Response to Reviewer 1:

First of all, we thank Reviewer 1 for her/his comments that significantly helped us to improve the quality of our manuscript. In the following, we first describe the main changes that we made on the text based on the suggestions of all three reviewers and, then, we provide point-to-point answers to Reviewer 1's comments.

- We separated the "Methods" section into "Study Area and Datasets" and "Methods".

- We better focused the main analyses and results of the manuscript, which can be summarized as follows:
    1. Validation of cosmic-ray neutron probe sensing (CRNS) through distributed sensors and a novel method based on the water balance closing.
    2. Utility of CRNS for hydrologic studies at the footprint scale, including (i) the quantification of the water balance fluxes over the 19-month period, and (ii) the improvement of the relations between evapotranspiration (ET) and soil moisture.

  These changes implied significant modifications in the Introduction, Methods and Results sections.

- To give more importance to the main results reported in the previous point:
    - We reduced the part focused on the spatial variability of soil moisture and moved it to the section on the validation of the CRNS method through the distributed sensor network of soil moisture probes.
    - We completely removed analysis, discussion and one figure about the relations between spatial variability of soil moisture and ET.

- We improved the description of the water balance approach for (i) validating the CRNS method and (ii) studying the fluxes at the CRNS footprint in continuous fashion. In doing so, we carefully explained each assumption to avoid any misunderstandings.

- In the computation of the event-based water balance, we adopted a different measurement depth (z^*) for each event, as requested by all reviewers. This implied an update of two figures and metrics reported in Table 4.

<u>Point-by-point responses to Reviewer 1's comments:</u>

Reviewer 1 Comments	Author Response
1. The paper deals with many different topics (e.g. CRNS validation, water balance closing, soil moisture variability, comparison of two test sites). In consequence each of these topics is only dealt with in a rather superficially way and the reader is lost in too much and inconsistent information. In order to focus the paper, I suggest removing the sections on soil moisture variability.	As mentioned above, we reorganized the text to highlight the main two contributions of the paper: (i) improve our understanding of the CRNS method through two independent validation methods, and (ii) show how CRNS can be applied to study hydrologic processes at the footprint scale. For this aim: 1. We modified the main analyses and results of the manuscript to focus attention on a few important points, which can be summarized as follows: • Validation of cosmic-ray neutron probe sensing (CRNS) through distributed sensors and a novel method based on the water balance closing. • Utility of CRNS for hydrologic studies at the footprint scale, including (i) the quantification of the water balance fluxes over the 19-month period, and (ii) the improvement of the relations between evapotranspiration (ET) and soil moisture. The motivations for these studies have been discussed in the "Introduction" from page 3, line 18 to page 5, line 5. 2. We reduced the analysis on the relations between spatial variability and mean of soil moisture and we used it as further confirmation of the correspondence between soil moisture measurements from the distributed sensors and CRNS. As a result, this part was moved to Section 3.1 in the "Methods" (page 12 and line 17 on the new manuscript version) and to Section 4.1 in the "Results and Discussion" (page 17 and line 11 on the new manuscript version). In addition, Fig. 9 of the first draft is now Fig. 6. 3. We removed the analysis and discussion of the relations between spatial variability of soil moisture and ET. As a result, Fig. 11 was removed.
2. There already exists a long list of papers dealing with the validation of the CRNS method for soil moisture determination and it was already shown	This is an important and thoughtful comment. To address this, we propose a possible physical explanation for the reasons causing the deviations between the sensor network and the CRNS methods during soil moisture recessions. We

that the methods works very well in arid systems due to the relatively low hydrogen content. Therefore, the good agreement with the in-situ measurements is of no surprise. However, also deviations were shown, e.g. during soil recessions. For the growing community it would be more interesting to learn more about reasons for such deviations.	think that, due to terrain features, soil moisture converges near the channels after the storms. While the CRNS sensor has the ability to measure soil moisture in these wetter areas, the distributed sensor network is not able to account for their presence, because only one sensor was located in a channel. This has been reported on page 16, lines 10-12.
3. There are several contradictions in the manuscript. For instance, on the one hand it is stated that percolation at both site is mainly restricted to the first 40 cm and on the other hand it is stated that substantial amounts of precipitation percolated to deeper layers. In addition there are many ambiguities in the methods (e.g. assumptions concerning z*, z_m, and leakage).	Thank you for pointing this out. In the revised manuscript, we modified the text to explain each step of our methods. Specifically, in section 3.2, we distinguished the application of the water balance in event-based and in continuous fashions. For these cases, we justified our assumptions: <u>Event-based application of the water balance:</u> 1. We modified the assumptions concerning z_m. In the manuscript, we adopted a different depth z* for each event to calculate the water balance. This is important to reflect the varying measurement depth of CRNS. As a result, we did not use the symbol z_m. This change is reflected in Fig. 6, and the text on page 14. 2. The event-based application of the water balance is focused on the rising limb of the soil moisture response. In this period, it is very unlikely that percolation to deeper layers occurs. As a result, for this case we assumed a leakage equal to zero (i.e., L = 0). This assumption has been tested at each site by checking the soil moisture measurements of sensors installed along a 1-m profile next to the EC tower. Note that z* is always above 1 m. We found that the percolation beyond a depth of ~40 cm is infrequent at both sites during the duration of summer monsoon storms. This is explained in page 14, lines 1-5. 3. When we applied the water balance at the Jornada site (JER), we found 5 events where leakage most likely occurred (i.e., the change in soil moisture at the sensors at 30-cm depth is not negligible). This can be explained by the combination of: (i) high initial soil moisture due to the occurrence of these events near the end of the monsoon, and (ii) the large amount of rainfall for these storms.

	<u>Continuous application of the water balance:</u> 1. The measurement depth was varied every day, selecting the minimum daily-average measurement depth between the two days being compared (see equation 7 in new manuscript). 2. Percolation can occur on a time scale of several days during winter precipitation (e.g., Franz et al., 2012b; Templeton et al., 2014; Pierini et al., 2014). Thus, in principle, L is not 0 and it is calculated as L= O – ET, where O is the flux (f_{CNRS}) out the depth z*, measured by the CRNS, and ET is the evapotranspiration measured by the EC tower. This is explained in page 14, lines 18-22.
4. The methods section should be better structured. For instance, the soil water balance based on the CRS and the water balance closing should be presented together.	We agree with Reviewer 1. Given the length of the "Methods" section, we have created a section on "Study Areas and Datasets", including: 2.1: Study Sites and Their General Characteristics (as in the first version of the draft). 2.2: Distributed Sensor Networks at the Small Watershed Scale (as in the first version of the draft). 2.3: Cosmic-ray Soil Moisture Sensing Method The "Methods" section is now organized into the following sub-sections: 3.1: Comparison of CRNS to Distributed Network of Soil Moisture Sensors (Validation of CRNS via distributed soil moisture measurements. In the new manuscript version, we moved here the analysis of the relations between spatial variability and soil moisture). 3.2: CRNS Water Balance Analyses Methods **(**Water balance approaches used for the validation of the CRNS method and the analysis of the water balance fluxes at the footprint). 3.3: Relation between Evapotranspiration and Soil Moisture
5. Chapter "summary and results" is quite extensive. It should be shortened and focused on the main results of the paper	As described in the answer to comment 1: • We focused on the validation and utility of CRNS method. • We shortened the analysis on the relation between spatial variability and mean of soil moisture. • We removed the analysis and discussion of the relations between spatial variability of soil moisture and ET

	These changes have reduced the overall length of the "Summary and Conclusions" section.
P3L18: Since the probe presented in this paper measures secondary fast neutron intensity above ground (and not cosmic-rays in general), it should called cosmic-ray neutron probe or in short CRNS.	We adopted the acronym CRNS (cosmic-ray neutron sensing) suggested by Reviewer 1 throughout the manuscript.
P4L7: This equation is not correct since it assumes that all storage changes are taking place within the effective sensing depth of the CRNS. Instead z should represent the depth of the root zone.	Thank you for pointing this out. Since the application of the water balance equation (#6 in the new manuscript version) is made for storm event periods, ET is negligible and plant water uptake is not occurring. As a result, the use of z* instead of the plant rooting depth is justified. We clarified this point in Section 3.2 (page 13, lines 20-21). Note that we moved the water balance equation from the original location to the section on the CRNS water balance.
P4L18: Be more specific. Which spatial properties are you referring to?	Since we modified the "Introduction" to better focus the paper, this part is not present anymore in the paper.
P5L1-4: Recently Qu et al. (2015) demonstrated that variability of soil moisture can be explained by mean soil hydraulic parameters and their standard deviations in different ecosystems and climates. In addition this study showed that dry environments can also experience a decrease of SM variability in the wetter range.	Thank you for sharing this paper. We included a citation in the "Methods" section, page 13, line 1.
P5L8-10: The sensor network can provide both catchment scale average and spatial variability of soil moisture. Please explain why a combination of both techniques is still necessary for this kind of studies.	The relations between ET and soil moisture are usually studied using eddy covariance (EC) measurements of ET and soil moisture observations at single sites, or, less often, through networks of probes. An important advantage of the CRNS technique is that its measurement scale is comparable to the footprint of ET measurements based on the EC technique. Thus, in the paper, we compare the relations between ET and soil moisture based on the two methods for measuring soil moisture at different scales. This has been explained in the "Introduction" from page 4, line 20 to page 5, line 5. Since we removed the discussion of the effects of soil moisture variability on ET, we have also removed the line that this comment refers to.

P5L17: This study does not present a validation of CRNS in a strict sense, but rather a comparison with other methods. First, the soil moisture sensor network of both test sites is not well distributed within the CRNS footprint (the sensor networks do not cover well the CRNS foot and also do not consider the decreasing sensitivity of the CRNS with distance). Second, the water balance approach makes strong assumptions (e.g. CRNS measurement depth is assumed to be 40 cm). However, the actual sensing depth will strongly vary and given the variety in plant species of these ecosystems, the root zone is very heterogeneous and is not restricted to 40 cm everywhere. In addition, large parts of both test sites are not vegetated and which are only subject to evaporation. Here the soil depth that contributes to evaporation will be highly variable in time depending on SM content and soil properties.	We modified the assumption on the fixed CRNS measurement depth (z^* = 40 cm) and assumed a variable depth z^* for each event, as discussed in comment #3. The sensor networks were designed to capture the spatial variability of soil moisture within each watershed, by accounting for the primary controls on the variability at each site (i.e. topography at JER and vegetation at Santa Rita - SRER). While the sensors are not distributed to the further reaches of the CRNS footprint, we applied averaging methods based on the spatial distributions of terrain at JER and of vegetation at SRER (see page 8, line 18 to page 9, line 2). Specifically: - At SRER, the soil moisture sensors were distributed under different vegetation cover. The differences in the soil moisture responses between diverse vegetation cover are larger than the horizontal spatial variability of soil moisture within the same vegetation class. So, we weighted the sensor network based on the amount of certain vegetation types, rather than on the distance to the CRNS sensor because this will provide a more accurate estimation of large-scale soil moisture. - At JER, topography plays an important role in the soil moisture due to a more incised watershed. This results in soil moisture redistribution, as well as sharp differences based on aspect. We therefore weighted the sensor network based on an aspect-elevation relation presented in Templeton et al. (2014). As a result, we believe that these soil moisture means are representative of the mean soil moisture state in the CRNS footprint. In this regard, the recent paper by Köhli et al. (2015) shows that the CRNS footprint is actually smaller than we originally thought, thus providing further confidence on the representativeness of our soil sensor networks. Regarding the comment on the sensing depth, we recognize that a possible problem with our validation stems from the fact that we do not have soil moisture sensors in the topographic depressions caused by channels, leading to an overestimation of soil moisture by the CRNS method. This

	has been highlighted on page 16, lines 10-12. We also added a comment explaining how the bare soil areas in the study watersheds are most likely also under the influence of plant transpiration as the desert shrubs and trees have expansive lateral roots extending into bare soil patches, see page 14, line 5-8.
P5L22: "evapotranspiration" instead of "root water uptake"	We have changed this word on page 5, line 14.
P5L22: The term "leakage" typically not used in vadose zone hydrology in this respect. The correct term would be "deep drainage" or "deep percolation".	We have changed this term to "percolation on page 5, line 14.
P6L8: Soil properties and topographic features of both sites need to be presented as well.	Soil properties are presented in page 6, lines 5-6 and page 6, lines 14-15 in the text and topographic features are presented in Table 1. We referenced a more detailed study of the site soils as Anderson (2013). We also added a new table 3 with more soil information.
P7L15: The watersheds are much smaller than the footprints of CRNS and EC. Please comment on why you believe that measurement still can be compared, especially in the light of soil heterogeneity.	While we acknowledge that the watersheds are in general smaller than the full extent of the EC and CRNS footprints, we also underline that: • The sizes of the watersheds are comparable or larger than the 50% contributing areas for each site shown in Fig. 2. • The vegetation distribution does not significantly change at the scales of watersheds and footprints. In other words, it can be considered homogeneous at both scales, as also presented in Vivoni et al. (2014). This is stated in page 11, lines 13-15. • Anderson (2013) performed a soil texture analysis in the footprint of the EC tower at both sites and found small variations, as stated on page 11, line 15. • The paper by Kohli et al. (2015) shows that the footprint of the CRNS method is smaller than we originally thought, improving the representativeness of the watersheds for validation of the CRNS method.
P7L21: How many rain gauges were used in each site?	There were 4 rain gauges used at each site, as shown in Fig. 1. Since one of more of these gages reported different periods of malfunction, in the new manuscript version we indicated that we used up to four rain gages (page 7, line 12). Clearly, the Thiessen polygons used the estimate the mean areal precipitation were modified to reflect this.

P8L20-21: Statements in Campbell (1990) are not related to the measurement volume of the Hydra Probes used in this study.	Thank you, this is correct. It was our intention to cite Campbell (1990) in reference to the measurement of the impedance of an electric signal. The measurement volume is simply a physical characteristic of the sensor. We have modified the text on page 8, line 3 to reflect these changes.
P9L6-9: It is unclear why you are using different methods for each site. Please describe in more detail the reasoning behind the method selection. In addition, comment on why you are not accounting for the decreasing sensitivity of the CRNS with radial distance, like e.g. Bogena et al. (2013).	See answer to comment on P5L17 for justification of the different weighting methods at each site. We do not apply a method similar to that of Bogena et al. (2013) to weigh our sensor network because we focus our efforts on watershed-scale soil moisture. The sensor networks were installed to capture the variability and mean conditions within the watersheds. Another reason that we focus our weighting of the sensor network on the watershed is so that all three estimates of soil moisture (sensor network, CRNS method, and water balance calculation) are measuring the same control volume. We clarify this on page 8, line 19 to page 9, line 2.
P9L13: I thought the CRS-1000 was used in SRER.	The CRS-1000/B was used at both sites.
P9L21: The recent paper of Köhli et al. (2015) found different estimates for the CRNS footprint.	Thanks for your recommendation. In the new manuscript version, we have included the estimates from Kohli et al. (2015) (note that this paper was accepted after we submitted our manuscript). This is reflected in Fig. 2, and in the text on page 9, line 15.
P10L4: Eq. 2 gives gravimetric water content (see Bogena et al., 2013)	We performed a volumetric calibration, so that our N_o values reflect volumetric soil water. This implies that using neutron counts into this equation gives volumetric water content.
P10L13-17: Please give more information on the soil sampling (e.g. disturbed or undisturbed samples, dates etc.) as well as on the properties (e.g. mean values, standard deviations etc.).	The mean values with standard deviations of the bulk densities have been included on page 10, lines 17-21. The dates are presented in the caption to table 3.
P10L21: Please give more information on this method (e.g. how exactly rainfall periods have been ignored).	If we are correct, Reviewer 1's comment is referred to the boxcar filter method. We applied this rule: if rainfall events were large enough to increase the volumetric soil moisture by 6% or more, the boxcar filter was not applied. A line has been added on page 11, line 18-20 to clarify this.

P11L6: According to Templeton et al. (2014), the clay content at JER is 20.8%. Thus, lattice water needs to be accounted for at the JER site. Deviations between CRNS and in-situ SM at JER might be partly due to the false assumption of lattice water content.	A much more detailed classification of the soil properties was performed after Templeton et al. (2014) by Anderson (2013) and is used in this study. The new soil analysis included 60 samples throughout the site and found a clay content of 4.8%, therefore the assumptions of constant lattice water are justified.
P11L10-11: This is a very rough procedure. The horizontal weighing scheme of Bogena et al., 2013, should be applied instead.	When preparing this manuscript we considered a horizontal weighting scheme similar to that of Bogena et al. (2013), but we focused our weighting schemes on estimating the mean soil moisture in each watershed for several reasons: 1) The soil moisture sensors were installed to examine different processes at the two sites. At SRER, the soil moisture sensors were distributed under different vegetation cover. The differences in the soil moisture responses between diverse vegetation cover are larger than the horizontal spatial variability of soil moisture within the same vegetation class. So, we weighted the sensor network based on the amount of certain vegetation types, rather than distance to the CRNS sensor because this will provide a more accurate estimation of watershed-scale soil moisture. At JER, topography plays an important role in the soil moisture due to a more incised watershed. This results in soil moisture redistribution, as well as sharp differences based on aspect. We therefore weighted the sensor network based on an aspect-elevation relation presented in Templeton et al. (2014). 2) We wanted to use the watershed as our control volume so that we could compare soil moisture measured with the CRNS method, the point scale sensor network, and the calculation of the water balance. 3) As previously stated, one of the foci of this paper is to demonstrate the utility of the CRNS method to study and quantify hydrological processes. This was done through the application of the water balance that required the watersheds as control volumes.
P11L14-17: Please comment on possible influences of soil heterogeneity.	Please see our answer to comment P7L15.

P11L17: According to Köhli et al. (2015) the CRNS shows considerable variations in horizontal footprint size.	Thank you for pointing this out. The text has been updated on page 11, line 11-12.
P11L21: According to Templeton et al. (2014), the bulk soil density at JER is 1.37 g/cm^3	During the calibration of the CRNS sensor, we performed an analysis of the soil bulk density with a larger number of samples and found that the bulk density was 1.30 g/cm^3, slightly different from Templeton et al. (2014).
P11L22: There are large differences in clay contents indicating differences in lattice water contents.	Please see our response to comment P11L6.
P12L5 and L17-18: Please present the temporal variations in z* for both sites and discuss implications for the soil water storage change estimations.	This is a good idea, thank you. Temporal variations in z* have been included in Fig. 3. The temporal variation in z* should have little effect on the comparison between the sensor network and the CRNS method, because the soil moisture from the sensor network were averaged through a method that accounted for differences in depth.
P12L20-22: According to results shown in Fig. 8 there is a considerable amount of deep drainage taking place at JER for several weeks during winter. What are the consequences of this violation of the "no-leakage" assumption?	As described in previous answers, in the new manuscript version, we have further explained the assumptions for the application of the water balance. Fig. 9 in the new version is referred to the application in continuous fashion of the water balance, where we have not made any assumptions on the leakage term. In fact, leakage can be obtained in this application as L = O – ET, when f_{CRNS} is negative (i.e, water is leaving the soil depth z*). We also added a comment on page 20, lines 11-12, describing the winter time drainage and its link to precipitation events occurring when drought-deciduous plants are inactive since they lose their leaves and do not consume water through ET.
P13L5: Eq. 6 is not from Franz et al. (2012). Why are you using the minimum z*-value? Elsewhere you assume that z* equals z_m.	This approach was introduced by Franz et al. (2012b) without explicitly presenting the equation, which we deduced from the section "Cosmic-Ray Sensor Mass Balance". The approach uses the minimum measurement depth between the two consecutive days, because we want to account for the water in the same layer of soil available for both days. Finally, as previously discussed, we have removed the use of z_m throughout the paper.
P13L7: I think it would be better to speak of "net" inflow and "net" outflow into/from the representative volume.	We agree with this suggestion and it has been incorporated in page 14, line 15 and line 19.

