

1  
2  
3  
4  
5  
6  
7  
8  
9  
10  
11  
12  
13  
14  
15  
16  
17  
18  
19  
20  
21  
22  
23  
24  
25  
26  
27  
28  
29  
30  
31  
32  
33  
34  
35  
36  
37  
38  
39  
40  
41  
42  
43

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

Adam P. Schreiner-McGraw<sup>1</sup>, Enrique R. Vivoni<sup>1,2\*</sup>, Giuseppe Mascaro<sup>3</sup>, and Trenton E. Franz<sup>4</sup>

1. School of Earth and Space Exploration,  
Arizona State University, Tempe, AZ, 85287.

2. School of Sustainable Engineering and the Built Environment,  
Arizona State University, Tempe, AZ, 85287.

3. Julie Ann Wrigley Global Institute of Sustainability,  
Arizona State University, Tempe, AZ, 85287.

4. School of Natural Resources,  
University of Nebraska-Lincoln, Lincoln, NE, 68583.

Revised version submitted to *Hydrology and Earth System Sciences*  
December 9, 2015

---

\* *Corresponding author address:* Enrique R. Vivoni, School of Earth and Space Exploration and School of Sustainable Engineering and the Built Environment, Arizona State University, ISTB4, Building 75, Room 769, Tempe, AZ, 85287-6004, Tel: (480) 727-3575, email: [vivoni@asu.edu](mailto:vivoni@asu.edu).

1 **Abstract**

2           Soil moisture dynamics reflect the complex interactions of meteorological conditions  
3 with soil, vegetation and terrain properties. In this study, intermediate scale soil moisture  
4 estimates from the cosmic-ray neutron sensing (CRNS) method are evaluated for two semiarid  
5 ecosystems in the southwestern United States: a mesquite savanna at the Santa Rita Experimental  
6 Range (SRER) and a mixed shrubland at the Jornada Experimental Range (JER). Evaluations of  
7 the CRNS method are performed for small watersheds instrumented with a distributed sensor  
8 network consisting of soil moisture sensor profiles, an eddy covariance tower and runoff flumes  
9 used to close the water balance. We found a very good agreement between the CRNS method  
10 and the distributed sensor network (RMSE of 0.009 and 0.013 m<sup>3</sup>/m<sup>3</sup> at SRER and JER) at the  
11 hourly time scale over the 19-month study period, primarily due to the inclusion of 5 cm  
12 observations of shallow soil moisture. Good agreement was also obtained in soil moisture  
13 changes estimated from the CRNS and watershed water balance methods (RMSE = 0.001 and  
14 0.082 m<sup>3</sup>/m<sup>3</sup> at SRER and JER), with deviations due to bypassing of the CRNS measurement  
15 depth during large rainfall events. Once validated, the CRNS soil moisture estimates were used  
16 to investigate hydrological processes at the footprint scale at each site. Through the computation  
17 of the water balance, we showed that drier-than-average conditions at SRER promoted plant  
18 water uptake from deeper soil layers, while the wetter-than-average period at JER resulted in  
19 percolation towards deeper soils. The CRNS measurements were then used to quantify the link  
20 between evapotranspiration and soil moisture at a commensurate scale, finding similar predictive  
21 relations at both sites that are applicable to other semiarid ecosystems in the southwestern U.S.

22  
23 **Keywords:** watershed hydrology, soil moisture variability, evapotranspiration, land-atmosphere  
24 interactions, COSMOS, North American monsoon.  
25

# 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 (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 (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 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.,

1 2012a), and horizontal heterogeneity (Franz et al., 2013b). To date, the validation of the CRNS  
2 technique has been performed using single site measurements, spatial aggregations of different  
3 measurement locations, and particle transport models (Desilets et al., 2010; Franz et al., 2013b;  
4 Zhu et al., 2015). Distributed sensor networks measuring the water balance components of small  
5 watersheds and the spatial variability of soil moisture within a watershed offer the opportunity to  
6 test the accuracy of the CRNS method through multiple, independent approaches. For instance,  
7 the CRNS technique can be validated based upon the application of the watershed water balance,  
8 as performed for the eddy covariance (EC) technique which is often used to measure surface  
9 turbulent fluxes (Scott, 2010; Templeton et al., 2014). Once validated, CRNS soil moisture  
10 estimates can be used to apply the water balance equation in a continuous fashion with the aim of  
11 quantifying hydrological fluxes during storm and interstorm periods, including the occurrence of  
12 percolation to deep soils or the transfer of water from the deeper vadose zone to the atmosphere.

13         An important advantage of the CRNS technique is that its measurement scale is  
14 comparable to the footprint of evapotranspiration (*ET*) measurements based on the EC technique,  
15 whose extent depends on wind speed and direction, atmospheric stability, and instrument and  
16 surface roughness heights (e.g., Hsieh et al., 2000; Kormann and Meixner, 2001; Falge et al.,  
17 2002). Furthermore, the relation between *ET* and soil moisture is an important parameterization  
18 in land surface models (e.g., Laio et al., 2001; Rodríguez-Iturbe and Porporato, 2004; Vivoni et  
19 al., 2008a) and, in most cases, has been investigated using EC measurements of *ET* and soil  
20 moisture observations at single sites. A number of studies, however, have shown that accounting  
21 for the spatial variability of land surface states is important to properly identify the linkage with  
22 EC measurements (e.g., Detto et al., 2006; Vivoni et al., 2010; Alfieri and Blanken, 2012). In  
23 other words, aggregated turbulent fluxes should be compared to spatially-averaged surface states



1 obtained at commensurate measurement scales. As a result, CRNS soil moisture estimates could  
2 be useful to improve the characterization of the relation between evapotranspiration flux and soil  
3 moisture. To our knowledge, soil moisture estimates from the CRNS technique have only been  
4 recently used to study the hydrological processes occurring in small watersheds that overlap with  
5 the CRNS measurement footprint or for improving the parameterization of land surface models  
6 (Shuttleworth et al., 2013; Rosolem et al., 2014).

7         In this contribution, we study the soil moisture dynamics of small semiarid watersheds in  
8 Arizona and New Mexico each instrumented with a cosmic-ray neutron sensor, eddy covariance  
9 tower, runoff flume and a network of soil moisture sensor profiles. The watersheds represent the  
10 heterogeneous vegetation and soil conditions observed in the Sonoran and Chihuahuan Deserts  
11 of the southwestern U.S. (Templeton et al., 2014; Pierini et al., 2014). We first compare the  
12 CRNS method with the distributed sensor network and estimates from a novel method based on  
13 closing the water balance at each site. Given the simultaneous observations during the study  
14 period (March 2013 to September 2014, 19 months), we quantify the variations in hydrological  
15 processes (e.g., infiltration, evapotranspiration, percolation) that differentially occur at each site  
16 in response to varying precipitation. Combining these measurement techniques also affords the  
17 capacity to construct and compare relationships between the spatially-averaged CRNS estimates  
18 and the spatially-averaged *ET* obtained from the EC method. To our knowledge, this is the first  
19 study where CRNS measurements are validated via two independent methods at the small  
20 watershed scale and used to make new inferences about watershed hydrological processes.

21  
22  
23  
24  
25  
26

## 1 **2. Study Areas and Datasets**

### 2 **2.1. Study Sites and Their General Characteristics**

3           The two study sites are long-term experimental watersheds in semiarid ecosystems of the  
4 southwestern United States. Watershed monitoring began in 1975 at the Santa Rita Experimental  
5 Range (SRER), located 45 km south of Tucson, Arizona, in the Sonoran Desert (Fig. 1), as  
6 described by Polyakov et al. (2010) and Scott (2010). Precipitation at the site varies considerably  
7 during the year, with 54% of the long-term mean amount (364 mm/yr) occurring during the  
8 summer months of July to September due to the North American monsoon (Vivoni et al., 2008a;  
9 Pierini et al., 2014). Soils at the SRER site are a coarse-textured sandy loam (Anderson, 2013)  
10 derived from Holocene-aged alluvium from the nearby Santa Rita Mountains. The savanna  
11 ecosystem at the site consists of the velvet mesquite tree (*Prosopis velutina* Woot.), interspersed  
12 with grasses (*Eragrostis lehmanniana*, *Bouteloua rothrockii*, *Muhlenbergia porteri* and *Aristida*  
13 *glabrata*) and various cacti species (*Opuntia spinosior*, *Opuntia engelmannii* and *Ferocactus*  
14 *wislizeni*). Similarly, watershed monitoring began in 1977 at the Jornada Experimental Range  
15 (JER), located 30 km north of Las Cruces, New Mexico, in the Chihuahuan Desert (Fig. 1), as  
16 described by Turnbull et al. (2013). Mean annual precipitation at the JER is considerably lower  
17 than SRER (251 mm/yr), with a similar proportion (53%) occurring during the summer monsoon  
18 (Templeton et al., 2014). Soils at the JER site are primarily sandy loam with high gravel contents  
19 (Anderson, 2013) transported from the San Andreas Mountains. The mixed shrubland ecosystem  
20 at the site consists of creosote bush (*Larrea tridentata*), honey mesquite (*Prosopis glandulosa*  
21 Torr.), several grass species (*Muhlenbergia porteri*, *Pleuraphis mutica* and *Sporobolus*  
22 *cryptandrus*), and other shrubs (*Parthenium incanum*, *Flourensia cernua* and *Gutierrezia*  
23 *sarothrae*). Fig. 2 presents a vegetation classification at each site grouped into major categories:  
24 (1) SRER has velvet mesquite (labeled mesquite), grasses, cacti (*Opuntia engelmannii* or prickly

1 pear) and bare soil, while (2) JER has honey mesquite (labeled mesquite), creosote bush, other  
2 shrubs, grasses and bare soil. Table 1 presents the vegetation and terrain properties for the site  
3 watersheds obtained from 1-m digital elevation models (DEMs) and 1-m vegetation maps (Fig.  
4 2). Pierini et al. (2014) and Templeton et al. (2014) describe the image acquisition and  
5 processing methods employed to derive these products at SRER and JER, respectively.

