Response to reviewers

Please find here our response to the remaining reviewer comments. In our opinion, all concerns raised by the reviewer were addressed and this has further strengthened the message and variety of the manuscript. We hope that this revised version of the manuscript can be accepted for publication in Geoscientific Instrumentation, Methods and Data Systems.

Response to Reviewer 1

Thank you very much for carefully considering all review comments and for comprehensively elaborating on all raised concerns. I agree to most of them, while I think that few concerns are still not sufficiently met and require minor additions.

We believe we have addressed the additional concerns. Please find below a point-by-point reply.

My major concerns 2 and 3, all minor concerns, and all specific comments were sufficiently addressed, thank you.

Major concern 1: The authors defended their choice of a constant soil moisture profile from 0 to 160 cm with good arguments ("typical" profile shapes, near-field sensitivity, high complexity). However, the added text to the revised manuscript does not sufficiently address the limitations of this study in a useful way. When strong conclusions about the feasibility of irrigation detection are made, then the underlying assumptions and limitations should be strongly communicated as well! Here, I would expect more than two sentences, and a better quantification than "reduction of performance". The readership should clearly understand that these results are only valid for a very specific set of soil properties and vertical profiles. Otherwise, I see the risk that readers may misinterpret and unintentionally miscommunicate the results (e.g., by comparing them with observations and finding weak agreement). Without opening a full new dimension of complexity, I think a rough quantitative statement about the ranges and uncertainties could be achieved by a few quick simulations of a single scenario (e.g., 1 ha and 25mmG, theta=0.01, dtheta=0.20) with irrigation of the first 10 cm instead of 160 cm. My hypothesis would be that this more realistic soil moisture profile would lead to much less impact of the outer region. By a quick comparison the 10 cm and the 160 cm results you would be able to either support your conclusion (soil profile has low impact) or quantify the limitations (impact may vary by X % depending on soil profile). Moreover, the conclusion which shield is the best may depend on the vertical soil profile, while it might lead to very impactful economical decisions for manufacturers and customers in the future. So, also here the authors should take the responsibility by making a few tests with more realistic soil profiles to quantify the robustness of the 25mmG performance. Also here, a rough estimate from just a few sample simulations would be better than no estimate.

We understand the concern of the reviewer regarding the brevity of the limitations and outlook section. This section discusses a wide range of possible limitations and all of these, although briefly described for the sake of conciseness, are clearly pointed out. But we also understand the need for a quantification of this specific limitation so that readers that are not familiar with the methods can have a better overall understanding of the applicability of the results.

In our opinion, a comprehensive quantification of the impact of vertical soil moisture heterogeneity and of the wetting of the upper soil would necessitate a) the definition of one or better multiple exemplary vertical SM heterogeneity patterns, b) large number of additional simulations, and c) a considerable addition to the "Results and Discussion" section. We believe that such a comprehensive quantification goes beyond the scope of the study and is sufficient material for a completely new study. We also think that real-world data would be useful to support such a new study.

Thus, we followed the reviewer's suggestion to include a brief quantification of the possible reduction in CRNS performance due to the wetting of the topsoil. For this, the new version of the manuscript includes a new Fig. 10 (see Figure R 1 below) and relative descriptions in Chapter 4 "Limitations and outlook". This new text also includes elements that were added in response to Major Concern 5. The overall content of this new text and responses to the reviewer's concerns and hypothesis are described in detail in the following, whereas the new text in the manuscript is briefer on certain points for the sake of conciseness.