P13L11: Change into "…between soil domains above and below z*."	The change has been made on page 14, line 20-21.
P13L16: The results of the soil sample analysis should to be presented in a Table (e.g. mean and std of grav. soil water content (SWC), soil density etc.). How did grav. SWC compare to sensor network SWC at both sites? How did grav. SWC compare to calibrated CRNS SWC at both sites?	We added a new table presenting the results of our soils analyses at both sites, including samples taken for calibration of the CRNS and for particle size analysis. Table 3 is now introduced in page 10, lines 16-18. We also added the available soil properties, such as porosity, bulk density and particle size distribution to the table for providing further details on the site soil characteristics.
P14L11-12: Please describe in more detail how you derived these analytical relationships.	We have removed these relationships in the new manuscript version.
P15L5-7: Differences of 3 to 6 Vol.% SWC are not large.	These differences between seasonal averages are significant if referred to these dry systems. Thus, we have added the word "relatively" to this line to highlight this point.
P15L11: Channels or linear structures are not visible in Fig. 1. What was the distance to a channel? Typically, water in channels shows very low effect on CRNS given their large measurement footprint.	The channels are generally quite small and rarely have flowing water. However, we are postulating that the topographic depressions in proximity of the channels remain wetter than hillslope areas after rainfall events. This assumption has been confirmed by one sensor placed in a channel at SRER, which reported consistently higher soil moisture values than the rest of the network (unfortunately, we do not have point scale sensors in or very near the channels at JER). As a result, we attribute the lower values measured by the distributed sensors during the recession to the presence of wetter areas near the channels. To address this, we have added the text "and their associated zones of soil water convergence" to page 16, line 11.
P15L21: There is a huge scatter and even bias shown in Fig. 5. Therefore the term "excellent" is not appropriate.	We have changed this to "very good".
P16L9-11: Is it really realistic that the soil completely dries out? Looking at Fig. 4 it becomes apparent that during very dry periods the statistical noise in the CRNS data (which is in the range of the SWC) produces values near zero which are clearly artefacts. In addition, the N0-method is not valid for SWC	This line has been removed.

<0.2 (Desilets et al., 2010).	
P16L11: What kind of limitations?	We meant limitations in measuring soil moisture at very dry levels. We have removed this sentence.
P17L9: Why should more homogenous soil lead to a shallower infiltration front? This should only influence the variability of the infiltration front. To support any discussion on influences of soil properties on hydrological processes, more detailed soil data of both catchments need to be provided.	Thank you for pointing this out. With this sentence, we were referring to the fact that there are less rocks in the soils at SRER. Thus, we changed “more homogeneous” into “less rocky”. We added more detailed soil information in a new Table (#3 in the revised manuscript).
P17L11: Undulated terrain typically promotes lateral water flow and not vertical water flow. Please explain why vertical flow is increased in JER by topography.	The undulated terrain can promote lateral flow to channel beds that typically have large sandy beds, which in turn promote vertical infiltration to deeper layers. This has been addressed on page 19, lines 3-4.
P17L16-18: Obviously the comparison between both sites is hampered by the non-average precipitation amounts in both. For an unbiased comparison longer time series would be needed to balance out any climatic anomalies.	We agree with this comment. Unfortunately, our records currently cover only 19 months.
P18L1: “more soil water” instead of “more ET”	Thank you for catching this. This has been changed to “produces more ET”.
P18L7-9: Earlier you have stated that deep percolation at SRER is very limited (only few days).	We have clarified our use of the assumption of no leakage for calculating soil moisture using the water balance on page 14, lines 1-5. This assumption is only valid over the short timescale of a rain event and the rising limb of the soil moisture response. We are not assuming that there is never any deep percolation. Additionally, we believe that most of the deep percolation occurs near the channels where sediments are coarser and topography causes water to collect. This deep percolation in the channel is not detected by the deep sensor profile installed near the EC tower. We provide justification based on three sets of reasoning, on page 20, lines 13-17, but the primary one that applies to SRER is that we have one sensor profile installed in a channel and we see here that water commonly infiltrates past 30 cm depth.

P20L12: The term "excellent" is not appropriate given the large differences	We changed to the term "suitable".
P20L17-18: How do you come to this conclusion?	We come to this conclusion based on the fact that the relationships in Fig. 10 shows that ET-θ_{CRS} looks more realistic under dry conditions. The bare soil evaporation part of this function is well represented and shows a gradual increase with soil moisture. In the relationship between ET-θ_{SN}, this part of the function is too steep and does not represent the way bare soil evaporation changes with soil moisture. This has been discussed in page 21, line 15-19.
P20L21-22: But you stated earlier that the mesquite trees are extracting water below z*	We think that the two statements are not in contradiction. Higher soil moisture values sensed by CRNS within z* are still able to provide a larger ET due to extraction of water from the mesquite trees.
Fig. 1: Should be combined with Fig. 2	We believe that the amount of information presented in Fig. 1 and Fig. 2 deserves two separate figures.
Fig. 2: Why do you present the 50 % contributing areas of CRNS and EC?	The main reason that we used the 50% footprint is that larger footprints (i.e. 86% or 100%) for the EC tower and the CRNS sensor will extend well beyond the watershed domains, as could be discerned from Fig. 2. In addition, the 50% footprints fully contain the soil, terrain and vegetation layers available to characterize the sites and avoid large variations introduced by nearby channels outside of the sensor network sampling areas. Page 11, lines 9-11 have been updated to explain this.
Fig. 4: Please add calibration points.	The calibration was performed in February of 2013 for both sites, which is before our continuous study period so we cannot add those points to the figure. While CRNS operated prior to our study period, we began the comparisons on March 1 of 2013 because there was a malfunction in our eddy covariance tower during February of 2013. We now mention the calibration dates in the caption of new Table 3.
Table 2: Not important. Consider deletion.	We believe this table is important for the validation and comparison between f_{CRNS} and the measured ET. We would like to provide quantitative evidence that the eddy covariance method is effectively capturing ET in order to have confidence in these measurements.
Table 3: Remove equations from the caption.	We removed the equations and added the reference Vivoni et al. (2008b) where the metrics are defined.

Table 4: Precipitation and ET were measured and should be listed separately	We changed “sensor estimates” into “sensor measurements” to reflect this.

Response to Reviewer 2:

First of all, we thank Reviewer 2 for her/his comments that significantly helped us to improve the quality of our manuscript. In the following, we first describe the main changes that we made on the text based on the suggestions of all three reviewers and, then, we provide point-to-point answers to Reviewer 2's comments.

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    - We reduced the part focused on the spatial variability of soil moisture and moved it to the section on the validation of the CRNS method through the distributed sensor network of soil moisture probes.
    - We completely removed analysis, discussion and one figure about the relations between spatial variability of soil moisture and ET.

- We improved the description of the water balance approach for (i) validating the CRNS method and (ii) studying the fluxes at the CRNS footprint in continuous fashion. In doing so, we carefully explained each assumption to avoid any misunderstandings.

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Point-by-point responses to Reviewer 2's comments:

<table>
<tr><th>Reviewer 2 Comments</th><th>Author Response</th></tr>
<tr><td>1) The paper contains a lot of material and information which is good from a scientific perspective but that forced the authors to not go into much details of some important concepts and descriptions. I suggest to focus on the most important results (the authors could follow the suggestions of Reviewer 1).</td><td>We agree with Reviewer 2 on the need to present a lower number of results with a higher level of detail. We addressed this as follows:

1. We better focused the main analyses and results of the manuscript in order to focus the reader's attention on a few important points, which can be summarized as follows:
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• Utility of CRNS for hydrologic studies at the footprint scale, including (i) the quantification of the water balance fluxes over the 19-month period, and (ii) the improvement of the relations between evapotranspiration (ET) and soil moisture.
The motivations for these studies have been discussed in the Introduction from page 3, line 18 to page 5, line 5..

2. We reduced the analysis on the relations between spatial variability and mean of soil moisture and we used it as further confirmation of the correspondence between soil moisture measurements from the distributed sensors and CRNS. As a result, this part was moved in Section 3.1 in the Methods (page 12 and line 17 on the new manuscript version) and to Section 4.1 in the "Results and Discussion" (page 17 and line 11 on the new manuscript version). In addition, Fig. 9 of the first draft is now Fig. 6.

3. We removed the analysis and discussion of the relations between spatial variability of soil moisture and ET. As a result, Fig. 11 was removed.</td></tr>
<tr><td>2) Related to the previous point, I would emphasize and improve the "closing the water balance approach" through a better description of the concepts behind it. There a number of assumptions and contradictions that need to be addressed and justified otherwise it is difficult to follow this part (e.g., L=0 assumption and its consequences on the subsequent analysis should be better explained).</td><td>In the revised manuscript, we modified the text to clearly explain each step of our methodology, thus avoiding any potential misunderstandings. Specifically, in section 3.2, we distinguished the application of the water balance in an event-based and in a continuous fashion. For each of these two cases, we explained and justified our assumptions related to the leakage:

The <u>event-based application of the water balance</u> is focused on the rising limb of the soil moisture response. In this period, it is very unlikely that percolation to deeper layers occurs. As a</td></tr>
</table>

Establishing a clear method of analysis prior to present the results, other than improving the comprehension of the paper, would add value to it and to its alternative approach.	result, for this case we assumed a leakage equal to zero (i.e., L = 0). This assumption has been tested at each site by checking the soil moisture measurements of sensors installed along a 1-m profile next to the EC tower. Note that z* is always above 1 m. We found that the percolation beyond a depth of ~40 cm is infrequent at both sites during the duration of summer monsoon storms. This has now been explained in page 14, lines 1-5. When we applied the water balance at JER, we found 5 events where leakage occurred (i.e., the change in soil moisture at the 30-cm depth sensors is not negligible). This can be explained by the combination of a high starting soil moisture due to the occurrence near the end of the monsoon season, and the large amount of rainfall for these storms. Percolation can occur on a time scale of several days during winter precipitation (e.g., Franz et al., 2012b; Templeton et al., 2014; Pierini et al., 2014). Thus, in the continuous application of the water balance, L is not assumed to be 0 and is instead obtained as L= O – ET, where O is the CNRS flux (f_{CNRS}) out the depth z*, and ET is the evapotranspiration measured by the EC tower. This has been explained in page 14, lines 4-5.
3) The role of z* and its relation with zm and the maximum measurement depth of the probes requires a more clear description. The authors should deserve at least a brief paragraph to this issue. Indeed, it looks like that z* has a strong influence on the results so I suggest for instance to analyze the z* time series and discuss further the limitations associated to its time variability ant its potential effects on the result interpretation.	In the computation of the event-based water balance, we modified the assumptions concerning z_m and we adopted a different measurement depth (z*) for each event. This change is reflected in Fig. 6 and in Table 4, as well as the text presented in page 13. The temporal variations in z* have also been included in Fig. 3. Such variations should have little effect on the comparison between the sensor network and the CRNS method, because the soil moisture data from the sensor network were averaged through a method that accounted for the variation in time of the CRNS measurement depth as discussed in page 12, line 15. In the application of the water balance in a continuous fashion, temporal variations in z* do affect our estimate of the flux of water into and out of the CRNS measurement footprint. This is why we use the minimum value of z* over the two day period, this ensures that we are using the same control volume for the calculation. These concepts have been clarified on page 14, lines 13-14 of the new manuscript version.
4) With so much information and analyses, it is not easy to follow the manuscript. I would deserve some	As previously described, we have reorganized the paper to limit the number of analyses and associated results. We believe that, in the new manuscript version, we have been able to

space in the discussion section for a table summarizing the most important points (especially those associated with the water balance approach) or include a smaller conclusion section highlighting the main findings along with the limitations associated with the CRS method. I list below that main issues I found in the paper in the order of appearance:	clearly highlight the most important points throughout the different sections, by: • Focusing the "Introduction" on the main analyses of the paper. • Separating the "Methods" section into "Study Area and Datasets" and "Methods". • Shortening and improving the "Methods" section by removing the analyses on the effect of spatial variability in soil moisture on ET. • Better focusing the "Results" section. • Shortening the "Conclusions". As a result, we think that a table that summarizes the main points is not necessary.
1) P5345 L. 14-18. Many satellite SM missions are now available and include not only passive sensors (Kerr et al. 2001) but also active (Bartalis et al. 2007) and combined (passive plus active, Entekhabi et al. 2010) sensors. I suggest to add this references to the manuscript.	These citations have been added on page 3, line 15.
2) P5346 L5. I would move Eq. (6) and its description to the method block. It is ok to say something but putting details in the method avoids to jump from one page to another and improves the readability of the manuscript. Moreover, in this case the "closing the water balance approach" will be presented in a more consistent and general manner.	We assume this is in reference to Eq. (1). We have moved it to the methods block and created a single section in the Methods ("3.2 CRNS Water Balance Analyses Methods") regarding the water balance. These suggestions have helped clarify the manuscript.
3) P5350L19: could you provide a brief justification for these choices? (i.e. the method used for averaging SM time series). I guess some info is contained in the references added but it would be beneficial to have something in the manuscript since the spatial mean of the probes is used as a benchmark for the comparison.	The soil moisture sensors in the transects were installed prior to this experiment in order to examine different hydrologic processes at the two sites. At SRER, the soil moisture sensors were distributed under different vegetation cover. Here, the differences in soil moisture responses among different vegetation covers are larger than the horizontal spatial variability of soil moisture within the same vegetation class. Thus, we weighted the sensor network based on the vegetation distribution, rather than distance to the CRNS sensor because this will provide a more accurate estimation of large scale soil moisture. At JER, topography plays an important role in the soil moisture due to a more incised watershed. This results in

	soil moisture redistribution, as well as sharp differences based on aspect. We therefore weighted the sensor network based on an aspect-elevation relation presented in Templeton et al. (2014). We added this information to clarity the concern in the text on page 8, lines 8-12.
4) P5352 L12: boxcar filter. Please add a reference.	Since the description of this relatively popular averaging technique is available in textbooks, we decided not to add a reference. However, we have added some extra text to explain the details on how we applied this filter.
5) P5352 L23: Could you provide a clearer justification for limiting the analysis to the 50% of the source area? Which are the effects of considering smaller or larger contributions?	The main reason that we used the 50% footprint is that larger footprints (i.e. 86% or 100%) for the EC tower and the CRNS sensor will extend well beyond the watershed domains, as could be discerned from Fig. 2. In addition, the 50% footprints fully contain the soil, terrain and vegetation layers available to characterize the sites and avoid large variations introduced by nearby channels outside of the sensor network sampling areas. Page 11, lines 9-11 have been updated to explain this.
6) P5354 Section 2.4. This section is particularly important and should be explained better. Examples are: -L=0 for short rainfall events could be reasonable but later in the manuscript L is supposed different from zero in many cases. If understand well this refers to a longer analysis period, however, I found this a bit confusing. Could you improve this part and make the text more clear?	We significantly revised this section (now Section 3.2) to make this distinction more clear. See response to comments #2 and #3 from this review.
-P5354 L8-10. Zm=40 cm. Which are the potential consequences of this assumptions?	See response to point #3. We have removed z_m and only use z* now to eliminate unnecessary assumptions.
-P5354L15-18. Describe the performance metrics in separate section and remove them from the caption of Table 3.	We have removed the performance metrics from the caption and provided a citation to an in-depth discussion of the metrics we used (Vivoni et al. 2008b) in the caption to table 4.
-Can you explain min(zt*, z*t-1) in Eq. (6)?	We have explained that this represents the minimum z* between the two days in question on page 14, lines 13-14.
-If this is true that fCRS>0 implies infiltration, it cannot be generally said	We thank Reviewer 2 for pointing this out. We have changed this to be called "Net Infiltration into the surface soil". The

that f=I. Indeed, at daily temporal resolution the effect of others water balance components cannot be neglected, e.g., the effect of the deep percolation, especially for JER site	change is on page 14, line 15.
-It is not sufficiently clear how the authors compare the two SM measurements (CRS and probes) with the water balance components. For instance it is said at P5354 that Q can be derived from P-I when fCRS>0 and can be compared with Q measured but I did not find any of this comparison in the result section.	As clarified in the new manuscript, the water balance was applied in an event-based approach and in a continuous fashion. In both cases, only the CRNS soil moisture estimates were used. Soil moisture measurements from CNRS and sensor networks were compared prior to the application of the water balance through a scatterplot (Fig. 5). We have updated the "Method" sections to make each of these points clearer. In the application of the water balance in a continuous fashion, we use the CRNS measurements to compute f_{CRNS}. This, in turn, is used to derive an estimate of the surface runoff (Q) from measurements of precipitation (P) as Q = P – I (where I = f_{CRNS} when $f_{CRNS} > 0$). The comparison against the observed runoff is performed in Table 4 via the runoff coefficient Q/P.
-I cannot well understand from this part how the "closing the soil water balance approach" is finally used. I think the authors should significantly improve this part	The expression "closing the soil water balance approach" has been used to indicate the use of the water balance equation to (i) validate the CRNS method and (ii) show how the soil moisture estimates from CRNS can be used to quantify its components.
7) P5356 L13-19. " Relative…at JER". I would move this part from the results to the section 2.2	Since Fig. 4 and related comments show a first comparison between CNRS and sensor networks, we prefer leaving this part in the "Results" section that is dedicated to such comparison.
8) P5356 L21-26. Why not using the SSE to quantify the seasonal differences?	Given the fairly small differences between the two estimates reported in Fig. 4, we decided not to add the SEE in the text.
9) P5358 L10. "This suggest that the three approaches" The sentence is not clear, consider revising. Three approaches?	The three approaches are the sensor network, the CRNS method, and by closing the water balance. We have updated the text on page 18, lines 11-12 to reflect this change.
10) P5358 L14. "A closer revealing". Remove this sentence it is not clear.	This sentence has been modified, page 18, lines 15-16.
11) P5359 L 1-30 – P5360 L1-8. I found this part really hard to follow.	We have clarified this section by adding materials requested in the revisions. This discussion section is linked to the analyses

It is overall clear that the two sites show strong ecosystem differences but I am expecting a larger discussion on whether theta_CRS is able to close the water balance or not with respect to theta_SN. (in the title the authors claim this). Something is provided at P5360 L1-8 but I think it has to be expanded.	presented in Fig. 9 and Table 5 which now are more clearly labeled as a section addressing the utility of CRNS for hydrologic process investigation. We have also clarified how the soil water balance is used in this study to: 1) derive an independent soil moisture estimate to compare to CRNS and the sensor network and 2) to make inferences on water balance fluxes through CRNS observations.
12) Table 2 information can be put in Table 1.	Given the relatively large content of the caption of Table 2, we decided to leave it as a separate Table. In addition, the two topics are fairly different and thus warrant separate treatment.

Response to Reviewer 3:

First of all, we thank Reviewer 3 for her/his comments that significantly helped us to improve the quality of our manuscript. In the following, we first describe the main changes that we made on the text based on the suggestions of all three reviewers and, then, we provide point-to-point answers to Reviewer 3's comments.

- We separated the "Methods" section into "Study Area and Datasets" and "Methods".

- We better focused the main analyses and results of the manuscript, which can be summarized as follows:
    1. Validation of cosmic-ray neutron probe sensing (CRNS) through distributed sensors and a novel method based on the water balance closing.
    2. Utility of CRNS for hydrologic studies at the footprint scale, including (i) the quantification of the water balance fluxes over the 19-month period, and (ii) the improvement of the relations between evapotranspiration (ET) and soil moisture.

  These changes implied significant modifications in the Introduction, Methods and Results sections.

- To give more importance to the main results reported in the previous point:
    - We reduced the part focused on the spatial variability of soil moisture and moved it to the section on the validation of the CRNS method through the distributed sensor network of soil moisture probes.
    - We completely removed analysis, discussion and one figure about the relations between spatial variability of soil moisture and ET.

- We improved the description of the water balance approach for (i) validating the CRNS method and (ii) studying the fluxes at the CRNS footprint in continuous fashion. In doing so, we carefully explained each assumption to avoid any misunderstandings.

- In the computation of the event-based water balance, we adopted a different measurement depth (z^*) for each event, as requested by all reviewers. This implied an update of two figures and metrics reported in Table 4.