## 6 7 **2.2. Distributed Sensor Networks at the Small Watershed Scale**

8 Long-term watershed monitoring at the SRER and JER sites consisted of rainfall and  
9 runoff observations at Watersheds 7 and 8 (SRER, 1.25 ha) and the Tromble Weir (JER, 4.67  
10 ha). Pierini et al. (2014) and Templeton et al. (2014) describe recent monitoring efforts using a  
11 network of rainfall, runoff, soil moisture and temperature observations, as well as radiation and  
12 energy balance measurements at EC towers, commencing in 2011 and 2010 at SRER and JER.  
13 This brief description of the distributed sensor networks is focused on the spatially-averaged  
14 measurements used for comparisons to the CRNS method. Precipitation ( $P$ ) was measured using  
15 up to 4 tipping-bucket rain gauges (TE525MM, Texas Electronics) to construct a 30-min  
16 resolution spatial average based on Thiessen polygons within the watershed boundaries. At the  
17 watershed outlets, streamflow ( $Q$ ) was estimated at Santa Rita supercritical runoff flumes (Smith  
18 et al., 1981) using a pressure transducer (CS450, Campbell Scientific Inc.) and an *in-situ* linear  
19 calibration to obtain 30-min resolution observations. Evapotranspiration ( $ET$ ) was obtained at 30-  
20 min resolution using the EC technique that employs a three-dimensional sonic anemometer  
21 (CSAT3, Campbell Scientific Inc.) and an open path infrared gas analyzer (LI-7500, LI-COR  
22 Inc.) installed at 7-m height on each tower. Flux corrections for the EC measurements followed  
23 Scott et al. (2004) and were verified using an energy balance closure approach reported in Table  
24 2 for the study period. Energy balance closure at both sites is within the reported values across a

1 range of other locations where the ratio of  $\Sigma(\lambda E + H)/\Sigma(R_n - G)$  has an average value of 0.8  
2 (Wilson et al., 2002; Scott, 2010). To summarize these observations, Fig. 3 shows the spatially-  
3 averaged  $P$ ,  $Q$  and  $ET$  (mm/hr), each aggregated to hourly resolution, at each study site during  
4 March 1, 2013 to September 30, 2014, along with seasonal precipitation amounts. While the  
5 results compare favorably to previous measurements (Turnbull et al., 2013; Pierini et al., 2014;  
6 Templeton et al., 2014), it should be noted that  $ET$  and  $Q$  data are assumed to represent the  
7 spatially-averaged watershed conditions, despite the small mismatch between the watershed  
8 boundaries and EC footprints (Fig. 2) and the summation of  $Q$  in the two watersheds at SRER.

9         Distributed soil moisture measurements were obtained using soil dielectric probes (Hydra  
10 Probe, Stevens Water) organized as profiles (sensors placed at 5, 15 and 30 cm depths) in each  
11 study site. Profiles were originally installed at multiple locations along transects to investigate  
12 the different primary controls on soil moisture at each site: (1) at SRER, we installed four  
13 transects of 5 profiles each located under different vegetation classes (mesquite, grass, prickly  
14 pear and bare soil), and (2) at JER, we established three transects of 5 profiles each installed  
15 along different hillslopes (north-, south- and west-facing), as shown in Fig. 1. Individual sensors  
16 measure the impedance of an electric signal, as described in Campbell (1990), through a 40.3  
17 cm<sup>3</sup> soil volume (5.7 cm in length and 3.0 cm in diameter, see Stevens Water Monitoring System  
18 (1998)) to determine the volumetric soil moisture ( $\theta$ ) in m<sup>3</sup>/m<sup>3</sup> and soil temperature in °C as 30-  
19 min averaged values. A ‘loam’ calibration equation was used in the conversion to  $\theta$  (Seyfried et  
20 al., 2005) and corrected using relations established through gravimetric soil sampling at each  
21 study site (a power law relation at SRER with  $R^2 = 0.99$  and a linear relation at JER with  $R^2 =$   
22 0.97), following Pierini (2013). Given that sensors were originally installed to conduct watershed  
23 studies, spatial averaging was performed using site-specific weighting schemes accounting for

1 the main controls on the soil moisture distribution. Thus: (1) at SRER, we utilized the percentage  
2 area of each vegetation class (Table 1) and the associated sensor locations within each type  
3 (Pierini et al., 2014), and (2) at JER, we accounted for the aspect and elevation at the sensor  
4 locations and used these to extrapolate to other locations with similar characteristics based on the  
5 1-m DEM (Templeton et al., 2014).

### 6 7 **2.3. Cosmic-ray Neutron Sensing Method for Soil Moisture Estimation**

8 The CRNS method relates soil moisture to the density of fast or moderated neutrons  
9 (Zreda et al., 2008) measured above the soil surface. A cosmic-ray neutron sensor (CRS-1000/B,  
10 Hydroinnova LLC) was installed in each watershed in January 2013 to record neutron counts at  
11 hourly intervals. We selected the study period (March 1, 2013 to September 30, 2014) to  
12 coincide with the availability of data from the distributed sensor networks. While the theory of  
13 using neutrons for soil moisture measurements has a long history (e.g., Gardner and Kirkham,  
14 1952), recent developments in the measurement of neutrons generated from cosmic rays has  
15 increased the horizontal scale, reduced the need for manual sampling, and led to a non-invasive  
16 approach. Zreda et al. (2008) and Desilets and Zreda (2013) describe the horizontal scale as  
17 having a radius of ~300 m at sea level and a vertical aggregation scale ranging from 12 to 76 cm  
18 depending on soil wetness, while the work of Köhli et al. (2015) found a smaller horizontal scale  
19 with a radius of ~230 m at sea level. Since the travel speed of fast neutrons is >10 km/s, neutron  
20 mixing occurs almost instantaneously in the air above the soil surface (Glasstone and Edlund,  
21 1952), providing a well-mixed region that can be sampled with a single detector.

22 Using a particle transport model, Desilets et al. (2010) found a theoretical relationship  
23 between the neutron count rate at a detector and soil moisture for homogeneous SiO<sub>2</sub> sand:

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

2 where  $\theta$  ( $\text{m}^3/\text{m}^3$ ) is volumetric soil moisture (adjusted from gravimetric content to account for the  
3 soil bulk density),  $N$  is the neutron count rate (counts/hr) normalized to the atmospheric pressure  
4 and solar activity level, and  $N_o$  (counts/hr) is the count rate over a dry soil under the same  
5 reference conditions. The corrections applied to the neutron count rate are detailed in Desilets  
6 and Zreda (2003) and Zreda et al. (2012) and are applied automatically in the COSMOS website  
7 (<http://cosmos.hwr.arizona.edu/>). Additionally, since neutron counts are affected by all sources  
8 of hydrogen in the support volume, we apply a correction ( $C_{wv}$ ) for atmospheric water vapor that  
9 was derived by Rosolem et al. (2013) as:

$$C_{wv} = 1 + 0.0054(\rho_v^o - \rho_v^{ref}) \quad , \quad (2)$$

11 where  $\rho_v^o$  ( $\text{g}/\text{m}^3$ ) and  $\rho_v^{ref}$  ( $\text{g}/\text{m}^3$ ) are absolute water vapors at current and reference conditions.

12 To estimate  $N_o$ , we performed a manual soil sampling at 18 locations within the CRNS footprint  
13 (sampled every 60 degrees at radial distances of 25, 75 and 200 m from the detector) at 6 depths  
14 (0-5, 5-10, 10-15, 15-20, 20-25, 25-30 cm) for a total of 108 samples per site. Gravimetric soil  
15 moisture measurements were made following oven drying at 105 °C for 48 hrs (Dane and Topp,  
16 2002) and converted to volumetric soil moisture using the soil bulk density ( $1.54 \pm 0.18 \text{ g}/\text{cm}^3$  at  
17 SRER and  $1.3 \pm 0.15 \text{ g}/\text{cm}^3$  at JER). The spatially-averaged volumetric soil moisture was related  
18 to the average neutron count obtained for the same time period (6-hr average) resulting in  $N_o =$   
19 3973 at SRER and  $N_o = 3944$  at JER, considered to be in line with the expected amounts given  
20 the elevations of both sites. Table 3 compares the gravimetric measurements and the CRNS soil  
21 moisture estimates during the calibration dates and provides further details on the soil properties  
22 at the two sites. We applied a 12-hr boxcar filter to the measured count rates to remove the

1 statistical noise associated with the measurement method (Zreda et al., 2012). On days where soil  
 2 moisture changed by more than  $0.06 \text{ m}^3/\text{m}^3$  due to rainfall, the boxcar filter was not applied. We  
 3 note that additional terms to the calibration accounting for variations in lattice water, soil organic  
 4 carbon and vegetation have been proposed (Zreda et al., 2012; Bogen et al., 2013; McJannet et  
 5 al., 2014; Coopersmith et al. 2014). However, given the relatively small amount of biomass ( $\sim 2.5$   
 6  $\text{kg}/\text{m}^2$  at SRER, Huang et al., 2007; and  $\sim 0.5 \text{ kg}/\text{m}^2$  at JER, Huenneke et al., 2001), low soil  
 7 organic carbon (4.2 mg C/g soil at SRER; and 2.7 mg C/g soil at JER, Throop et al., 2011), and  
 8 low clay percent (5.2% at SRER; and 4.9% at JER, Anderson, 2013), and thus low lattice water  
 9 amounts (Greacen, 1981), we have neglected these terms in the analysis.

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

$$23 \quad z^*(\theta) = \frac{5.8}{\rho_b \tau + \theta + 0.0829} \quad , \quad (3)$$

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

$$7 \quad wt(z) = a \left( 1 - \left( \frac{z}{z^*} \right)^b \right) \quad \text{for } 0 \leq wt \leq z^* \quad , \quad (4)$$

8 where  $wt(z)$  is the weight at depth  $z$ ,  $a$  is a constant defined to integrate the profile to unity ( $a =$   
 9  $1/(z^* - \{z^{*b+1}/[z^{*b}(b+1)]\})$ ), and  $b$  controls the shape of the weighting function. For simplicity,  
 10 we assumed a value of  $b = 1$  leading to a linear relationship (Franz et al., 2012b).

