Testing a novel sensor design to jointly measure cosmic-ray neutrons, muons and gamma rays for non-invasive soil moisture estimation by Gianessi et al. https://doi.org/10.5194/gi-2022-20

Author Response to Reviewer #1

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

RC: The authors present a novel set of experiments using a new sensor to simultaneously measure neutrons, muons, and gammas. The new sensor is compared to conventional sensors with satisfactory results for longer time periods of integration (i.e. 6 hrs for neutrons). The technology is lighter and potentially a lower cost, which will open up doors for more applications in science and in practical applications. The manuscript is well written and appropriate for the journal. I have a few suggestions that should be addressed prior to publication. Some instances of English grammar and word choice will need to be addressed.

AR: Thank you for the very quick and very positive feedback. All the comments and suggestions have been implemented in the new version of the manuscript as described in the point-by-point response below.

RC: L33: "Runoff generation"

AR: Thanks, corrected.

RC: L 40: "More recently, attention"

AR: Thanks, corrected.

RC: L 44: "has shown"

AR: Thanks, corrected.

RC: Figure 1: Are events outside of the blue and red ovals not included in the analysis?

AR: Figure 1 is only descriptive. The PSD vs. integrated charge plane is the simplest way to show where most of the neutrons and muons lie. In contrast, the actual selection of the events is based on the analysis of statistical outliers over different parameters. The text in the new version of the manuscript has been modified as follows to better clarify this aspect. Please also note that Figure 1 has been replaced to improve the readability.

> Among others, a typical parameter used in this analysis is the so-called pulse-shape-discrimination parameter (PSD), given by the ratio of the integrated charge in the tail of the signal with respect to the total integrated charge. An example is shown in Figure 1a, which shows how different particles (here thermal neutrons and cosmic muons) populate very different regions in the PSD *vs.* integrated-charge plane. For more details on the analysis and on the parameters used for the identification of the single events we refer to more specific studies (e.g., Cester et al., 2016).

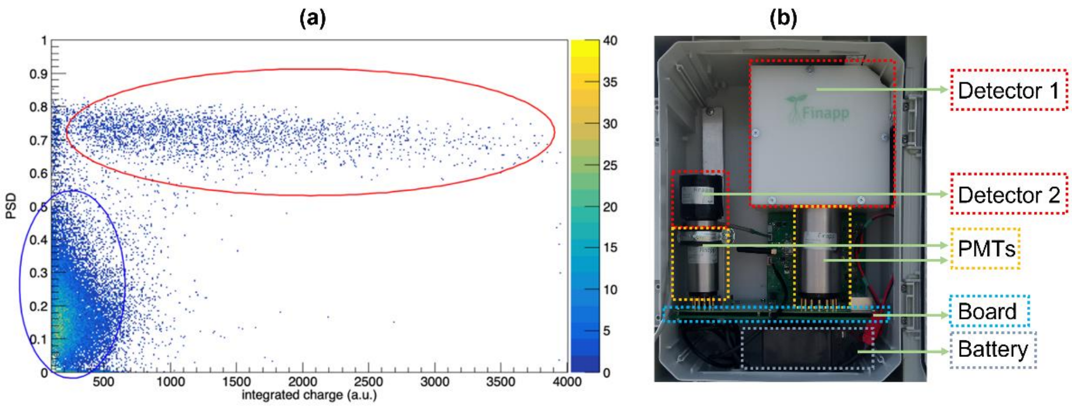

Figure 1. (a) Typical Pulse Shape Discrimination (PSD) *vs.* integrated charge plot for a FINAPP3 detector. Red and blue ovals indicate the neutron and muon region respectively; (b) scintillator-based sensor FINAPP3 with the two main detectors, photomultiplier (PMTs), board, and battery.

RC: L165: For the gammas are there any corrections needed for pressure or air temperature/humidity variations?

AR: Based on current literature (Baldoncini et al., 2018; Serafini et al., 2021; Strati et al., 2018), *gammas do not require corrections for air pressure, air temperature and air humidity. We agree that this has some advantages in comparison to neutrons and we have added this information in the new version of the manuscript. Please note that, based on comments from Reviewer #2, all the discussion about gamma is now placed in a new section "2.5 Assessment of total gamma rays".*

> Noteworthy, the gamma signal should not be corrected for other effects (i.e., air pressure, air temperature and air humidity). For these reasons, it can provide some advantages to the use of neutrons for soil moisture application.

RC: L247: I would use the SG filter on the neutron/gamma count time series, not the soil moisture time series that have been transformed by the calibration function.

AR: Thank you for the suggestion. We did not see relevant differences when applying the filter to the neutron/gamma time series or to the estimated soil moisture. But we acknowledge that the filter could be applied directly to the raw data. We have integrated this information into the new version of the manuscript as follows.

> Before the transformation, the corrected hourly neutron values were smoothed with a Savitzky-Golay filter to decrease the random fluctuations at short time period as suggested in literature (Franz et al., 2020).

RC: L 302-305: This sentence is confusing and long. Please rewrite.

AR: We have received from the Reviewer #2 and from Daniel Rasche (community comment) several comments and suggestions to improve the discussion about the use of muons for CRNS soil moisture estimation. Based on that, we have added in the new version of the manuscript many more details on the detected muon behavior and a comparison to the dynamic measured at a neutron monitoring data base. Accordingly, section 3.3 has been completely revised. We refer to this session of the new version of the manuscript to see the changes that have been integrated.

RC: Figure 7. Will be interesting to compare the Muon detection with the correction factor being proposed by McJannet and Desilets using cutoff rigidity and atmospheric depth with the NMDB historical data. Unfortunately, that work is in the review process still.

AR: Thank you for sharing this ongoing study. We have searched for this publication, and we have seen that the paper has just now been accepted. Indeed, a comparison between this new proposed correction approach and the use of muons would be very interesting. As discussed also in the response to Reviewer #2, our current time series, however, are relatively short and do not capture strong incoming variability. For this reason, we consider this comparison beyond the scope of the present study. In contrast, we have stressed in different parts of the new version of the manuscript that this new sensor design can provide, in a longer term, relevant data that can be used for testing different incoming correction approaches. The reference to the paper of McJannet and Desilets is also integrated in the conclusion. We refer to the new version of the manuscript to see the changes that have been integrated.

RC: Figure 8. So the soil moisture data is from FINAPP and not depth weighted following the Schron method? If you did have gravimetric surveys how would you depth weight them for the gamma sensitivity? From my understanding they would have a similar sensitivity with depth as the neutrons but be a little shallower (10-15cm?)?

AR: *Yes, the Reviewer is right: soil moisture data is from the neutrons from Finapp. This estimated soil moisture is compared to total gammas. We are not aware of analytic functions that have been published to weight point-scale soil moisture data to correspond to gamma signal. However, current literature suggests exponential decreases in both vertical and horizonal direction* (Baldoncini et al., 2018). *So, we agree that gamma should have a similar sensitivity to neutrons but shallower depth and smaller footprint. We have added this information into the new manuscript to clarify how to better compare gamma signals to soil moisture series in future studies.*

> Among others, the weak correlation can be attributed to the smaller horizonal and vertical footprint of the gamma fluxes (<25 m radius, <15 cm depth) in comparison to the neutron (~100 m radius, ~40 cm depth). Thus, a dedicated soil sampling campaign within the theoretical soil volume detected by the gamma particles should be performed for better assessment. An exponential decrease of the sensitivity of the signal has also been suggested in literature in both horizontal and vertical directions (Baldoncini et al., 2018). However, considering that the gamma footprint is strongly affected by the height of the detector installation (van der Veeke et al., 2021), further and more dedicated experiments should be performed to develop specific weighting functions and to conduct a proper assessment.