Point-by-point responses to Reviewer 3's comments:

<table>
<tr><th>Reviewer 3 Comments</th><th>Author Response</th></tr>
<tr><td>There are a lot of analyses and approaches proposed in the manuscript but they are presented and discussed rather superficially which makes the manuscript very hard to follow, and sometimes not very well connected. What is/are the scientific question/s the authors are trying to answer? What is the main motivation? It is not clear to me what exactly the authors are trying to show (i.e., comparison of CRS with SN at both sites; relationships of within-footprint variability; evaluating use of CRS with EC fluxes; testing a simplified water balance approach with the data). This needs to be better clarified and organized in the revised version, hence I recommend major revisions.</td><td>We agree with Reviewer 3 on the need to make clearer the scientific motivation of our work. As outlined above, we have significantly modified the manuscript to address this comment. Specifically, we clarified that the main focus of our analyses are two issues:

• Validation of cosmic-ray neutron probe sensing (CRNS) through distributed sensors and a novel method based on the water balance closing.
• Utility of CRNS for hydrologic studies at the footprint scale, including (i) the quantification of the water balance fluxes over the 19-month period, and (ii) the improvement of the relations between evapotranspiration (ET) and soil moisture.

All sections of the papers have been modified to reflect these changes.</td></tr>
<tr><td>1. The water balance approach employed in the paper assumes the control volume is defined by the effective depth of the CRS (~ 40cm). However, we usually assume the control volume to be defined by the layer containing contribution from active roots, in the process of root water uptake - evapotranspiration. Authors should comment on the potential limitations of using a control volume represented by the measurement directly. Also, how about the lack of energy closure by the EC method (80% closure calculated)?</td><td>Since the application of the water balance of equation (6 in the new manuscript version) is made for rainfall events, ET is negligible. As a result, the use of z* instead of the plant rooting depth is justified. We clarified this point in page 13, lines 20-21.

The error inherent to the EC method that is reflected in the estimates of energy balance closure also plays a negligible role in the validation of the water balance approach applied for events since ET is very low at the scale of the single event. We have updated the text in the methods section page 13, lines 20-21 to explain this. At longer time scales (weeks to years), ET is an important part of the watershed water balance. For these applications, the errors in the energy balance closure are important. Unfortunately, the error balance closure error from the eddy covariance technique is unavoidable. Our estimates are well in line with eddy covariance studies across a wide range of ecosystems.</td></tr>
<tr><td>2. The authors justify the use of Eq. 2 in its simplest form (i.e., without accounting for additional hydrogen</td><td>Thanks for pointing this out. We updated the methods section to clarify this. The lattice water does not need to be accounted for when applying Eq. 2 because it was</td></tr>
</table>

sources). However, lattice water is then accounted for when calculating the CRS measurement depth (z*) in Eq. 4. Can the authors explain why lattice water does not matter for theta(N) but seems to matter for z*(theta)? This seems to be rather inconsistent!	accounted for during our local calibration process. It is unlikely that the lattice water will change over time due to the low clay contents. Furthermore, since the CRNS method measures relative differences in soil moisture (calibrated to obtain an absolute soil moisture), the lack of inclusion of the lattice water does not represent an issue for obtaining soil moisture. When calculating the z* measurement depth, however, we need to have estimates of the absolute values of hydrogen in the soil because there is not a way to locally calibrate the measurement depth. As a result, we utilize values for lattice water for that calculation. To address this comment, we have updated the text on page 11, lines 4-6, and page 11, lines 22-23.
3. As pointed out by the authors, there are already studies that focused on understanding the use of CRS in semi-arid sites. In this case, the good agreement between CRS and SN is not necessarily novel (in fact, SRER has been used quite extensively for such comparison). According to the authors, most of this good agreement happens under relatively dry conditions, as "the CRS method was not able to capture the soil moisture conditions during large rainfall events". Can the authors comment on possible limitations on the use of CRS for monitoring and predicting (in combination to hydrological models) flash floods events in semi-arid region?	The CRNS performs well as compared to the sensor network over a full range of different soil moisture conditions, though the errors tend to increase asymptotically with the soil moisture content. In the water balance approach, the major limitation for the large storm events was due to our assumptions on z* and not to the CRNS measurement itself. We have modified the sentence quoted here because it did not accurately reflect our conclusions. We changed line 13, on page 22 to say: "In the water balance comparisons, we identified that our assumptions of no leakage beneath z* were not met during large rainfall events, therefore the CRNS method was not able to capture all of the soil water in its measurement. We attribute this to rapid bypassing of the measurement depth promoted by soil and terrain characteristics." With regard to the application of CRNS for flash flood studies in arid and semiarid regions, we believe it is too premature in this work to comment or speculate on this aspect. Nevertheless, the reviewer brings up an interesting point that we might pursue in the future through the use of a hydrologic model and a data assimilation scheme using the CRNS as a spatially-aggregated observation.
4. Figure 2a: The land cover within the EC footprint suggests less bare soil fraction than the area covered by both CRS and SN. Figure 2b: How strongly do the authors consider the SN placement to be representative of the entire watershed? In addition, there is	The land cover in the watershed, EC footprint, and CRNS footprint is actually quite similar, as showed in a previous paper through UAV images (Vivoni et al., 2014). Thus, we made explicit reference to that paper on page 11, line 15. The soil moisture sensors were installed to examine different hydrologic processes at the two sites. We improved the explanation of the motivation in the revised

little overlap between EC footprint and CRS and SN spatial coverage. Can the authors comment on possible impacts and limitations in the analyses due to those issues?	manuscript. • At SRER, the soil moisture sensors were distributed under different vegetation cover. Here, the differences in soil moisture responses among different vegetation covers are larger than the horizontal spatial variability of soil moisture within the same vegetation class. Thus, we weighted the sensor network based on the amount of certain vegetation types, rather than distance to the CRNS sensor because this will provide a more accurate estimation of large-scale soil moisture. • At JER, topography plays an important role in the soil moisture due to a more incised watershed. This results in soil moisture redistribution, as well as sharp differences based on aspect. We therefore weighted the sensor network based on an aspect-elevation relation shown in Templeton et al. (2014). Regarding the question on the overlap between EC footprint and CRNS and SN spatial coverage, we think that differences in footprints and lack of overlap do not significantly affect our results, because: • The vegetation distribution does not significantly change at the scales of watersheds and footprints. In other words, it can be considered homogeneous at both scales (see Vivoni et al., 2014). This is stated on page 11, line 13-16. • While the soil may have different features within the channels, the only channels outside of the watershed are on the fringes of the footprints and are not expected to have a large influence. In addition, Anderson (2013) performed a soil texture analysis in the footprint of the EC tower at both sites and found small variations. This has been now stated on line 15, page 11.
5. Authors need to explain exactly what they are trying to show in Figure 11. Is there any strong relationship when individual points? There is only one case in which ET seems to respond to sigma (JER) but the error bars for individual bins are quite large.	We appreciate the reviewer comment. However, we decided to remove the analyses on the relationship between soil moisture heterogeneity and ET. Thus, Fig. 11 is no longer in the manuscript.

Closing the Water Balance with Cosmic-ray Soil Moisture Measurements and Assessing Their ~~Spatial Variability with~~Relation to Evapotranspiration in Two Semiarid Watersheds

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Abstract

Soil moisture dynamics reflect the complex interactions of meteorological conditions with soil, vegetation and terrain properties. In this study, intermediate scale soil moisture estimates from the cosmic-ray neutron sensing (~~CRS~~CRNS) method are evaluated for two semiarid ecosystems in the southwestern United States: a mesquite savanna at the Santa Rita Experimental Range (SRER) and a mixed shrubland at the Jornada Experimental Range (JER). Evaluations of the ~~CRS~~CRNS method are performed for small watersheds instrumented with a distributed sensor network consisting of soil moisture sensor profiles, an eddy covariance tower and runoff flumes used to close the water balance. We found ~~an excellent~~a very good agreement between the ~~CRS~~CRNS method and the distributed sensor network (RMSE of 0.009 and 0.013 m^3/m^3 at SRER and JER) at the hourly time scale over the 19-month study period, primarily due to the inclusion of 5 cm observations of shallow soil moisture. Good agreement was also obtained in soil moisture changes estimated from the ~~CRS~~CRNS and watershed water balance methods (RMSE = 0.001 and 0.~~038~~082 m^3/m^3 at SRER and JER), with deviations due to bypassing of the ~~CRS~~CRNS measurement depth during large rainfall events. ~~This limitation, however, was~~Once validated, the CRNS soil moisture estimates were used to ~~show~~investigate hydrological processes at the footprint scale at each site. Through the computation of the water balance, we showed that drier-than-average conditions at SRER promoted plant water uptake from deeper soil layers, while the wetter-than-average period at JER resulted in ~~leakage~~percolation towards deeper soils. ~~Using the distributed sensor network, we quantified the spatial variability of soil moisture in the CRS footprint and the relation~~The CRNS measurements were then used to quantify the link between evapotranspiration and soil moisture~~, in both cases~~ at

a commensurate scale, finding similar predictive relations at both sites that are applicable to other semiarid ecosystems in the southwestern U.S. Furthermore, soil moisture spatial variability was related to evapotranspiration in a manner consistent with analytical relations derived using the CRS method, opening up new possibilities for understanding land-atmosphere interactions.

Keywords: watershed hydrology, soil moisture variability, evapotranspiration, land-atmosphere interactions, COSMOS, North American monsoon.

1. Introduction

Soil moisture is a key land surface variable that governs important processes such as the rainfall-runoff transformation, the partitioning of latent and sensible heat fluxes and the spatial distribution of vegetation in semiarid regions (e.g., Entekhabi, 1995; Eltahir, 1998; Vivoni, 2012). Semiarid watersheds with heterogeneous vegetation in the southwestern United States (Gibbens and Beck, 1987; Browning et al., 2014) exhibit variations in soil moisture that challenge our ability to quantify land-atmosphere interactions and their role in hydrological processes (Dugas et al., 1996; Small and Kurc, 2003; Scott et al., 2006; Gutiérrez-Jurado et al., 2013; Pierini et al., 2014). Moreover, accurate measurements of soil moisture over scales relevant to land-atmosphere interactions in watersheds are difficult to obtain. Traditionally, soil moisture is measured continuously at single locations using techniques such as time domain reflectometry and then aggregated in space using a number of methods (Topp et al., 1980; Western et al., 2002; Vivoni et al., 2008b). Soil moisture is also estimated using satellite-based techniques, such as passive or active microwave sensors~~, but spatial resolutions are typically coarse and overpass times infrequent~~ (e.g., Kustas et al., 1998; Moran et al., 2000; Kerr et al., 2001; Bartalis et al., 2007; Narayan and Lakshmi, 2008~~),~~ ; Entekhabi et al., 2010), but spatial resolutions are typically coarse and overpass times infrequent as compared to the spatiotemporal variability of soil moisture occurring within semiarid watersheds.

One approach to address the scale gap in soil moisture estimation is through the use of cosmic-ray neutron sensing (~~CRS~~CRNS) measurements (Zreda et al., 2008, 2012) that provide soil moisture with a measurement footprint of several hectares (Desilets et al., 2010). Developments of the ~~CRS~~CRNS method have focused on understanding the processes affecting the measurement technique, for example, the effects of vegetation growth (Franz et al., 2013a;

Coopersmith et al., 2014), atmospheric water vapor (Rosolem et al., 2013), soil wetting and drying (Franz et al., 2012a)), and horizontal heterogeneity (Franz et al., 2013b). To date, the validation of the CRS method CRNS technique has been performed using single site measurements, spatial aggregations of different measurement locations, and particle transport models (Desilets et al., 2010; Franz et al., 2013b; Zhu et al., 2015). AtDistributed sensor networks measuring the water balance components of small watersheds and the spatial variability of soil moisture within a watershed scale, however,offer the CRSopportunity to test the accuracy of the CRNS method through multiple, independent approaches. For instance, the CRNS technique can also be validated based upon the application of the watershed water balance equation, as performed for the eddy covariance (EC) technique often used to measure surface turbulent fluxes (Scott, 2010; Templeton et al., 2014). In small watersheds of comparable size to the CRS measurement footprint, the water balance Once validated, CRNS soil moisture estimates can be expressed as:

$$z_m \frac{\Delta\theta}{\Delta t} = P - ET - Q - L \quad , \quad (1)$$

where θ is volumetric soil moisture, P is precipitation, ET is evapotranspiration, Q is streamflow, and L is leakage,used to apply the water balance equation in a continuous fashion with all of the terms expressed as spatially-averaged quantitiesthe aim of quantifying hydrological fluxes during storm and valid over the effective soil measurement depth (z_m). Closing the water balance, or the estimation of each term of (1), would be a novel way for comparinginterstorm periods, including the CRS method to independent observations valid at a commensurate spatial and temporal scale. Nevertheless, the applicationoccurrence of (1) can be fraught with issues relatedpercolation to measurement limitations and representativenessdeeper soil layers or when spatially-averaged quantities are difficult the transfer of water from the deeper vadose zone to obtain in heterogeneous watersheds.

Soil moisture measurements at the intermediate scales provided by the CRS method do not capture the spatial variability within the measurement footprint (Zreda et al., 2008). As a result, distributed sensor networks consisting of different locations in a watershed are essential for establishing how the spatially-averaged properties are obtained (e.g., Franz et al., 2012b). Capturing the soil moisture spatial variability within a measurement footprint is alsoatmosphere.

An important for improving the representationadvantage of land-atmosphere interactions and hydrologic processes in models (Famiglietti and Wood, 1994; Bindlish et al., 2009; Mascaro and Vivoni, 2012). Basedthe CRNS technique is that its measurement scale is comparable to the footprint of evapotranspiration (*ET*) measurements based on prior studiesthe EC technique, whose extent depends on wind speed and direction, atmospheric stability, and instrument and surface roughness heights (e.g., Hsieh et al., 2000; Kormann and Meixner, 2001; Falge et al., 2002). Furthermore, the relation between *ET* and soil moisture is an important parameterization in land surface models (e.g., Laio et al., 2001; Rodríguez-Iturbe and Porporato, 2004; Vivoni et al., 2008a) and, in most cases, has been investigated using distributed sensor networks, the spatial variability of soil moisture is expected to increase with wetter spatially-averaged conditions in the range EC measurements of values observed in semiarid areas (Famiglietti et al., 1999; Lawrence and Hornberger, 2007; Fernández and Ceballos, 2003; Vivoni et al., 2008b; Mascaro et al., 2011), as heterogeneities related*ET* and soil moisture observations at single sites. A number of studies, however, have shown that accounting for the spatial variability of land surface states is important to vegetation, terrain position and soil properties progressively leadproperly identify the linkage with EC measurements (e.g., Detto et al., 2006; Vivoni et al., 2010; Alfieri and Blanken, 2012). In other words, aggregated turbulent fluxes should be compared to ~~larger spatial differences within a watershed. Soil~~ spatially-averaged surface states obtained at commensurate measurement scales. As a result, CRNS soil moisture ~~variability also impacts land-atmosphere interactions by influencing soil evaporation and plant transpiration. *ET* measurements using the EC technique also have an intermediate spatial scale depending on wind speed and direction, atmospheric stability, and instrument and surface roughness heights (e.g., Hsieh et al., 2000; Kormann and Meixner, 2001; Falge et al., 2002). Thus, the use of the CRS method and a distributed sensor network~~ estimates could ~~yield valuable information on how~~ be useful to improve the characterization of the relation between evapotranspiration flux and soil moisture ~~and its spatial variability affect evapotranspiration losses. Furthermore, the relation between *ET* and soil moisture is an important parameterization in models (e.g., Laio et al., 2001; Rodríguez-Iturbe and Porporato, 2004; Vivoni et al., 2008a), which could be improved at intermediate spatial scales through a link between the spatial variability of soil moisture and the aggregated evapotranspiration flux.~~ . To our knowledge, soil moisture estimates from the CRNS technique have not been used to study the hydrological processes occurring in small watersheds overlapping with the measurement footprint or for improving the parameterization of land surface models.

In this contribution, we study the soil moisture dynamics of ~~two~~small semiarid watersheds in Arizona and New Mexico ~~through a comparison of the CRS method~~instrumented with a ~~distributed sensor network and estimates from closing the water balance at each site. To our knowledge, this is the first study where CRS measurements are validated to two independent methods at the small watershed scale~~cosmic-ray neutron sensor, an eddy covariance tower, a runoff flume and a network of soil moisture sensor profiles. The ~~two~~ watersheds represent the heterogeneous vegetation and soil conditions observed in the Sonoran and Chihuahuan Deserts of the southwestern U.S. (Templeton et al., 2014; Pierini et al., 2014). ~~Given the simultaneous observations during the study period (March 2013 to September 2014, 19 months) at both sites, we~~ We first compare the CRNS method with the distributed sensor network and estimates from a novel method based on closing the water balance at each site. Given the simultaneous observations during the study period (March 2013 to September 2014, 19 months), we quantify the variations in ~~vadose zone~~ hydrological processes (e.g., infiltration, ~~plant water uptake, leakage~~evapotranspiration, percolation) that differentially occur at each site in response to varying precipitation. Combining these ~~various~~ measurement techniques also affords the capacity to construct and compare relationships between the spatially-averaged ~~CRS~~CRNS estimates and the ~~spatial variability of soil moisture in the measurement footprint as well as with the~~ spatially-averaged *ET* obtained from the EC method. ~~Finally, by complementing the CRS and EC observations with the distributed sensor network, we propose and test an analytical relation that describes how evapotranspiration varies with the spatial variability of soil moisture.~~ To our knowledge, this is the first study where CRNS measurements are validated via two independent methods at the small watershed scale and used to make new inferences about watershed hydrological processes.

2. ~~Methods~~Study Areas and Datasets

2.1. Study Sites and Their General Characteristics

The two study sites are long-term experimental watersheds in semiarid ecosystems of the southwestern United States. Watershed monitoring began in 1975 at the Santa Rita Experimental Range (SRER), located 45 km south of Tucson, Arizona, in the Sonoran Desert (Fig. 1), as described by Polyakov et al. (2010) and Scott (2010). Precipitation at the site varies considerably during the year, with 54% of the long-term mean amount (364 mm/yr) occurring during the summer months of July to September due to the North American monsoon (Vivoni et al., 2008a; Pierini et al., 2014). Soils at the SRER site are a coarse-textured sandy loam (Anderson, 2013) derived from Holocene-aged alluvium from the nearby Santa Rita Mountains. The savanna ecosystem at the site consists of the velvet mesquite tree (*Prosopis velutina* Woot.), interspersed with grasses (*Eragrostis lehmanniana*, *Bouteloua rothrockii*, *Muhlenbergia porteri* and *Aristida glabrata*) and various cacti species (*Opuntia spinosior*, *Opuntia engelmannii* and *Ferocactus wislizeni*). Similarly, watershed monitoring began in 1977 at the Jornada Experimental Range (JER), located 30 km north of Las Cruces, New Mexico, in the Chihuahuan Desert (Fig. 1), as described by Turnbull et al. (2013). Mean annual precipitation at the JER is considerably lower than SRER (251 mm/yr), with a similar proportion (53%) occurring during the summer monsoon (Templeton et al., 2014). Soils at the JER site are primarily sandy loam with high gravel contents (Anderson, 2013) transported from the San Andreas Mountains. The mixed shrubland ecosystem at the site consists of creosote bush (*Larrea tridentata*), honey mesquite (*Prosopis glandulosa* Torr.), several grass species (*Muhlenbergia porteri*, *Pleuraphis mutica* and *Sporobolus cryptandrus*), and other shrubs (*Parthenium incanum*, *Flourensia cernua* and *Gutierrezia sarothrae*). Fig. 2 presents a vegetation classification at each site grouped into major categories: (1) SRER has velvet mesquite (labeled mesquite), grasses, cacti (*Opuntia engelmannii* or prickly pear) and bare soil, while (2) JER has honey mesquite (labeled mesquite), creosote bush, other shrubs, grasses and bare soil. Table 1 presents the vegetation and ~~geomorphological~~terrain properties for the site watersheds obtained from 1-m digital elevation models (DEMs) and 1-m vegetation maps (Fig. 2). Pierini et al. (2014) and Templeton et al. (2014) describe the image acquisition and processing methods employed to derive these products at SRER and JER, respectively.