## 11 12 **3. Methods**

### 13 **3.1. Comparison of CRNS to Distributed Network of Soil Moisture Sensors**

14 The CRNS method was first validated against the distributed network of soil moisture  
 15 sensors. As done in previous studies, we compared hourly soil moisture observations obtained  
 16 from the CRNS method ( $\theta_{CRNS}$ ) to estimates from the distributed sensor network ( $\theta_{SN}$ ) that have  
 17 been averaged in space (i.e., based on vegetation type at SRER and elevation/aspect location at  
 18 JER) and depth-weighted according to the time-varying CRNS measurement depth ( $z^*$ ). We used  
 19 several metrics to quantitatively assess the comparisons, including Root Mean Square Error  
 20 (RMSE), Correlation Coefficient (CC), Bias (B) and Standard Error of Estimates (SEE). We  
 21 performed an additional test of the CRNS technique by comparing relations between the mean  
 22 soil moisture ( $\langle \theta \rangle$ ), obtained from either  $\theta_{CRNS}$  or  $\theta_{SN}$ , and the spatial standard deviation ( $\sigma$ ) of  
 23 soil moisture measured in the distributed sensor network. This relation has been studied



1 previously with the goal of evaluating the role of heterogeneities related to vegetation, terrain  
 2 position and soil properties (Famiglietti et al., 1999; Lawrence and Hornberger, 2007; Fernández  
 3 and Ceballos, 2003; Vivoni et al., 2008b; Mascaro et al., 2011; Qu et al., 2015). Based on  
 4 Famiglietti et al. (2008), we fitted an empirical function to the observations at each site:

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

5  
 6 where  $k_1$  and  $k_2$  are regression parameters, and compared these to prior studies in the region (e.g.,  
 7 Vivoni et al., 2008b; Mascaro and Vivoni, 2012; Stillman et al., 2014).

### 8 9 **3.2. CRNS Water Balance Analyses Methods**

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

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

12  
 13 where  $\Delta \theta$  is the change in volumetric soil moisture over the time interval  $\Delta t$ ,  $P$  is precipitation,  
 14  $ET$  is evapotranspiration,  $Q$  is streamflow, and  $L$  is leakage or deep percolation, with all of the  
 15 terms expressed as spatially-averaged quantities and valid over the effective soil measurement  
 16 depth ( $z^*$ ). The water balance was applied to validate the accuracy of the CRNS observations  
 17 using measurements of the spatially-averaged fluxes ( $P$ ,  $ET$  and  $Q$ ) for a set of storm events. For  
 18 each event, we computed the change in soil moisture measured by the CRNS,  $\Delta \theta_{CRNS}$ , and the  
 19 change calculated from the water balance,  $\Delta \theta_{WB}$ . In both cases, changes were computed as the  
 20 difference between the pre-storm soil moisture and the peak amount due to a rainfall event. For  
 21 the application of (6), the soil measurement depth  $z^*$  was calculated as the average value over the  
 22 duration of the soil moisture response to each individual storm. Note that, during a storm,  $ET$  is  
 23 very low and the use of  $z^*$  in (6) instead of the plant rooting depth is justified. In addition, since

1 this comparison is performed over a short time interval during the rising limb of the soil moisture  
 2 response, we assumed no leakage (i.e.,  $L = 0$ ). To test the validity of this hypothesis, we analyzed  
 3 the soil moisture records measured at the EC towers, where sensors were installed to measure the  
 4 profile up to 1 m (i.e., a depth larger than  $z^*$ ). We found that the percolation beyond a depth of  
 5 ~40 cm is infrequent at both sites during summer monsoon storms, thus sustaining our  
 6 assumption. However, percolation can occur on a time scale of several days during winter  
 7 precipitation (e.g., Franz et al., 2012b; Templeton et al., 2014; Pierini et al., 2014). Although  
 8 there are large amounts of bare soil in the watersheds, shrub and tree roots have been shown to  
 9 extend laterally for 10 m or more (Heitschmidt et al., 1988), such that most of contributing area  
 10 will be under the influence of both bare soil evaporation and plant transpiration.

11 Once validated against the distributed sensors and the application of the water balance,  
 12 the CRNS estimates were subsequently used to determine the daily spatially-averaged fluxes into  
 13 and out from the measurement depth ( $z^*$ ) as proposed by Franz et al. (2012b):

$$14 \quad f_{CRNS}(t) = (\theta_{CRNS,t} - \theta_{CRNS,t-1}) \min(z^*_t, z^*_{t-1}) / \Delta t . \quad (7)$$

15 In (7),  $f_{CRNS}$  is the daily flux (mm/day),  $\Delta t$  is the time step (1 day), and  $\min(z^*_t, z^*_{t-1})$  represents  
 16 the minimum daily-averaged measurement depth between the two days being compared. Positive  
 17 values of  $f_{CRNS}$  indicate an increase in soil moisture and, thus, represent net infiltration ( $f_{CRNS} = I$ )  
 18 into the measurement depth, usually occurring after a rainfall event. As a result, assuming  
 19 negligible plant interception, daily  $P$  data can be used to estimate  $Q$  as  $P - I$ , which in turn can be  
 20 compared to the runoff measurements in the watersheds. On the other hand, negative values of  
 21  $f_{CRNS}$  are equal to the net outflow ( $f_{CRNS} = O$ ), which can occur either as evapotranspiration or  
 22 leakage. Using the EC method to obtain daily  $ET$ ,  $L = O - ET$  can be determined as a measure of

1 exchanges between the soil layers above and below  $z^*$ :  $L$  is positive when there is drainage to  
 2 deeper soil layers and negative when deeper water is being drawn to support plant transpiration.

3  
 4 **3.3. Relation between Evapotranspiration and Soil Moisture at Commensurate Scale**

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

$$9 \quad ET(\theta) = \begin{cases} 0 & 0 < \theta \leq \theta_h \\ E_w \frac{\theta - \theta_h}{\theta_w - \theta_h} & \theta_h < \theta \leq \theta_w \\ E_w + (ET_{max} - E_w) \frac{\theta - \theta_h}{\theta^* - \theta_h} & \theta_w < \theta \leq \theta^* \\ ET_{max} & \theta^* < \theta \leq \phi \end{cases}, \quad (8)$$

10 where  $E_w$  is soil evaporation,  $ET_{max}$  is maximum evapotranspiration,  $\theta_h$ ,  $\theta_w$ , and  $\theta^*$  are the  
 11 hygroscopic, wilting and plant stress soil moisture thresholds, and  $\phi$  is the soil porosity. Vivoni  
 12 et al. (2008a) applied (8) to observations of  $ET$  from the EC method and  $\theta$  at single locations to  
 13 derive the relation parameters using a nonlinear optimization algorithm (Gill et al., 1981). We  
 14 evaluate this approach using the spatially-averaged soil moisture estimates ( $\theta_{CRNS}$  and  $\theta_{SN}$ ) whose  
 15 spatial scale is more commensurate with the  $ET$  measurements than single measurement sites.

16  
 17 **4. Results and Discussion**

18 **4.1. Comparison of CRNS Method to Distributed Sensor Network**

19 Fig. 4 presents a comparison of the spatially-averaged, hourly soil moisture obtained  
 20 from the CRNS method ( $\theta_{CRNS}$ ) and the distributed sensor network ( $\theta_{SN}$ ), as well as the time-  
 21 varying measurement depth ( $z^*$ ) of CRNS. Relative to the long-term summer precipitation

1 (Table 1), the study period had below average (188 and 153 mm in 2013 and 2014) and  
2 significantly above average (246 and 247 mm) rainfall at SRER and JER, respectively. The fall-  
3 winter period in the record had below average precipitation (99 mm) at SRER and significantly  
4 below average amounts (21 mm) at JER. Overall, the spring periods were dry, consistent with the  
5 long-term averages. In response, the temporal variability of soil moisture clearly shows the  
6 seasonal conditions at the two sites, with relatively wetter conditions during the summer  
7 monsoons. Seasonally-averaged  $\theta_{CRNS}$  compares favorably with seasonally-averaged  $\theta_{SN}$  (Fig. 4),  
8 with both estimates showing relatively large differences between wetter summer conditions  
9 (0.065 and 0.085 m<sup>3</sup>/m<sup>3</sup> at SRER and JER) and drier spring values (0.028 and 0.021 m<sup>3</sup>/m<sup>3</sup> at  
10 SRER and JER, respectively). As shown in prior studies (e.g., Zreda et al., 2008; Franz et al.,  
11 2012b), the CRNS method tracks very well the sensor observations. Nevertheless, there is an  
12 indication that  $\theta_{CRNS}$  has a tendency to dry less quickly during some rainfall events (i.e.,  
13 overestimate soil moisture during recession limbs). This might be due to landscape features such  
14 as nearby channels (Fig. 1) and their associated zones of soil water convergence that remain  
15 wetter than areas measured by the distributed sensor network. Overall, however, there is an  
16 excellent match between  $\theta_{CRNS}$  and  $\theta_{SN}$  in terms of capturing the occurrence and magnitude of  
17 soil moisture peaks across the different seasons, thus reducing some issues noted by Franz et al.  
18 (2012b) with respect to a purported oversensitivity of  $\theta_{CRNS}$  for small rainfall events (<5 mm).  
19 We attribute this improvement to the use of a 5 cm sensor in each profile that tracks important  
20 soil moisture dynamics occurring in the shallow surface layer within semiarid ecosystems.

21 To complement this, Fig. 5 compares  $\theta_{CRNS}$  and  $\theta_{SN}$  as a scatterplot along with the sample  
22 size (N) and the Standard Error of Estimates (SEE) which quantify the deviations from the 1:1  
23 line. Table 4 provides the full set of statistical metrics for the comparison of  $\theta_{CRNS}$  versus  $\theta_{SN}$  at

1 the two study sites. The correspondence between both methods is very good, with low RMSE  
2 and SEE, a high CC, and a Bias close to 1. These values are comparable to previous validation  
3 efforts where the RMSE was found to be  $0.011 \text{ m}^3/\text{m}^3$  (Franz et al., 2012b) and less than  $0.03$   
4  $\text{m}^3/\text{m}^3$  (Bogena et al., 2013; Coopersmith et al., 2014; Zhu et al., 2015). The comparison of the  
5 semiarid sites is also illustrative of the ability of the CRNS method to estimate soil moisture over  
6 a range of conditions. Despite the more arid climate at JER (Table 1), the study period consisted  
7 of higher precipitation (247 mm) and higher soil moisture values during the summer ( $0.085$   
8  $\text{m}^3/\text{m}^3$ ), as compared to SRER (170 mm,  $0.065 \text{ m}^3/\text{m}^3$ ), indicating a more active monsoon in the  
9 Chihuahuan Desert. In contrast, the fall-winter period is generally drier at JER (21 mm,  $0.039$   
10  $\text{m}^3/\text{m}^3$ ), as compared to SRER (99 mm,  $0.057 \text{ m}^3/\text{m}^3$ ), where high  $P$  and low  $ET$  in the winter  
11 promoted infiltration below the CRNS measurement depth, as observed at a 1-m sensor profile at  
12 SRER (not shown). These two effects lead to a larger range of soil moisture at JER as compared  
13 to SRER in Fig. 5. As a result, the CRNS method is found to be a reliable method for measuring  
14 soil moisture in the observed range of values at SRER and JER during the study period.

