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*

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. 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, we will improve the assessment of the gammas by showing a comparison between data collected by the Finapp sensor and by a gamma-ray spectrometer detector. For the muons, we will show the collected data and we will compare the dynamic to 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 will also extend the description and the discussion on the use of muons for soil moisture correction. We will better highlight that the use of muon for CRNS correction will be not fully addressed within this study but, as suggested by the Reviewer, rather that this sensor can provide data to test this hypothesis in future studies. Overall, we will rephrase the sentences to be more rigorous in the assessment. We think that the manuscript will be 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 for comparison. We believe, however, that a proper comparison can only be performed when the sensors are collocated (installed at the same place) to avoid spatial differences in the signal driven by (among others) soil moisture and local atmospheric conditions.

For the gammas, we have data collected by a standard gamma-ray spectrometer (https://medusa-online.com/en/) installed at Ceregnano site. As it is shown below (Figure 1 a), the correlation is low at 1 h resolution, mainly due to the presence of some outliers. The correlation increases at 6 h resolution and the dynamic is well captured (Figure 1b). We will add information on the gamma ray spectrometer and this comparison will be integrated into the new version of the manuscript.

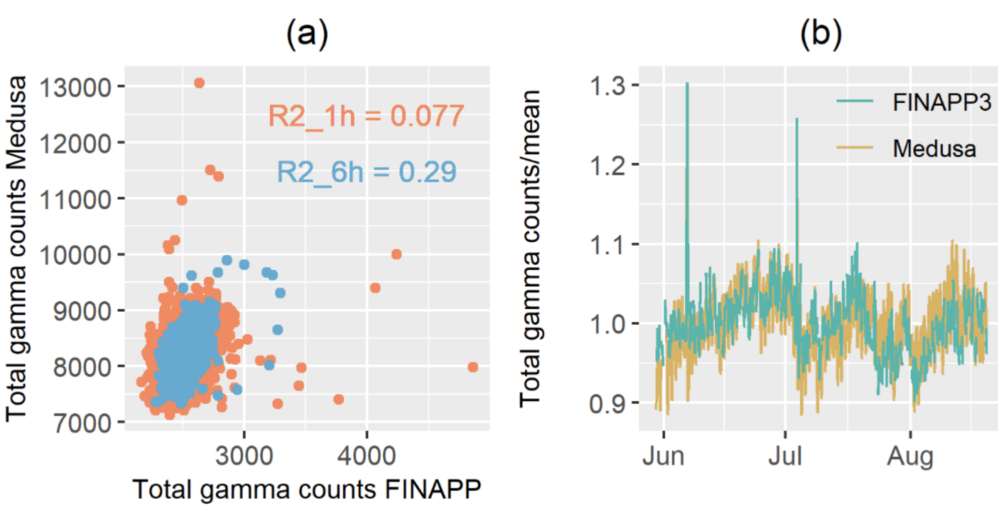


Figure 1. Comparison between total gamma counts measured by Finapp3 and Medusa gamma-ray spectrometer.

The use of the gamma signal to discriminate precipitation and irrigation will be better visualized based on the Figure 2 below: from top, precipitation and irrigation, soil moisture by CRNS Finapp, gammas total counts. The left panels show the increase of total gamma counts during a precipitation event. In contrast (right panels), no such increase has been detected with the irrigation. These Figure 1&2 will replace Figure 8 of the first version of the manuscript.