2.2. Distributed Sensor Networks at the Small Watershed Scale

Long-term watershed monitoring at the SRER and JER sites consisted of rainfall and runoff observations at Watersheds 7 and 8 (SRER, 1.25 ha) and the Tromble Weir (JER, 4.67 ha). Pierini et al. (2014) and Templeton et al. (2014) describe recent monitoring efforts using a network of rainfall, runoff, soil moisture and temperature observations, as well as radiation and energy balance measurements at EC towers, commencing in 2011 and 2010 at SRER and JER. This brief description of the distributed sensor networks is focused on the spatially-averaged measurements used for comparisons to the ~~CRS~~CRNS method. Precipitation (*P*) was measured using ~~multiple~~ up to 4 tipping-bucket rain gauges (TE525MM, Texas Electronics) to construct a 30-min resolution spatial average based on Thiessen polygons within the watershed boundaries. At the watershed outlets, streamflow (*Q*) was estimated at Santa Rita supercritical runoff flumes (Smith et al., 1981) using a pressure transducer (CS450, Campbell Scientific Inc.) and an *in-situ* linear calibration to obtain 30-min resolution observations. Evapotranspiration (*ET*) was obtained at 30-min resolution using the EC technique that employs a three-dimensional sonic anemometer (CSAT3, Campbell Scientific Inc.) and an open path infrared gas analyzer (LI-7500, LI-COR Inc.) installed at 7-m height on each tower. Flux corrections for the EC measurements followed Scott et al. (2004) and were verified using an energy balance closure approach reported in Table 2 for the study period. Energy balance closure at both sites is within the reported values across a range of other locations where the ratio of $\Sigma(\lambda E + H)/\Sigma(R_n - G)$ has an average value of 0.8 (Wilson et al., 2002; Scott, 2010). To summarize these observations, Fig. 3 shows the spatially-averaged *P*, *Q* and *ET* (mm/hr), each aggregated to hourly resolution, at each study site during

March 1, 2013 to September 30, 2014, along with seasonal precipitation amounts. While the results compare favorably to previous measurements (Turnbull et al., 2013; Pierini et al., 2014; Templeton et al., 2014), it should be noted that *ET* and *Q* data are assumed to represent the spatially-averaged watershed conditions, despite the small mismatch between the watershed boundaries and EC footprints (Fig. 2) and the summation of *Q* in the two watersheds at SRER.

Distributed soil moisture measurements were obtained using soil dielectric probes (Hydra Probe, Stevens Water) organized as profiles (sensors placed at 5, 15 and 30 cm depths) in each study site~~ as~~. Profiles were originally installed at multiple locations along transects to investigate the different primary controls on soil moisture at each site: (1) at SRER, we installed ~~three~~four transects of 5 profiles each located under different vegetation classes (mesquite, grass, prickly pear and bare soil), and (2) at JER, we established three transects of 5 profiles each installed along different hillslopes (north-, south- and west-facing), as shown in Fig. 1. ~~As described in Campbell (1990), individual~~Individual sensors measure the impedance of an electric signal~~-~~, as described in Campbell (1990), through a 40.3 cm^3 soil volume (5.7 cm in length and 3.0 cm in diameter) to determine the volumetric soil moisture (θ) in m^3/m^3 and soil temperature in ºC as 30-min averaged values. A 'loam' calibration equation was used in the conversion to θ (Seyfried et al., 2005) and corrected using relations established through gravimetric soil sampling at each study site (a power law relation at SRER with R^2 = 0.99 and a linear relation at JER with R^2 = 0.97), following Pierini (2013). ~~Spatial~~Given that sensors were originally installed to conduct watershed studies, spatial averaging ~~of the sensor profiles within the watersheds aggregated to an hourly resolution~~ was performed using ~~a~~ site-specific weighting ~~scheme~~schemes accounting for ~~each site based on~~ the main controls on the soil moisture distribution~~ depending on watershed characteristics~~. Thus: (1) at SRER, we utilized the percentage area of each vegetation class

(Table 1) and the associated sensor locations within each type (Pierini et al., 2014), and (2) at JER, we accounted for the aspect and elevation at the sensor locations and used these to extrapolate to other locations with similar characteristics based on the 1-m DEM (Templeton et al., 2014).

2.3. Cosmic-ray ~~Soil Moisture~~ Neutron Sensing Method for Soil Moisture Estimation

The ~~CRS~~CRNS method relates soil moisture to the density of fast or moderated neutrons (Zreda et al., 2008) measured above the soil surface. A cosmic-ray neutron sensor (CRS-1000/B, Hydroinnova LLC) was installed in each watershed in January 2013 to record neutron counts at hourly intervals. We selected the study period (March 1, 2013 to September 30, 2014) to coincide with the availability of data from the distributed sensor networks. While the theory of using neutrons for soil moisture measurements has a long history (e.g., Gardner and Kirkham, 1952), recent developments in the measurement of neutrons generated from cosmic rays has increased the horizontal scale, reduced the need for manual sampling, and led to a non-invasive approach. Zreda et al. (2008) and Desilets and Zreda (2013) describe the horizontal scale as having a radius of ~300 m at sea level and a vertical aggregation scale ranging from 12 to 76 cm depending on soil wetness, while the work of Köhli et al. (2015) found a smaller horizontal scale with a radius of ~230 m at sea level. Since the travel speed of fast neutrons is >10 km/s, neutron mixing occurs ~~instantaneous~~almost instantaneously in the air above the soil surface (Glasstone and Edlund, 1952), providing a well-mixed region that can be sampled with a single detector.

Using a particle transport model, Desilets et al. (2010) found a theoretical relationship between the neutron count rate at a detector and soil moisture for homogeneous SiO_2 sand:

$$\theta(N) = \frac{0.0808}{\left(\frac{N}{N_o}\right) - 0.372} - 0.115 \qquad , \qquad (~~2~~1)$$

where θ (m^3/m^3) is volumetric soil moisture, N is the neutron count rate (counts/hr) normalized to the atmospheric pressure and solar activity level, and N_o (counts/hr) is the count rate over a dry soil under the same reference conditions. The corrections applied to the neutron count rate are detailed in Desilets and Zreda (2003) and Zreda et al. (2012) and are applied automatically in the COSMOS website (http://cosmos.hwr.arizona.edu/). Additionally, since neutron counts are affected by all sources of hydrogen in the support volume, we apply a correction (C_{WV}) for atmospheric water vapor that was derived by Rosolem et al. (2013) as:

$$C_{WV} = 1 + 0.0054\left(\rho_v^o - \rho_v^{ref}\right) \quad , \qquad (~~3~~2)$$

where $\rho_v{}^o$ (g/m^3) and $\rho_v{}^{ref}$ (g/m^3) are absolute water vapors at current and reference conditions. To estimate N_o, we performed a manual soil sampling at 18 locations within the ~~CRS~~CRNS footprint (sampled every 60 degrees at radial distances of 25, 75 and 200 m from the detector) at 6 depths (0-5, 5-10, 10-15, 15-20, 20-25, 25-30 cm) for a total of 108 samples per site. Gravimetric soil moisture measurements were made following oven drying at 105 ºC for 48 hrs (Dane and Topp, 2002) and converted to volumetric soil moisture using the soil bulk density (1.54 ± 0.18 g/cm^3 at SRER and 1.3 ± 0.15 g/cm^3 at JER). The spatially-averaged volumetric soil moisture was related to the average neutron count obtained for the same time period (6-hr average) resulting in N_o = 3973 at SRER and N_o = ~~4724~~3944 at JER, considered to be in line with the expected amounts given the elevations of both sites~~(~~. Table ~~1)~~3 compares the gravimetric measurements and the CRNS soil moisture estimates during the calibration dates and provides further details on the soil properties at the two sites. We applied a 12-hr boxcar filter~~, which ignored rainfall periods with large increase in θ,~~ to the measured count rates to remove the statistical noise associated with the measurement method (Zreda et al., 2012). On days where soil moisture changed by more than 0.06 m^3/m^3 due to rainfall, the boxcar filter was not applied. We note that additional terms to the calibration accounting for variations in lattice water, soil organic carbon and vegetation have been proposed (Zreda et al., 2012; Bogena et al., 2013; McJannet et al., 2014; Coopersmith et al. 2014). However, given the relatively small amount of biomass ~~(>~~(~2.5 kg/m^2 at SRER, Huang et al., 2007; and ~~>~~~0.5 kg/m^2 at JER, Huenneke et al., 2001), low soil organic carbon (4.2 mg C/g soil at SRER; and 2.7 mg C/g soil at JER, Throop et al., 2011), and low clay percent (5.~~1~~2% at SRER; and 4.~~8~~9% at JER, Anderson, 2013), and thus low lattice water amounts (Greacen, 1981), we have neglected these ~~small~~ terms in the analysis. In addition, since a local calibration was performed, lattice water, biomass, and soil organic carbon are implicitly accounted for in the calculation of volumetric soil moisture from the calibration relation.

Fig. 2 presents the horizontal aggregation scale of the ~~CRS~~CRNS method in comparison to the watershed boundaries and to the EC footprints obtained for summer 2013 (Anderson, 2013). Since both the ~~CRS~~CRNS and EC footprints have horizontally-decaying contributions, we limited the size of the analysis region to the 50% contribution or source area~~. While the CRS horizontal footprint is nearly fixed in time at a 120 m radius at SRER and 125 m radius at JER for the 50% contribution,~~ to enhance the overlap with the watershed boundaries and sensor networks. The footprints for both the CRNS method and the EC ~~footprint varies~~ method vary considerably (Anderson, 2013; Köhli et al., 2015), with temporal changes occurring in the amount of overlap with the watersheds and ~~CRS footprints~~between each other. Nevertheless, the vegetation distributions sampled in the ~~CRS~~CRNS, EC, and watershed areas (Fig. 2) are nearly the same (Vivoni et al., 2014), and the soils have low spatial variability (Anderson, 2013; Table 3), such that ~~CRS~~CRNS and EC measurements are considered representative of the watershed conditions. In ~~contrast~~addition to the ~~fixed~~changing horizontal scale, the ~~CRS~~CRNS method measures a time-varying vertical scale that depends on the soil water content. Franz et al. (2012b) used a particle transport model to determine that the ~~CRS~~CRNS measurement depth, z^*, varied with soil moisture as:

$$z^*(\theta) = \frac{5.8}{\rho_b \tau + \theta + 0.0829} \quad , \qquad (~~4~~3)$$

where $\rho_{b\,d}$ is ~~dry~~ bulk density of the soil (~~1.535 g/cm^3 at SRER and 1.300 g/cm^3 at JER~~Table 3) and τ is the weight fraction of lattice water in the mineral grains and bound water~~,~~. Lattice water must be considered here since a local calibration of (3) is not possible. As a result, lattice water content was established at 0.02 g/g at each site given the weathered soils ~~(~~and the measurements from Franz et al~~.,~~. (2012b). To account for ~~this~~ the temporal variation of z^*, the ~~distributed~~ sensor profiles representing different soil layers (0-10 cm, 10-20 cm, and 20-40 cm in depth) were weighted based on z^* at each hourly time step according to:

$$wt(z) = a\left(1 - \left(\frac{z}{z^*}\right)^b\right) \qquad \text{for } 0 \le wt \le z^* \quad , \qquad (~~5)~~4)$$

where $wt(z)$ is the weight at depth z, a is a constant defined to integrate the profile to unity (a = 1/(z^* - {z^{*b+1}/[z^{*b}(b + 1~~)]}}~~)]}), and b controls the shape of the weighting function. For simplicity, we assumed a value of b = 1 leading to a linear relationship (Franz et al., 2012b).

~~**2.4. CRS and**~~

3. Methods

3.1. Comparison of CRNS to Distributed ~~Sensor~~ Network ~~Analyses Methods~~ of Soil Moisture Sensors

~~We~~ The CRNS method was first validated against the distributed network of soil moisture sensors. As done in previous studies, we compared hourly soil moisture observations obtained from the ~~CRS~~CRNS method (~~θ_{CRS}~~θ_{CRNS}) to estimates from the distributed sensor network (θ_{SN}) that have been averaged in space (i.e., based on vegetation type at SRER and elevation/aspect location at JER) and depth-weighted according to the time-varying ~~CRS~~CRNS measurement depth (z^*). We ~~also assessed the CRS method relative to estimates from closing the water balance (1) using spatially-averaged P, Q and ET. For this comparison, the change in soil moisture from the water balance ($\Delta\theta_{WB}$) was compared to $\Delta\theta_{CRS}$, both calculated as differences over the time scale of a rainfall event and its soil moisture response (i.e., the change from pre-storm soil moisture to the peak amount due to a rainfall event). This relative comparison assumes~~used several metrics to quantitatively assess the comparisons, including Root Mean Square Error (RMSE), Correlation Coefficient (CC), Bias (B) and Standard Error of Estimates (SEE). We performed an ~~effective soil measurement depth (z_m) of 40 cm determined as the time-averaged z^* from the CRS method at each site. Since this comparison is performed over a short time interval during the rising limb of the soil moisture response, we tested whether the assumption of no leakage (i.e., $L = 0$) is valid given that there are small losses below z_m to the deep vadose zone. Leakage beyond 40 cm is infrequent at both sites during the summer monsoon, but can occur on a time scale of several days during winter precipitation (e.g., Franz et al., 2012b; Templeton et al., 2014; Pierini et al., 2014). We used several metrics to quantitatively assess the comparisons~~additional test of the CRNS technique by comparing relations between the mean soil moisture ($\langle\theta\rangle$), obtained from either θ_{CRNS} or θ_{SN}, and the spatial standard deviation (σ) of soil moisture measured in the distributed sensor network. This relation has been studied previously with the ~~CRS method: Root Mean Square Error (RMSE), Correlation Coefficient (CC), Bias (B) and Standard Error of Estimates (SEE).~~ goal of evaluating the role of heterogeneities related to vegetation, terrain position and soil properties (Famiglietti et al., 1999; Lawrence and Hornberger, 2007; Fernández and Ceballos, 2003; Vivoni et al., 2008b; Mascaro et al., 2011; Qu et al., 2015). Based on Famiglietti et al. (2008), we fitted an empirical function to the observations at each site:

We also calculated a soil water balance based on the CRS method to determine the spatially-averaged fluxes into and out from the measurement depth (z*) as (Franz et al., 2012b):

$$\sigma = k_1 \langle \theta \rangle e^{-k_2 \langle \theta \rangle} \quad ; \quad (5)$$

where k_1 and k_2 are regression parameters, and compared these to prior studies in the region (e.g., Vivoni et al., 2008b; Mascaro and Vivoni, 2012; Stillman et al., 2014).

3.2. CRNS Water Balance Analyses Methods

In small watersheds of comparable size to the CRNS measurement footprint, the water balance can be expressed as:

$$z^* \frac{\Delta \theta}{\Delta t} = P - ET - Q - L \quad , \quad (6)$$

where f_{CRS} is the daily flux (mm/day) and Δt is the time step (1 day). Positive values of f_{CRS} represent infiltration (I) into the measurement depth, while negative values equal outflow (O), occurring either as $\Delta\theta$ is the change in volumetric soil moisture over the time interval Δt, P is precipitation, ET is evapotranspiration or leakage. Based on daily P data, , Q is streamflow, and L is leakage or deep percolation, with all of the terms expressed as spatially-averaged quantities and valid over the effective soil measurement depth (z*). The water balance was applied to validate the accuracy of the CRNS observations using measurements of the spatially-averaged fluxes (P, ET and Q can be derived as P – I, assuming negligible plant interception, and compared to Q measurements in the watersheds. Using the EC method to obtain daily ET, $L = O$ – ET can be obtained as a measure of exchanges between the CRS measurement depth and soil below) for a set of storm events. For each event, we computed the change in soil moisture measured by the CRNS, $\Delta\theta_{CRNS}$, and the change calculated from the water balance, $\Delta\theta_{WB}$. In both cases, changes were computed as the difference between the pre-storm soil moisture and the peak amount due to a rainfall event. For the application of (6), the soil measurement depth z*. L is positive when there is leakage to deeper soil layers and negative when deeper water is being drawn to support plant transpiration.

2.5. Soil Moisture Variability and Its Link* was calculated as the average value over the duration of the soil moisture response to each individual storm. Note that, during a storm, ET is very low and the use of z* in (6) instead of the plant rooting depth is justified. In addition, since this comparison is performed over a short time interval during the rising limb of the soil moisture response, we assumed no leakage (i.e., $L = 0$). To test the validity of this hypothesis, we analyzed the soil moisture records measured at the EC towers, where sensors were installed to **Evapotranspiration** measure the profile up to 1 m (i.e., a depth larger than z*). We found that the percolation beyond a depth of ~40 cm is infrequent at both sites during summer monsoon storms, thus sustaining our assumption. However, percolation can occur on a time scale of several days during winter precipitation (e.g., Franz et al., 2012b; Templeton et al., 2014; Pierini et al., 2014). Although there are large amounts of bare soil in the watersheds, shrub and tree roots have been shown to extend laterally for 10 m or more (Heitschmidt et al., 1988), such that most of contributing area will be under the influence of both bare soil evaporation and plant transpiration.

The spatial variability within the CRS footprint was assessed using the distributed sensor network by constructing relations between the spatial standard deviation (σ) and coefficient of variation ($CV = \sigma/\langle\theta\rangle$) with the mean soil moisture state ($\langle\theta\rangle$), obtained either from the CRS method (θ_{CRS}) or Once validated against the distributed sensor network (θ_{SN}). Based on the methods sensors and the application of the water balance, the CRNS estimates were subsequently used to determine the daily spatially-averaged fluxes into and out from the measurement depth (z^*) as proposed by FamigliettiFranz et al. (2008), we fitted the following empirical functions to the observations at each site:2012b):

$$f_{CRNS}(t) = \left(\theta_{CRNS,t} - \theta_{CRNS,t-1}\right)\min(z^*_t, z^*_{t-1}) / \Delta t \quad \text{and} \quad . \qquad (7)$$

$$CV = k_1 e^{-k_2\langle\theta\rangle} \,, \qquad (8)$$

where k_1 and k_2 are regression parameters, and compared these to prior studies in the region (e.g., Vivoni et al., 2008b; Mascaro and Vivoni, 2012; Stillman et al., 2014). Soil moisture at single locations is typically linked to In (7), f_{CRNS} is the daily flux (mm/day), Δt is the time step (1 day), and $\min(z^*_t, z^*_{t-1})$ represents the minimum daily-averaged measurement depth between the two days being compared. Positive values of f_{CRNS} indicate an increase in soil moisture and, thus, represent net infiltration ($f_{CRNS} = I$) into the measurement depth, usually occurring after a rainfall event. As a result, assuming negligible plant interception, daily P data can be used to estimate Q as $P - I$, which in turn can be compared to the runoff measurements in the watersheds. On the other hand, negative values of f_{CRNS} are equal to the net outflow ($f_{CRNS} = O$), which can occur either as evapotranspiration or leakage. Using the EC method to obtain daily ET, $L = O - ET$ can be determined as a measure of exchanges between the soil layers above and below z^*: L is positive when there is drainage to deeper soil layers and negative when deeper water is being drawn to support plant transpiration.