15 To further test the CRNS method against the distributed sensor network, Fig. 6 depicts  
16 the relations between the spatial variability of soil moisture ( $\sigma$ ) and the spatially-averaged  
17 conditions ( $\langle\theta\rangle$ ). For illustration purposes, bin-averages and standard deviations are also  
18 presented for each relation. Least squares regressions of (5) based on hourly observations were  
19 applied to estimate  $k_1$  and  $k_2$  for the relations  $\sigma$  vs.  $\theta_{SN}$  ( $k_1 = 0.75$  and  $k_2 = 4.23$  at SRER;  $k_1 =$   
20  $0.74$  and  $k_2 = 2.75$  at JER) and these parameters were adopted to interpret the relations of  $\sigma$  vs.  
21  $\theta_{CRNS}$ . The RMSE are very low and similar in both cases (RMSE =  $0.007$  and  $0.008 \text{ m}^3/\text{m}^3$  at  
22 SRER and  $0.005$  and  $0.008 \text{ m}^3/\text{m}^3$  at JER for the relation with  $\theta_{SN}$  and  $\theta_{CRNS}$ , respectively), thus  
23 confirming the good correspondence between the two methods. As shown in prior efforts in

1 semiarid ecosystems using sensor networks or aircraft observations (e.g., Fernández and  
2 Ceballos, 2003; Vivoni et al., 2008b; Mascaro et al., 2011; Stillman et al., 2014), there is a  
3 general increase in  $\sigma$  with  $\langle\theta\rangle$ , explained by the role played by local heterogeneities (e.g.,  
4 vegetation types, surface soil variations, topography) as well as the bounded nature of the soil  
5 moisture process at the driest state. The similar relations derived in these different sites might be  
6 broadly applicable to other semiarid ecosystems in the southwestern U.S.

7

#### 8 **4.2. Validation of CRNS Method with Water Balance Estimates**

9 Fig. 7 presents the comparison of the spatially-averaged  $\Delta\theta_{CRNS}$  and  $\Delta\theta_{WB}$  as a scatterplot  
10 for approximately 40 rainfall events with a total depth larger than 10 mm and durations ranging  
11 from 0.5 to 31 hours (mean of 6 hours). The statistical metrics are presented in Table 4. The  
12 correspondence between the methods is very good, with low RMSE and SEE, a high CC, and a  
13 Bias close to 1, with a closer match at SRER. For example, the SEE at SRER ( $0.024 \text{ m}^3/\text{m}^3$ ) is  
14 significantly less than the value at JER ( $0.095 \text{ m}^3/\text{m}^3$ ) and close to the SEE of the comparison of  
15  $\theta_{CRNS}$  and  $\theta_{SN}$ . This suggests that the three approaches (i.e., CRNS, sensor network, water  
16 balance) are in agreement at the SRER. For the JER, the lower correspondence between  $\Delta\theta_{CRNS}$   
17 and  $\Delta\theta_{WB}$  is attributed to five large events where  $\Delta\theta_{WB}$  is above  $0.2 \text{ m}^3/\text{m}^3$ . Removing these  
18 events lowers the SEE at JER to  $0.020 \text{ m}^3/\text{m}^3$ , in line with SRER and the comparison of  $\theta_{CRNS}$   
19 and  $\theta_{SN}$  at JER. A closer inspection of the soil moisture response at JER allows investigating the  
20 physical reasons causing the different behavior of these five events. Fig. 8 shows the soil  
21 moisture change ( $\Delta\theta_{SN}$ ) at different sensor depths averaged for the selected large events and for  
22 the remaining events, as well as the mean of CRNS measurement depths ( $z^*$ ) for each case. The  
23 five large events exhibit high soil moisture changes at 30 cm depth (i.e.,  $0.08 \text{ m}^3/\text{m}^3$ ) below  $z^*$   
24 (i.e., 17 cm), while other events have soil moisture changes near zero at 30 cm and are captured

1 well within  $z^*$ . This indicates that infiltration fronts during the larger events penetrated beyond  
2  $z^*$  and were not entirely captured by the CRNS method, leading to an underestimate of  $\Delta\theta_{WB}$ . For  
3 these events, the assumption  $L=0$  in equation (6) is not fully supported. In contrast, the better  
4 correspondence at SRER suggests that infiltration fronts were contained within  $z^*$ . This is  
5 plausible given the less rocky soil and flatter terrain at SRER as compared to JER (Anderson,  
6 2013). At JER, soil water movement to deeper layers can be promoted by higher gravel contents  
7 and the presence of calcium carbonate and undulated terrain which facilitate lateral water  
8 transfer to sandy channel beds (Templeton et al., 2014).

### 9 10 **4.3. Utility of CRNS for Investigating Hydrological Processes**

11         Given the confidence gained with respect to the CRNS estimates, we utilized these  
12 observations to quantify the water balance fluxes during storm and interstorm periods at the two  
13 sites. Fig. 9 shows the cumulative  $f_{CRNS}$  and the cumulative, spatially-averaged  $P$  and  $ET$   
14 measured by the distributed sensor network. An overall drying trend is present at SRER during  
15 the study period (i.e., cumulative  $f_{CRNS}$  becomes more negative), while JER exhibits a relatively  
16 small change in cumulative  $f_{CRNS}$ , both in response to the below average (SRER) and above  
17 average (JER) precipitation. An important contrast at the sites is the overall water balance (Table  
18 5), where higher  $P$ , lower  $ET$ , and lower  $Q$  at JER (measured  $ET/P = 0.54$ ,  $Q/P = 0.01$ ) implies  
19 that more soil water is available for leakage to deeper soil layers. This is reflected in a large  
20 positive difference between cumulative outflow ( $O = ET + L$ ) and  $ET$  at JER (i.e.,  $L > 0$  from  $z^*$ ,  
21 soil water movement to lower layers, as depicted in the soil water balance diagram). In contrast,  
22 SRER exhibits a higher  $ET/P = 0.96$  and  $Q/P = 0.14$ , such that negative differences occur  
23 between  $O$  and  $ET$  (i.e.,  $L < 0$  into  $z^*$ , movement from lower layers, as depicted in the soil water  
24 balance diagram). This is particularly important during the summers when vegetation is active

1 and produces more *ET* than the outflow from the CRNS measurement depth, indicating that soil  
2 water is obtained from deeper soil layers that are readily accessed by velvet mesquite roots (e.g.,  
3 Snyder and Williams, 2003; Scott et al., 2008; Potts et al., 2010). This is consistent with the  
4 sustained *ET* during interstorm periods in the summer season at SRER despite the low  $\theta_{CRNS}$ ,  
5 while JER exhibits sharp declines in *ET* when  $\theta_{CRNS}$  is reduced between storms.

6 Overall, the soil water balance from the CRNS method shows stark ecosystem  
7 differences at the two sites during the study period. The mesquite savanna at SRER extracted  
8 substantial amounts of water from deeper soil layers during the summer season such that losses  
9 to runoff and the atmosphere are in excess of seasonal precipitation. Deeper soil water is  
10 recharged beyond the CRNS measurement depth during winter periods, as observed by Scott et  
11 al. (2000), and subsequently accessed by deep-rooted trees during the summer (Scott et al.,  
12 2008). In contrast, the mixed shrubland at JER lost a substantial amount of precipitation to  
13 deeper soil layers throughout the year, due to the low values of runoff and evapotranspiration,  
14 and the soil, terrain and channel conditions promoting recharge (Templeton et al., 2014). Winter  
15 recharge is fostered by the lack of *ET* from drought-deciduous plants that lose their leaves in the  
16 wintertime. We hypothesize that deep percolation is likely occurring in the channels, since: (i)  
17 soil moisture observations in the hillslopes (i.e., far from the channel) show a lack of deep  
18 percolation, (ii) the runoff ratio decreases with the basin contributing area, indicating  
19 transmission losses along the channel (Templeton et al., 2014), and (iii) one sensor profile  
20 installed in a channel at SRER shows that the wetting front frequently reaches at least 30 cm  
21 depth. Furthermore, the  $f_{CRNS}$  approach provided estimates that can be compared to the watershed  
22 water balance since these are at a similar spatial scale (Table 5). Estimates of outflow (*O*) from  
23 the measurement depth and leakage (*L*) are higher when calculated with  $\theta_{SN}$ , consistent with



1 more rapid drying as compared to the CRNS method. On the other hand, the CRNS method  
2 results in higher values of the runoff ratio ( $Q/P$ ) than observed in the distributed sensor network,  
3 in particular for JER. This is likely due to the daily scale of the CRNS analysis, which limits the  
4 suitability of the runoff estimate for semiarid watersheds characterized by runoff responses  
5 lasting minutes to hours.

#### 6 7 **4.4. Utility of CRNS for Improving $ET$ Estimates**

8 Fig. 10 compares the relationships between the measured daily  $ET$  using the EC method  
9 and the spatially-averaged soil moisture values ( $\theta_{SN}$  and  $\theta_{CRNS}$ ) at the SRER and JER sites along  
10 with the piecewise linear regressions estimated using (8) and a nonlinear optimization approach.  
11 Following Vivoni et al. (2008a), regression parameters related to soil and vegetation conditions  
12 are presented in Table 6. For illustration purposes, bin-averages and standard deviations are also  
13 shown. Clearly, the piecewise linear relation is a suitable approach for capturing the  $ET$ - $\theta$   
14 observations, yielding a relatively low RMSE at the two sites. A lower RMSE for the relation  
15 using  $\theta_{CRNS}$  as compared to  $\theta_{SN}$  at SRER is attributed to its ability to detect a wider range of dry  
16 conditions and the improved match in the spatial scales of  $ET$  and  $\theta_{CRNS}$ , in an analogous fashion  
17 to the comparison between a single sensor and the distributed sensor network (Templeton et al.,  
18 2014). In addition, the CRNS method represents soil evaporation ( $E_w$ ) in a more realistic way as  
19 it discriminates differences in drier states, illustrated by the realistic gradual increase of bare soil  
20 evaporation with increasing soil water (Fig. 10). For  $ET$  and  $\theta_{SN}$ , the dry portions of the relations  
21 have too steep of a slope and do not represent well how bare soil evaporation changes with soil  
22 moisture. When comparing both sites through the  $ET$ - $\theta$  relation, the SRER has a larger  $E_w$  and  
23  $ET_{max}$  and lower  $\theta^*$ , as compared to JER, tested to be significantly different at the 95%  
24 confidence level using a bootstrap approach. Together, these parameters indicate that SRER has

1 a higher overall *ET*, consistent with higher extractions from the CRNS measurement depth due to  
2 the mesquite trees, extensive grass cover and higher soil evaporation.

