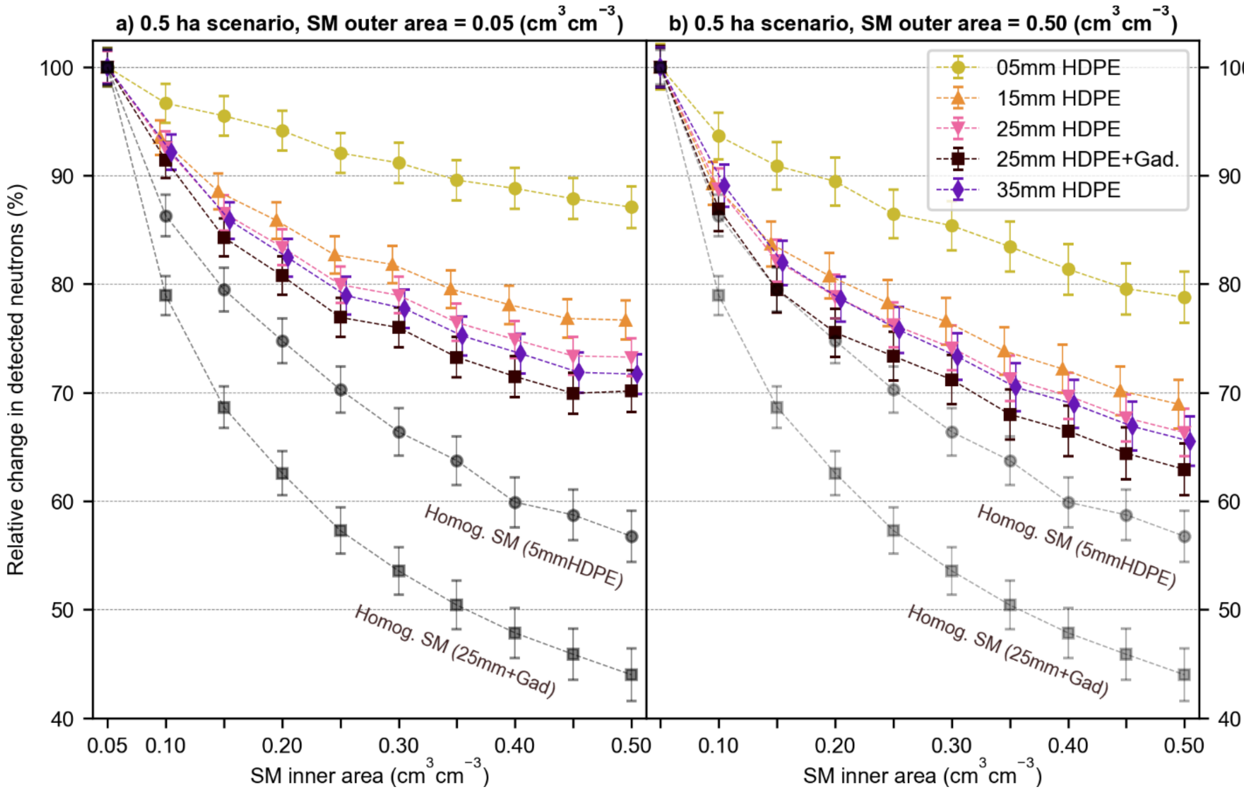

Figure 8: alternative figure that substitutes Fig.6 in the new version of the manuscript.

- Figure 8: Why are some bars larger for higher sm than others at lower sm? Is this an effect of the simulation uncertainty? Can you provide an errorbar for the bars?

*The results of this study are subject to statistical uncertainties. When looking at small differences, results are often influenced by fluctuations, which we for example see in Fig.8. In order to quantitatively understand and classify our findings, we provide a measure of certainty by comparing them to the standard deviation of the respective data set. In our opinion, the dashed lines show the error bars of the bars in a clearer and simpler manner. We thank the reviewer here as we also noticed that the red area below σ+α mentioned in the caption of Fig.8 was not visible. We also now use multiple simulation results for the initial homogeneous soil moisture conditions. We will thus provide a new version (*Figure 9*) of the figure where such area is clearly marked, which will also help the reader in this context. We also will modify part of the caption to have a clearer description: "The bars show the relative change in detected neutrons induced by the irrigation event while the dashed lines show the prescribed detection certainty thresholds.". Please note that further modifications to Fig.8 were made according to the comments of reviewer n.2.*