3.3. Relation between Evapotranspiration and Soil Moisture at Commensurate Scale

Soil moisture at single locations is typically linked to ET in hydrologic models (e.g., Chen et al., 1996; Ivanov et al., 2004) and empirical studies (e.g., Small and Kurc, 2003; Vivoni et al., 2008a) using relations such as $ET = f(\theta)$. For example, a commonly used approach is based on a piecewise linear relation between daily ET and θ (Rodríguez-Iturbe and Porporato, 2004):

$$ET(\theta) = \begin{cases} 0 & 0 < \theta \le \theta_h \\ E_w \dfrac{\theta - \theta_h}{\theta_w - \theta_h} & \theta_h < \theta \le \theta_w \\ E_w + \left(ET_{\max} - E_w\right)\dfrac{\theta - \theta_h}{\theta^* - \theta_h} & \theta_w < \theta \le \theta^* \\ ET_{\max} & \theta^* < \theta \le \phi \end{cases}, \qquad (~~9~~8)$$

where E_w is soil evaporation, ET_{max} is maximum evapotranspiration, θ_h, θ_w, and θ^* are the hygroscopic, wilting and plant stress soil moisture thresholds, and ϕ is the soil porosity. Vivoni et al. (2008a) applied (~~9)~~8) to observations of ET from the EC method and θ at single locations to derive the relation parameters using a nonlinear optimization algorithm (Gill et al., 1981). We evaluate this approach using the spatially-averaged soil moisture estimates (~~θ_{CRS}~~θ_{CRNS} and θ_{SN}) whose spatial scale is more commensurate with the ET measurements~~. In addition, we combine (9) with (7) and (8) to obtain analytical relations between evapotranspiration and the spatial variability of soil moisture, $ET = f(\sigma)$ and $ET = f(CV)$, and test these with θ_{CRS} and θ_{SN} observations.~~ than single measurement sites.

~~3~~4. Results and Discussion

~~3~~4.1. Comparison of ~~CRS~~CRNS Method to Distributed Sensor Network

Fig. 4 presents a comparison of the spatially-averaged, hourly soil moisture obtained from the ~~CRS~~CRNS method (~~θ_{CRS}~~θ_{CRNS}) and the distributed sensor network (θ_{SN}~~) during the study period~~), as well as the time-varying measurement depth (z^*) of CRNS. Relative to the long-term summer precipitation (Table 1), the study period had below average (188 and 153 mm in 2013 and 2014) and significantly above average (246 and 247 mm) rainfall at SRER and JER, respectively. The fall-winter period in the record had below average precipitation (99 mm) at SRER and significantly below average amounts (21 mm) at JER. Overall, the spring periods were dry, consistent with the long-term averages. In response, the temporal variability of soil moisture clearly shows the seasonal conditions at the two sites, with relatively wetter conditions during the summer monsoons. Seasonally-averaged ~~θ_{CRS}~~θ_{CRNS} compares favorably with seasonally-averaged θ_{SN} (Fig. 4), with both estimates showing relatively large differences between wetter summer conditions (0.065 and 0.085 m^3/m^3 at SRER and JER) and drier spring values (0.028 and 0.021 m^3/m^3 at SRER and JER, respectively). As shown in prior studies (e.g., Zreda et al., 2008; Franz et al., 2012b), the ~~CRS~~CRNS method tracks very well the sensor observations. Nevertheless, there is an indication that ~~θ_{CRS}~~θ_{CRNS} has a tendency to dry less quickly during some rainfall events (i.e., overestimate soil moisture during recession limbs), possibly due to landscape features such as nearby channels (Fig. 1) and their associated zones of soil water convergence that remain wetter than areas measured by the distributed sensor network. Overall, however, there is an excellent match between ~~θ_{CRS}~~θ_{CRNS} and θ_{SN} in terms of capturing the occurrence and magnitude of soil moisture peaks across the different seasons, thus reducing some issues noted by Franz et al. (2012b) with respect to a purported oversensitivity of ~~θ_{CRS}~~θ_{CRNS} for small rainfall events (<5 mm). We attribute this improvement ~~primarily to including~~ to the use of a 5 cm sensor in each profile that tracks ~~the~~ important soil moisture dynamics occurring in the shallow surface layer within semiarid ecosystems.

To complement this, Fig. 5 compares ~~θ_{CRS}~~θ_{CRNS} and θ_{SN} as a scatterplot along with the sample size (N) and the Standard Error of Estimates (SEE) which quantify the deviations from the 1:1 line. Table ~~3~~4 provides the full set of statistical metrics for the comparison of ~~θ_{CRS}~~θ_{CRNS}

versus θ_{SN} at the two study sites. The correspondence between both methods is ~~excellent~~very good, with low RMSE and SEE, a high CC, and a Bias close to 1. These values are comparable to previous validation efforts where the RMSE was found to be 0.011 m^3/m^3 (Franz et al., 2012b) and less than 0.03 m^3/m^3 (Bogena et al., 2013; Coopersmith et al., 2014; Zhu et al., 2015). The comparison across the sites is also illustrative. Despite the more arid climate at JER (Table 1), the study period consisted of higher precipitation (247 mm) and higher soil moisture values during the summer (0.085 m^3/m^3), as compared to SRER (170 mm, 0.065 m^3/m^3), indicating a more active ~~North American~~ monsoon in the Chihuahuan Desert. In contrast, the fall-winter period is generally drier at JER (21 mm, 0.039 m^3/m^3), as compared to SRER (99 mm, 0.057 m^3/m^3), where high *P* and low *ET* in the winter promoted infiltration ~~beyond~~below the ~~CRS~~CRNS measurement depth, as observed at a 1-m sensor profile at SRER (not shown). These two effects ~~are observed as~~lead to a larger range of soil moisture ~~values~~ at JER as compared to SRER in Fig. 5 ~~for JER. It is also worth noting that θ_{CRS} has a larger dynamic~~ . As a result, the CRNS method is found to be a reliable method for measuring soil moisture in the observed range ~~for dry conditions (i.e., θ_{CRS} values can reach zero, whereas θ_{SN} does not), indicating that the~~of values at SRER and JER.

To further test the CRNS method ~~overcomes the measurement limitations discussed by Vereecken et al. (2014). Based on these comparisons, the CRS method is found to be a reliable approach for measuring intermediate scale soil moisture across the observed range of soil moistures at SRER and JER.~~

~~**3.2. Comparison and Analyses of CRS Method and Water Balance Estimates**~~

~~Fig.~~ against the distributed sensor network, Fig. 6 ~~presents the comparison of the spatially-averaged $\Delta\theta_{CRS}$ and $\Delta\theta_{WB}$ as a scatterplot for approximately 40 rainfall events larger~~

than 10 mm, with statistical metrics shown in Table 3. The correspondence between the methods is very good, with low RMSE and SEE, a high CC, and a Bias close to 1, with a closer match at the depicts the relations between the spatial variability of soil moisture (σ) and the spatially-averaged conditions (<θ>). For illustration purposes, bin-averages and standard deviations are also presented for each relation. Least squares regressions of (5) based on hourly observations were applied to estimate k_1 and k_2 for the relations σ vs. θ_{SN} (k_1 = 0.75 and k_2 = 4.23 at SRER site. For example, the SEE at SRER (0.020 m^3/m^3) is about one half of the value ; k_1 = 0.74 and k_2 = 2.75 at JER) and these parameters were adopted to interpret the relations of σ vs. θ_{CRNS}. The RMSE are very low and similar in both cases (RMSE = 0.007 and 0.008 m^3/m^3 at SRER and 0.005 and 0.008 m^3/m^3 at JER (0.049 m^3/m^3) and close to the SEE of the comparison of θ_{CRS} and θ_{SN}. This suggests that the three approaches for estimating soil moisture are in agreement at the SRER. For the JER, the lower correspondence between $\Delta\theta_{CRS}$ and $\Delta\theta_{WB}$ is attributed to five large events where $\Delta\theta_{WB}$ is above 0.2 m^3/m^3. Removing these events lowers the SEE at JER to 0.020 m^3/m^3, in line with SRER and the comparison of θ_{CRS} and θ_{SN} at JER. A closer inspection of the soil moisture response at JER is revealing. Fig. for the relation with θ_{SN} and θ_{CRNS}, respectively), thus confirming the good correspondence between the two methods. As shown in prior efforts in semiarid ecosystems using sensor networks or aircraft observations (e.g., Fernández and Ceballos, 2003; Vivoni et al., 2008b; Mascaro et al., 2011; Stillman et al., 2014), there is a general increase in σ with <θ>, explained by the role played by local heterogeneities (e.g., vegetation types, surface soil variations, topography) as well as the bounded nature of the soil moisture process at the driest state. The similar relations derived in these different sites might be broadly applicable to other semiarid ecosystems in the southwestern U.S.

4.2. Validation of CRNS Method with Water Balance Estimates

Fig. 7 presents the comparison of the spatially-averaged $\Delta\theta_{CRNS}$ and $\Delta\theta_{WB}$ as a scatterplot for approximately 40 rainfall events with a total depth larger than 10 mm and durations ranging from 0.5 to 31 hours (mean of 6 hours). The statistical metrics are presented in Table 4. The correspondence between the methods is very good, with low RMSE and SEE, a high CC, and a Bias close to 1, with a closer match at SRER. For example, the SEE at SRER (0.024 m^3/m^3) is significantly less than the value at JER (0.095 m^3/m^3) and close to the SEE of the comparison of θ_{CRNS} and θ_{SN}. This suggests that the three approaches (i.e., CRNS, sensor network, water balance) are in agreement at the SRER. For the JER, the lower correspondence between $\Delta\theta_{CRNS}$ and $\Delta\theta_{WB}$ is attributed to five large events where $\Delta\theta_{WB}$ is above 0.2 m^3/m^3. Removing these events lowers the SEE at JER to 0.020 m^3/m^3, in line with SRER and the comparison of θ_{CRNS} and θ_{SN} at JER. A closer inspection of the soil moisture response at JER allows investigating the physical reasons causing the different behavior of these five events. Fig. 8 shows the soil moisture change ($\Delta\theta_{SN}$) at different sensor depths averaged for the selected large events and for the remaining events, as well as the ~~CRS~~mean of CRNS measurement depths (z*) for each case. The five large events exhibit high soil moisture changes at 30 cm depth (i.e., 0.08 m^3/m^3) below z* (i.e., 17 cm), while other events have soil moisture changes near zero at 30 cm and are captured well within z*. This indicates that infiltration fronts during the larger events penetrated beyond z* and were not entirely captured by the ~~CRS~~CRNS method, leading to an underestimate of $\Delta\theta_{WB}$. For these events, the assumption L =0 in equation (6) is not fully supported. In contrast, the better correspondence at SRER suggests that infiltration fronts were contained within z~~* (see Table 3).~~*. This is plausible given the ~~more homogeneous~~less rocky soil and flatter terrain at SRER as compared to JER (Anderson, 2013~~), where~~). At JER, soil water movement to deeper layers can be promoted by higher gravel contents~~,~~ and the presence of calcium carbonate and undulated terrain can promote soil water movement to deeper layers which facilitate lateral water transfer to channels with sandy bottoms (Templeton et al., 2014).

To explore this further,

4.3. Utility of CRNS for Investigating Hydrological Processes

Given the confidence gained with respect to the CRNS estimates, we utilized these observations to quantify the water balance fluxes during storm and interstorm periods at the two sites. Fig. 89 shows the cumulative $f_{CRS}f_{CRNS}$ and the cumulative, spatially-averaged *P* and *ET* measured by the distributed sensor network. An overall drying trend is present at SRER during the study period (i.e., cumulative $f_{CRS}f_{CRNS}$ becomes more negative), while JER exhibits a relatively small change in cumulative $f_{CRS}f_{CRNS}$, both in response to the below average (SRER) and above average (JER) precipitation. An important contrast at the sites is the overall water balance (Table 45), where higher *P*, lower *ET*, and lower *Q* at JER (measured $ET/P = 0.54$, $Q/P = 0.01$) implies that more soil water is available for leakage to deeper soil layers. This is reflected in a large positive difference between cumulative outflow ($O = ET + L$) and *ET* at JER (i.e., $L > 0$ from z^*, soil water movement to lower layers, as depicted in the soil water balance diagram). In contrast, SRER exhibits a higher $ET/P = 0.96$ and $Q/P = 0.14$, such that negative differences occur between *O* and *ET* (i.e., $L < 0$ into z^*, movement from lower layers, as depicted in the soil water balance diagram). This is particularly important during the summers when vegetation is active and drawsproduces more *ET* than the outflow from the CRSCRNS measurement depth, indicating that soil water is obtained from deeper soil layers that are readily accessed by velvet mesquite roots (e.g., Snyder and Williams, 2003; Scott et al., 2008; Potts et al., 2010). This is consistent with the sustained *ET* during interstorm periods in the summer season at SRER despite the low $\theta_{CRS}\theta_{CRNS}$, while JER exhibits sharp declines in *ET* when $\theta_{CRS}\theta_{CRNS}$ is reduced between storms.

Overall, the soil water balance from the ~~CRS~~CRNS method shows stark ecosystem differences at the two sites during the study period. The mesquite savanna at SRER extracted substantial amounts of water from deeper soil layers during the summer season such that losses to runoff and the atmosphere are in excess of seasonal precipitation. ~~It is likely that the deeper~~Deeper soil water is recharged beyond the ~~CRS~~CRNS measurement depth during winter periods ~~(~~, as observed by Scott et al., 2000~~)~~, and subsequently accessed by deep-rooted trees during the summer (Scott et al., 2008). In contrast, the mixed shrubland at JER lost a substantial amount of precipitation to deeper soil layers throughout the year, due to the low values of runoff and evapotranspiration, and the soil, terrain and channel conditions promoting recharge (Templeton et al., 2014). Winter recharge is fostered by the lack of *ET* from drought-deciduous plants that lose their leaves in the wintertime. We hypothesize that deep percolation is likely occurring in the channels, since: (i) soil moisture observations in the hillslopes (i.e., far from the channel) show a lack of deep percolation, (ii) the runoff ratio decreases with the basin contributing area, indicating transmission losses along the channel (Templeton et al., 2014), and (iii) one sensor profile installed in a channel at SRER shows that the wetting front frequently reaches at least 30 cm depth. Furthermore, the ~~f_{CRS}~~f_{CRNS} approach provided estimates that can be compared to the watershed water balance since these are at a similar spatial scale (Table ~~4~~5). Estimates of outflow (*O*) from the measurement depth and leakage (*L*) are higher when calculated with θ_{SN}, consistent with more rapid drying as compared to the ~~CRS~~CRNS method. On the other hand, the ~~CRS~~CRNS method results in higher values of the runoff ratio (*Q*/*P*) than observed in the distributed sensor network, in particular for JER. This is likely due to the daily scale of the ~~CRS~~CRNS analysis, which ~~significantly~~ limits the suitability of the runoff estimate for semiarid watersheds characterized by runoff responses lasting minutes to hours.

3.3. Soil Moisture Spatial Variability within CRS Footprint

Fig. 9 depicts the relations between the absolute (σ) and relative (CV) spatial variability of soil moisture and the spatially-averaged conditions ($<\theta>$) derived from either θ_{SN} or θ_{CRS} at each study site. Least squares regressions of (7) and (8) based on hourly observations were used to obtain k_1 and k_2, as shown in Table 5. For illustration purposes, bin-averages and standard deviations are also presented for each relation. As shown in prior efforts in semiarid ecosystems using sensor networks or aircraft observations (e.g., Fernández and Ceballos, 2003; Vivoni et al., 2008b; Mascaro et al., 2011), there is a general increase in σ with $<\theta>$ and a decrease of CV with $<\theta>$. The increase in spatial variability of soil moisture in absolute terms with wetter conditions is explained by the role played by local heterogeneities (e.g., vegetation types, surface soil variations, topography) as well as the bounded nature of the soil moisture process at the driest state (i.e., spatial variations are small in absolute terms when an area is very dry). Interestingly, both sites exhibit an asymptotic σ for the wettest values (above 0.1 m^3/m^3 at SRER and 0.15 m^3/m^3 at JER), as more clearly observed for θ_{SN}, indicating that the summer monsoon has wet soil moisture states that might be described as sub-humid, following the classification of Lawrence and Hornberger (2007). The observed relations of σ-$<\theta>$ and CV-$<\theta>$ at both sites are captured well by the exponential functions (7 and 8) leading to a low RMSE. Furthermore, a bootstrap analysis based on a random removal 100 points was conducted to generate 95% level confidence intervals for k_1 and k_2. We found that the set of k_1 and k_2 obtained**4.4. Utility of CRNS for** each site (Table 5) are included within the confidence intervals for both θ_{SN} or θ_{CRS}. This indicates the relations derived in these different sites might be broadly applicable to other semiarid ecosystems in the southwestern U.S. Nevertheless, there are some small discrepancies between the relations obtained for θ_{SN} and θ_{CRS} and the regressions parameters were shown to be significantly different at the 95% confidence interval through a similar bootstrap analysis. We attribute these differences to the asymptotic behavior at the wettest states occurring after a rainfall event when θ_{CRS} has a slightly higher value than θ_{SN}, likely due to the instantaneous contribution of water above the ground surface (e.g., water in channels, surface depressions or on vegetation canopies). **Improving *ET* Estimates**

3.4. Controls of Soil Moisture and Its Spatial Variability on Evapotranspiration

Fig. 10 compares the relationships between the measured daily *ET* using the EC method and the spatially-averaged soil moisture values (θ_{SN} and $\theta_{CRS}$$\theta_{CRNS}$) at the SRER and JER sites along with the piecewise linear regressions estimated using (98) and a nonlinear optimization approach. Following Vivoni et al. (2008a), regression parameters related to soil and vegetation conditions are presented in Table 6. For illustration purposes, bin-averages and standard deviations are also shown. Clearly, the piecewise linear relation is an excellenta suitable approach for capturing the *ET*-θ observations, yielding a relatively low RMSE at the two sites. A lower RMSE for the relation using $\theta_{CRS}$$\theta_{CRNS}$ as compared to θ_{SN} at SRER is attributed to its ability to detect a wider range of dry conditions and the improved match in the spatial scales of *ET* and $\theta_{CRS}$$\theta_{CRNS}$, in an analogous fashion to the comparison between a single sensor and the distributed sensor network (Templeton et al., 2014). In addition, the CRSCRNS method represents soil evaporation (E_w) in a more realistic way as it discriminates differences in drier states, illustrated by the realistic gradual increase of bare soil evaporation with increasing soil water (Fig. 10). For *ET* and θ_{SN}, the dry portions of the relations have too steep of a slope and do not represent well how bare soil evaporation changes with soil moisture. When comparing both sites through the *ET*-θ relation, the SRER has a larger E_w and ET_{max} and lower θ^*, as compared to JER, tested to be significantly different at the 95% confidence level using a bootstrap approach. Together, these parameters indicate that SRER has a higher overall *ET*, consistent with higher extractions from the ~~CRS~~CRNS measurement depth due to the mesquite trees, extensive grass cover and higher soil evaporation.

~~We explore whether a daily relationship exists between the absolute (σ) and relative (*CV*) spatial variability of soil moisture and evapotranspiration in Fig. 11. Daily observations and bin-averages with standard deviations are derived entirely from the distributed sensor network and EC measurements. Given the relations linking σ and *ET* with the mean soil moisture (Figs. 9 and 10), the *ET*-σ relations exhibit an increase in *ET* with higher σ at both sites, though this is clearer at JER~~

5. Summary and Conclusions

In this study, we utilized distributed sensor networks to examine the cosmic-ray neutron sensing soil moisture method at the small watershed scale in two semiarid ecosystems of the southwestern U.S. To our knowledge, this is the first study to compare CRNS measurements to two complementary approaches for obtaining spatially-averaged soil moisture at a commensurate scale: (1) a distributed set of sensor profiles weighted in the horizontal and vertical scales within each watershed, and (2) a watershed-averaged quantity obtained from closing the water balance. We highlighted a few novel advantages of the CRNS method revealed through the comparisons, including the ability to resolve the shallow soil moisture dynamics and to match the estimates obtained from closing the water balance for most rainfall events. In the distributed sensor comparisons, we found that the CRNS method overestimated soil moisture during the recession limbs of rainfall events, possibly due to ~~the wider range of θ_{SN}. This indicates that high absolute variability of soil moisture is associated with larger *ET*, likely due to the growth of wet patches supporting progressively more evapotranspiration. In contrast, the *ET*-*CV* relations exhibit a weaker negative trend such that a higher relative variability implies a lower *ET*. This occurs due to the role of the mean soil moisture state~~landscape features such ~~that dry conditions have a relatively high *CV* (Fig. 9) and support a low *ET* (Fig. 10). Observations are compared to the~~

analytical relations obtained by combining (9) with (7) and (8) using θ_{CRS} as the spatially-averaged value for *ET*-σ and *ET*-*CV*, respectively (solid lines). While the analytical relations approximate the data fairly well, it is clear that the ET_{max} limit (horizontal lines) does not represent the growth of *ET* with higher σ and lower *CV*. Nevertheless, the analytical functions are a promising application of the CRS method that can yield valuable information for understanding land-atmosphere interactions, under the assumption the σ-$\langle\theta\rangle$ and *ET*-θ relations have been established (e.g., Table 5 and 6).