### 3 4 **5. Summary and Conclusions**

5 In this study, we utilized distributed sensor networks to examine the CRNS soil moisture  
6 method at the small watershed scale in two semiarid ecosystems of the southwestern U.S. To our  
7 knowledge, this is the first study to compare CRNS measurements to two complementary  
8 approaches for obtaining spatially-averaged soil moisture at a commensurate scale: (1) a  
9 distributed set of sensor profiles weighted in the horizontal and vertical scales within each  
10 watershed, and (2) a watershed-averaged quantity obtained from closing the water balance. We  
11 highlighted a few novel advantages of the CRNS method revealed through the comparisons,  
12 including the ability to resolve the shallow soil moisture dynamics and to match the estimates  
13 obtained from closing the water balance for most rainfall events. In the distributed sensor  
14 comparisons, we found that the CRNS method overestimated soil moisture during the recession  
15 limbs of rainfall events, possibly due to landscape features such as nearby channels remaining  
16 wet. In the water balance comparisons, we identified that our assumption of no leakage beneath  
17  $z^*$  was not met during large rainfall events and the CRNS method was not able to capture all of  
18 the soil water present. We attribute this to rapid bypassing of the measurement depth due to soil  
19 and terrain characteristics. Due to this observed bypass flow, we suggest that future studies using  
20 the CRNS method include a few soil moisture sensor profiles below  $z^*$  to detect leakage events.

21 The CRNS soil moisture estimates were used in combination with the various  
22 measurement methods to explore the relative magnitudes of the water balance components at  
23 each site given the different precipitation amounts during the study period. The drier than  
24 average conditions in the mesquite savanna ecosystem at SRER lead to drier surface soils

1 incapable of supporting the measured evapotranspiration unless supplemented by plant water  
2 uptake from deeper soil layers. In contrast, wetter than average summer periods in the mixed  
3 shrubland at JER had wet surface soils that promoted leakage into the deeper vadose zone which  
4 was subsequently unavailable for runoff and evapotranspiration losses. Comparisons across  
5 different seasons also suggested that carryover of soil water from winter leakage toward deeper  
6 soil layers is consumed during the summer season by active plants. These novel inferences  
7 within the two ecosystems relied heavily on the application of the CRNS method and its limited  
8 measurement depth to discriminate between shallow and deeper vadose zone processes as well as  
9 on the direct measurement of the water balance components, in particular evapotranspiration. It  
10 is important to keep in mind, however, that the ability to resolve watershed-scale hydrological  
11 processes, such as the interaction between shallow and deep soil layers attributed to plant water  
12 uptake and leakage, depends to a large degree on the accuracy and representativeness of the  
13 distributed sensor network measurements and how their horizontal and vertical scales overlap  
14 with the CRNS measurement footprint. We expect these limitations to be especially critical in  
15 semiarid ecosystems with high spatial heterogeneity induced by vegetation and bare soil patches.

16         The collocation of a distributed sensor network within the CRNS measurement footprint  
17 also allowed us to examine important process-based relations that are often incorporated into  
18 hydrologic models or remote sensing analyses (e.g., Famiglietti and Wood, 1994; Famiglietti et  
19 al., 2008). The spatial variability of soil moisture is linked to the spatially-averaged conditions  
20 through predictable relations that do not vary significantly across the study sites. For higher  
21 mean soil moisture, we observed a nearly linear increase in spatial variability followed by an  
22 asymptotic behavior attributed to the seasonally-wet conditions during the North American  
23 monsoon. Based on these relations ( $k_1$  and  $k_2$ ), the spatial variability within a CRNS

1 measurement footprint can be approximated for other semiarid ecosystems in the region. In  
2 addition, combining fixed and mobile CRNS methods can establish landscape scale ( $10^2$  to  $10^3$   
3  $\text{km}^2$ ) soil moisture monitoring networks at grid sizes ( $\sim 1 \text{ km}^2$ ) comparable to land surface  
4 modeling (Franz et al., 2015). Similarly, intermediate scale soil moisture sensing can be linked  
5 effectively to daily evapotranspiration and used to obtain soil and vegetation parameters ( $E_w$ ,  
6  $ET_{max}$ ,  $\theta_h$ ,  $\theta_w$ , and  $\theta^*$ ) tailored to each ecosystem. In term of the  $ET$ - $\theta$  relation, the CRNS method  
7 has the potential to significantly improve land-atmosphere interaction studies since it possesses a  
8 measurement scale that is commensurate to the sampling area of the EC technique.

## 9 10 **Acknowledgements**

11 We thank Heye Bogena and three anonymous reviewers for their useful comments that  
12 helped to improve the manuscript. We also thank Mitch P. McClaran and Mark Heitlinger from  
13 the University of Arizona for help at the Santa Rita Experimental Range and John Anderson, Al  
14 Rango and other staff members at the USDA-ARS Jornada Experimental Range for their  
15 assistance. We thank funding from the U.S. Army Research Office (Grant 56059-EV-PCS) and  
16 the Jornada Long-Term Ecological Research project (National Science Foundation Grant DEB-  
17 1235828). We are also grateful to Nicole A. Pierini and Cody A. Anderson for help with field  
18 activities.

## 1 **References**

- 2 Alfieri, J.G., and Blanken, P.D.: How representative is a point? The spatial variability of surface  
3 energy fluxes across short distances in a sand-sagebrush ecosystem. *Journal of Arid*  
4 *Environments*, 87, 42-49, 2012.
- 5 Anderson, C.A.: Assessing land-atmosphere interactions through distributed footprint sampling  
6 at two eddy covariance towers in semiarid ecosystems of the southwestern U.S. *Masters of*  
7 *Science in Civil, Environmental and Sustainable Engineering*, Arizona State University, 243 pp.,  
8 2013.
- 9 Bartalis, Z., Wagner, W., Naeimi, V., Hasenauer, S., Scipal, K., Bonekamp, H., Figa, J., and  
10 Anderson, C.: Initial soil moisture retrievals from the METOP-A Advanced Scatterometer  
11 (ASCAT). *Geophysical Research Letters*, 34, L20401, 2007, doi: 10.1029/2007GL031088.
- 12 Bogena, H.R., Huisman, J.A., Baatz, R., Franssen, H.J.H., and Vereecken, H.: Accuracy of the  
13 cosmic-ray soil water content probe in humid forest ecosystems: The worst case scenario. *Water*  
14 *Resources Research*, 49(9), 5778-5791, 2013.
- 15 Browning, D.M., Franklin, J., Archer, S.R., Gillan, J.K., and Guertin, D.P.: Spatial patterns of  
16 grassland-shrubland state transitions: a 74-year record on grazed and protected areas. *Ecological*  
17 *Applications*, 24(6), 1421-1433, 2014.
- 18 Campbell, J.E.: Dielectric properties and influence of conductivity in soils at one to fifty  
19 Megahertz. *Soil Science Society of America Journal*, 54, 332-341, 1990.
- 20 Chen, F., Mitchell, K., Schaake, J., Xue, Y., Pan, H.-L., Koren, V., Duan, Q.Y., Ek, M., and  
21 Betts, A.: Modeling of land surface evaporation by four schemes and comparisons with FIFE  
22 observations. *Journal of Geophysical Research*, 101, 7251-7268, 1996.
- 23 Coopersmith, E.J., Cosh, M.H., and Daughtry, C.S.T.: Field-scale moisture estimates using  
24 COSMOS sensors: A validation study with temporary networks and Leaf-Area-Indices. *Journal*  
25 *of Hydrology*, 519, 637-643, 2014.
- 26 Dane, J.H., and Topp, C.G.: *Methods of soil analysis. Part 4. Physical methods. SSSA Book Ser.*  
27 *5. SSSA, Madison, WI, 2002.*
- 28 Desilets, D., and Zreda, M.: Spatial and temporal distribution of secondary cosmic-ray nucleon  
29 intensities and applications to in-situ cosmogenic dating. *Earth and Planetary Science Letters*,  
30 206, 21-42, 2003.
- 31 Desilets, D., and Zreda, M.: Footprint diameter for a cosmic-ray soil moisture probe: Theory and  
32 Monte Carlo simulations. *Water Resources Research*, 49, 3566-3575, 2013.

- 1 Desilets, D., Zreda, M., and Ferré, T.P.A.: Nature's neutron probe: Land surface hydrology at an  
2 elusive scale with cosmic rays. *Water Resources Research*, 46, W11505, 2010,  
3 doi:10.1029/2009WR008726.
- 4 Detto, M., Montaldo, N., Albertson, J.D., Mancini, M., and Katul, G.: Soil moisture and  
5 vegetation controls on evapotranspiration in a heterogeneous Mediterranean ecosystem on  
6 Sardinia, Italy. *Water Resources Research*, 42, W08419, 2006, doi:10.1029/2005WR004693.
- 7 Dugas, W.A., Hicks, R.A., and Gibbens, R.P.: Structure and function of C3 and C4 Chihuahuan  
8 Desert plant communities: Energy balance components. *Journal of Arid Environments*, 34, 63-  
9 79, 1996.
- 10 Eltahir, E.A.B.: A soil moisture rainfall feedback mechanism 1. Theory and observations. *Water*  
11 *Resources Research*, 34(4), 765-776, 1998.
- 12 Entekhabi, D.: Recent advances in land-atmosphere interaction research. *Reviews of Geophysics*,  
13 33(S1), 995-1004, 1995.
- 14 Entekhabi, D., Njoku, E.G., O'Neill, P. E., Kellogg, K.H., Crow, W.T., Edelstein, W.N., Entin, J.  
15 K., Goodman, S.D., Jackson, T.J., Johnson, J., Kimball, J., Piepmeier, J.R., Koster, R.D., Martin,  
16 N., McDonald, K.C., Moghaddam, M., Moran, S., Reichle, R., Shi, J.C., Spencer, M.W.,  
17 Thurman, S.W., Tsang, L., and Van Zyl, J.: The soil moisture active passive (SMAP) mission,  
18 *Proceedings of the IEEE*, 98, 704-716, 2010,
- 19 Falge, E., Baldocchi, D., Tenhunen, J., Aubinet, M., Bakwin, P., Berbigier, P., Bernhofer, C.,  
20 Burba, G., Clement, R., Davis, K.J., Elbers, J.A., Goldstein, A.H., Grelle, A., Granier, A.,  
21 Gudmundsson, J., Hollinger, D., Kowalski, A.S., Katul, G., Law, B.E., Malhi, Y., Meyers, T.,  
22 Monson, R.K., Munger, J.W., Oechel, W., Paw, K.T., Pilegaard, K., Rannik, U., Rebmann, C.,  
23 Suyker, A., Valentini, R., Wilson, K., and Wofsy, S.: Seasonality of ecosystem respiration and  
24 gross primary production as derived from FLUXNET measurements. *Agricultural and Forest*  
25 *Meteorology*, 113(1-4), 53-74, 2002.
- 26 Fernández, J.M., and Ceballos, A.: Temporal stability of soil moisture in a large-field experiment  
27 in Spain. *Soil Science Society of America Journal*, 67, 1647-1656, 2003.
- 28 Famiglietti, J.S., and Wood, E.F.: Multiscale modeling of spatially variable water and energy  
29 balance processes. *Water Resources Research*, 30, 3061-3078, 1994.
- 30 Famiglietti, J.S., Devereaux, J.A., Laymon, C.A., Tsegaye, T., Houser, P.R., Jackson, T.J.,  
31 Graham, S.T., Rodell, M., and van Oevelen, P.J.: Ground-based investigation of soil moisture  
32 variability within remote sensing footprints during the Southern Great Plains 1997(SGP97)  
33 Hydrology Experiment. *Water Resources Research*, 35, 1839-1851, 1999.