RC: Table 1. Iwema et al. 2015 recommends 3 calibrations for estimating N0. From the variability here I would do at least 3 to estimate some uncertainty on N0. I agree additional gravimetric studies are needed, particularly for establishing the gamma to soil moisture dependence, especially when used in cropping systems with significant temporal variations in vegetation biomass. Unfortunately, for CRNS and GRS studies all roads don't lead to Rome but to more gravimetric sampling :)

Iwema, J., Rosolem, R., Baatz, R., Wagener, T., & Bogena, H. (2015). Investigating temporal field sampling strategies for site-specific calibration of three soil moisture–neutron intensity parameterisation methods. HESS, 19, 3203–3216. https://doi.org/10.5194/hess-19-3203-2015

AR: *Thank you for the comment and for the reference. We agree that soil surveys still play an important role in assessing calibration functions and validating modelling results. We have integrated this comment and this reference in the new version of the manuscript in section 3.2.*

> Anyway, these results confirm the need to conduct when possible more than one calibration campaign to account for some of these effects as it has been suggested in literature (Heidbüchel et al., 2016; Iwema et al., 2015).

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Strati, V., Albéri, M., Anconelli, S., Baldoncini, M., Bittelli, M., Bottardi, C., Chiarelli, E., Fabbri, B., Guidi, V., Raptis, K.G.C., Solimando, D., Tomei, F., Villani, G., Mantovani, F., 2018.

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Testing a novel sensor design to jointly measure cosmic-ray neutrons, muons and gamma rays for non-invasive soil moisture estimation by Gianessi et al. https://doi.org/10.5194/gi-2022-20

Author Response to Reviewer #2

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

RC: The study presents a new sensor system to monitor epithermal neutrons, cosmic-ray muons, and total (i.e. non-spectrometric) gamma rays all in one device. The novelty of this work is not only the individual technology of the three components, it is rather the combination of them and its potential for research and applications. Hence, it is important to demonstrate that each of the three signals can be reliably and simultaneously measured, and how they can be used for the greater good.

The neutron measurements seem to correlate well with traditional neutron detector signals, at least the scale of several days to months. Although the idea of correcting incoming neutron radiation with local muon measurements is not yet established and still an active field of research, the presented sensor may provide a fantastic opportunity to collect a large data set that could help to falsify this hypothesis in the future. The rather high RMSE of soil moisture calibration data and neutron products (up to 10 m3/m3 , Fig 5) is not a big issue, since every neutron probe would probably see similar deviation considering the substatial spatial heterogeneity, biomass, etc. I highly appreciate the elaborate discussion of influencing factors led by the authors.

A major weakness of the study is that no muon data was shown and comparisons to existing muon and gamma data sets are missing. This hinders proper falsification of these two measurement approaches. Many claims made in this study require better rigorous support. If possible, I'd suggest to add data to the study that provides evidence of the proper functioning of all three detectors, since it is key to covince the readers about the reliable measurement of three different particles at once.

The work is highly relevant to the journal and will have a great impact in the science community. However, I suggest major revisions to better streamline the focus of the paper on falsification and evaluation of the three components, of which muons and gammas are yet insufficiently addressed. The detailed comments below could help to quickly address the missing pieces before publication.

AC: We thank the Reviewer for the overall positive feedback. On the one hand, the Reviewer highlighted some weaknesses in the study. On the other hand, he/she also gave us very clear details on how these limitations could be addressed. Specifically, we thank the Reviewer who appreciated the comparison and discussion about neutrons, and we agree that, in comparison, the assessment of gammas and muons have been less addressed. As discussed in more detail in the point-by-point response below, in the new version of the manuscript we have improved the assessment of the gammas by showing a comparison between data collected by the FINAPP3 sensor and by a gamma-ray spectrometer. Concerning the muons, we have shown a comparison with the neutron fluxes measured at a neutron monitoring station (e.g., Jungfraujoch), as also suggested in the Community Comment by Daniel Rasche (for details please also see Authors response to his comments). We have also extended the description and the discussion on the use of muons for soil moisture correction. Finally, we have better highlighted that the aim of the present study was not to fully address the use of muons for CRNS correction, but to show that this sensor can provide valuable data to test this hypothesis in future studies. We think that the manuscript has been strongly improved based on all these suggestions and changes and we are looking forward to further feedback.

Major concerns

RC: The authors present a new device which combines three existing measurement principles, but only evaluate one of them with conventional devices (here, only neutron counter vs. other CRNS probes). Since the main novelty is the availability of three detectors at the same time, I would have expected also a validation of (or at least evidence for) the proper functioning of the muon and gamma detectors. This could be easily done with existing gamma ray probes from national authorities, and muon telescopes or the global muon network. Also consider plotting measured muon time series together with Jungfraujoch data to identify differences in their response to cosmic rays.

AC: We agree with the Reviewer, and we thank you for the suggestion to add additional data and analyses for improving the assessment of muons and gammas. For the muon signal, we have integrated the discussion on the muon behavior and its dependences on air pressure and air temperature. Moreover, a comparison with incoming neutron fluxes has been presented and the discussion about the effect on the soil moisture estimation has been improved. For the gammas, a comparison with data collected by a standard gamma-ray spectrometer (https://medusa-online.com/en/) installed at the Ceregnano site has been integrated. The potentiality of this signal for agro-environmental applications has been better visualized and discussed. The new version of the manuscript has been improved and extended accordingly in several parts. We refer to the new version of the manuscript for details and we only summarize below the main changes:

- *In the description of the detector assembly (section 2.1), the capability to discriminate muon and gamma has been better explained and additional references have been cited.*
- *Two new sections have been added: "2.4 Assessment of muons counting rate" and "2.5 Assessment of total gamma rays" with the description on how these signals have been assessed.*
- *In the result section "3.3 On the use of muons for incoming corrections", Figure 7 has been replaced with two new Figures (Figure 7 and 8 below). The text has been extended with the description of the analysis and of the results (see section 3.3). Specifically, to better show the proper functioning of the muon detector, Figure 7 below shows the correlation between the relative muon vs. atmospheric pressure and air temperature at Legnaro site, as example. Figure 8 shows the comparison with incoming neutron fluxes and the effect on the estimated soil moisture.*