4. Summary and Conclusions

In this study, we utilized distributed sensor networks to examine the cosmic-ray sensing (CRS) soil moisture method at the small watershed scale in two semiarid ecosystems of the southwestern U.S. (Pierini et al., 2014; Templeton et al., 2014). To our knowledge, this is the first study to compare CRS measurements to two complementary approaches for obtaining spatially-averaged soil moisture at a commensurate scale: (1) a distributed set of sensor profiles weighted in the horizontal and vertical scales within each watershed, and (2) a watershed-averaged quantity obtained from closing the water balance. Coordinated efforts at the two small watersheds with varying landscape characteristics and precipitation conditions during the study period afforded the opportunity to conduct comparisons of soil moisture, evapotranspiration and vadose zone processes (infiltration, plant water uptake,as nearby channels remaining wet. In the water balance comparisons, we identified that our assumption of no leakage). We highlighted a few novel advantages of the CRS method revealed through the intercomparisons, including the ability to discriminate dry soil moisture states that is not possible through a sensor network, to resolve the shallow soil moisture dynamics captured well at the 5 cm sensors, and to match the independent soil moisture estimates from closing the water balance for most rainfall events. In

~~the distributed sensor comparisons, we found that the CRS method overestimated the maximum soil moisture during rainfall events, likely due to the presence of water in surface depressions, plant canopies or channels. In the water balance comparisons, we identified that the CRS~~ beneath *z** was not met during large rainfall events and the CRNS method was not able to capture ~~the soil moisture conditions during large rainfall events and attributed~~ all of the soil water present. We attribute this to rapid bypassing of the measurement depth ~~promoted by watershed~~ due to soil and terrain characteristics. Due to this observed bypass flow, we suggest that future ~~seasonal water balance~~ studies using the ~~CRS~~CRNS method include a few soil moisture sensor profiles below *z** to detect leakage events.

~~We utilized the~~ The CRNS soil moisture estimates were used in combination with the various measurement methods to explore the relative magnitudes of the water balance components at each site given the different precipitation amounts during the study period. The drier than average conditions in the mesquite savanna ecosystem at SRER lead to drier surface soils incapable of supporting the measured evapotranspiration unless supplemented by plant water uptake from deeper soil layers ~~(Scott et al., 2008)~~. In contrast, wetter than average summer periods in the mixed shrubland at JER had wet surface soils that promoted leakage into the deeper vadose zone which was subsequently unavailable for runoff and evapotranspiration losses ~~(Duniway et al., 2010)~~. Comparisons across different seasons ~~at each site~~ also suggested that carryover of soil water from winter leakage toward deeper soil layers is consumed during the summer season by active plants. These novel inferences within the two ecosystems relied heavily on the application of the ~~CRS~~CRNS method and its limited measurement depth to discriminate between shallow and deeper vadose zone processes as well as on the direct measurement of the water balance components, in particular evapotranspiration ~~from the eddy covariance technique~~.

It is important to keep in mind, however, that the ability to resolve watershed-scale ~~hydrologic~~hydrological processes, such as the interaction between shallow and deep soil layers attributed to plant water uptake and leakage, depends to a large degree on the accuracy and representativeness of the distributed sensor network measurements and how their horizontal and vertical scales overlap with the ~~CRS~~CRNS measurement footprint. We expect these limitations to be especially critical in semiarid ecosystems with high spatial heterogeneity induced by vegetation and bare soil patches.

The collocation of a distributed sensor network within the ~~CRS~~CRNS measurement footprint also allowed us to examine important process-based relations that are often incorporated into hydrologic models or remote sensing analyses (e.g., Famiglietti and Wood, 1994; Famiglietti et al., 2008). The spatial variability of soil moisture is linked to the spatially-averaged conditions through predictable relations that do not vary significantly across the study sites. For higher mean soil moisture, we observed a ~~near~~ nearly linear increase in spatial variability followed by an asymptotic behavior attributed to the seasonally-wet conditions during the North American monsoon. Based on these relations (k_1 and k_2), the spatial variability within a ~~CRS~~CRNS measurement footprint can be approximated for other semiarid ecosystems in the region. In addition, combining fixed and mobile ~~CRS~~CRNS methods can establish landscape scale (10^2 to 10^3 km^2) soil moisture monitoring networks at grid sizes (~1 km^2) comparable to land surface modeling (Franz et al~~.~~., 2015). Similarly, intermediate scale soil moisture sensing can be linked effectively to daily evapotranspiration and used to obtain soil and vegetation parameters (E_w, ET_{max}, θ_h, θ_w, and θ^*) tailored to each ecosystem. In term of the ET-θ relation, the ~~CRS~~CRNS method has the potential to significantly improve land-atmosphere interaction studies through the commensurate scale achieved to the EC technique. ~~Furthermore, we found that~~

~~analytical relations linking soil moisture spatial variability with evapotranspiration exhibit similar characteristics to the observed datasets. As the spatial variability in soil moisture grows in the two semiarid ecosystems there is a concomitant increase in evapotranspiration. While this suggests that wet patches in a drier background sustain higher atmospheric losses, further investigations are needed to disentangle the individual roles of soil evaporation and plant water uptake on setting both the soil moisture spatial variability and the resulting evapotranspiration averaged in its measurement footprint.~~

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Figure Captions

Fig. 1: (a) Location of the study sites in Arizona and New Mexico. Watershed representations and sensor locations at (b) SRER and (c) JER, shown at the same scale.

Fig. 2: Vegetation classification for (a) SRER and (b) JER derived from aerial image analyses along with sensor locations and the 50% contributing areas of the ~~CRS~~CRNS and EC footprints.

Fig. 3: Hourly precipitation, streamflow and evapotranspiration at the (a) SRER and (b) JER sites during the study period (March 2013 to September 2014). Gaps in *ET* data indicate periods of EC tower malfunction due to equipment failures, data collection problems or vandalism. Vertical dashed lines indicate the seasonal definitions and their corresponding total precipitation.

Fig. 4: Comparison of the spatially-averaged, hourly soil moisture (m^3/m^3) from ~~CRS~~CRNS method (~~θ_{CRS}~~θ_{CRNS}, black lines) and distributed sensor network (θ_{SN}, gray lines) at (a) SRER and (b) JER, along with spatially-averaged, hourly precipitation during March 1, 2013 to September 30, 2014. Vertical dashed lines indicate the seasonal definitions and their corresponding seasonally-averaged ~~θ_{CRS}~~θ_{CRNS} and θ_{SN} in m^3/m^3. Also shown are the time-varying measurement depths (z^*).

Fig. 5: Scatterplots of the spatially-averaged, hourly soil moisture (m^3/m^3) from ~~CRS~~CRNS method (~~θ_{CRS}~~θ_{CRNS}) and distributed sensor network (θ_{SN}) at (a) SRER and (b) JER. The SEE and the number of hourly samples (N) are shown for each site. Bin averages and ±1 standard deviation are shown (circles and error bars) for bin widths of 0.025 m^3/m^3 ~~for each estimate~~.

Fig. 6: ~~Scatterplots of the spatially-averaged change in soil moisture (m^3/m^3) derived from CRS~~Soil moisture spatial variability as a function of the spatially-averaged distributed sensor

network (θ_{SN}, top) and the CRNS method (~~$\Delta\theta_{CRS}$~~θ_{CRNS}, bottom) for (a, c) SRER and (b, d) JER. Bin averages and ±1 standard deviation are shown (circles and error bars) for bin widths of 0.015 m^3/m^3 at SRER and 0.025 m^3/m^3 at JER. Regressions for the relations of σ with <θ> are valid for the entire dataset.

Fig. 7: Scatterplots of the spatially-averaged change in soil moisture (m^3/m^3) derived from CRNS method ($\Delta\theta_{CRNS}$) and the application of the water balance ($\Delta\theta_{WB}$) at (a) SRER and (b) JER. The SEE and the number of event samples (N) are shown for each site.

Fig. ~~7~~8: Change in soil moisture ($\Delta\theta_{SN}$) at depths of 5, 15 and 30 cm at the JER for the five large events ('Selected Events') and the remaining cases ('Other Events') ~~cases~~. Horizontal lines are the ~~CRS~~time-averaged CRNS measurement depths averaged over ~~the corresponding cases (black is~~ Selected Events~~, gray is~~ (black; standard deviation of 3.8 cm) and Other Events (gray; standard deviation of 6.5 cm).

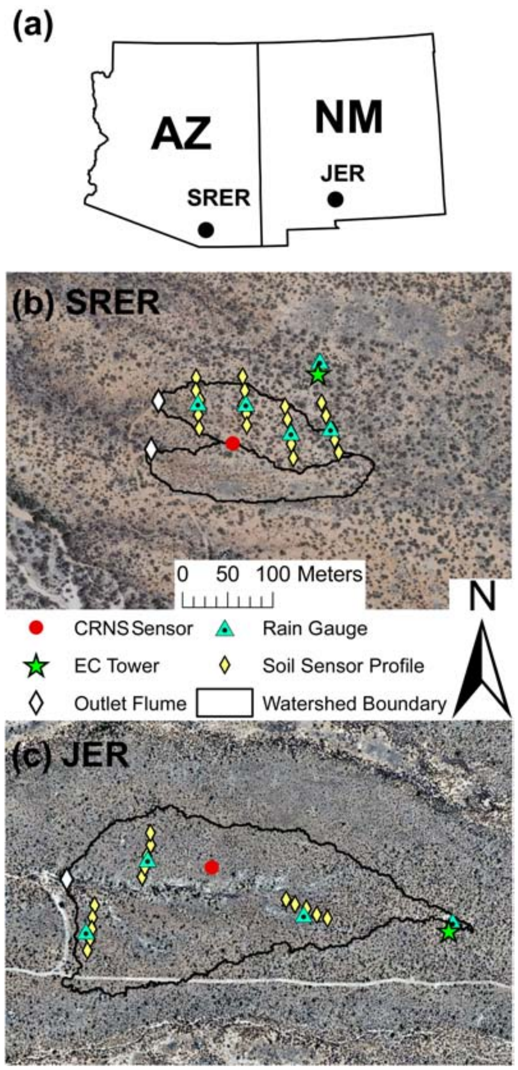
Fig. ~~8~~9: Comparison of cumulative ~~f_{CRS}~~f_{CRNS} and measured water balance fluxes (P and ET) during study period. ~~CRS~~CRNS estimates of infiltration (I), outflow (O) and leakage (L) are either depicted as cumulative fluxes ($O = ET + L$) or as total amounts during the study period (I and L) as arrows in the soil water balance box of depth z*. Shaded regions indicate the summer seasons (July-September). The horizontal line represents ~~f_{CRS}~~$f_{CRNS} = 0$.

~~**Fig. 9:** Soil moisture spatial variability as a function of the spatially-averaged distributed sensor network (θ_{SN}, top) and the CRS method (θ_{CRS}, bottom) for (a, c) SRER and (b, d) JER. Black symbols represent the standard deviation (σ) and gray symbols depict the coefficient of variation (CV). Bin averages and ±1 standard deviation are shown (circles and error bars) for bin widths of~~

~~0.015 m^3/m^3 at SRER and 0.025 m^3/m^3 at JER. Regressions for the relations of σ and *CV* with <θ> are valid for the entire dataset.~~

Fig. 10: Evapotranspiration relation with the spatially-averaged distributed sensor network (θ_{SN}, top) and the ~~CRS~~CRNS method (~~θ_{CRS}~~θ_{CRNS}, bottom) for (a, c) SRER and (b, d) JER. Bin averages and ±1 standard deviation are shown (circles and error bars) for bin widths of 0.015 m^3/m^3 at SRER and 0.025 m^3/m^3 at JER. Regressions for the relations of *ET* with <θ> are valid for the entire dataset.

~~**Fig. 11:** Evapotranspiration relation with the soil moisture standard deviation (σ, left) and the coefficient of variation (*CV*, right) for (a, b) SRER and (c, d) JER. Bin averages and ±1 standard deviation are shown (circles and error bars) for bin widths of 0.33 mm/day. Solid lines represent predicted analytical relationships (not regressions).~~



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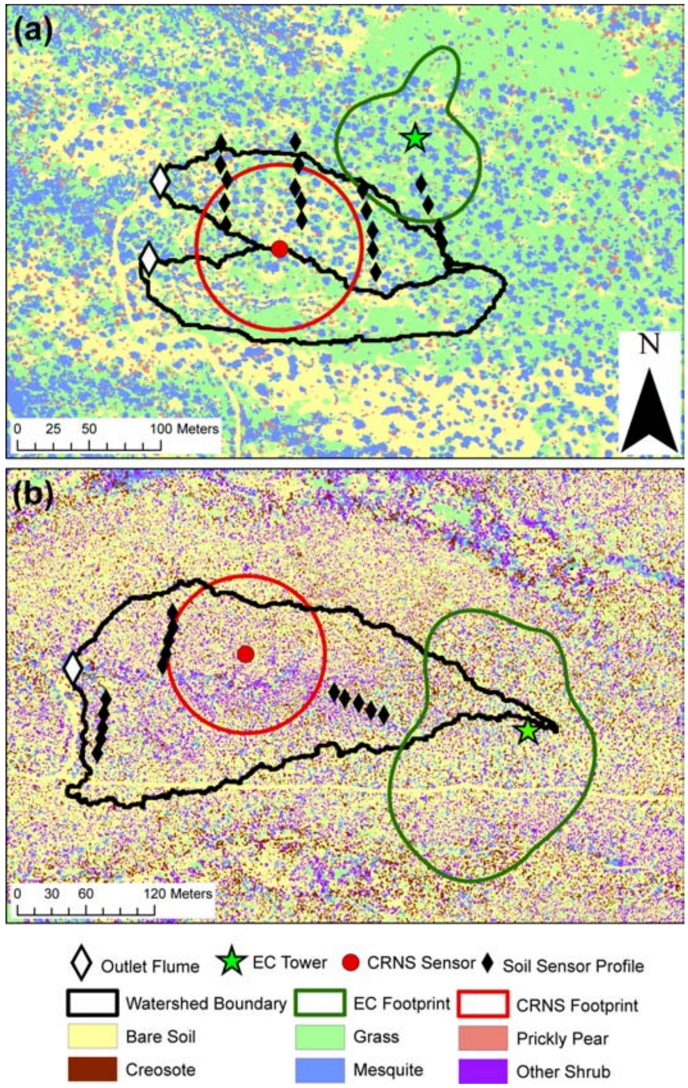
(Schreiner-McGraw et al., 2015, Fig. 1)



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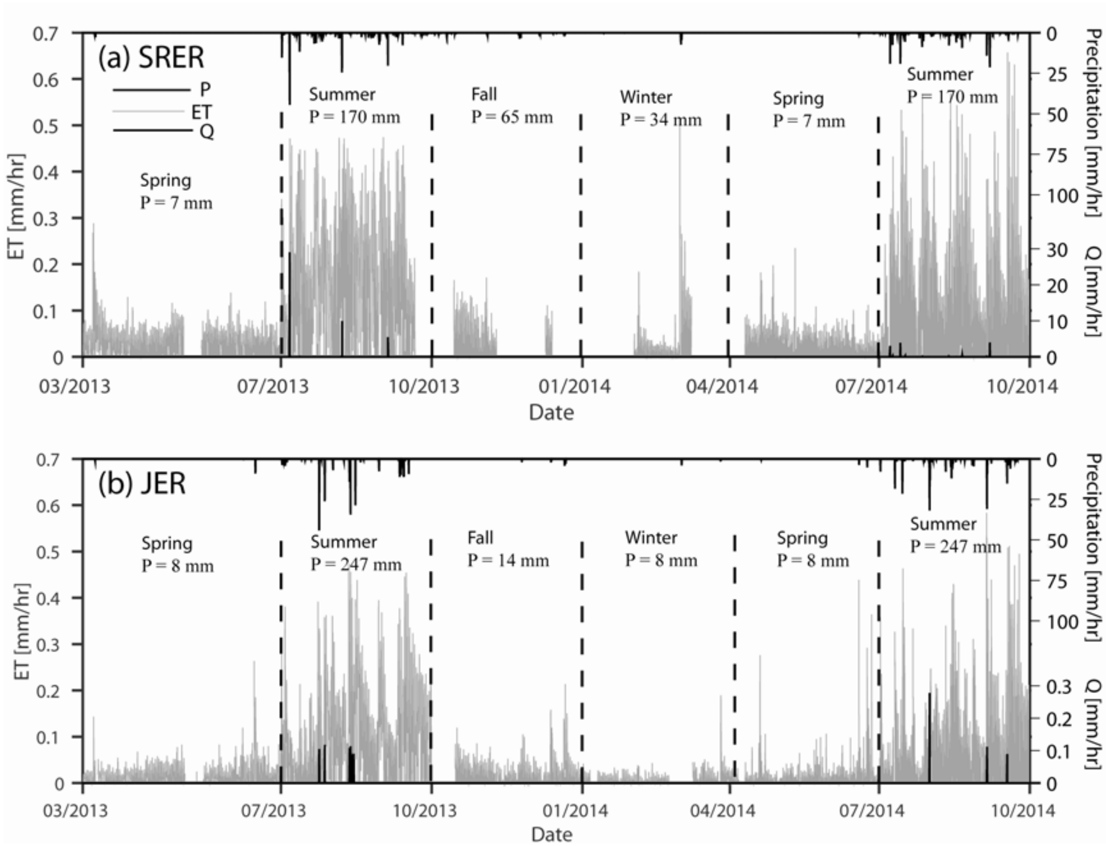

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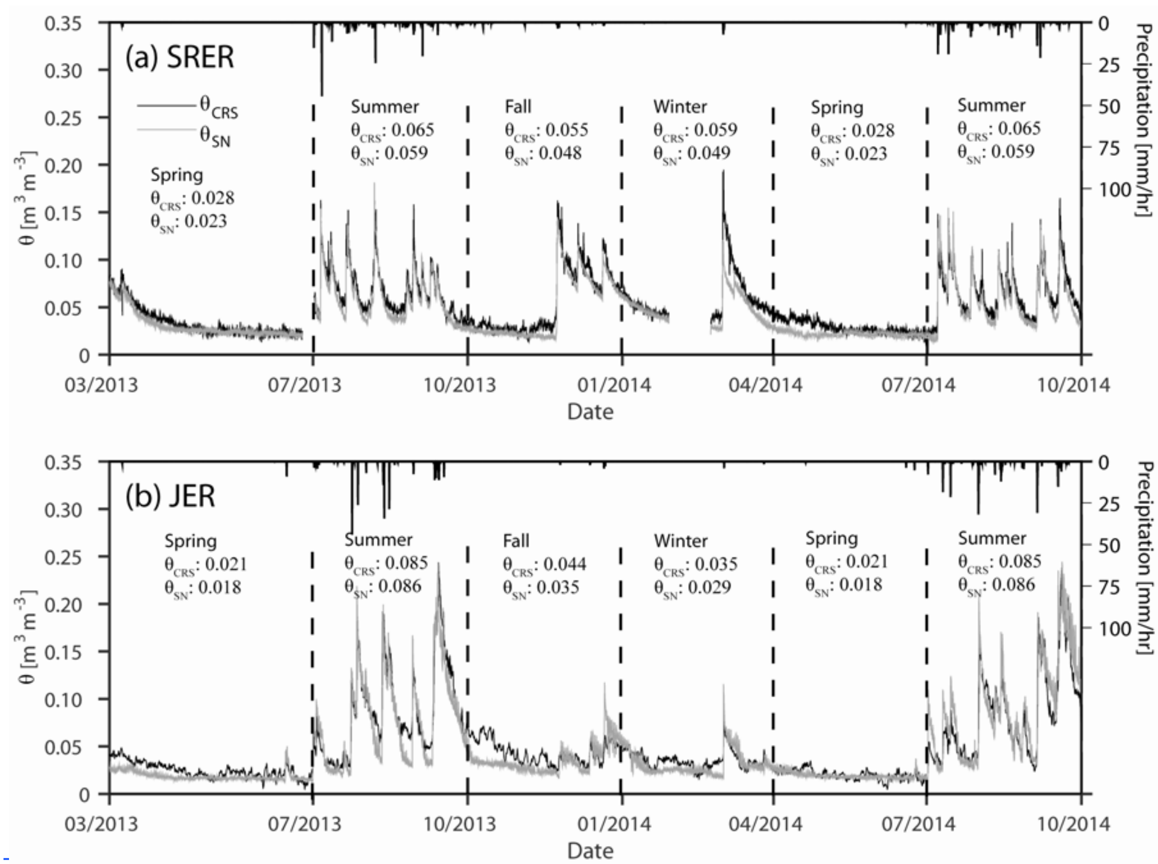
(Schreiner-McGraw et al., 2015, Fig. 3)