- 1 Famiglietti, J. S., Ryu, D., Berg, A.A., Rodell, M., and Jackson, T.J.: Field observations of soil  
2 moisture variability across scales. *Water Resources Research*, 44, W01423, 2008, doi:  
3 10.1029/2006WR005804.
- 4 Franz, T.E., Zreda, M., Ferré, T.P.A., Rosolem, R., Zweck, C., Stillman, S., Zeng, X., and  
5 Shuttleworth, W.J.: Measurement depth of the cosmic-ray soil moisture probe affected by  
6 hydrogen from various sources. *Water Resources Research*, 48, W08515, 2012a,  
7 doi:10.1029/2012WR011871.
- 8 Franz, T.E., Zreda, M., Rosolem, R., and Ferré, T.P.A.: Field validation of a cosmic-ray neutron  
9 sensor using a distributed sensor network. *Vadose Zone Journal*, 11(4), 2012b, doi:  
10 10.2136/vzj2012.0046.
- 11 Franz, T.E., Zreda, M., Rosolem, R., Hornbuckle, B.K., Irvin, S.L., Adams, H., Kolb, T.E.,  
12 Zweck, C., and Shuttleworth, W.J.: Ecosystem-scale measurements of biomass water using  
13 cosmic ray neutrons. *Geophysical Research Letters*, 40, 3929-3933, 2013a.
- 14 Franz, T.E., Zreda, M., Ferré, T.P.A., and Rosolem, R.: An assessment of the effect of horizontal  
15 soil moisture heterogeneity on the area-average measurement of cosmic-ray neutrons. *Water*  
16 *Resources Research*, 49, 6450-6458, 2013b.
- 17 Franz, T.E., Wang, T., Avery, W., Finkenbiner, C., and Brocca, L.: Combined analysis of soil  
18 moisture measurements from roving and fixed cosmic ray neutron probes for multiscale real-time  
19 monitoring. *Geophysical Research Letters*, 42, 2015, doi:10.1002/2015GL063963.
- 20 Gardner, W.H., and Kirkham, D.: Determination of soil moisture by neutron scattering. *Soil*  
21 *Science*, 73, 391-401, 1952.
- 22 Gibbens, R.P., and Beck, R.F.: Increase in number of dominant plants and dominance-classes on  
23 a grassland in the northern Chihuahuan Desert. *Journal of Range Management*, 40(2), 136-139,  
24 1987.
- 25 Gill, P.E., Murray, W., and Wright, M.H.: *Practical Optimization*. Academic Press, London, UK,  
26 pp. 402, 1981.
- 27 Glasstone, S., and M. C. Edlund: *Elements of Nuclear Reactor Theory*, 416 pp., Van Nostrand,  
28 New York, 1952.
- 29 Greacen, E.L.: *Soil Water Assessment by the Neutron Method*, CSIRO, Melbourne, Australia,  
30 148 pp., 1981.
- 31 Gutiérrez-Jurado, H.A., Vivoni, E.R., Cikoski, C., Harrison, J.B.J., Bras, R.L., and  
32 Istanbuluoglu, E.I.: On the observed ecohydrologic dynamics of a semiarid basin with aspect-  
33 delimited ecosystems. *Water Resources Research*, 49, 8263-8284, 2013.

- 1 Heitschmidt, R.K., Ansley, R.J., Dowhower, S.L., Jacoby, P.W., and Price, D.L.: Some  
2 observations from the excavation of honey mesquite root systems. *Journal of Range*  
3 *Management*, 41(3), 227-231, 1988.
- 4 Hsieh C.-I., Katul, G., and Chi, T.: An approximate analytical model for footprint estimation of  
5 scalar fluxes in thermally stratified atmospheric flows. *Advances in Water Resources*, 23, 765-  
6 772, 2000.
- 7 Huang, C., March, S.E., McClaran, M.P., and Archer, S.R.: Postfire stand structure in a semiarid  
8 savanna: cross-scale challenges estimating biomass. *Ecological Applications*, 17(7), 1899-1910,  
9 2007.
- 10 Huenneke, L.F., Clason, D., and Muldavin, E.: Spatial heterogeneity in Chihuahuan Desert  
11 vegetation: implications for sampling methods in semi-arid ecosystems. *Journal of Arid*  
12 *Environments*, 47, 257-270, 2001.
- 13 Ivanov, V.Y., Vivoni, E.R., Bras, R.L., and Entekhabi, D.: Catchment hydrologic response with  
14 a fully-distributed triangulated irregular network model. *Water Resources Research*, 40,  
15 W11102, 2004, doi: 10.1029/2004WR003218.
- 16 Kerr, Y.H., Waldteufel, P., Wigneron, J.P., Martinuzzi, J.M., Font, J., and Berger, M.: Soil  
17 moisture retrieval from space: The Soil Moisture and Ocean Salinity (SMOS) mission. *IEEE*  
18 *Transactions on Geoscience and Remote Sensing*, 39, 1729-1735, 2001.
- 19 Köhli, M., Schrön, M., Zreda, M., Schmidt, U., Dietrich, P., and Zacharias, S.: Footprint  
20 characteristics revised for field-scale soil moisture monitoring with cosmic-ray neutrons. *Water*  
21 *Resources Research*, 51, 5772-5790, 2015.
- 22 Kormann, R., and Meixner, F.X.: An analytical footprint model for non-neutral stratification.  
23 *Boundary Layer Meteorology*, 99, 207-224, 2001.
- 24 Kustas, W.P., Zhan, X., and Schmugge, T.J.: Combining optical and microwave remote sensing  
25 for mapping energy fluxes in a semiarid watershed. *Remote Sensing of Environment*, 64, 116-  
26 131, 1998.
- 27 Laio, F., Porporato, A., Ridolfi, L., and Rodríguez-Iturbe, I.: Plants in water-controlled  
28 ecosystems: active role in hydrologic processes and response to water stress II. Probabilistic soil  
29 moisture dynamics. *Advances in Water Resources*, 24, 707-723, 2001.
- 30 Lawrence, J.E., and Hornberger, G.M.: Soil moisture variability across climate zones.  
31 *Geophysical Research Letters*, 34, L20402, 2007, doi: 10.1029/2007GL031382.
- 32 Mascaro, G., and Vivoni, E.R.: Utility of coarse and downscaled soil moisture products at L-  
33 band for hydrologic modeling at the catchment scale. *Geophysical Research Letters*, 39, L10403,  
34 2012, doi: 10.1029/2012GL051809.



- 1 Mascaro, G., Vivoni, E.R., and Deidda, R.: Soil moisture downscaling across climate regions and  
2 its emergent properties. *Journal of Geophysical Research*, 116, D22114, 2011, doi:  
3 10.1029/2011JD016231.
- 4 McJannet, D., Franz, T.E., Hawdon, A., Boadle, D., Baker, B., Almeida, A., Silberstein, R.,  
5 Lambert, T., and Desilets, D.: Field testing of the universal calibration function for determination  
6 of soil moisture with cosmic-ray neutrons. *Water Resources Research*, 50(6), 5235-5248, 2014.
- 7 Moran, M.S., Hymer, D.C., Qi, J.G., and Sano, E.E.: Soil moisture evaluation using multi-  
8 temporal synthetic aperture radar (SAR) in semiarid rangeland. *Agricultural and Forest*  
9 *Meteorology*, 105, 69-80, 2000.
- 10 Narayan, U., and Lakshmi, V.: Characterizing subpixel variability of low resolution radiometer  
11 derived soil moisture using high resolution radar data. *Water Resources Research*, 44, W06425,  
12 2008, doi:10.1029/2006WR005817.
- 13 Pierini, N.P., Vivoni, E.R., Robles-Morua, A., Scott, R.L., and Nearing, M.A.: Using  
14 observations and a distributed hydrologic model to explore runoff thresholds linked with  
15 mesquite encroachment in the Sonoran Desert. *Water Resources Research*, 50, 2014, doi:  
16 10.1002/2014WR015781.
- 17 Pierini, N.A.: Exploring the ecohydrological impacts of woody plant encroachment in paired  
18 watersheds of the Sonoran Desert, Arizona. Master of Science Thesis in Civil, Environmental  
19 and Sustainable Engineering, Arizona State University, Tempe, AZ, 160 pp., 2013.
- 20 Polyakov, V.O., Nearing, M.A., Nichols, M.H., Scott, R.L., Stone, J.J., and McClaran, M.P.:  
21 Long-term runoff and sediment yields from small semiarid watersheds in southern Arizona.  
22 *Water Resources Research*, 46, W09512, 2010, 10.1029/2009WR009001.
- 23 Potts, D.L., Scott, R.S., Bayram, S., and Carbonara, J.: Woody plants modulate the temporal  
24 dynamics of soil moisture in a semi-arid mesquite savanna. *Ecohydrology*, 3, 20-27, 2010.
- 25 Qu, W., Boga, H.R., Huisman, J.A., Vanderborght, J., Schuh, M., Priesack, E., and Vereecken,  
26 H.: Predicting sub-grid variability of soil water content from basic soil information. *Geophysical*  
27 *Research Letters*, 42, 789-796, 2015.
- 28 Rodríguez-Iturbe, I., and Porporato, A.: *Ecohydrology of Water-Controlled Ecosystems*, 442 pp.,  
29 Cambridge Univ. Press, Cambridge, U.K., 2004.
- 30 Rosolem, R., Shuttleworth, W.J., Zreda, M., Franz, T., Zeng, X., and Kurc, S.A.: The effect of  
31 atmospheric water vapor on neutron count in the cosmic-ray soil moisture observing system.  
32 *Journal of Hydrometeorology*, 14, 1659-1671, 2013.