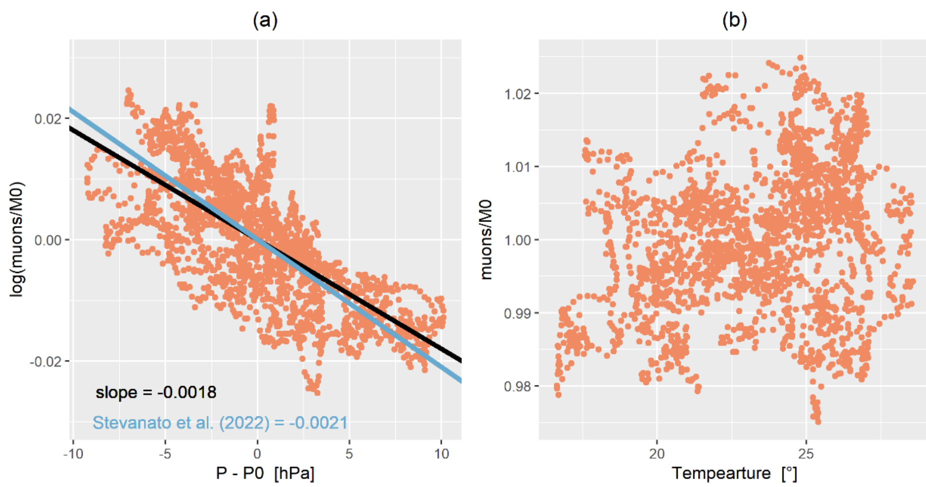


Figure 7. Comparison of data collected at Legnaro site: (a) relative air pressure vs. muon counting rate; (b) air temperature vs. corrected pressure muon counting rate.

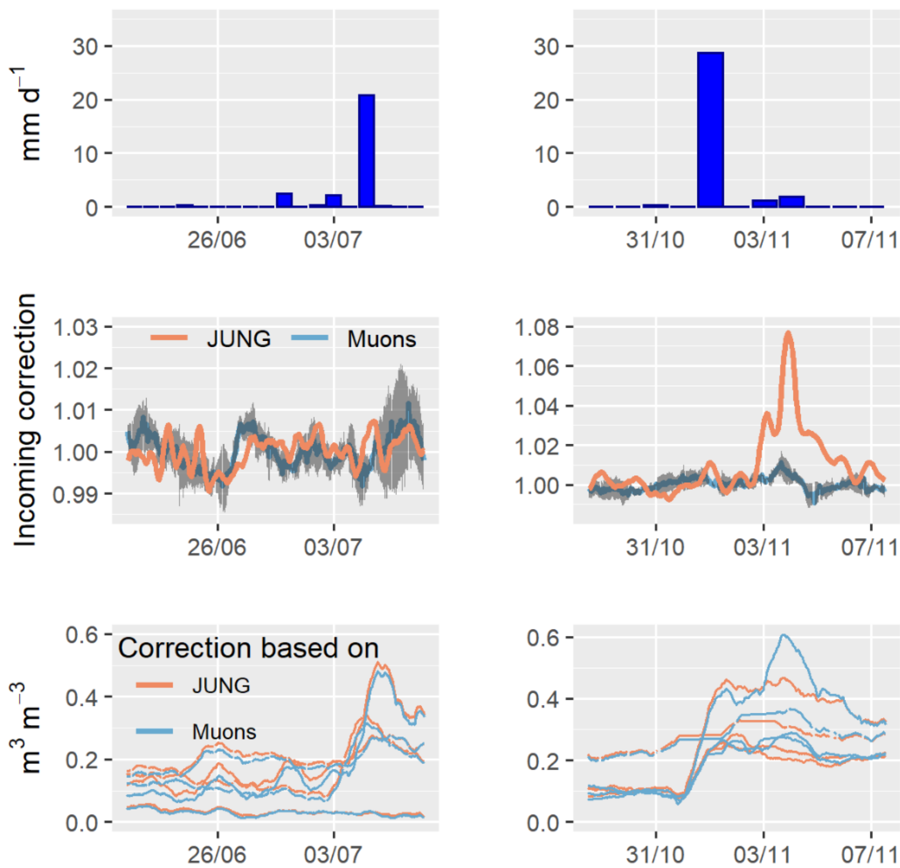


Figure 8. The plots in the top row show the average precipitation over the four Italian experimental sites. The plots at the middle row show the incoming correction based on neutron monitoring station (JUNG) and based on the average muon detected at the four experimental sites. Standard deviation is also shown in grey area. Bottom plots show estimated soil moisture using the two different approaches for the incoming correction of the signal: based on the standard approach of data from neutron data base (e.g., JUNG plotted as orange line) and using locally detected muons (blue line).

- *In the result section "3.4 Assessment of measured total gamma rays", Figure 8 has been replaced with the new Figures 9 and 10 below. The discussion has been extended accordingly. Specifically, Figure 9 shows the correlation between total gamma counts measured by FINAPP3 and by the gamma ray spectrometer Medusa at different integration time (1 hour and 6 hours, respectively). Figure 10 better visualizes the use of the gamma signal to discriminate precipitation and irrigation events.*

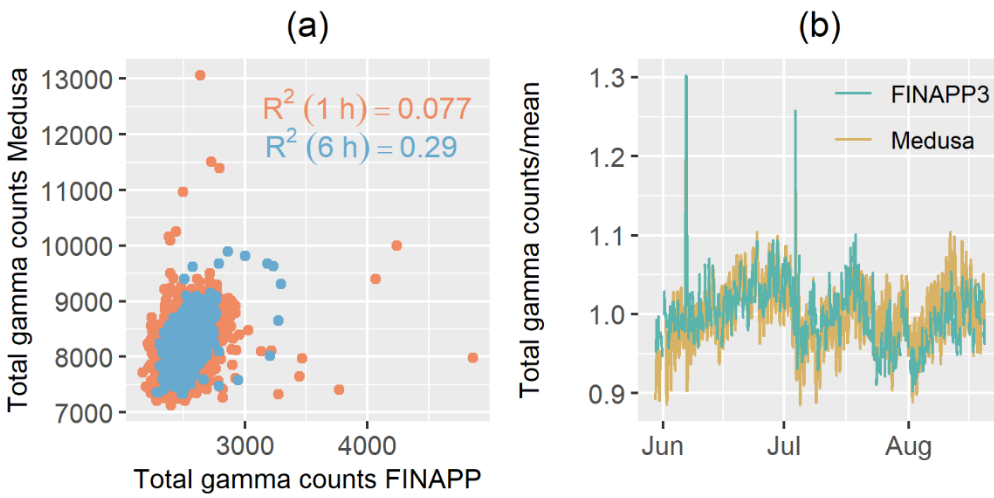


Figure 9. Comparison between total gamma counts measured by FINAPP3 and Medusa gamma-ray spectrometer.