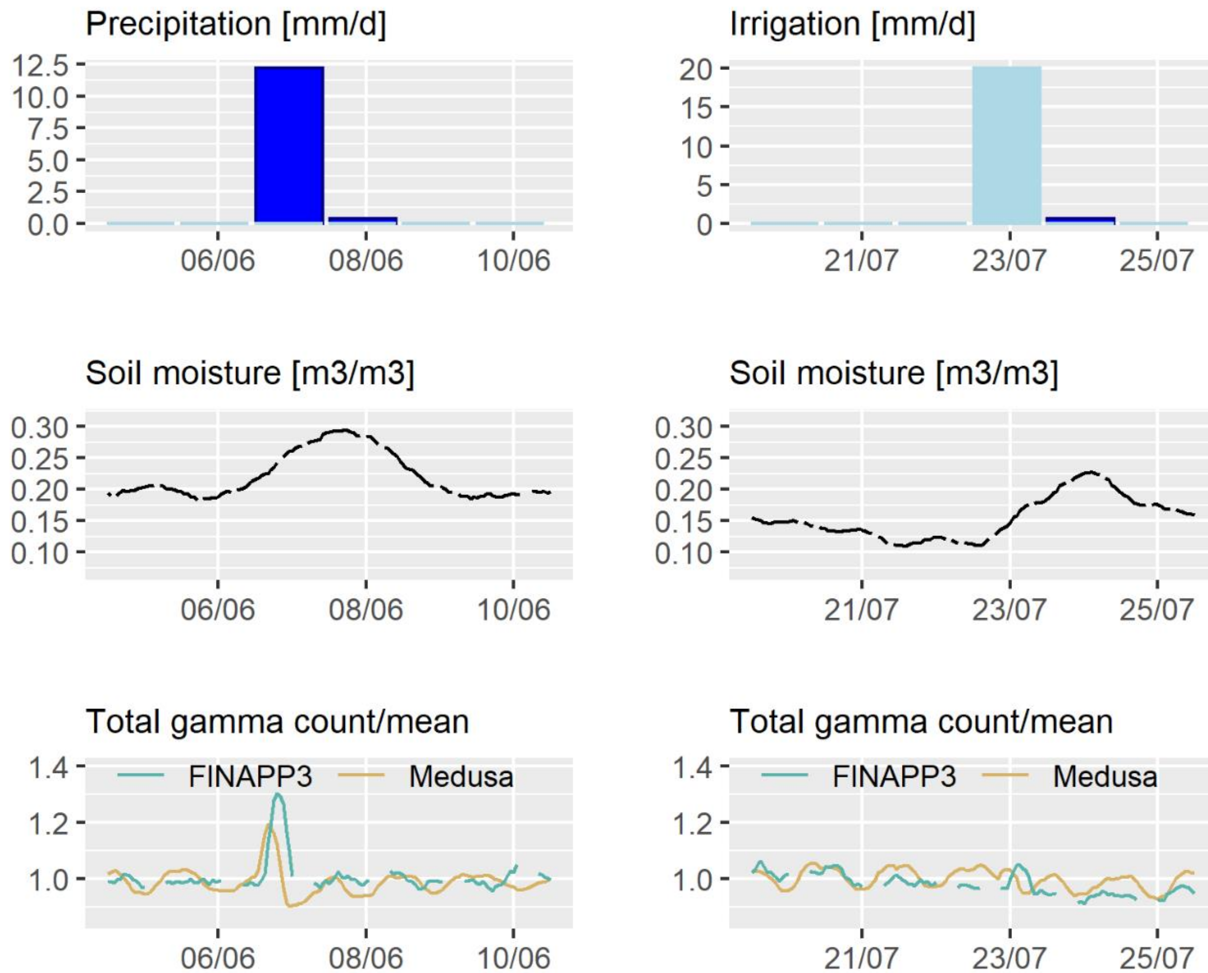


Figure 2: from top, precipitation (left) and irrigation (right), soil moisture and total gamma counts.

Regarding muon detection in the Finapp probe, the possibility to detect muons in the same device which detects neutrons is the subject of one of the Finapp's Italian patents (no. IT102021000003728). This was proven by the comparison with standard muon telescopes (the Finapp probe was used both as single muon detector and as part of a telescope, providing the same identification output results as far as muons are concerned). This reference will be added in the new version of the manuscript.

In contrast, for the present study, we do not have muons measured independently for comparison. Still, as suggested by the Reviewer and by the Daniel Rasche in his community comment, we provide *better evidence of the muons behavior and a direct comparison to incoming neutrons fluxes from neutron monitoring station (e.g., Jungfraujoch station). Based on that, we also better discuss the effect on the CRNS correction.*

Specifically, to better show the proper functioning of the muon detector, Figure 3a below shows the correlation between the relative muon vs. atmospheric pressure at Ceregnano site (but similar results are obtained at the other sites – data not shown). The behaviour shows the inverse correlation that can be removed with an exponential factor (see eq.6 in the present manuscript). Please also note that the slope of this relation is very similar to the value obtained by Stevanato et al. (-0.0021). On the figure 2b below, the relation between muons and air temperature is shown. In this case, however, the correlation is low and it is not possibile to identify a clear relation. The main reason is attributed to the relative short time series and the small temperature range (±5 degree). For this reason, for the current study, we applied the parameters for the muon correction obtained based on the longer experiment conducted nearby presented and discussed in (Stevanato et al., 2022). *The site is located at around 200 km distance from our experimental sites and it has similar characteristics (low land). For these reasons the parameters are considered valid. Still, the representativness of air temperature at 2 m hight is also still under study (see* (de Mendonça et al., 2016)*).*