1 Rosolem, R., Hoar, T., Arellano, A., Anderson, J.L., Shuttleworth, W.J., Zeng, X., and Franz,  
2 T.E.: Translating aboveground cosmic-ray neutron intensity to high-frequency soil moisture  
3 profiles at sub-kilometer scale. *Hydrology and Earth System Sciences*, 18, 4363-4379, 2014.

4 Scott, R.L., Shuttleworth, W.J., Keefer, T.O., and Warrick, A.W.: Modeling multi-year  
5 observations of soil moisture recharge in the semiarid American Southwest. *Water Resources*  
6 *Research*, 36(8), 2233-2247, 2000.

7 Scott, R.L.: Using watershed water balance to evaluate the accuracy of eddy covariance  
8 evaporation measurements for three semiarid ecosystems. *Agricultural and Forest Meteorology*,  
9 150, 219-225, 2010.

10 Scott, R.L., Edwards, E.A., Shuttleworth, W.J., Huxman, T.E., Watts, C., and Goodrich, D.C.:  
11 Interannual and seasonal variation in fluxes of water and carbon dioxide from a riparian  
12 woodland ecosystem. *Agricultural and Forest Meteorology*, 122, 65-84, 2004.

13 Scott, R.L., Huxman, T.E., Williams, D.G., and Goodrich, D.C.: Ecohydrological impacts of  
14 woody-plant encroachment: seasonal patterns of water and carbon dioxide exchange within a  
15 semiarid riparian environment. *Global Change Biology*, 12, 311-324, 2006.

16 Scott, R.L., Cable, W.L., and Hultine, K.R.: The ecohydrologic significance of hydraulic  
17 redistribution in a semiarid savanna. *Water Resources Research*, 44, W02440, 2008, doi:  
18 10.1029/2007WR006149.

19 Seyfried, M.S., Grant, L.E., Du, E., and Humes, K.: Dielectric loss and calibration of the Hydra  
20 probe soil water sensor. *Vadose Zone Journal*, 4, 1070-1079, 2005.

21 Shuttleworth, W.J., Rosolem, R., Zreda, M., and Franz, T.E.: The COsmic-ray Soil Moisture  
22 Interaction Code (COSMIC) for use in data assimilation. *Hydrology and Earth System Sciences*,  
23 17, 3205-3217, 2013.

24 Small, E.E., and Kurc, S.A.: Tight coupling between soil moisture and the surface radiation  
25 budget in semiarid environments: Implications for land-atmosphere interactions. *Water*  
26 *Resources Research*, 39(10), 1278, 2003, doi: 10.1029/2002WR00129.

27 Smith, R.E., Chery, D.L., Renard, K.G., and Gwinn, W.R.: Supercritical flow flumes for  
28 measuring sediment-laden flow, *Tech. Bull. 1655*, 70 pp., U.S. Gov. Print. Off., Washington, D.  
29 C., 1981.

30 Snyder, K.A., and Williams, D.G.: Defoliation alters water uptake by deep and shallow roots of  
31 *Prosopis velutina* (velvet mesquite). *Functional Ecology*, 17, 363-374, 2003.

32 Stevens Water Monitoring System: Comprehensive Stevens Hydra Probe User Manual, 62 pp.,  
33 1998.

- 1 Stillman, S., Ninneman, J., Zeng, X., Franz, T., Scott, R.L., Shuttleworth, W.J., and Cummins,  
2 K.: Summer soil moisture spatiotemporal variability in southeastern Arizona. *Journal of*  
3 *Hydrometeorology*, 15(4), 1473-1485, 2014.
- 4 Templeton, R.C., Vivoni, E.R., Méndez-Barroso, L.A., Pierini, N.A., Anderson, C.A., Rango, A.,  
5 Laliberte, A.S., and Scott, R.L.: High-resolution characterization of a semiarid watershed:  
6 Implications on evapotranspiration estimates. *Journal of Hydrology*, 509, 306-319, 2014.
- 7 Throop, H.L., Archer, S.R., Monger, H.C., and Waltman, S.: When bulk density methods matter:  
8 Implications for estimating soil organic carbon pools in rocky soils. *Journal of Arid*  
9 *Environments*, 77, 66-71, 2011.
- 10 Topp, G.C., Davis, J.L., and Annan, A.P.: Electromagnetic determination of soil water content:  
11 Measurements in coaxial transmission lines. *Water Resources Research*, 16(3), 574-582, 1980.
- 12 Turnbull, L., Parsons, A.J., and Wainwright, J.: Runoff responses to long-term rainfall variability  
13 in creosotebush-dominated shrubland. *Journal of Arid Environments*, 91, 88-94, 2013.
- 14 Vereecken, H., Huisman, J.A., Pachepsky, Y., Montzka, C., van der Kruk, J., Bogaen, H.,  
15 Weihermuller, L., Herbst, M., Martinez, G., and Vanderborght, J.: On the spatio-temporal  
16 dynamics of soil moisture at the field scale, *Journal of Hydrology*, 516, 76-96, 2014.
- 17 Vivoni, E.R., Moreno, H.A., Mascaro, G., Rodríguez, J.C., Watts, C.J., Garatuza-Payán, J., and  
18 Scott, R.L.: Observed relation between evapotranspiration and soil moisture in the North  
19 American monsoon region. *Geophysical Research Letters*, 35, L22403, 2008a, doi:  
20 10.1029/2008GL036001.
- 21 Vivoni, E.R., Gebremichael, M., Watts, C.J., Bindlish, R., and Jackson, T.J.: Comparison of  
22 ground-based and remotely-sensed surface soil moisture estimates over complex terrain during  
23 SMEX04. *Remote Sensing of Environment*, 112(2), 314-325, 2008b.
- 24 Vivoni, E.R.: Spatial patterns, processes and predictions in ecohydrology: Integrating  
25 technologies to meet the challenge. *Ecohydrology*, 5(3), 235-241, 2012.
- 26 Vivoni, E.R., Watts, C.J., Rodriguez, J.C., Garatuza-Payan, J., Mendez-Barroso, L.A., and Saiz-  
27 Hernandez, J.A.: Improved land-atmosphere relations through distributed footprint sampling in a  
28 subtropical scrubland during the North American monsoon. *Journal of Arid Environments*, 74(5),  
29 579-584, 2010.
- 30 Vivoni, E.R., Rango, A., Anderson, C.A., Pierini, N.A., Schreiner-McGraw, A.P., Saripalli, S.,  
31 and Laliberte, A.S.: Ecohydrology with unmanned aerial vehicles. *Ecosphere* 5(10), art 130,  
32 2014, <http://dx.doi.org/10.1890/ES14-00217.1>.
- 33 Western, A.W., Grayson, R.B., and Blöchl, G.: Scaling of soil moisture: A hydrologic  
34 perspective. *Annual Review of Earth and Planetary Sciences*, 30, 149-180, 2002.

1 Wilson, K., Goldstein, A., Falge, E., Aubinet, M., Baldocchi, D., Berbigier, P., Bernhofer, C.,  
2 Ceulemans, R., Dolman, H., Field, C., Grelle, A., Ibrom, A., Law, B.E., Kowalski, A., Meyers,  
3 T., Moncrieff, J., Monson, R., Oechel, W., Tenhunen, J., Valentini, R., and Verma, S.: Energy  
4 balance closure at FLUXNET sites. *Agricultural and Forest Meteorology*, 113, 223-243, 2002.

5 Zhu, Z., Tan, L., Gao, S., and Jiao, Q.: Observation on soil moisture of irrigation cropland by  
6 cosmic-ray probe. *IEEE Geoscience and Remote Sensing Letters*, 12(3), 2015, doi:  
7 10.1109/LGRS.2014.2346784.

8 Zreda, M., Desilets, D., Ferre, T.P.A., and Scott, R.L.: Measuring soil moisture content non-  
9 invasively at intermediate spatial scale using cosmic-ray neutrons. *Geophysical Research Letters*,  
10 35, L21402, 2008, doi: 10.1029/2008GL035655.

11 Zreda, M., Shuttleworth, W.J., Zeng, X., Zweck, C., Desilets, D., Franz, T., and Rosolem, R.:  
12 COSMOS: the Cosmic-ray Soil Moisture Observing System. *Hydrology and Earth System  
13 Sciences*, 16, 4079-4099, 2012.

14

## 1 **Figure Captions**

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

4  
5 **Fig. 2:** Vegetation classification for (a) SRER and (b) JER derived from aerial image analyses  
6 along with sensor locations and the 50% contributing areas of the CRNS and EC footprints.

7  
8 **Fig. 3:** Hourly precipitation, streamflow and evapotranspiration at the (a) SRER and (b) JER  
9 sites during the study period (March 2013 to September 2014). Gaps in *ET* data indicate periods  
10 of EC tower malfunction due to equipment failures, data collection problems or vandalism.  
11 Vertical dashed lines indicate the seasonal definitions and their corresponding total precipitation.

12  
13 **Fig. 4:** Comparison of the spatially-averaged, hourly soil moisture ( $\text{m}^3/\text{m}^3$ ) from CRNS method  
14 ( $\theta_{CRNS}$ , black lines) and distributed sensor network ( $\theta_{SN}$ , gray lines) at (a) SRER and (b) JER,  
15 along with spatially-averaged, hourly precipitation during March 1, 2013 to September 30, 2014.  
16 Vertical dashed lines indicate the seasonal definitions and their corresponding seasonally-  
17 averaged  $\theta_{CRNS}$  and  $\theta_{SN}$  in  $\text{m}^3/\text{m}^3$ . Also shown are the time-varying measurement depths ( $z^*$ ).