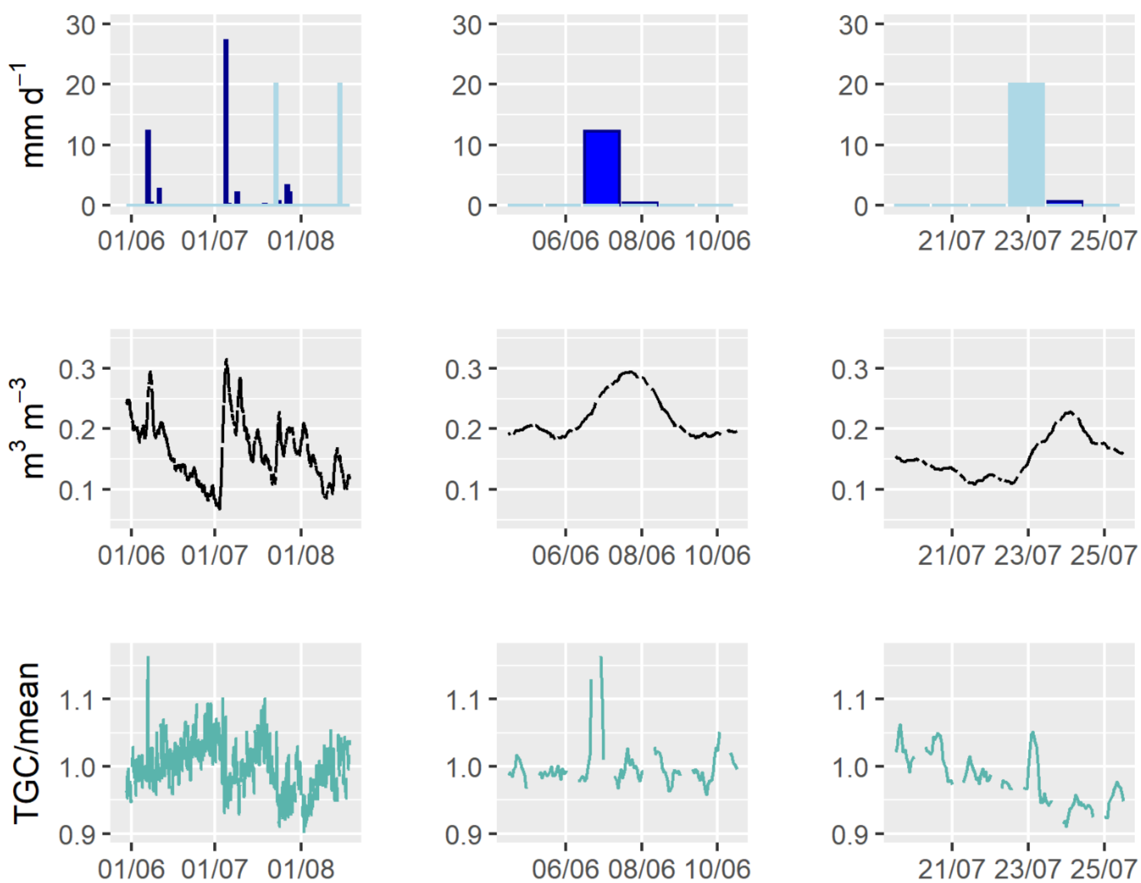


Figure 10. From top row, precipitation (blue) and irrigation (light blue) (mm d^{-1}), volumetric soil moisture estimated by FINAPP3 (m^3 m^{-3}) and total gamma counts (TGC) over the mean of the monitored period.

RC: Muon processing is a bit vague.

AC: we have improved the description of the muon processing. We refer to the new version of the manuscript for details and we go through the Reviewer's comments to highlight the main changes.

Why is there no correction for atmospheric humidity on the muon signal?

AC: as reported in literature (de Mendonça et al., 2016), *muons are affected by pressure and air temperature. The effect of relative humidity has been investigated less, due to the absence of a relationship between the two variables as suggested by some researchers* (Dorman, 2004; Maghrabi and Aldosary, 2018). *However, we cannot exclude this effect and we will also add this statement in the new version of the manuscript (see section 2.4).*

Where do you get the temperature data from? Local near-surface temperature is probably not suited to represent temperature effects in the upper atmosphere.

The temperature has been measured at 2 m height. We agree that temperature measured at the high atmosphere (or the whole air temperature profile) should better account for this effect. Some studies found however that also local near surface temperature can be a good proxy (de Mendonça et al., 2016). *We are currently using this approach, but we acknowledge however that further comparisons are necessary to provide better quantification of the related uncertainty. This information has been added in the new version of the manuscript (see section 2.4).*

The authors also mention that long-term local time series have been used to estimate the parameters, but the data is not shown and as they cite Stevanato et al, it is not clear whether this is valid for both, the German and the Italian sites.

AC: we extended the assessment of the muon signal by showing relation with air pressure and air temperature. See Figure 7 (above and in the new version of the manuscript). The muon-pressure relation agrees with previous study (Stevanato et al., 2022). *In contrast, the pressure-corrected muons relation does not identify a clear effect. This can be explained by the relatively small temperature range measured over the period (± 5°). For this reason, in the present study we use the parameters for pressure and temperature corrections that has been derived and presented by* (Stevanato et al., 2022). *In that study, the parameters have been extracted by the analysis of the one-year muon data series taken in Padova (Italy), from November 2019 to October 2020. The sensor location is within a distance of around 200 km from our experimental sites and at similar altitude. For these reasons, we assumed in the present study that the parameters are valid. In contrast, we did not use muons correction for Germany and Austria sites where we agree that differences could be relevant and locally adjusted parameters would be preferrable. This discussion is added in the new version of the manuscript. See section 3.3.*

RC: The authors present excellent agreement of their neutron data with conventional neutron detectors during 6 months. However, it is the short-scale effects which are particularly interesting, e.g. the coincident response to the onset of rain events, to dew formation, to atmospheric variations, to drying periods, etc. They could be different if detection energy or geometry differs, and could eventually shed light on the actual sensor performance. This is not identifiable from the presented data, at least not with the long x-scale chosen in Fig 4. I'd appreciate if the authors could provide a zoom-in of the data that allows for day-to-day analysis and comparison.

AC: Thank you for the suggestion. We have added in the new version of the manuscript the new Figure 4 below with a zoom-in of the data during a fast drop of the neutron signal to better highlight the short-

scale differences. Please only note that we have shown corrected neutron data and not derived soil moisture dynamic because the aim is to compare the performance of detecting neutron by the different detector. The discussion of the results has been extended accordingly (see section 3.1).