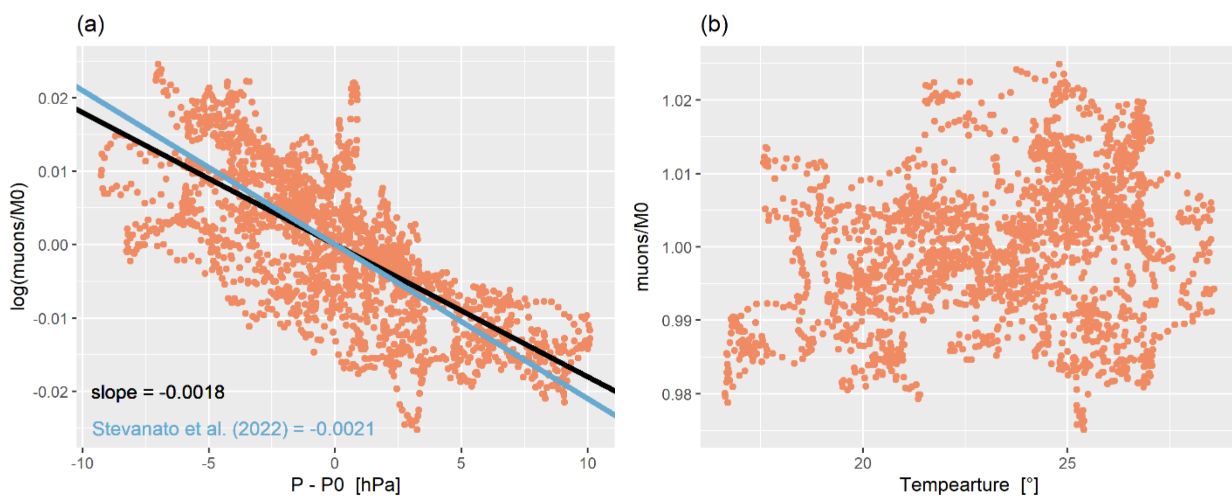


Figure 2. (a) relative pressure vs muon ; (b) Air temperature vs muons.

Finally, Figure 3 below shows the comparison between the incoming neutron flux measured by the neutron monitoring station Jungfraujoch and the Finapp probe muon measurement. The derived soil moisture is also plotted. As it is possible to see, the main fluctuations are clearly visible in both time series. In some periods (e.g., on 16th July), however, a deviation is detected. These differences could be related to the different locations where the detectors are placed. This hypothesis is still under study. However, since the variability is low, these differences in incoming correction do not propagate into significant soil moisture changes. For this reason, the collected data do not support further investigation and we acknowledge the need of longer time series with stronger incoming variability (e.g., years).

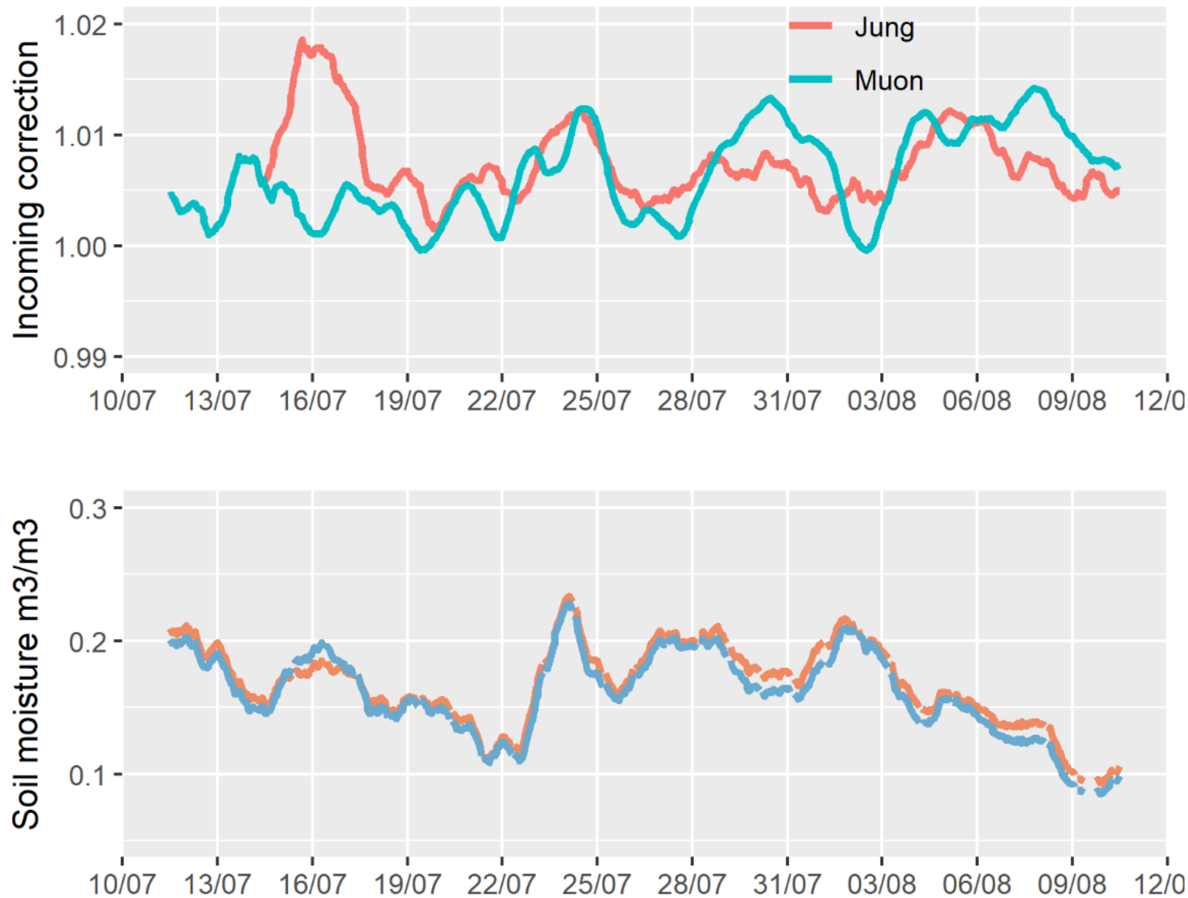


Figure 3: (top) Incoming correction factor based on neutron monitoring data base Jungfraujoch (Jung) and based on muon measured locally (Muon); (Bottom) effect of the different incoming corrections on estimated soil moisture at Ceregnano site.