We tested the scenario proposed by the reviewer with one simulation that had a SM of 0.01 cm^3 cm^{-3} and a second simulation where the SM of a 1 ha irrigated field was increased to 0.20 cm^3 cm^{-3} only in the upper 10 cm of soil (thus, the SM in the non-irrigated area and in the irrigated soil below 10 cm remained at 0.01 cm^3 cm^{-3}). With a 25 mm HDPE moderator with gadolinium shielding, the number of detected neutrons dropped by 26.2 %. This reduction easily satisfies the thresholds that were used in the manuscript and is stronger than any of the scenarios proposed in Fig. 8 of the manuscript (the strongest variation for a 1 ha scenario being ~19 % with a SM increase of 10 cm^3 cm^{-3} from a starting SM of 0.05 cm^3 cm^{-3}). We believe this is due to the relatively low initial SM and to a relatively large SM variation. Consequently, we decided to not use this scenario and instead added additional simulations to address the concerns. The newly added simulations are consistent with the simulations presented in Fig. 8 of the original manuscript to achieve consistent text flow and to minimize the complexity of the newly added text. The new results are shown in Figure R 1 (panels a and d-e).

In these new simulations, we considered two scenarios that were applied to the 1 ha case:

1. *A wetting of only the first 10 cm of soil with a SM variation of 0.05 and 0.10 cm^3 cm^{-3}. This could correspond to the initial wetting that takes place after irrigation starts. In fact, such SM variation equals to only 5 mm (0.05 cm^3 cm^{-3} variation) and 10 mm (0.10 cm^3 cm^{-3} variation) of irrigation that penetrates the soil, which is generally a rather small amount.*
2. *A wetting of the first 30 cm of soil with a SM variation of 0.05 and 0.10 cm^3 cm^{-3}. This could correspond to a later stage of irrigation when, for example, the water has moved through the plough layer. We believe that this new depth is suitable and still conservative as the roots can reach deeper soils. These SM variations are equal to 15 mm (0.05 cm^3 cm^{-3} variation) and 30 mm (0.10 cm^3 cm^{-3} variation) of irrigation. Although larger than in scenario 1, such irrigation amounts are consistent with real-world irrigation practices.*

These new results did not clearly provide new proofs of a possible reduction of the impact of the other region. We could not calculate the impact directly from our simulations, as we only modified the SM in the irrigated area. Such calculation would require additional simulations. However, we analysed the partitioning between neutrons that originate inside or outside the irrigated field. The *partitioning obtained with the new simulations (10 cm and 30 cm wetting) was rather similar to that of the previous simulations with homogeneous vertical SM. Only minor differences of ±2 % could be observed and the percentage of detected neutrons that originate in the outer region was not consistently higher or lower in these new simulations. One could think that changing the SM of the outer region only in the topsoil could lead to a lower influence of such region (because the overall SM change is smaller). However, the reduction of the depth of investigation of a CRNS with distance should be considered here. Also, such influence would strongly depend on the SM difference between topsoil and deeper soil, both within and outside the irrigated area. All in all:*

- *we do not think we can either support or clearly reject the hypothesis of the reviewer, even with the additional simulations that were performed.*
- *we do not think that we have sufficient material to discuss the influence of the outer region for this specific case*
- *and we believe that the assessment of a possible variation in the influence of the outer region due to vertical SM heterogeneity goes beyond the scope of the current study.*

Thus, we did not mention these aspects in the revised text.

We compared the use of a 25 mm HDPE moderator with Gadolinium shielding to that of a 25 mm and of a 5 mm HDPE moderator without shielding in the context of Fig.10 of the revised manuscript (i.e., 1 ha field). In general, the performance of the unshielded versions was poorer than that of the gadolinium shielded version. In particular, the 25 mm HDPE moderator had performance reductions up to -29 % (this for 0.05 cm^3 cm^{-3} irrigation starting from SM = 0.05 cm^3 cm^{-3}). Such reduction was smaller when the initial SM was higher. When a 5 mm HDPE moderator was used, reductions in performance exceeded -90 %. Interestingly, when only the first 10 or 30 cm of soil were wetted, the performance of the unshielded versions was reduced even further (e.g., up to -55 % for 0.05 cm^3 cm^{-3} SM variation and initial SM = 0.05 cm^3 cm^{-3}, 25 mm HDPE moderator). Although these results are in principle interesting, we believe that such sensitivity differences are already discussed in detail in section 3.3 and in Fig. 6 of the manuscript). These new results do not change the findings of these sections. It is true that there is a general additional point in favour of the sensitivity of the gadolinium shielding version, but we believe that these new simulations are not sufficient to draw definitive conclusions. Thus, we did not include new parts on the best performing moderator-shielding in the new text of Chapter 4.