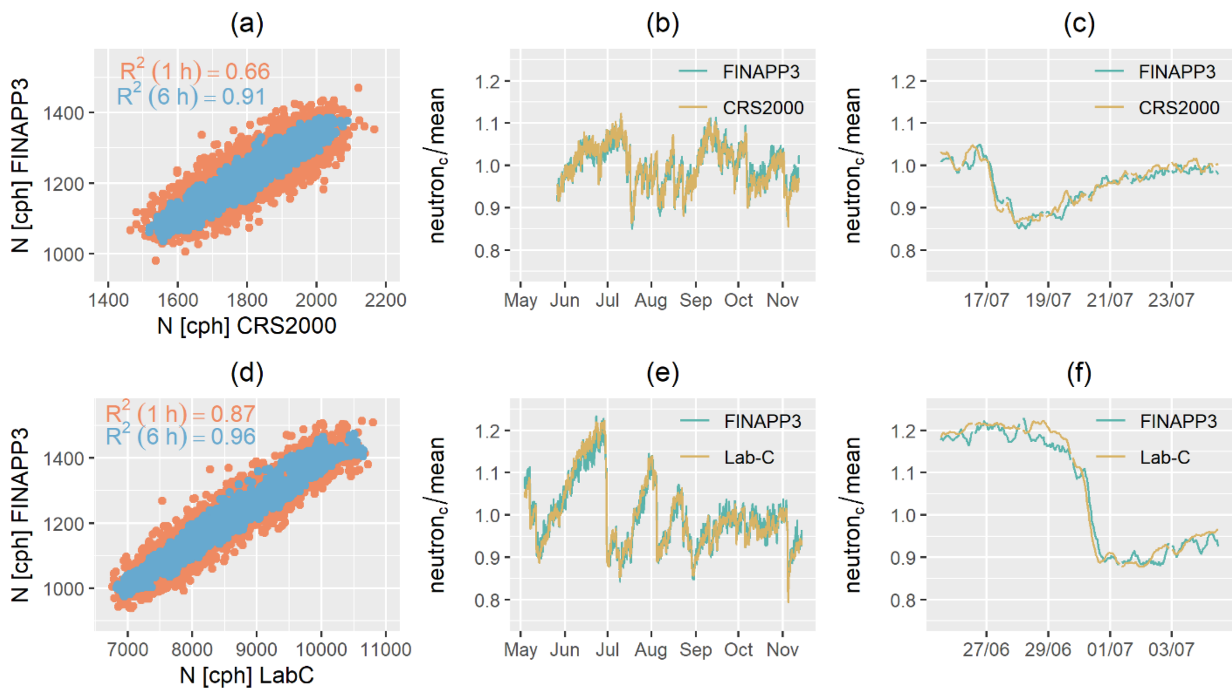


Figure 4. Comparison of measured neutrons at Marchfeld site, Vienna, Austria (top row) and Marquardt site, Potsdam, Germany (bottom row) by the two different sensor pairs (CRS2000 and FINAPP3; Lab-C and FINAPP3). Plots (a) and (d) show the hourly values in orange and based on a running average of 6 hours (blue). Plots (b) and (e) show the neutron fluxes corrected for air pressure and with a running average of 6 hours. The relative counts over the mean are shown for comparison. Plot (c) and plot (f) show a zoom-in during a fast drop of the neutron counts.

RC: The authors argue that Jungfraujoch data "completely fails" in correcting neutrons. However, a single evidence is only visible for one (the second) out of many precipitation events (Fig 7). And only in San Pietro, while in Legnaro the performance of Jungfraujoch looks ok, i.e. a small increase of soil moisture is still evident for the small precipitation event. Unfortunatelly, other sites were omitted. And since no measurement of actual soil moisture is presented, any improvemtent of the muon correction over NM correction remains just speculation. It is necessary here to show either additional soil moisture data, or muon vs Jungfraujoch data, or muon vs global muon database data, and to discuss any other influencing effects, such as high atmospheric temperature. Alternatively, rephrase the claims of this study to be more speculative and subject to future work.

AC: we agree with the Reviewer, and we have removed that sentence and reshaped the discussion. Specifically, we better emphasized in the new version of the manuscript that we cannot be conclusive with the use of muons within the present study. In contrast, we agree that the use of muons for CRNS soil moisture is at the early stage and only more data and studies can shed some light on the topic. The time series collected during this study are also relatively short for testing this hypothesis and we consider the assessment of the muon correction beyond the scope of the present study. See changes in 3.3 and in the conclusions. Still we agree that a direct comparison with incoming neutron fluxes from, e.g., Jungfraujoch is valuable also in this study. Figure 7 has been replaced with two new figures (see new

Figures 7 and 8 in the manuscript and reported also above). The discussion has been extended accordingly. See section 3.3.

RC: A better description and discussion of the gamma detection mechanism is missing beyond "0.3-3.0 MeV". How is the signal separated from unwanted gamma rays (e.g., from other energies, or from the detection products from the reactions in the adjacent detectors)? Is there an energy response function? What type of reactions are visible in this range beyond K, Th, and U, and what could be their source or influencing factors other than water accumulation? How is the instrument different from typical gamma-ray sensors used by national authorities or by Strati et al? How does the weak correlation to soil moisture compare to literature values?

AC: Thank you for the suggestion on how to improve the description and the discussion of the gamma signal. Accordingly, we have modified the manuscript in several parts. Description of the gamma detection is now better described in section (2.1). However, we also highlight that the gamma detection is based on a commercial scintillator. Thus, we believe that it is beyond the scope of the present study to present much more details. Instead, some new references are added. We have also added a new section (2.5 Assessment of total gamma rays) where we describe how we assessed this signal. Section 3.4 has been revised accordingly with extended discussion.

Minor concerns

RC: Multiple use of the word "good" to describe the performance of the sensor (L45, L69, L70, L73, L230, 253). In a scientific publication -- in contrast to advertising material -- it is necessary to more concretely measure the performance, provide quality statistics and an uncertainty assessment. Sometimes numbers were given in the figures, but mostly missing in the text.

AC: thank you for the suggestion. We have modified the discussion first presenting some performance metrices followed by a more general discussion. Please see the changes in the results sections of the revised manuscript for details.

RC: Improve description of the particle detection mechanisms and modules used, see comments below. Remember that your audience is GI.

AC: The description has been extended. Please see the changes in the results sections of the revised manuscript for details.

RC: Improve language to be more scientific and more concrete (not just "special property", "easily detect", "considred reliable", etc), see comments below.

AC: we have rephrased several statements to be more concrete. We refer to the changes in the new version of the manuscript for details. Some specific changes are listed below.

RC: The authors claim to describe the "current state of the art of data processing", while sometimes they are missing out relevant and newer literature (see specific comments below). If the authors do not want to update their processing procedures with newer (but admittedly less established) methods -- which would be ok -- at least the above statement should be removed or properly discussed why the provided approaches were used.

AC: Thanks. We agree and we have removed the statement.

RC: The above comment is particularly relevant as the soil moisture presented in Fig 5 sometimes goes below zero, which is a common artefact of the Desilets et al 2010 approach, for instance.

AC: Thanks for the comments. The following statement has been added in the discussion of the soil moisture estimation (see section 3.2).

> The use of more recently proposed soil moisture-neutron relation could also be tested to see possible compensation for these effects (Köhli et al., 2021).

RC: The authors seem to advertise a new excel tool to support CRNS calibration and data processing (Baroni et al 2022). Has it been peer reviewed elsewhere? I would reject to publish it as a supplement to this work, since it is very general and out of scope here, and explanation of the methods used were not given in the manuscript.

AC: we consider good practice to share the tools that have been used to process the data, when possible. The tools, in these cases, are two spreadsheets that have been developed to process soil samples and neutron data. The tools integrated the methods cited in the manuscript and proposed by other Authors (Schrön et al., 2017). *For these reasons, we do not claim that these are new tools but Readers are welcome to check and use them. We also acknowledge that these tools could be considered by Readers as a starting base for CRNS data processing but we also already cited in the first version of the manuscript more advanced tools in case Readers have bit more computer skills* (Power et al., 2021). *We have rephrased the statement in the manuscript to avoid misunderstanding as follows.*

> The data processing described above has been implemented in a simple spreadsheet available from (Baroni, 2022). For a more advanced data processing integrating also additional external data-sets readers can refer to (Power et al., 2021).

RC: The authors argue that a dedicated soil sampling campaign should be conducted to the evaluate gamma-ray data. However, the soil sample campaigns performed for neutron calibration were partly taken in <25 m distance, I suppose from looking at Fig 3. Wouldn't this be helpful to evaluate the gamma footprint?