The main relevant incoming neutron variability is detected on 4th of November. During this period, a fast drop in the incoming fluxes has been detected, producing a 10% increase in the incoming correction. In contrast, the muons have not been affected (see Figure 4 below). At the current stage, we cannot conclude the reasons of these differences but only some hypotheses are formulated.

First of all, currently, the Finapp muon detector has been optimized to follow relative long term variability (weeks to months). The muons count rate is relatively low and we smooth the signal over relative longer time period to remove noise . The muon detector currently integrated in the Finapp probe is also not directional (e.g., as a telescope looking upward) but it measures muon particles that are scattered in all directions. This could produce some differences in comparison to directional detector when these fast and strong events are considered. For this reason, it is under investigation the need of a bigger muon detector to detect such an event that occurs in relatively short period.

Still, it is interesting to note the propagation of these corrections into soil moisture. Specifically, as discussed in the first version of the manuscript and also reported in the figure 4 below, the drop of *the incoming fluxes occurred during a precipitation event that affect most of the Italian sites, even if with different degree. Reasonably, soil moisture should have increased based on that precipitation event. The effect of the incoming correction based on the neutron monitoring station, however, smooth this effect and the soil moisture remains constant or even started to dry down. In contrast, by using the muon signal, the soil moisture is not dumped and rather increases. We fully acknowledge that at the current stage we cannot argue if the correction with muons improves soil moisture estimation or not. In contrast, we believe that the use of muons for CRNS soil moisture correction is at the early stage and this hypothesis should be tested in future studies with, e.g., time series of independent soil moisture measurements. For this reason, we agree with the Reviewer to better highlight in the new version of the manuscript that this type of sensor can provide an excellent data-sets to further investigate this behavior.*

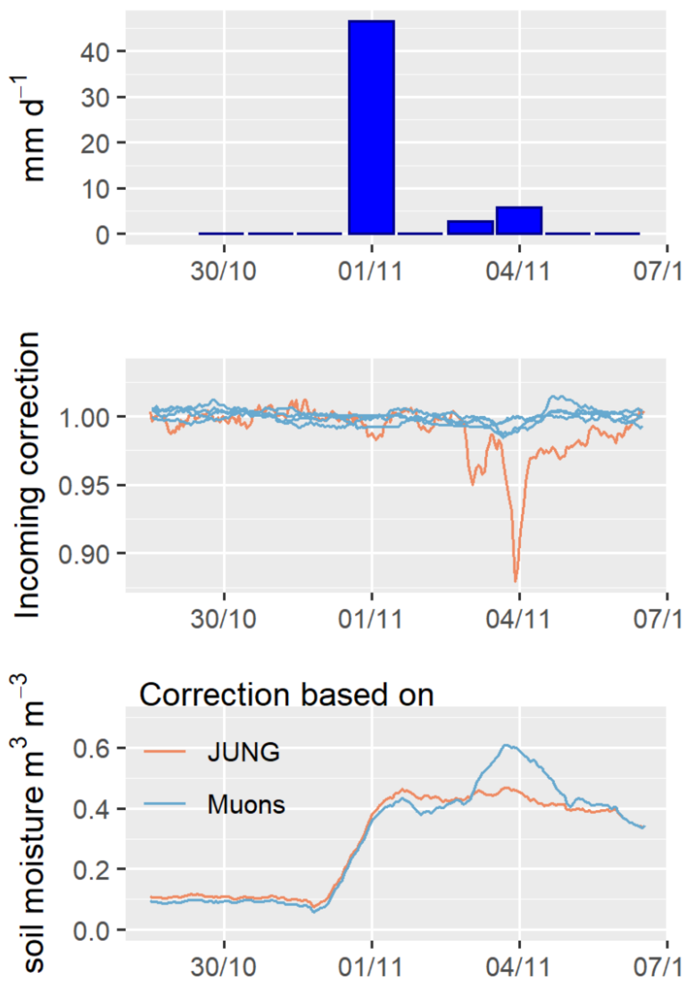


Figure 4. From top: precipitation; incoming variability based on muons measured at the four Italian sites and based on incoming neutrons measured at Jungfraujoch; derived soil moisture at Ceregnano site based on muons and Jungfraujoch incoming neutron correction.

RC: Muon processing is a bit vague. Why is there no correction for atmospheric humidity on the muon signal? 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 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 will better describe the muon processing as discussed below.

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. The pressure can be measured locally and used for correction. In contrast, we agree that temperature measured at the high atmosphere should be used to 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 that has shown to be valid within the requested precision for the soil moisture application. We acknowledge however that further comparisons are necessary to provide better quantification of the related uncertainty.*

Finally, in the present study we use the parameters for pressure and temperature correction that has been derived and presented by (Stevanato et al., 2022)*. 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. In contrast, the data-sets collected and presented in the present study are too small to establish site-specific relations (see also comments above). Moreover, the stations are within a distance of around 200 km 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 will be added in the new version of the manuscript.*

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: for Marchfeld and Marquardt sites we showed neutrons dynamics (and not derived soil moisture) since the aim was to compare the performance of Finapp sensor to more conventional neutron sensor. But we agree that a zoom-in can help understand possible differences and the Figure 5 below will replace in the new version of the manuscript the one in the original manuscript to better highlight the short-scale differences.