The reduction in performance of the CRNS when only the first 10 cm or 30 cm of soil are wetted is shown in Figure R 1 (and Fig.10 of the revised text). It is clearly shown (panel d) how there is a strong reduction of performance for a wetting of the first 10 cm and a SM variation of 0.05 cm^3 cm^{-3} (blue bars in Figure R 1d). The performance reduction is less pronounced with a SM variation of 0.10 cm^3 cm^{-3} (green bars in Figure R 1d). Even though this reduction in performance is apparent, we do not believe that this results in the unsuitability of CRNS for irrigation monitoring or in a strong undermining of our previous results. As pointed out earlier, such irrigation events are limited to 5 mm and 10 mm of water that penetrates the soil, which is a rather small amount and could correspond to the initial phase of a larger irrigation event (or daily irrigation events). Thus, we emphasized in the revised text that CRNS may prove less suited to monitor initial irrigation stages of a larger irrigation event as well as daily small irrigation events.

In the case of 30 cm of wetted soil (Figure R 1e), the results are rather similar to those of a homogeneous vertical wetting (see red dashed bars). In general, a small reduction in performance *could be observed at times, but the results show an overall good performance in this scenario that is comparable to that of a homogeneous vertical SM distribution. We believe that these results are a consequence of the CRNS sensitivity that peaks in the topsoil (especially when the topsoil is wetted) and of the fact that the CRNS depth of penetration decreases far from the instrument.*

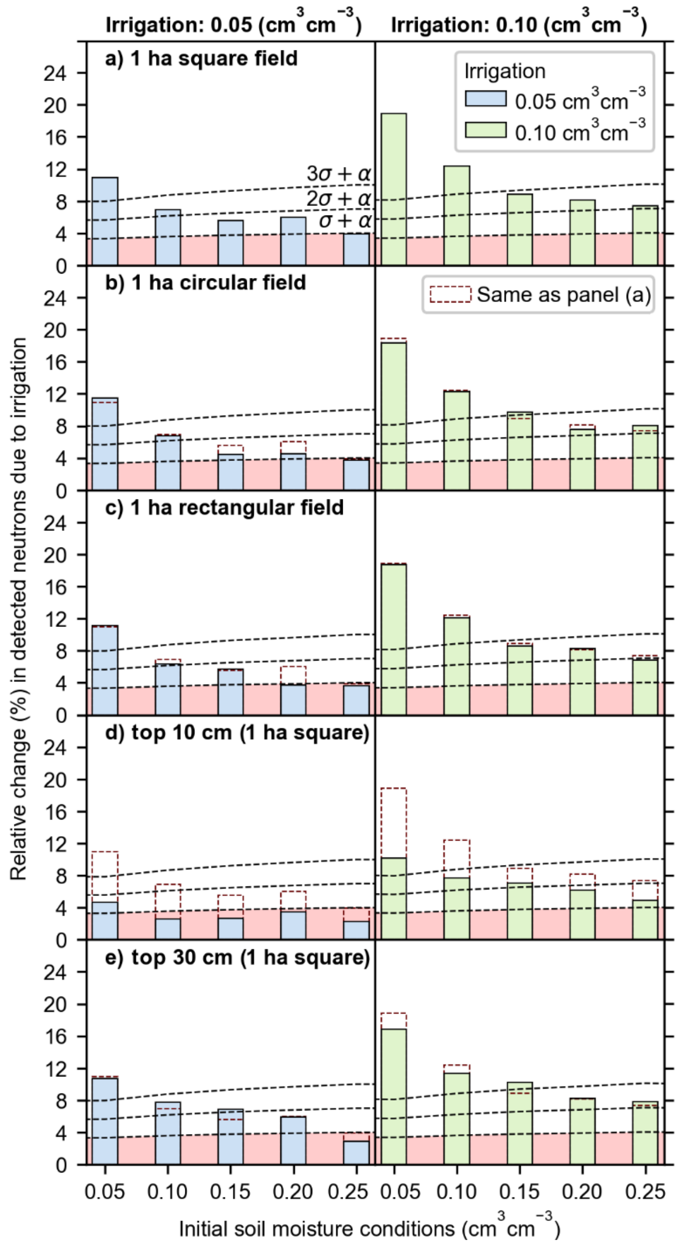

Figure R 1: new Fig.10 of the revised manuscript.