AC: yes, the Reviewer is right that we have collected samples at short distance that might be used for the assessment of the moisture-gamma relation. However, we still believe that this analysis would require some more insight on the signal response to environmental conditions and the data collected are limited or difficult to compare. Specifically, a soil moisture-gamma relation has been derived in literature but only for 40-K or Tl-208 peaks (Baldoncini et al., 2018). *So, most likely the comparison of these relations with our measured total gamma counts is misleading. Moreover, the sensitivity of the signal has been found to decrease exponentially (horizontally and vertically) with a strong dependency to the height of the installation of the sensor* (van der Veeke et al., 2021). *No analytic functions have been proposed however as far as we are aware. For this reason, a direct comparison with point-scale soil moisture is not straightforward. Moreover, few field studies have been reported in literature about the use of gamma for soil moisture estimation. For this reason, we think that a greater number of samples over short distances and more campaigns should be performed to test this relation. Some modelling scenarios should also be performed when possible to provide some new insights and support the empirical results. For these reasons, we believe that this analysis is beyond the scope of the present study, and it has not been integrated in the new version of the manuscript.*

Instead, in the new version of the manuscript, we have focused the discussion on the description of the data collected and we have added the quantitative comparison to a gamma ray spectrometer (Medusa).

The signal is further described in comparison to the environmental conditions (precipitation, irrigation and neutron derived soil moisture). The discussion has been extended accordingly. We refer to the changes in section 3.4 of the new version of the manuscript for details.

RC: The authors mention that the use of gamma rays for soil moisture estimation would "require additional refinements". For sure, this would be capabilities of a spectrometer, since total gamma rays are not well correlated as this study and as other literature has shown. Are spectrometric capabilities possible in future improvements of this device?

AR: Yes, it is possible to substitute the current standard plastic detector with an inorganic scintillator like NaI(Tl) to get a spectrometric response at a fair price. More expansive detectors with better spectroscopic features (like LBC) could also be considered. It should be evaluated however if a dedicated sensor would be better instead of a composite sensor like FINAPP3 type. No upgrade of the FINAPP device has been currently developed.

RC: Fig 8 shows only a short period of gamma data, shorter than the presented neutron data. So, is the measurement of three particles not simultaneous during the full period? If yes: isn't this the main key or if no, why not showing everything?

AR: Gammas are measured simultaneously by the sensor. Some data, however, have been lost due to setting in the electronic board and remote sensing transmission issues. These issues were fixed at the beginning of the experiments, but some data have been deprecated. For this reason, neutrons time series in figure 8 starts earlier than gamma's. Muons suffered the same problems. This information has been added in the new version of the manuscript. We refer to the new version of the manuscript for details.

Specific comments

RC: L32: replace "correct" by "reliable" or "accurate".

*AR: thanks, we have replaced with "*accurate*".*

RC: L47, L51: the correlation is "negative" rather than "inverse".

AR: thanks, we have replaced with negative.

RC: L45-46: the citations list appears random, at least try to briefly explain which author found what and to what degree of certainty (not simply "good performance"). Use citations to concretely support your statements.

AR: thanks, we have arranged the citations by land-use and hydrological conditions. We believe there is no need to summarize more details about the results in each study but Readers are pointed to the specific paper for details.

RC: L48: "favourable" compared to what?

AR: thanks, we have rephrased in: "providing the base for monitoring"

RC: L47: try to cite literature that actually decribe the physical process of neutron-hydrogen interactions.

AR: thanks. Here we rephrase organizing the studies with the focus on soil moisture, biomass and snow applications.

RC: L51: replace "noise" by "nuisance"

AR: thanks, corrected.

RC: L54: rephrase or reorder: "1979" is not "decades later" than 1966, 2001, and 2021.

AR: Thank you. Corrected with "some years later".

RC: L60: add Köhli et al 2015 for up-to-date literature on the footprint.

AR: Reference has been added. Thank you.

RC: L63: what us "water management and assessment" and how do those cited papers contribute to it? Add also Evans et al 2016 for a reference to Cosmos-UK with regards to your mentioned national networks.

AR: thanks, we have also added Evans et al. that is indeed a good example of how CRNS network can be integrated for supporting water management and assessment. We believe it is beyond the scope of the paper to explain in more details how soil moisture observations can contribute to water management and assessment.

RC: L84: Use concrete and scientific language: how are scintillators "safer" than He-3?

AR: thank you. The term "safer" was intended to be related to boron 3 fluoride proportional gas tube. But we agree that the sentence was not clear and has been rephrased as follows.

> The main advantages are the use of cheaper and safer materials than proportional gas tubes based on helium-3 or boron trifluoride, respectively.

RC: L85: Use concrete and scientific language: how are scintillators "relatively compact" compared to He-3 tubes?

AC: thank you. The sentence has been rephrased as follows.

> Moreover, the flexibility in manipulating the detecting material (e.g., thin layers) allows to optimize the sensitive area and to develop relatively efficient but compact sensors.

RC: L87: Use concrete and scientific language: what is a "special property"?

AC: thank you. The sentence has been rephrased as follows.

> The scintillator materials used for neutron detection, in particular, have the unique property in comparison to inorganic scintillator to release the light in different ways when hit by different particles.

RC: L104: "easily detect", ok it is easy, but how exactly is the detection mechanism?

AR: the description of the detection mechanism has been extensively revised. We refer to section 2.1 of the new version of the manuscript for details on the changes.

RC: L106: this would be a good place to reference Fig 1a.

AC: thank you. We have added the reference to the figure here.

RC: L116-118: rephrase, as the paragraph is very unspecific and it is not clear what value the citations have provided. Please try to elaborate more on it, or remove the sentence. At least add "among others" to indicate an incomplete list.

AC: We have removed the sentence to avoid misunderstanding. Thank you.

RC: L118: rephrase "current state of the art" (see minor concerns above), as incoming correction does not account for rigidity (L125, Hawdon et al 2014), humidity correction ignores higher-mode dependency on soil moisture (L126, Köhli et al 2021), constant N0 ignore biomass dependency (Baatz et al 2014), and the neutron-moisture relationship might become invalid under dry conditions (eq 5, Köhli et al 2021). Not all of the approaches must be used here, as some have not been established yet, but the present approach should not be called "current ..."

AC: We have removed the sentence to avoid misunderstanding. Thank you.

RC: L130: note that it is risky to take mean values as references since they would change with every change of measurement period and are not transferrable to other places and times. Consider using constant values, e.g. from Bogena et al 2022.

AC: thanks for the suggestion. For the purpose of the current study the use of mean or a specific value would not affect the results. But we agree that for, e.g., an operational soil moisture network the use of constant values should be adopted. We have changed as follows:

> *href*, *pref* and *Iref* are reference values (here the average is taken) of air pressure, absolute air humidity and incoming neutron flux during the measuring period, respectively.

RC: L136: since you refer to data processing procedures used at various sites in Europe, it would be a good place to cite Bogena et al 2022.

AC: Thank you. We have added this reference here.