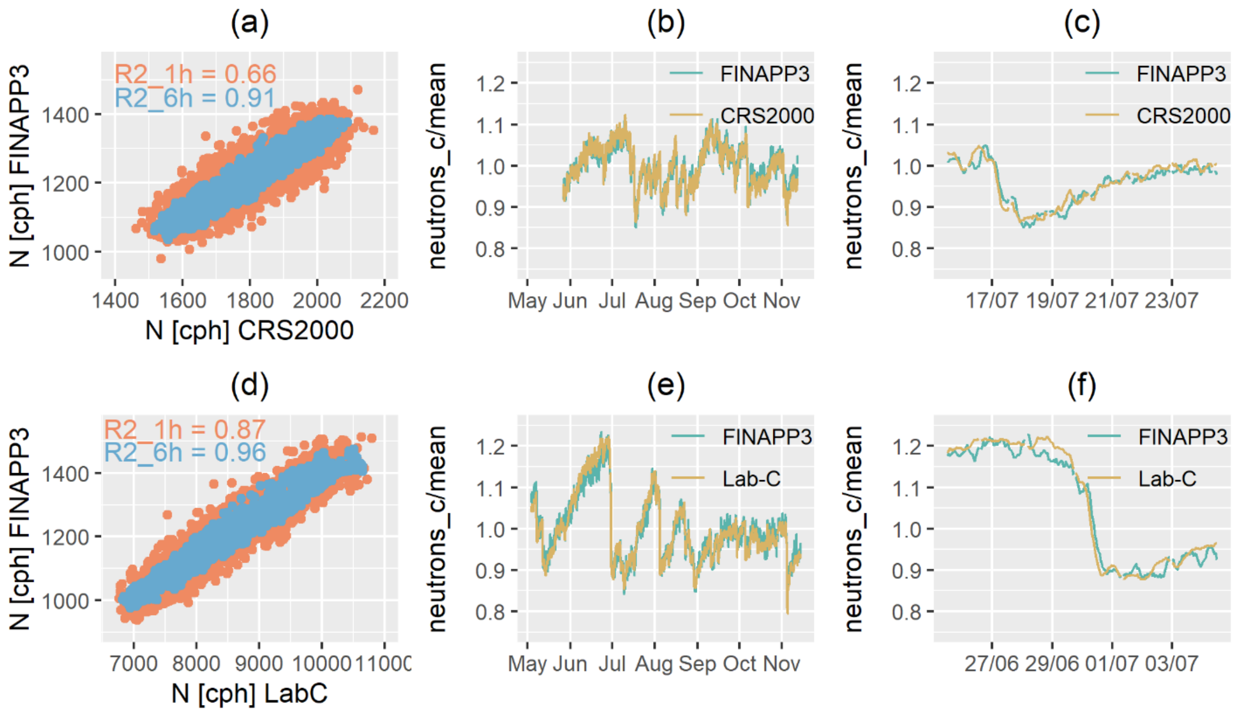


Figure 5. Comparison of neutron measured by Finapp and CRS 2000 at Marchfeld site (upper panels) and between Finapp and Lab-C at Marquardt.

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 that within the present study we cannot be conclusive with the use of muons. In contrast, we believe 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. For this reason, we will better clarify within the new version of the manuscript that the topic is a subject of future work. Still we agree that a direct comparison with incoming neutron fluxes from, e.g., Jungfraujoch is valuable also here. We will add in the new version of the manuscript the figure described above and extend the discussion accordingly (see also response to community comment).

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: the gamma detector of the Finapp3 probe installed at these experimental sites is a standard commercial organic scintillator (EJ-200, from Eljen Technology Inc.). Due to the low effective atomic number Z_{eff}, typical of organic materials, gamma rays interact with the scintillator mainly by Compton scattering providing the typical spectrum shape of the Compton continuum from zero to the Compton edges (see figure 6 below). Compton edge positions allow also for a quite good linear calibration of the energy response.