A full interpretation of these results would require additional simulations, but we believe that they offer an interesting picture. Although not exhaustive, we believe that they are a nice and informative addition to Chapter 4 "Limitations and outlook", but we emphasized in the revised text that further and more detailed simulations would be needed to better understand such effects.

The revised text, which includes Figure R 1 as the new Fig.10 together with additions from major concern 5, takes this into account and reads:

"Moreover, heterogeneous vertical SM distributions or different dimensions of the irrigated field, such as irregular or elongated shapes, might be more challenging for irrigation monitoring with CRNS. Figure 10 shows the sensitivity of a CRNS with a 25 mm HDPE moderator and gadolinium shielding to irrigation events that increase the SM of the irrigated area by 0.05 or by 0.10 cm^3 cm^{-3} starting from a homogeneous SM condition for different shapes of the irrigated area. The comparison between a circular (56 m radius), rectangular (142x70 m), and a square field of 1 ha (Figure 10a-c) shows that there is a small change in CRNS performance for given SM variations for different field geometries. However, the differences are small and the overall feasibility of irrigation monitoring with CRNS is not affected. Figure 10 also shows the sensitivity to irrigation events when only the first 10 cm or 30 cm of soil are wetted in a 1 ha square field. When irrigation affects SM only in the first 10 cm of soil (Figure 10d), the sensitivity of the CRNS is strongly reduced. This is especially the case for SM variations of 0.05 cm^3 cm^{-3} where the CRNS is able to detect irrigation only when the initial SM is 0.05 cm^3 cm^{-3}. However, it should be noted that SM variations of 0.05 and 0.10 cm^3 cm^{-3} correspond to irrigation events of 5 and 10 mm. This rather small irrigation amount might correspond to the initial SM variation during a larger irrigation event or to frequent events (e.g., daily irrigation). When irrigation affects SM in the first 30 cm of soil, the sensitivity of a CRNS is comparable to that of a homogeneous vertical distribution of SM (Figure 10a and e). The only differences are a drop from high to good detection chances for a 0.05 cm^3 cm^{-3} SM variation and from certain to high detection chances for a 0.10 cm^3 cm^{-3} SM variation when the initial SM is 0.15 cm^3 cm^{-3}. Overall, Figure 10 suggests that a small change in the field shape and irrigation affecting just the top 30 cm of soil will only have a small influence on the feasibility of irrigation monitoring with CRNS. However, it has to be noted that these results are based only on a limited number of simulations and real-world studies should assess in more detail the influence of the shape of the irrigated field in addition to the impact of the within-field SM heterogeneity."

The conclusions were also modified with the addition of the following text:

"For a 1 ha irrigated area, the use of a circular or rectangular shape instead of a square shape and SM increases in the first 30 cm of soil instead of the entire soil profile did not results in considerable changes in the CRNS sensitivity. On the contrary, when SM was increased only in the first 10 cm of soil (e.g., small daily events or the initial stage of larger irrigation event), a considerable reduction in sensitivity was observed."

Finally, Chapter 2.4 "Simulation Setup" and Chapter 2.6 "Investigation of the feasibility of irrigation monitoring with CRNS" were extended to include the simulation of these new scenarios.