RC: L148, rephrase "has been shown to be an alternative", since Stevanato et al may have provided first evidence, but final proof is still missing. Your new sensor could certainly contribute to collecting more data to better investigate this hypothesis in the future.

AC: Thank you. We agree that the use of muons for CRNS correction is at the early stage and we are not conclusive with the data collected within this study. But we appreciate the comment that this type of sensor can contribute to collect more data to better investigate this hypothesis. The sentence has been rephrased as follows and we have integrated this discussion in the new version of the manuscript. Please also see conclusion section.

> The use of muons has been shown to be a possible alternative to the use of the neutron monitoring stations for incoming correction since they are produced from the same cascade as

> cosmic-ray induced neutrons in the atmosphere (Stevanato et al., 2022).

RC: L149: be more careful here, you are presenting a new measurement method, but you cannot claim that this methodological approach actually works. Please discuss potential effects of atmospheric temperature, and suggest further research as this is out of scope here.

AC: Thanks. We agreed and better highlight assumptions, possible improvements, and further tests. See also general comments above.

RC: L157: do you mean air temperature instead of air humidity?

AC. Thank you. Here we refer to air pressure and air temperature. The sentence has been corrected accordingly.

RC: L160: remove second appearance of the link.

AC. Thank you. Corrected.

RC: L171: "this energy region", be more specific please, which region exactly?

AR: the description has been improved as follows.

> For this reason, the gamma-ray signal (i.e., the 40K full-energy peak at 1.46 MeV or, anyhow, in the energies between about 1.0 MeV to 2.5 MeV) shows a negative correlation with the amount of water in the soil and thus this relation can be used to estimate soil moisture dynamic (Strati et al., 2018).

RC: L176: do you mean "total signal" instead of "these signals"?

AR: The sentence has been removed and a new section 2.4 Assessment of muon and total gamma rays" has been integrated with more details about the comparison. Please see the new version of the manuscript for details on the changes.

RC: L198: in the discussion about meter-scale influences on neighboring sensors, add Schrön et al 2018 (GI) and Patrignani et al 2021 (Frontiers) who discussed exactly that.

AR: These references have been added. Thank you.

RC: Fig 2: add distances, meter scales, and more of the surrounding to better support your discussion on nearby influences.

AR: Fig 2 shows the installation of the sensors at Marchfeld and at Marquardt. We did not discuss the influences of the surroundings for these experimental sites. In contrast, this has been discussed for the Italian sites. A new Figure 3 has been integrated in the new version of the manuscript with a better legend and scale. We hope that this will address the comment of the Reviewer.

RC: L195: do you mean "long-term obervations and real-time data transmission"?

AR: thank you. Corrected.

RC: L233: please rephrase, relative to Lab-C?

AR: We have rephrased as follow:

> the relative lower sensitivity of FINAPP3 produced a higher amount of statistical noise when compared to its benchmark (CRS2000 or Lab-C, respectively).

RC: L235: "can be considered reliable", at this point of the text no mesures have been shown. There are measures in the Fig 4 legend, though, which should be mentioned in the text before claiming something reliable.

AR: thanks. We have reorganized the section presenting first the performance measures followed by more general comments. We refer to the new version of the manuscript for details about the changes.

RC: L253: Same as above, please mention and discuss RMSE before calling something reliable.

AR: Thanks. Corrected as before.

RC: L287: consider adding Jakobi et al 2018.

AR: thanks. Reference has been added.

RC: L300: the improvement seems to be only during the second event, not for all "precipitation events".

AR: The discussion of the muons has been completely revised with more details and data as discussed above. This statement has been modified accordingly. Please see the new version of the manuscript for details.

RC: Fig 8: what is the cause of the spike of the correlation plot? Can you add measures such as R squared?

AR: the spike is the wash out effect: the peak in the total gamma radiation generated by the deposition of atmospheric radon during the precipitation events. We have calculated the Pearson correlation coefficient (r =-0.18) to highlight the negative correlation. This value has been added to the new version of the manuscript and the discussion extended as follows.

> the total gamma counts show higher dynamic at sub-daily time scale in comparison to the estimated neutron-based soil moisture and the correlation between the signals is weak (Pearson correlation coefficient r = -0.18).

RC: L331: put concrete measures and uncertainties rather than just "performed well".

AC: we have added the measures also in the conclusion. Thank you for the comment.

Cosmetics

RC: Fig 3: use site names as panel titles instead of in a single legend. Color-blind people cannot identify which panel corresponds to what site.

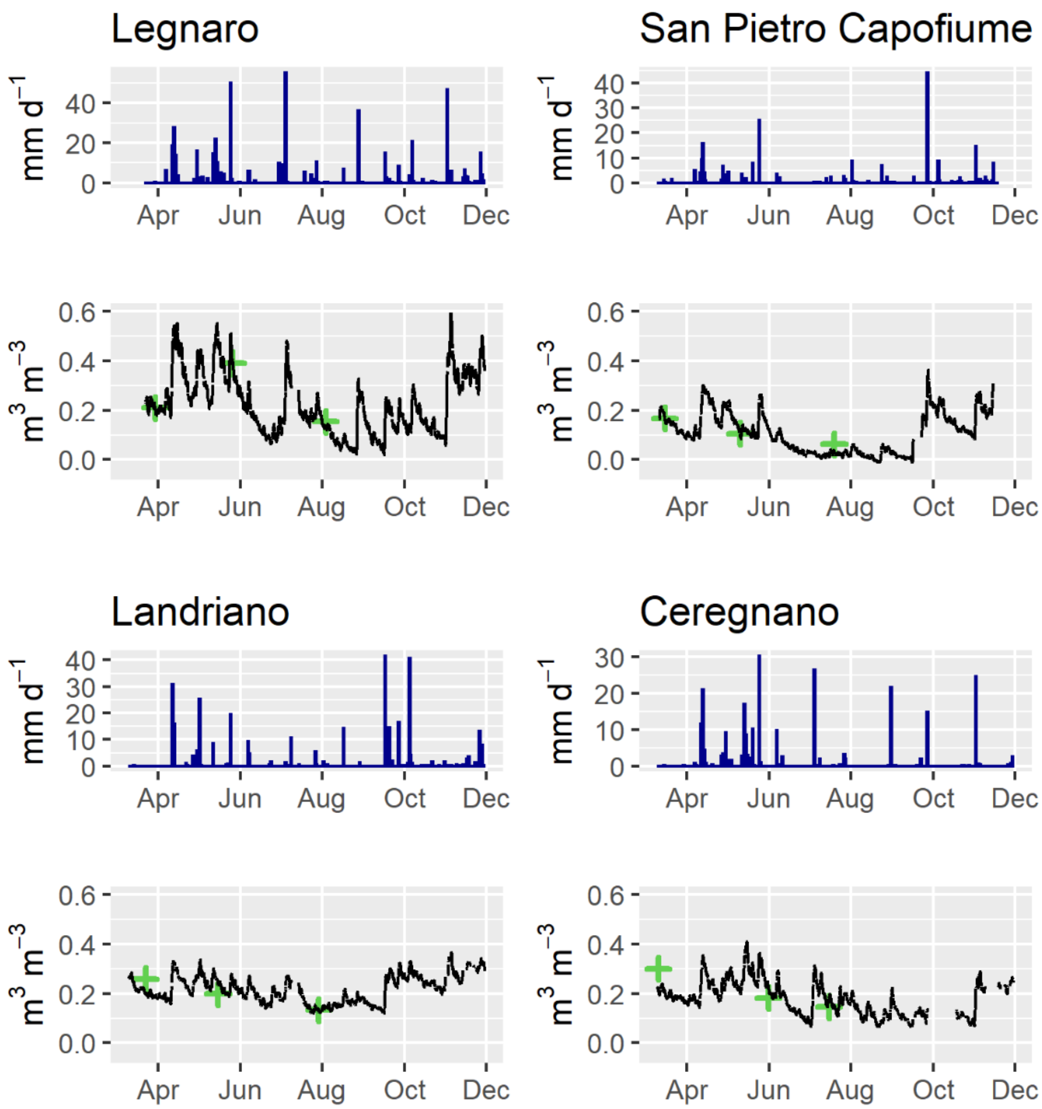
AC: thank you. We have changed the figure as below.