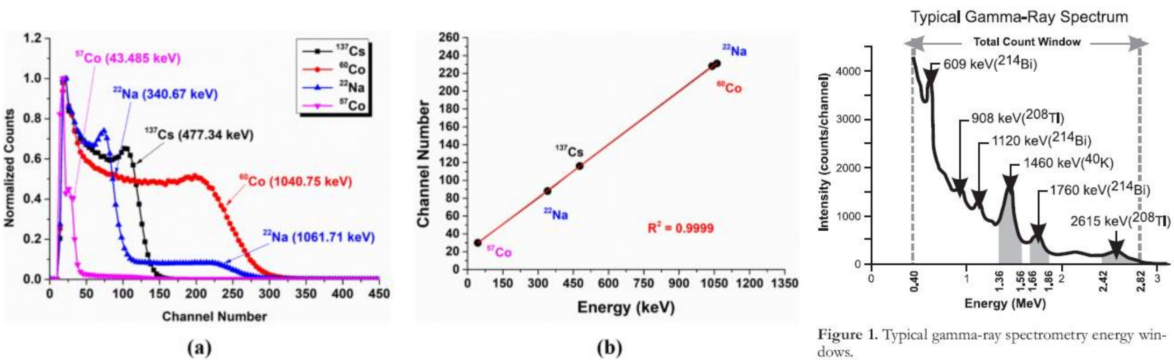


Figure 6 (a and b), typical spectrum plastic scint. from Boo, J., Hammig, M.D. & Jeong, M. Compact lightweight imager of both gamma rays and neutrons based on a pixelated stilbene scintillator coupled to a silicon photomultiplier array. Sci Rep 11, 3826 (2021). https://doi.org/10.1038/s41598-021-83530-4;right typical env. gamma spectrum from K. Ford et al. "Remote Predictive Mapping 2. Gamma-Ray Spectrometry: A Tool for Mapping Canada's North", Geoscience Canada, 35(3-4); https://journals.lib.unb.ca/index.php/gc/article/view/11270

The typical gamma environmental spectrum is shown here above (figure 6 right): basically no gammas are present above 3 MeV. What is seen above this energy range are signals with larger energy deposit due mainly to cosmic muons: being the typical energy deposit about 2 MeV/cm, the average energy deposit of muons in a 2 inches detector is around 10 MeV, well above the gamma region, even when a partial quenching is present, producing a well separated bump in the high energy part of the spectrum. Finally, some counts are present in between the muon bump and the 3 MeV gamma limit. They are peripheral interactions from muons that crossed only part of the active volume. The total yield of these signals is anyhow negligible with respect to the total gamma yield. The manuscript will be integrated with this information to better explain the gamma detection.

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: we adopted a plenary style for the text and left the performance metrices in the figures. But to be more precise, we will also add these values in the text. Thank you for the suggestions.

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

AC: a detailed description of the detection mechanism were explained in (Cester et al., 2016; Stevanato et al., 2019). *However, we agree that for sake of clarity a short description should be integrated also in the present manuscript. Specifically: incoming neutrons (fast) hit the soil and slow down by interacting with hydrogen. A part of them (slow) escape from the soil and can travel up to hundreds of meters before being absorbed. CRNS probes catch these neutrons moving above the soil. In the Fínapp detector, the Li-6 embedded inside the detectors has a large cross section for neutron capture. When a Li-6 nucleus captures a neutron, a nuclear reaction occurs and the compound Li-7 brakes into an alpha particle (He-4) and a triton (H-3) with a large energy release of almost 5 MeV. This energy is converted into light (a flash of optical photons) by the ZnS(Ag) crystals, one of the most common scintillator materials used also in the past in the cathode ray tubes to make the light spot where the electron beam was hitting the screen. Finally, a photo-multiplier tube (PMT) converts the light flash into an electrical signal, acquired by the digital electronics.*

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

AC: we will rephrase to be more concrete. See specific comment below. We will go through the manuscript and check additional text that needs further improvements.

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 will remove 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. We will add that in the discussion and refer to the newer literature for possible solutions.

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 understanding 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 will rephrase the statement in the manuscript to avoid misunderstanding.*

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: as far as we are aware, the footprint for the gammas is smaller (25 m radius max considering the height of the installed sensor). Moreover, while it is expected that the sensitivity of signal decreases exponentially (horizontally and vertically), no analytic functions have been proposed and tested in literature to weights point-scale soil moisture measurements. For these reasons, we did not consider the soil samples as good references for an assessment of the gammas. In contrast, we believe that soil samples at much smaller distances should be collected. This is currently under investigation based on dedicated experiments. Overall, we acknowledge that the use of total gamma counts for soil moisture estimation is not the focus of the present study. In the new version of the manuscript we will focus on the use of this signal for discriminating precipitation and irrigation and we will only highlight in the discussion additional applications that could be assessed in future studies, i.e., soil moisture.

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 Finapp 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 it was not possible to recover the previous data-sets. For this reason, neutrons time series in figure 8 starts earlier than gamma's. This information will be added in the new version of the manuscript.

Specific comments

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

AR: thanks, we will replace with reliable.

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

AR: thanks, we will replace 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 will re-arrange the citation by land-use and hydrological conditions.

RC: L48: "favourable" compared to what?

AR: thanks, we will rephrase 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 will refer to studies focusing on soil moisture, biomass and snow application.

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

AR: thanks, we will replace.

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

AR: we will change decades to years. Thank you.

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

AR: we will replace with this reference. 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 will add the COSMO-UK reference that is indeed a good example of how CRNS network can be integrated for supporting water management and assessment.

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

AR: thanks, 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 can be improved with more concrete and scientific language. We will add information about the material of a scintillator (see specific comment above) *and about the size in comparison to other commercial CRNS probe, and its advantage considering safety considerations in comparison to gas tubes.*

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

AC: see comment above.

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

AR: we use the term "special property" to refer to the different light emission between a classical inorganic scintillator, typically used as spectrometric gamma detector (e.g. NaI(Tl)) and a plastic scintillator with pulse shape discrimination capability. The first one has fixed pulse shape, only amplitude changes proportionally to the energy released in the active volume, while the latter show different shapes depending on the interacting particles (typically lighter particles (gamma/electrons/muons) produce shorter pulses with respect to heavier particles (protons/tritons/alphas/). A pulse shape analysis can be therefore used to identify the type of interacting particle in these particular plastic scintillators. But we agree that term can be misleading, and we will extend the description based on the text above.