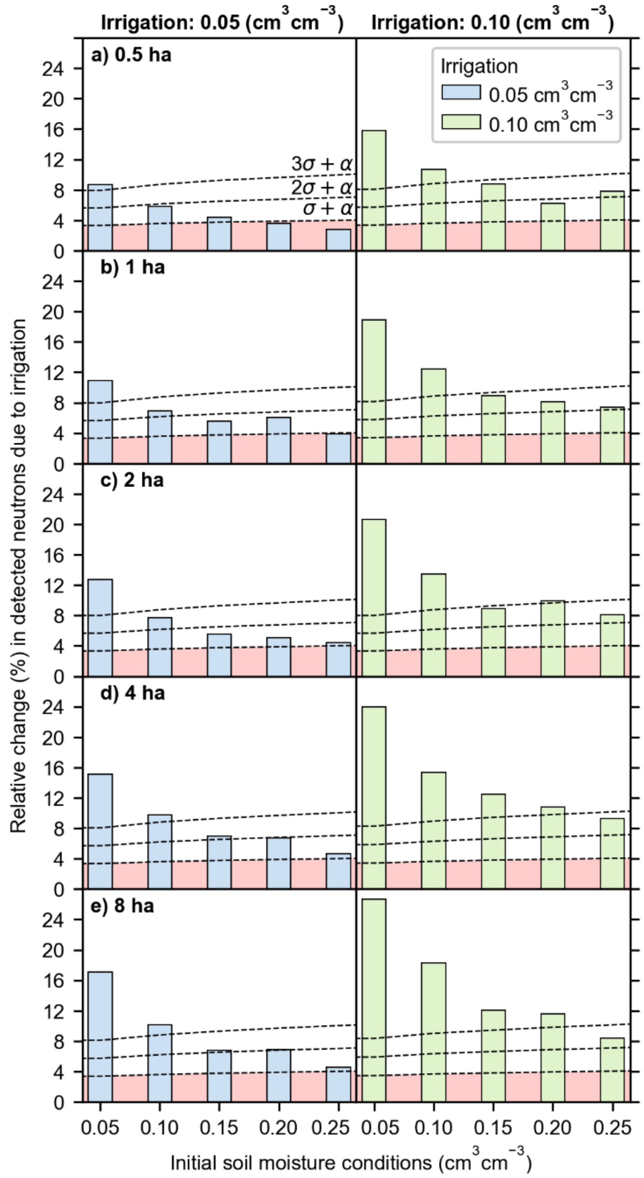

Figure 9: alternative figure that substitutes Fig.8 in the new version of the manuscript.

- Figure B1: % relative to what? Can you add the signal of a completely bare sensor (0 mm HDPE)?

As mentioned in the caption of the figure, it is "Boxplot of the percentage of detected thermal neutrons over total detected neutrons with different moderator types for the 1 ha scenario" and thus relative to the total number of neutrons detected. We decided to improve the caption which will reads: "Boxplot of the percentage of detected thermal neutrons over the total number of neutrons that are detected with different moderator types for the 1 ha scenario". As the figure shows the fraction of thermal neutrons that are detected and not the count rate, the inclusion of a bare counter to the plot by means of additional investigations would not, in our opinion, provide meaningful additions to the manuscript. According to the general understanding, a thermal counter counts 100 % thermal neutrons. That is, however, not exactly true and the neutron *absorption probability in a neutron converter has a 1/sqrt(E) dependence. Given the threshold of thermal energies, the thermal counter would rather lie around 90 % of thermal neutrons. Starting a discussion about why that is the case is not the focus of this publication. Also, we believe that at this point of the manuscript and of the study, the inclusion of a 0 mm HDPE moderator would not provide meaningful additions.*

- The reference list is sorted by first author name, but for the same author it is not sorted by publication year. This makes searching for references very cumbersome, especially for extensivley used author names (such as Bogena et al.). It should be fixed during typesetting.

This will be improved in the new version of the manuscript.

- With regard to the previous comment, please double-check whether such a high number of rather general references on soil moisture are necessary for this very specific manuscript about neutron detector simulations and irrigation.

We will remove the references of those parts of the introduction that will be shortened according to previous comments.