RC: Fig 4: rearrange or relabel, such that a,b are top and c,d are bottom (which is convention). Also, please put a comprehensive ylabel for c,d. In c,d, the two sensors are nit distinguishable for color-blind people, black/white displays or prints, etc. Use HCL color space and colors with different luminosity.

AC: we have changed the figure as shown in the general comment above. Thank you for the suggestion.

RC: Fig 5: use crosses instead of circles to better indicate the exact date and value of the data point. Also consider printing errorbars.

AC: we have changed point shape with crosses instead of circles. The errorbars in the gravimetric soil samples are not added according to a discussion that emerged during the review processes for other papers. Specifically, errorbars can be calculated based on the soil samples. But the values are misinterpreted because Readers tend to consider that as errors instead of showing the spatial variability from the point-scale measurements. The figure should be read as average soil moisture over a certain footprint and the point (cross) represents exactly the average value. In contrast we do not have an estimation of the error of the average soil moisture and for this reason we prefer to not add an error bar.



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Testing a novel sensor design to jointly measure cosmic-ray neutrons, muons and gamma rays for non-invasive soil moisture estimation by Gianessi et al. https://doi.org/10.5194/gi-2022-20

Author Response to Community Comment #1

CC: ***Community Comment,*** *AR: Author Response*

CC1: Dear authors,

I think that combining observations of neutrons for soil moisture estimation, gamma rays for distinguishing rainfall and irrigation as well as muons for correcting neutron observations as suggested by Stevanato et al. (2022) in a single sensor system is very interesting and would be a great advantage from a science and application perspective.

Cosmic-ray neutrons of different energies (e.g. Hubert et al. 2019) as well as muons (e.g. Braun et al. 2009) respond to solar events. As your observation period covers such an event, it poses an excellent opportunity to evaluate the muon data and their use for the correction of epithermal neutron observations. Thus, I suggest to add a time series plot covering the solar event (+/- a few weeks) showing the neutron monitor time series of the closest neutron monitors Jungfraujoch (JUNG) and Athens (ATHN) and the muon data of the four observation sites. A similar response to the solar event would underline the suitability of the sensor's muon product and the suggested correction approach.

Kind regards,

Daniel Rasche

AR: Dear Daniel Rasche, thank you for the comments and for the references. Based on your suggestions and from the comments of Reviewer #2, we have analyzed in more detail the dynamic recorded by neutron monitors (NMDBs) and the muons during our experiments. Figure 7 has been replaced with two new Figures (see Figure 7 and 8 in the new version of the manuscript). The text has been extended with the description of the analysis and of the results (see section 3.3). Specifically, Figure 8 reported also below shows the comparison with incoming neutron fluxes and the effect on the estimated soil moisture, as suggested. We refer to the new version of the manuscript for the new discussion that has been integrated. However, we want to underline also here that it was not the aim of the present study to conclude about the use of muons for CRNS soil moisture correction. In contrast, as discussed also in literature, this approach is at the early stage and only additional data will support this hypothesis and further developments. As also suggested by the Reviewer #2, we show that sensors like the one presented in this study provides an excellent base to collect these new data. We have rephrased any statements that could have been misleading into the new version of the manuscript and better clarified the focus of the present study.

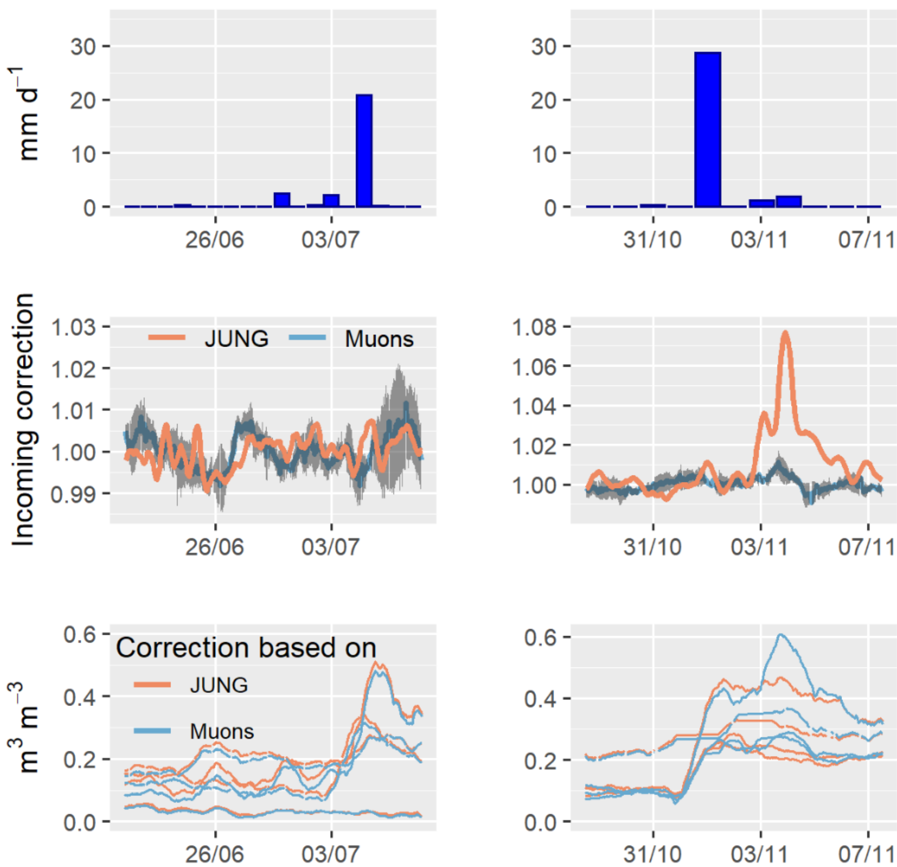

Figure 8. The plots in the top row show the average precipitation over the four Italian experimental sites. The plots at the middle row show the incoming correction based on neutron monitoring station (JUNG) and based on the average muon detected at the four experimental sites. Standard deviation is also shown in grey area. Bottom plots show estimated soil moisture using the two different approaches for the incoming correction of the signal: based on the standard approach of data from neutron data base (e.g., JUNG plotted as orange line) and using locally detected muons (blue line).