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

AR: the scintillator (ZnS(Ag) in this case) converts deposited energy in light, collected and converted into an electrical signal by the PMT. The energy release in the thin layers of the scintillator (a few hundreds of microns) is strong for local interactions coming from the n-Li capture reaction products, while is small for crossing muons and basically negligible for gamma rays. Consequently, the signal from a neutron capture reaction is "easily" detected, providing a large electrical signal, well above the typical voltage threshold used to cut the noise. This information will be added in the new version of the manuscript. Thanks for pointing this out.

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

AC: thank you. We will add the reference 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 will remove 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 will remove 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 will add a comment and the reference here.

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 will add 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 it is beyond the scope of the present study to derive any conclusions. But we appreciate the comment that this type of sensor can contribute to collecting more data to better investigate this hypothesis and we will integrate this discussion in the new version of the manuscript.

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. Yes, thank you. It will be corrected in the new version of the manuscript.

RC: L60: remove second appearance of the link.

AC. Thank you. It will be corrected in the new version of the manuscript.

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

AR: the characteristic 1.46 MeV gamma ray from K-40 decay is seen in a plastic scintillator mainly by Compton scattering interactions and generates therefore a sort of plateau from 0 to about 1.2 MeV, with an increased yield at the high edge (Compton Edge). The gamma counts in the spectrum with energies between about 1.0 MeV to 2.5 MeV came mostly from Compton interactions of K-40, Bi-214 and Tl-208 present in the soil (and therefore are affected by water attenuation). We will add this information in the new version of the manuscript.

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

AR: yes, thank you. It will be corrected.

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 will be 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 surrounding and it is not clear for us the comment. Maybe the Reviewer is pointing to figure 3? In that case the figure will be replaced, and more information will be integrated also based on additional comments that have been provided. See comment below.

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

AR: yes, thank you. We will correct.

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

AR: We will rephrase clarifying that neutron counting rate for Finapp3 is lower than both CRS2000 and Lab-C and thus it has higher statistical noise. Still when the signal is integrated over 6 hours and smoothed, the dynamic is well in agreement. Please note that the figure 4 will be also replaced with a zoom-in to show short-scale dynamics as suggested in the other comment.

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: yes, thanks. We will first indicate the measures and then comments.

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

AR: yes, thanks. We will first indicate the measures and then comments.

RC: L287: consider adding Jakobi et al 2018.

AR: yes, thanks. We will add that.

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

AR: The discussion of the muons will be completed revised with more details and data as discussed above. This statement will be removed and modified accordingly.

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. Please note that based on the overall comments provided also from the other Reviewer, we have decided to focus more on the use of total gamma for showing the capability to discriminate precipitation and irrigation event. In contrast, the use of total gammas for soil moisture estimation will be only mentioned and considered for further studies.

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

AC: we will add 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.

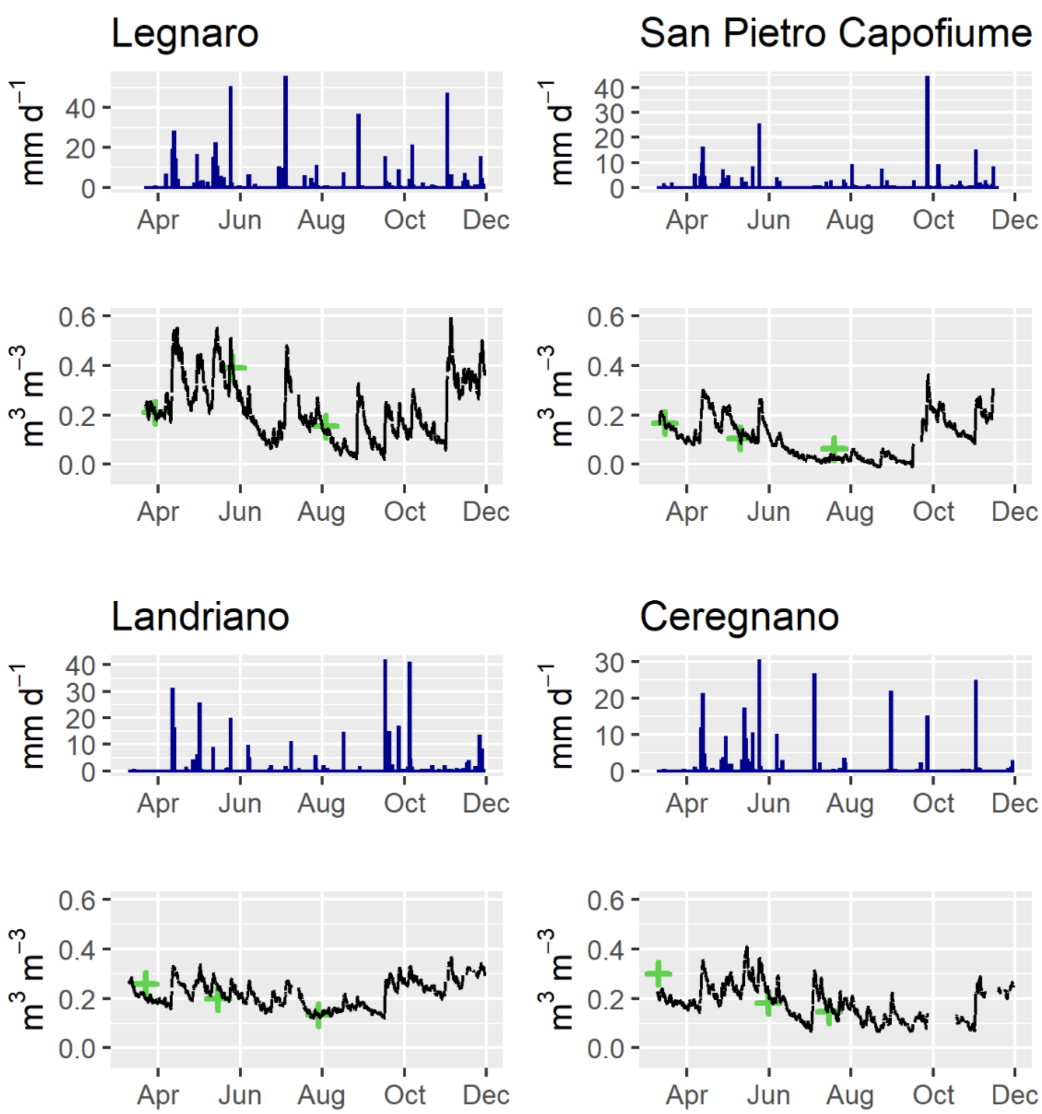
AC: thank you. We will change the figure as below.