Major concern 4: I am okay with the added explanation that a single soil moisture sensor may be installed outside the irrigated field to support the CRNS *if* the outside field is homogeneous. I just want to remind the authors that, if it is not homogeneous (probably in most cases), it would be more logical and less expensive to use the single soil moisture sensor in the irrigated field, and no CRNS. Since the inner field is always much smaller than the outer field, the single soil moisture sensor will be much more representative for the inner field than for the outer field. Hence, the overall representativity-related uncertainty introduced by your suggested solution might be much higher compared to the inner single SM sensor without CRNS. You might want to consider communicating this dilemma, although it does not support the recommendation of CRNS for small, irrigated fields.

We understand the concern of the reviewer here and agree that a crystal-clear text should be obtained to address this important point. However, we do not believe that installing a single point-scale SM sensor in the irrigated field is always the best option (although it is the cheapest one). The reviewer rightly points at the fact that the SM outside a target irrigated field is, in most cases, spatially heterogeneous. However, we think that it is rare to find homogeneous SM distributions in agricultural fields when these are surrounded by lands with heterogeneous SM distributions. Most agricultural fields will also have a heterogeneous SM distribution. When the irrigated field is very small, however, it has higher chances of showing a relatively homogeneous SM distribution. Nonetheless, in the case of a within-field heterogeneous SM distribution, a single sensor is of little use and sensor networks are generally necessary to avoid the risk that a single sensor is placed in a non-representative position and induces a considerable bias compared to the field average. Thus, CRNS are proposed as a method to get a field measurement with a single sensor, as mentioned in the introduction.

We understand that we did not communicate this message in a complete manner in Chapter 4. Also, we did not express sufficiently the comparison of a CRNS with sensor networks or single instruments in the case of small, irrigated fields. The revised text takes these considerations into account and reads:

"Another aspect that needs further investigation is the role of SM variations in the surroundings of a target irrigated field. Information on such SM variations may be necessary to correct CRNS-based SM products not only in relatively small fields (up to 2 ha) but also in larger ones. When a CRNS is installed in an irrigated field in place of a sensor network, the CRNS could be supported by a single and inexpensive point-scale SM monitoring instrument installed outside the target field. This would not substantially increase the installation and maintenance costs and would not interfere with agricultural management. Moreover, a single point-scale device could support multiple CRNS in an agricultural area if irrigated fields are sufficiently distanced and if the SM in the unmanaged area is relatively homogeneous in space. However, in small fields (e.g., < 0.5 ha) that have relatively homogeneous SM, a small sensor network could be more effective than a CRNS.".

Major concern 5: Thank you for the additional simulations. I recommend using these results to add a concrete number to the discussion: calculate the average deviation of circular and rectangular results from the square results. Then you can conclude that the shape of the field impacts the results by X %. Then, it is easier for the reader to decide about the transferability of your results to individual sites.

We believe that, given the results shown in Figure R 1, the best option is to include such results in the text of Chapter 4: "Limitations and outlook" together with the revisions of major concern 1. We tried to calculate an average value for the 3 scenarios proposed in such figure. These would *be a variation of 8.9 %, 8.7 %, and 8.5 % in scenarios a) 1 ha square, b) 1 ha circular, and c) 1ha rectangular field. These values are rather similar and are a strong simplification of the results of Figure R 1, which shows that the sensitivity depends on the initial SM conditions. Thus, the option to show the results in a new Fig.10 of the revised text is, in our opinion, the most appropriate choice. The revised Chapter 4 and conclusions (see comments to major concern 1) include this new figure as well as a description of the simulated scenarios and of the fact that only small differences were found when using a circular or rectangular field shape instead of a 1 ha squared shape. The new text also points at the fact that more studies and analysis are needed to get a complete picture of these effects as these few simulations can be considered only an indication and are not conclusive results. Chapter 2.4 "Simulation setup" was extended to include the simulation of these new scenarios.*

Other comments: The abstract reads "However, it was found that variations in SM outside a small, irrigated field (i.e., 0.5 and 1 ha) can affect the count rate more than SM variations due to irrigation." - Consider rephrasing to clarify that this is only true under some (and by no means all) conditions.

The revised text now reads: "However, variations in SM outside a 0.5 or 1 ha irrigated field (e.g., due to irrigation of neighbouring fields) can affect the count rate more than SM variations due to irrigation."