(a) SRER
θCRS
θSN
Spring
θCRS: 0.028
θSN: 0.023
Summer
θCRS: 0.065
θSN: 0.059
Fall
θCRS: 0.055
θSN: 0.048
Winter
θCRS: 0.059
θSN: 0.049
Spring
θCRS: 0.028
θSN: 0.023
Summer
θCRS: 0.065
θSN: 0.059
θ [m3 m-3]
Precipitation [mm/hr]
Date
03/2013
07/2013
10/2013
01/2014
04/2014
07/2014
10/2014
(b) JER
Spring
θCRS: 0.021
θSN: 0.018
Summer
θCRS: 0.085
θSN: 0.086
Fall
θCRS: 0.044
θSN: 0.035
Winter
θCRS: 0.035
θSN: 0.029
Spring
θCRS: 0.021
θSN: 0.018
Summer
θCRS: 0.085
θSN: 0.086
θ [m3 m-3]
Precipitation [mm/hr]
Date
03/2013
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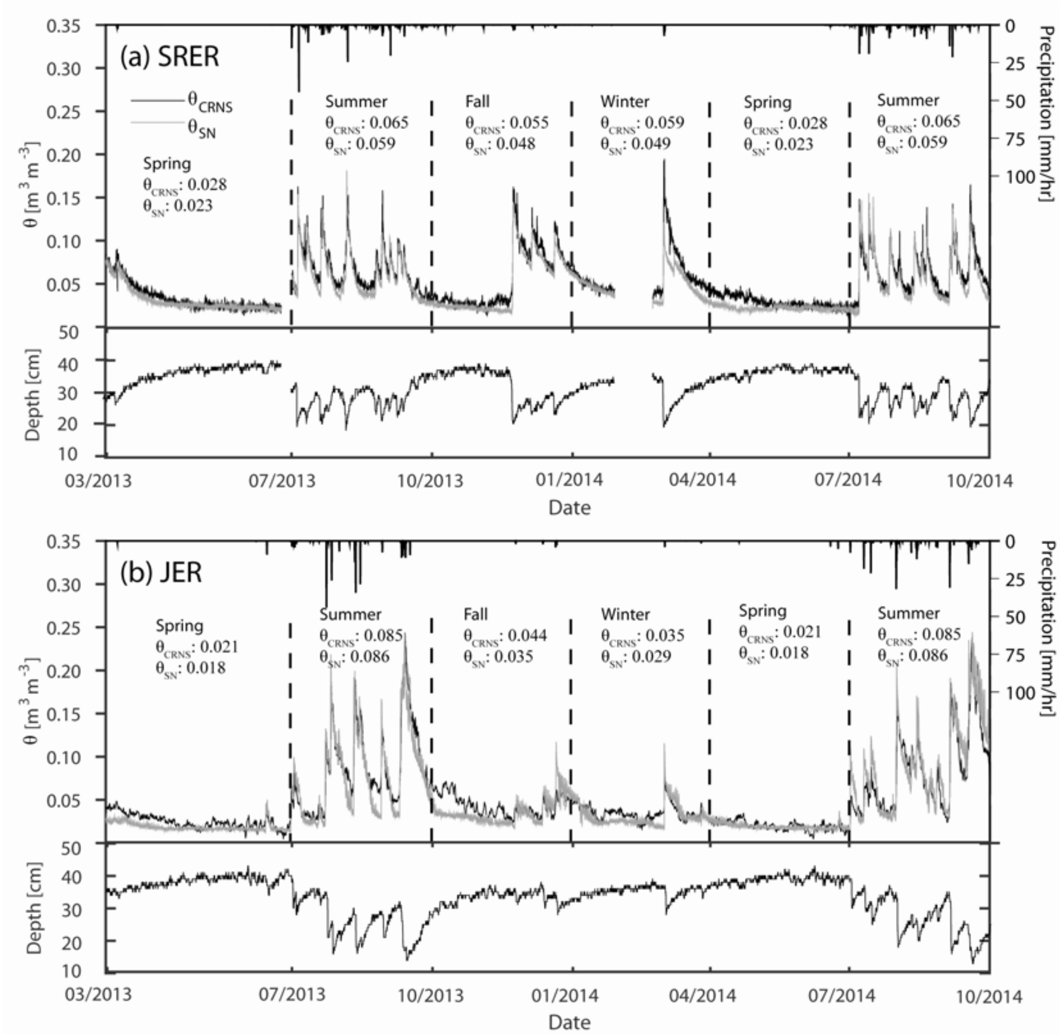
07/2014
10/2014



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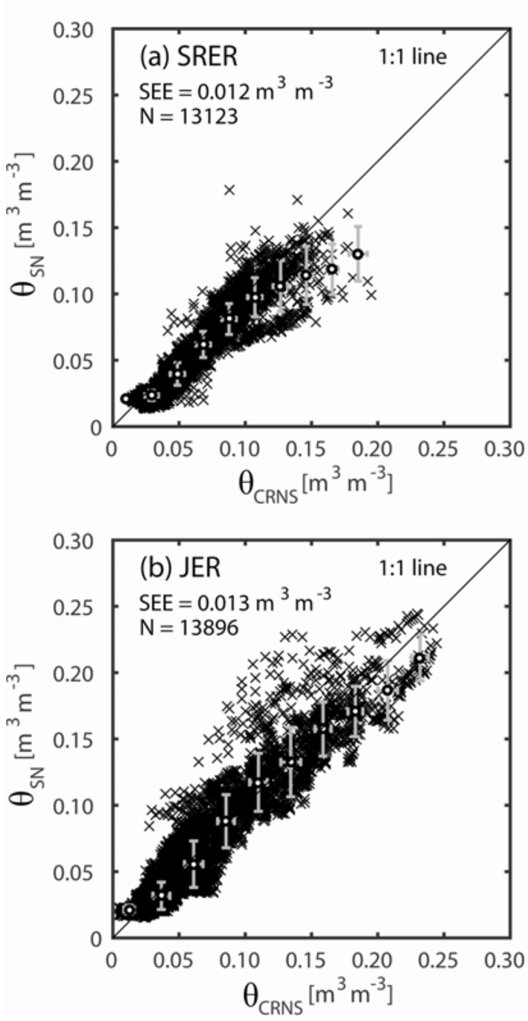
(Schreiner-McGraw et al., 2015, Fig. 4)



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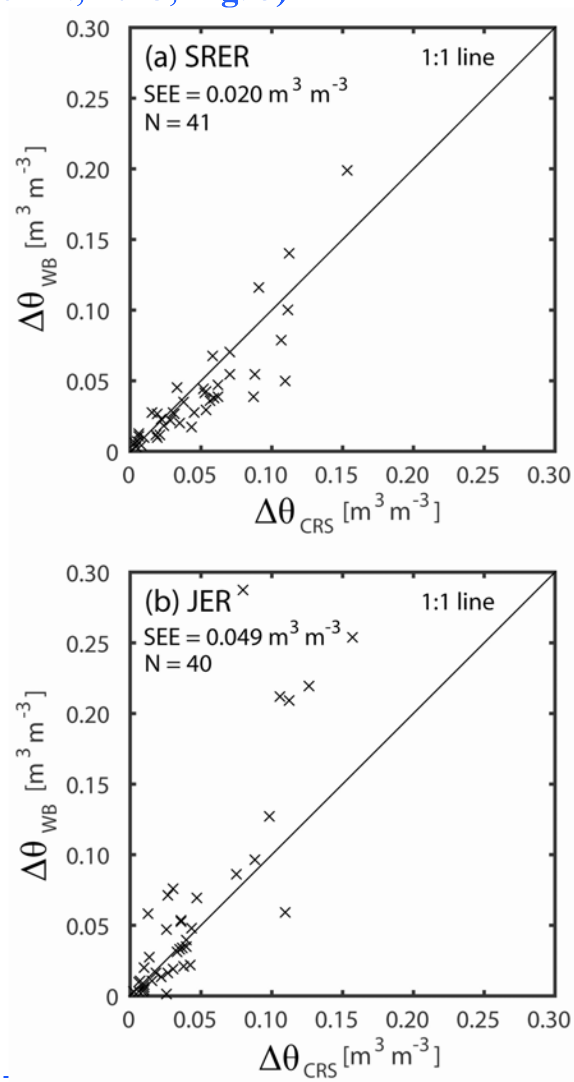
~~(Schreiner-McGraw et al., 2015, Fig. 5)~~



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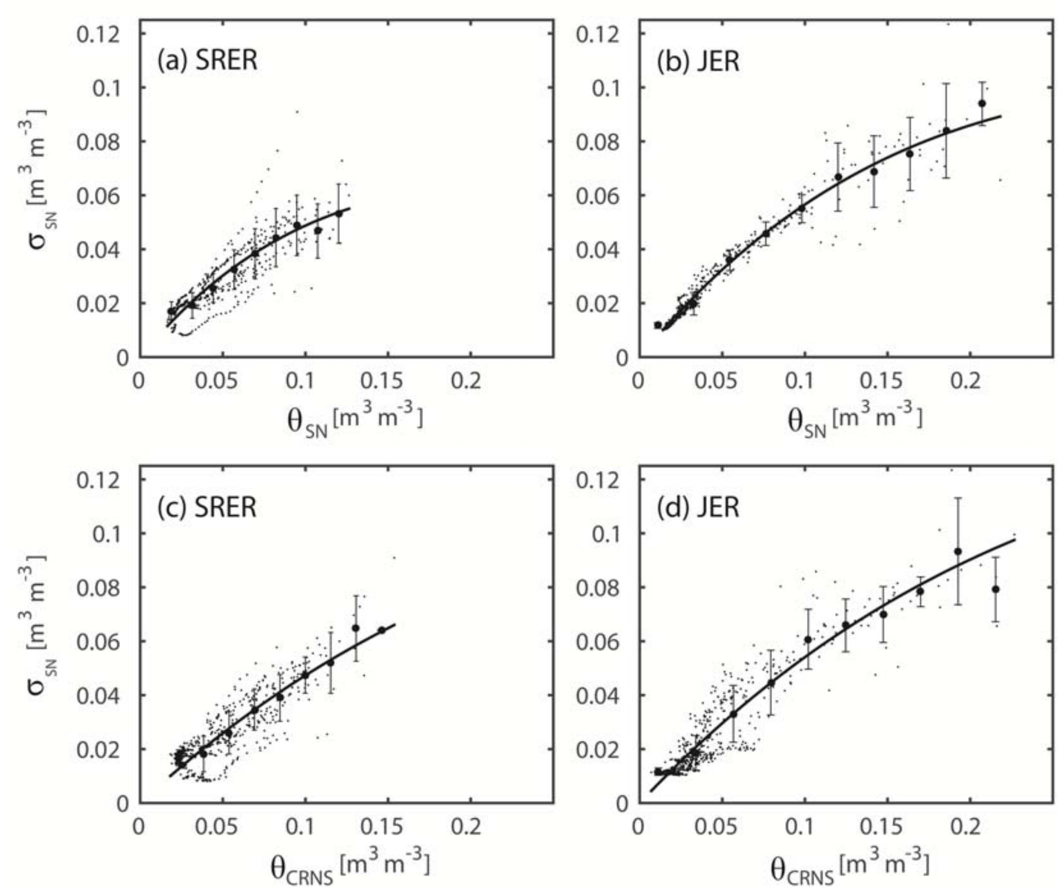

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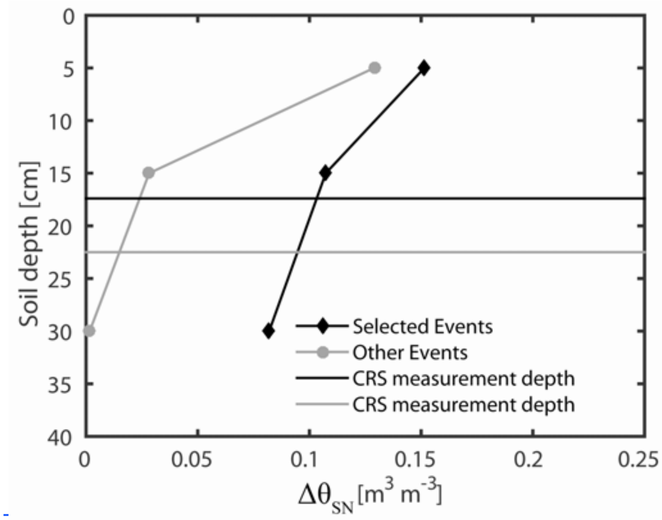

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~~**(Schreiner-McGraw et al., 2015, Fig. 7)**~~

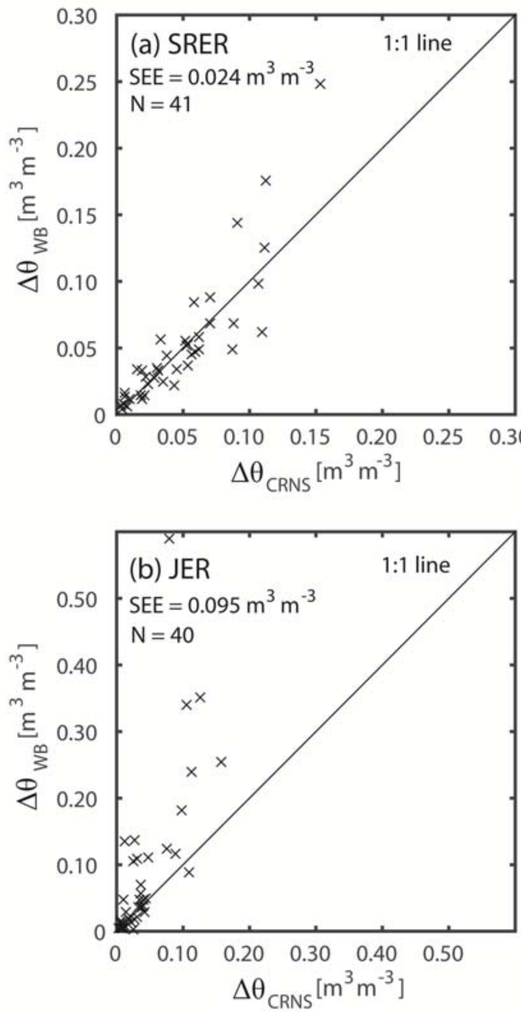

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Fig. 7: Scatterplots of the spatially-averaged change in soil moisture (m^3/m^3) derived from CRNS method ($\Delta\theta_{CRNS}$) and the application of the water balance ($\Delta\theta_{WB}$) at (a) SRER and (b) JER. The SEE and the number of event samples (N) are shown for each site.

(Schreiner-McGraw et al., 2015, Fig. 7)

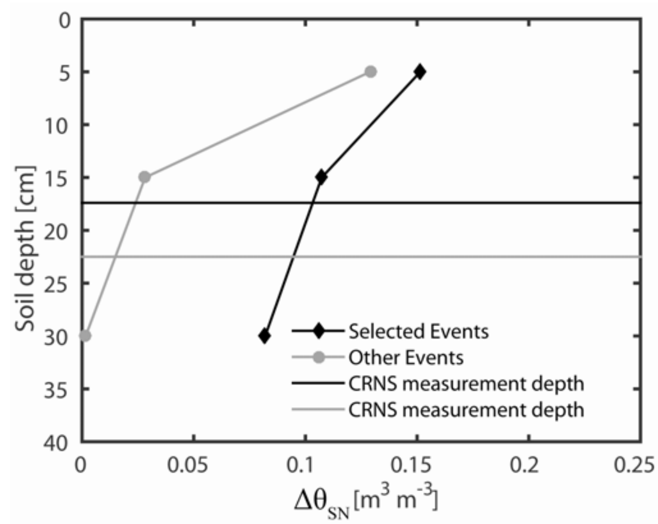
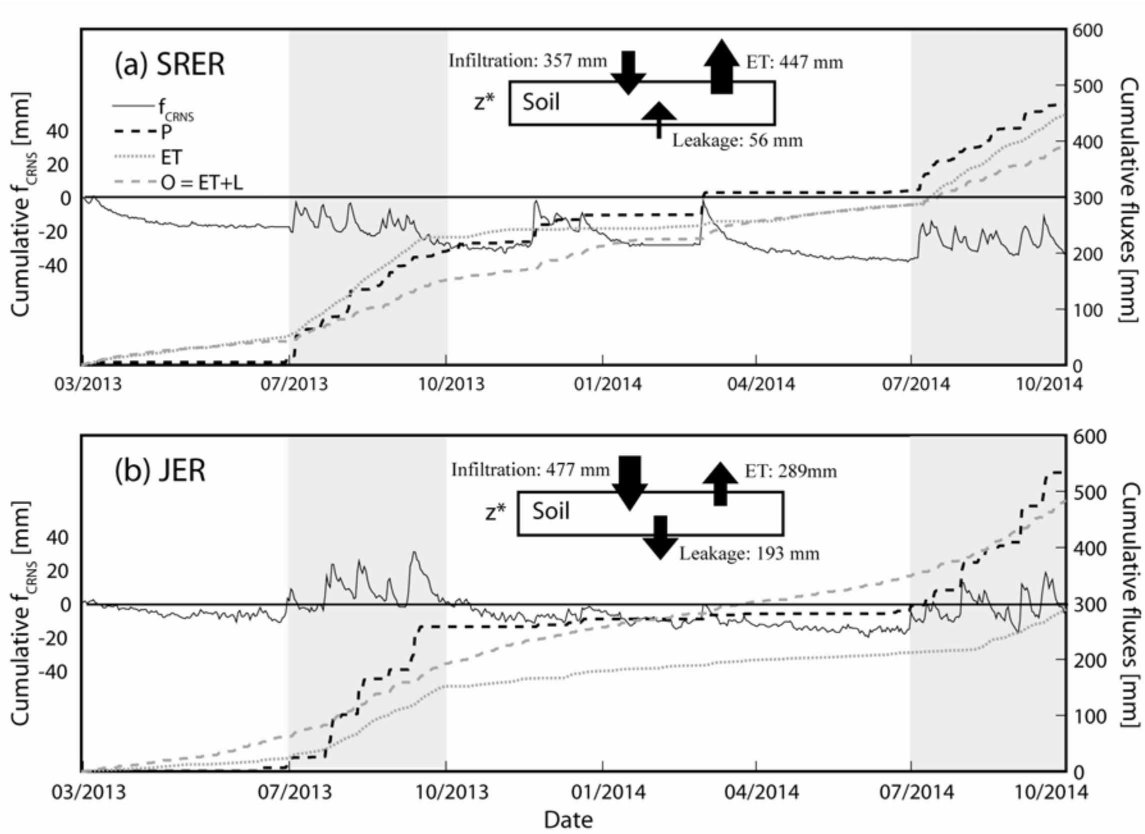


Fig. 8: Change in soil moisture ($\Delta\theta_{SN}$) at depths of 5, 15 and 30 cm at the JER for the five large events ('Selected Events') and the remaining cases ('Other Events'). Horizontal lines are the time-averaged CRNS measurement depths averaged over Selected Events (black, standard deviation of 3.8 cm) and Other Events (gray, standard deviation of 6.5 cm).