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 will change 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 will change point shape with crosses instead of circles as in the figure below. 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.



References

Cester, D., Lunardon, M., Moretto, S., Nebbia, G., Pino, F., Sajo-Bohus, L., Stevanato, L., Bonesso, I., Turato, F., 2016. A novel detector assembly for detecting thermal neutrons, fast neutrons and gamma rays. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 830, 191–196. https://doi.org/10.1016/j.nima.2016.05.079

de Mendonça, R.R.S., Braga, C.R., Echer, E., Dal Lago, A., Munakata, K., Kuwabara, T., Kozai, M., Kato, C., Rockenbach, M., Schuch, N.J., Al Jassar, H.K., Sharma, M.M., Tokumaru, M., Duldig, M.L., Humble, J.E., Evenson, P., Sabbah, I., 2016. The temperature effect in secondary cosmic rays (muons) observed at the ground: analysis of the global muon detector network data. The Astrophysical Journal 830, 88. https://doi.org/10.3847/0004-637X/830/2/88

Dorman, L.I., 2004. Cosmic Rays in the Earth's Atmosphere and Underground, Astrophysics and Space Science Library. Springer Netherlands, Dordrecht. https://doi.org/10.1007/978-1-4020-2113-8

Maghrabi, A., Aldosary, A.F., 2018. The Effect of Some Meteorological Parameters on the Cosmic Ray Muons detected by KACST detector, in: Proceedings of 35th International Cosmic Ray Conference — PoS(ICRC2017). Presented at the 35th International Cosmic Ray Conference, SISSA Medialab, p. 062. https://doi.org/10.22323/1.301.0062

Power, D., Rico-Ramirez, M.A., Desilets, S., Desilets, D., Rosolem, R., 2021. Cosmic-Ray neutron Sensor PYthon tool (crspy 1.2.1): an open-source tool for the processing of cosmic-ray neutron and soil moisture data. Geoscientific Model Development 14, 7287–7307. https://doi.org/10.5194/gmd-14-7287-2021

Schrön, M., Köhli, M., Scheiffele, L., Iwema, J., Bogena, H.R., Lv, L., Martini, E., Baroni, G., Rosolem, R., Weimar, J., Mai, J., Cuntz, M., Rebmann, C., Oswald, S.E., Dietrich, P., Schmidt, U., Zacharias, S., 2017. Improving calibration and validation of cosmic-ray neutron sensors in the light of spatial sensitivity. Hydrol. Earth Syst. Sci. 21, 5009–5030. https://doi.org/10.5194/hess-21-5009-2017

Stevanato, L., Baroni, G., Cohen, Y., Cristiano Lino, F., Gatto, S., Lunardon, M., Marinello, F., Moretto, S., Morselli, L., 2019. A Novel Cosmic-Ray Neutron Sensor for Soil Moisture Estimation over Large Areas. Agriculture 9, 202. https://doi.org/10.3390/agriculture9090202

Stevanato, L., Baroni, G., Oswald, S.E., Lunardon, M., Mares, V., Marinello, F., Moretto, S., Polo, M., Sartori, P., Schattan, P., Ruehm, W., 2022. An Alternative Incoming Correction for Cosmic-Ray Neutron Sensing Observations Using Local Muon Measurement. Geophysical Research Letters 49, e2021GL095383. https://doi.org/10.1029/2021GL095383