(Schreiner-McGraw et al., 2015, Fig. 8)



~~**Fig. 9:** Soil moisture spatial variability as a function of the spatially-averaged distributed sensor network (θ_{SN}, top) and the CRS method (θ_{CRS}, bottom) for (a, c) SRER and (b, d) JER. Black symbols represent the standard deviation (σ) and gray symbols depict the coefficient of variation (CV). Bin averages and ±1 standard deviation are shown (circles and error bars) for bin widths of 0.015 m^3/m^3 at SRER and 0.025 m^3/m^3 at JER. Regressions for the relations of σ and CV with $<\theta>$ are valid for the entire dataset.~~

Fig. 9: Comparison of cumulative f_{CRNS} and measured water balance fluxes (P and ET) during study period. CRNS estimates of infiltration (I), outflow (O) and leakage (L) are either depicted as cumulative fluxes ($O = ET + L$) or as total amounts during the study period (I and L) as arrows in the soil water balance box of depth z^*. Shaded regions indicate the summer seasons (July-September). The horizontal line represents $f_{CRNS} = 0$.

(Schreiner-McGraw et al., 2015, Fig. 9)

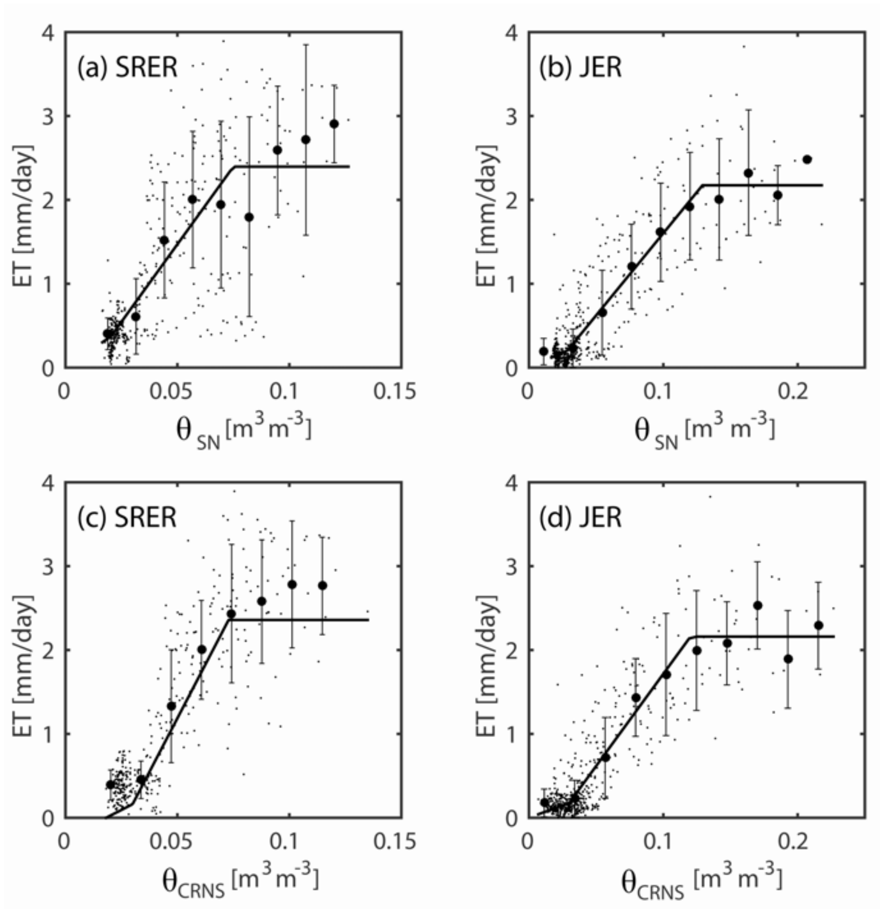


Fig. 10: Evapotranspiration relation with the spatially-averaged distributed sensor network (θ_{SN}, top) and the ~~CRS~~CRNS method (~~θ_{CRS}~~θ_{CRNS}, bottom) for (a, c) SRER and (b, d) JER. Bin averages and ±1 standard deviation are shown (circles and error bars) for bin widths of 0.015 m^3/m^3 at SRER and 0.025 m^3/m^3 at JER. Regressions for the relations of ET with $<\theta>$ are valid for the entire dataset.

(Schreiner-McGraw et al., 2015, Fig. 10)

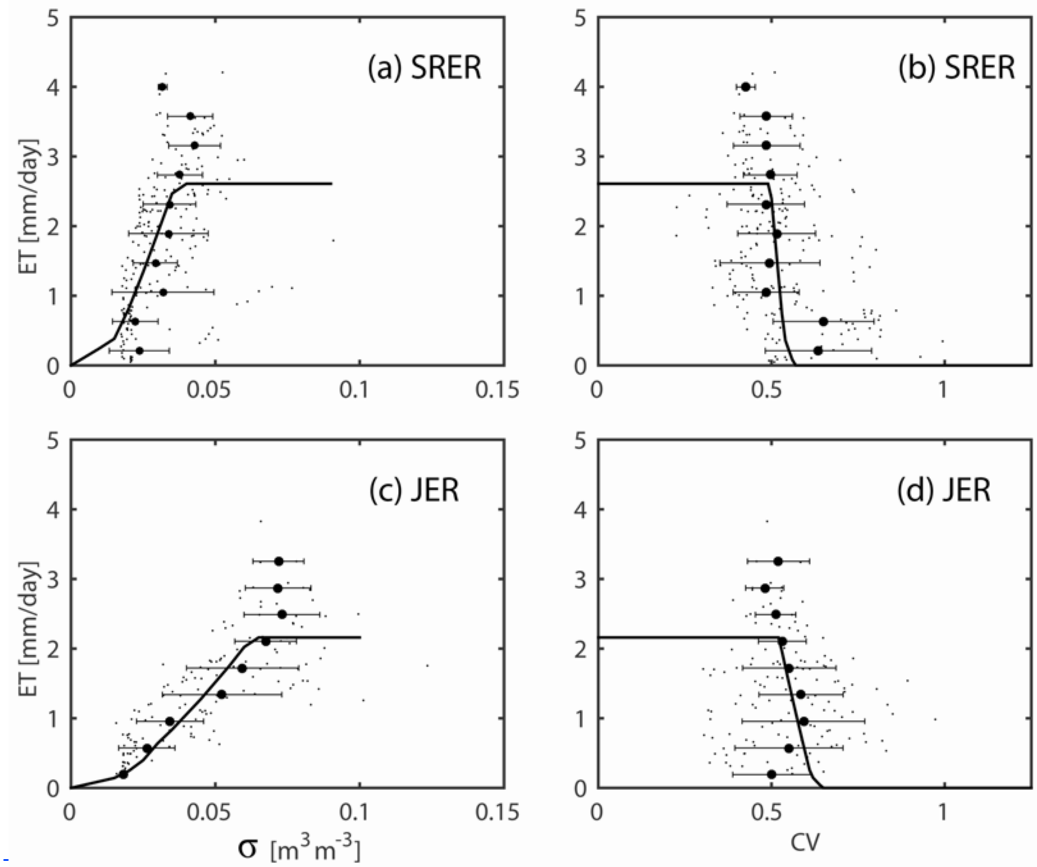


Fig. 11: Evapotranspiration relation with the soil moisture standard deviation (σ, left) and the coefficient of variation (*CV*, right) for (a, b) SRER and (c, d) JER. Bin averages and ±1 standard deviation are shown (circles and error bars) for bin widths of 0.33 mm/day. Solid lines represent predicted analytical relationships (not regressions).

~~(Schreiner-McGraw et al., 2015, Fig. 11)~~

Table Captions

Table 1: Watershed and precipitation characteristics at the SRER and JER sites. Precipitation values are long-term averages (1923-2014 at SRER and 1915-2006 at JER) for annual and seasonal quantities, defined as fall (October-December), winter (January-March), spring (April-June) and summer (July-September).

Table 2: Energy balance closure at SRER and JER using 30-min net radiation (R_n), ground (G), latent (λE) and sensible (H) heat fluxes. The parameters m and b are the slope and intercept in the relation $\lambda E + H = m(R_n - G) + b$, while the ratio of the sum of ($\lambda E + H$) to the sum of ($R_n - G$) is a measure of how much available energy is accounted for in the turbulent fluxes.

Table 3: ~~Statistical comparisons of CRS method with distributed sensor network and water balance estimates based on the Standard Error of Estimates,~~ $SEE = \sqrt{\frac{\sum(\theta_{SN} - \theta_{CRS})^2}{N}}$ ~~, Root Mean Square Error,~~ $RMSE = \sqrt{\frac{\sum(\theta'_{CRS} - \theta_{CRS})^2}{N}}$ ~~where θ'_{CRS} is~~ Soil properties at SRER and JER. Soil moisture values correspond to conditions during the CRNS calibration dates (February 13, 2013 at SRER and February 10, 2013 at JER) for the ~~predicted value of θ_{CRS} based on~~ gravimetric sampling at 18 locations with six depths (θ_G), CRNS (θ_{CRNS}) and the ~~best fit line with~~ sensor network (θ_{SN}~~, Bias,~~ $B = \frac{\overline{\theta}_{CRS}}{\overline{\theta}_{SN}}$ ~~and Correlation Coefficient,~~

$$CC = \frac{\sum_{i=1}^{N}\left(\theta_{CRS,i} - \overline{\theta_{CRS}}\right)\left(\theta_{SN,i} - \overline{\theta_{SN}}\right)}{\left[\sum_{i=1}^{N}\left(\theta_{CRS,i} - \overline{\theta_{CRS}}\right)^2\right]^{0.5}\left[\sum_{i=1}^{N}\left(\theta_{SN,i} - \overline{\theta_{SN}}\right)^2\right]^{0.5}}$$

~~where $\overline{\theta_{CRS}}$ and $\overline{\theta_{SN}}$ represent the mean soil moisture for~~), each ~~measurement method~~expressed as volumetric soil moisture using the soil bulk density (ρ_b) and ~~N is~~ soil porosity (ϕ) of the ~~number of~~ samples. ~~Values in parentheses for JER indicate metrics when large rainfall events are excluded.~~Mean values of θ_G, ρ_b and ϕ are shown along with the ± 1 standard deviations. Particle size distributions were obtained from soil auger sampling of the top 45 cm at 20 locations at each site (Anderson, 2013). Mean values of percent clay, silt, sand and gravel are shown along with the ± 1 standard deviations.

Table 4: Statistical comparisons of CRNS method with distributed sensor network and water balance estimates based on the Standard Error of Estimates (SEE), Root Mean Square Error (RMSE), Bias (B), and Correlation Coefficient (CC), described in Vivoni et al. (2008b). Values in parentheses for JER indicate metrics when large rainfall events are excluded.

Table 5: Total water flux estimates from daily ~~CRS~~CRNS soil water balance method (~~f_{CRS}~~f_{CRNS}) and daily sensor measurements during study period at the SRER and JER sites. P is from rain gauge measurements in both cases. L in ~~CRS~~CRNS is computed as $O - ET$ where ET is from EC method, while L in sensor estimates is calculated from solving the water balance.

Table ~~5: Regression parameters for the relations of the spatial variability of soil moisture (σ and CV) and <θ> at the SRER and JER sites along with the RMSE of the regressions.~~

~~**Table**~~ **6:** Regression parameters for the relations of evapotranspiration and soil moisture (θ_{SN} and ~~θ_{CRS}~~θ_{CRNS}) at the SRER and JER sites along with the RMSE of the regressions. $\theta_h = 0$ in all cases.

Characteristic (unit)	Value	SRER	JER
Watershed area (m^2)		12535	46734
Elevation (m)	mean	1166.6	1458.3
	max	1171.1	1467.5
	min	1160.9	1450.5
Slope (degree)	mean	3.2	3.9
	max	19.2	45
	min	2.1	0
Drainage density (1/m)		0.04	0.03
Major vegetation type (%)	shrubs	32%	27%
	cacti	6%	1%
	grasses	37%	6%
	bare soil	25%	66%
Precipitation (mm)	annual	364	251
	fall	72	54
	winter	69	31
	spring	26	32
	summer	197	134

Table 1: Watershed and precipitation characteristics at the SRER and JER sites. Precipitation values are long-term averages (1923-2014 at SRER and 1915-2006 at JER) for annual and seasonal quantities, defined as fall (October-December), winter (January-March), spring (April-June) and summer (July-September).

(Schreiner-McGraw et al., 2015, Table 1)

Site	$\lambda E + H = m(R_n - G) + b$		$\frac{\sum \lambda E + H}{\sum R_n - G}$
	m	***b***	
SRER	0.72	17	0.85
JER	0.72	9.9	0.82

Table 2: Energy balance closure at SRER and JER using 30-min net radiation (R_n), ground (G), latent (λE) and sensible (H) heat fluxes. The parameters m and b are the slope and intercept in the relation $\lambda E + H = m(R_n - G) + b$, while the ratio of the sum of ($\lambda E + H$) to the sum of ($R_n - G$) is a measure of how much available energy is accounted for in the turbulent fluxes.

(Schreiner-McGraw et al., 2015, Table 2)

Property (unit)	SRER	JER
Soil Moisture Calibration		
θ_G (m^3/m^3)	0.114 ± 0.023	0.056 ± 0.013
θ_{CRNS} (m^3/m^3)	0.114	0.056
θ_{SN} (m^3/m^3)	0.105	0.016
ρ_b (g/cm^3)	1.54 ± 0.18	1.30 ± 0.15
ϕ (m^3/m^3)	0.42 ± 0.07	0.51 ± 0.06
Particle Size Distribution		
Clay (%)	5.2 ± 1.3 %	4.9 ± 1.1 %
Silt (%)	13.0 ± 2.2 %	28.5 ± 5.0 %
Sand (%)	72.5 ± 5.7 %	34.9 ± 8.3 %
Gravel (%)	9.3 ± 5.1 %	34.7 ± 11.5 %

Table 3: Soil properties at SRER and JER. Soil moisture values correspond to conditions during the CRNS calibration dates (February 13, 2013 at SRER and February 10, 2013 at JER) for the gravimetric sampling at 18 locations with six depths (θ_G), CRNS (θ_{CRNS}) and the sensor network (θ_{SN}), each expressed as volumetric soil moisture using the soil bulk density (ρ_b) and soil porosity (ϕ) of the samples. Mean values of θ_G, ρ_b and ϕ are shown along with the ± 1 standard deviations. Particle size distributions were obtained from soil auger sampling of the top 45 cm at 20 locations at each site (Anderson, 2013). Mean values of percent clay, silt, sand and gravel are shown along with the ± 1 standard deviations.

(Schreiner-McGraw et al., 2015, Table 3)

Metric (unit)	**SREER**	**JER**
~~θ_{CRS}~~θ_{CRNS} versus θ_{SN}		
RMSE (m^3/m^3)	0.009	0.013
CC	0.949	0.946
B	1.117	1.019
SEE (m^3/m^3)	0.012	0.013
~~$\Delta\theta_{CRS}$~~$\Delta\theta_{CRNS}$ versus $\Delta\theta_{WB}$		
RMSE (m^3/m^3)	0.001	0.~~038~~082 (0.019)
CC	0.~~954~~949	0.~~945~~940 (0.~~946)~~945)
B	~~1.167~~0.936	0.~~702~~543 (0.903)
SEE (m^3/m^3)	0.~~020~~024	0.~~049~~095 (0.020)

Table ~~3~~4: Statistical comparisons of ~~CRS~~CRNS method with distributed sensor network and water balance estimates based on the Standard Error of Estimates~~,~~ $SEE=\sqrt{\frac{\sum(\theta_{SN}-\theta_{CRS})^2}{N}}$ ~~;~~ (SEE), Root Mean Square Error~~,~~ $RMSE=\sqrt{\frac{\sum(\theta'_{CRS}-\theta_{CRS})^2}{N}}$ ~~where θ'_{CRS} is the predicted value of θ_{CRS} based on the best fit line with θ_{SN}~~ (RMSE), Bias~~,~~ $B=\frac{\overline{\theta}_{CRS}}{\overline{\theta}_{SN}}$ (B), and Correlation Coefficient~~,~~ $CC=\frac{\sum_{i=1}^{N}(\theta_{CRS,i}-\overline{\theta_{CRS}})(\theta_{SN,i}-\overline{\theta_{SN}})}{\left[\sum_{i=1}^{N}(\theta_{CRS,i}-\overline{\theta_{CRS}})^2\right]^{0.5}\left[\sum_{i=1}^{N}(\theta_{SN,i}-\overline{\theta_{SN}})^2\right]^{0.5}}$ ~~where $\overline{\theta_{CRS}}$ and $\overline{\theta_{SN}}$ represent the mean soil moisture for each measurement method and N is the number of samples~~ (CC), described in Vivoni et al. (2008b). Values in parentheses for JER indicate metrics when large rainfall events are excluded.

(Schreiner-McGraw et al., 2015, Table ~~3)~~ 4)

Water Flux	SRER	JER
~~CRS~~CRNS Estimates		
Precipitation (*P*, mm)	464	533
Infiltration (*I*, mm)	357	477
Outflow (*O*, mm)	391	482
Leakage (*L*, mm)	-56	193
Outflow ratio (*O*/*P*)	0.84	0.90
Runoff ratio (*Q*/*P*)	0.23	0.11
Sensor ~~Estimates~~Measurements		
Precipitation (*P*, mm)	464	533
Storage change ($\Delta\theta$, mm)	-13	26
Outflow (*O*, mm)	437	506
Leakage (*L*, mm)	-10	217
Evapotranspiration (*ET*, mm)	447	289
Evaporation ratio (*ET*/*P*)	0.96	0.54
~~Outflow ratio (*O*/*P*)~~	~~0.94~~	~~0.95~~
Streamflow (*Q*, mm)	64	5
Runoff ratio (*Q*/*P*)	0.14	0.01

Table ~~4~~5: Total water flux estimates from daily ~~CRS~~CRNS soil water balance method (~~f_{CRS}~~f_{CRNS}) and daily sensor measurements during study period at the SRER and JER sites. *P* is from rain gauge measurements in both cases. *L* in ~~CRS~~CRNS is computed as *O* – *ET* where *ET* is from EC method, while *L* in sensor estimates is calculated from solving the water balance.

~~**(Schreiner-McGraw et al., 2015, Table 4)**~~

	SRER			JER		
Relation	**k_1**	**k_2**	**RMSE**	**k_1**	**k_2**	**RMSE**
$\sigma - \theta_{SN}$	0.75	4.23	0.007 m^3/m^3	0.74	2.75	0.005 m^3/m^3
$\sigma - \theta_{CRS}$	0.57	1.80	0.007 m^3/m^3	0.65	1.81	0.007 m^3/m^3
$CV - \theta_{SN}$	0.78	5.40	0.145	0.72	2.48	0.067
$CV - \theta_{CRS}$	0.87	6.36	0.020	0.72	2.24	0.071

Table 5: Regression parameters for the relations of the spatial variability of soil moisture (σ and *CV*) and <θ> at the SRER and JER sites along with the RMSE of the regressions.

(Schreiner-McGraw et al., 2015, Table 5)

Site	Relation	**ET_{max} (mm/day)**	**E_w (mm/day)**	**θ_w (m^3/m^3)**	**θ^* (m^3/m^3)**	**RMSE (mm/day)**
SRER	ET - θ_{SN}	2.61	0.41	0.03	0.07	1.15
	ET - ~~θ_{CRS}~~θ_{CRNS}	2.40	0.36	0.02	0.08	0.55
JER	ET - θ_{SN}	2.16	0.18	0.03	0.12	0.34
	ET - ~~θ_{CRS}~~θ_{CRNS}	2.17	0.21	0.03	0.13	0.34

Table 6: Regression parameters for the relations of evapotranspiration and soil moisture (θ_{SN} and ~~θ_{CRS}~~θ_{CRNS}) at the SRER and JER sites along with the RMSE of the regressions. $\theta_h = 0$ in all cases.

(Schreiner-McGraw et al., 2015, Table 6)