18  
19 **Fig. 5:** Scatterplots of the spatially-averaged, hourly soil moisture ( $\text{m}^3/\text{m}^3$ ) from CRNS method  
20 ( $\theta_{CRNS}$ ) and distributed sensor network ( $\theta_{SN}$ ) at (a) SRER and (b) JER. The SEE and the number  
21 of hourly samples (*N*) are shown for each site. Bin averages and  $\pm 1$  standard deviation are shown  
22 (circles and error bars) for bin widths of  $0.025 \text{ m}^3/\text{m}^3$ .

23  
24 **Fig. 6:** Soil moisture spatial variability as a function of the spatially-averaged distributed sensor  
25 network ( $\theta_{SN}$ , top) and the CRNS method ( $\theta_{CRNS}$ , bottom) for (a, c) SRER and (b, d) JER. Bin  
26 averages and  $\pm 1$  standard deviation are shown (circles and error bars) for bin widths of  $0.015$

1  $\text{m}^3/\text{m}^3$  at SRER and  $0.025 \text{ m}^3/\text{m}^3$  at JER. Regressions for the relations of  $\sigma$  with  $\langle\theta\rangle$  are valid  
2 for the entire dataset.

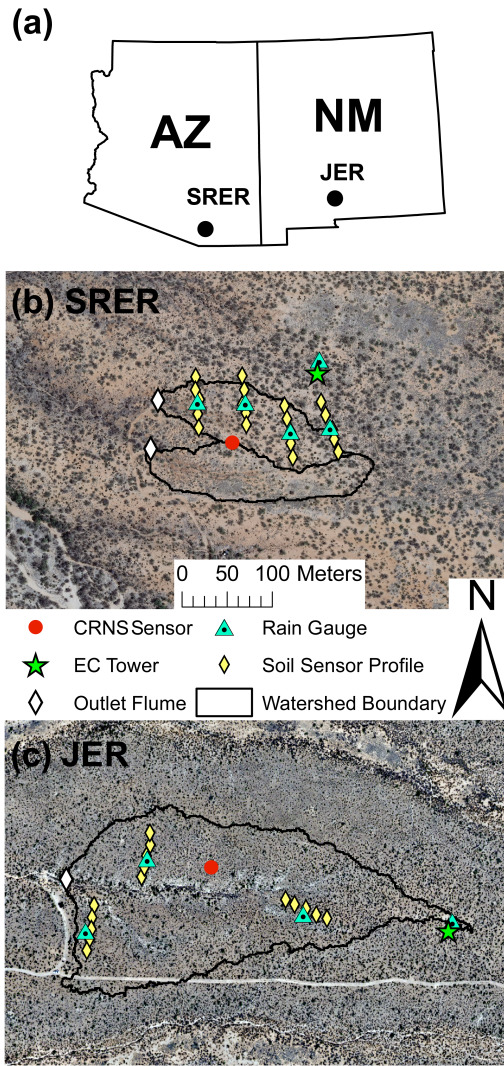
3  
4 **Fig. 7:** Scatterplots of the spatially-averaged change in soil moisture ( $\text{m}^3/\text{m}^3$ ) derived from  
5 CRNS method ( $\Delta\theta_{CRNS}$ ) and the application of the water balance ( $\Delta\theta_{WB}$ ) at (a) SRER and (b)  
6 JER. The SEE and the number of event samples (N)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

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

12  
13 **Fig. 9:** Comparison of cumulative  $f_{CRNS}$  and measured water balance fluxes ( $P$  and  $ET$ ) during  
14 study period. CRNS estimates of infiltration ( $I$ ), outflow ( $O$ ) and leakage ( $L$ ) are either depicted  
15 as cumulative fluxes ( $O = ET + L$ ) or as total amounts during the study period ( $I$  and  $L$ ) as arrows  
16 in the soil water balance box of depth  $z^*$ . Shaded regions indicate the summer seasons (July-  
17 September). The horizontal line represents  $f_{CRNS} = 0$ .

18  
19 **Fig. 10:** Evapotranspiration relation with the spatially-averaged distributed sensor network ( $\theta_{SN}$ ,  
20 top) and the CRNS method ( $\theta_{CRNS}$ , bottom) for (a, c) SRER and (b, d) JER. Bin averages and  $\pm 1$   
21 standard deviation are shown (circles and error bars) for bin widths of  $0.015 \text{ m}^3/\text{m}^3$  at SRER and  
22  $0.025 \text{ m}^3/\text{m}^3$  at JER. Regressions for the relations of  $ET$  with  $\langle\theta\rangle$  are valid for the entire dataset.

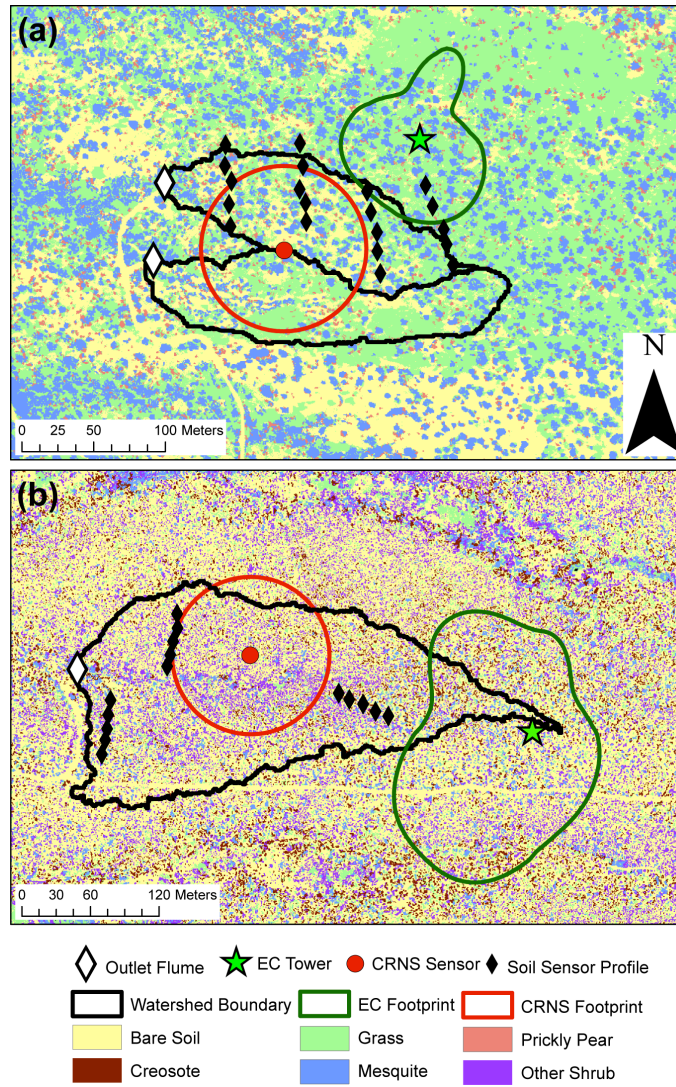
23



1  
 2  
 3  
 4  
 5  
 6  
 7  
 8  
 9  
 10  
 11  
 12  
 13  
 14  
 15  
 16

**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.

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

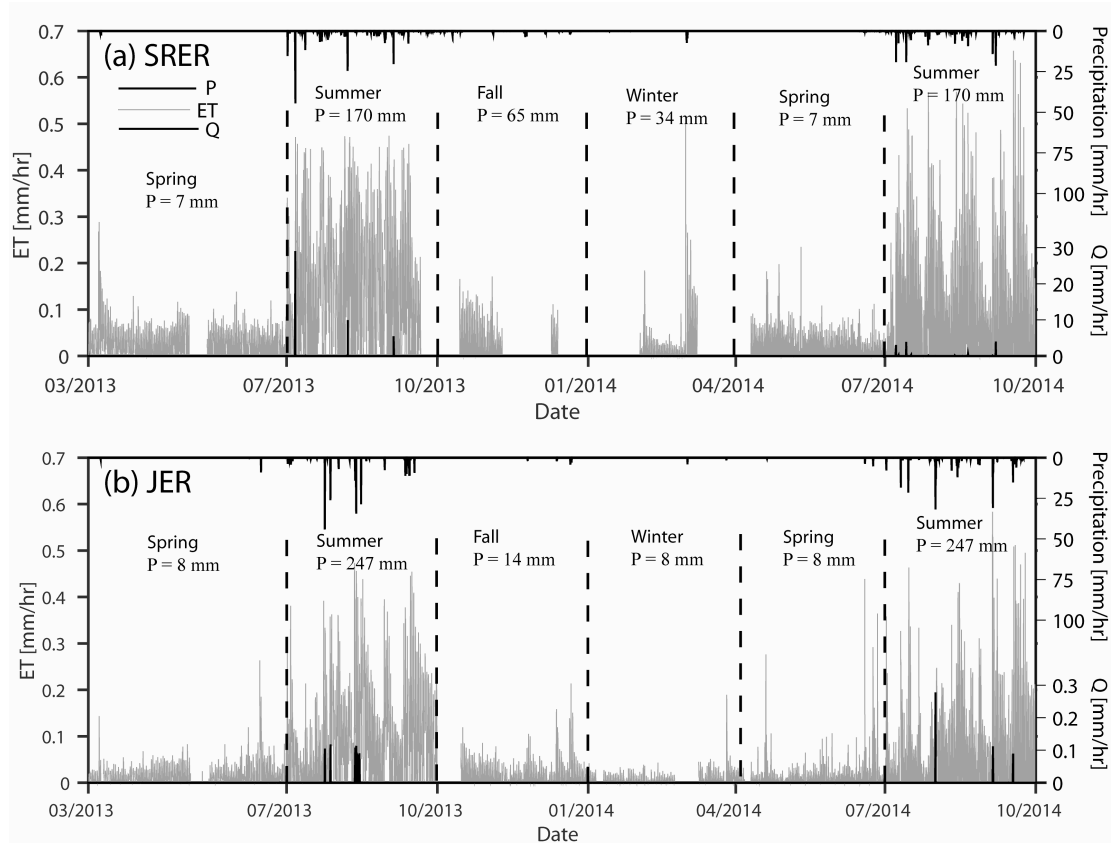


**Fig. 2:** Vegetation classification for (a) SRER and (b) JER derived from aerial image analyses along with sensor locations and the 50% contributing areas of the CRNS and EC footprints.

1  
2  
3  
4  
5  
6  
7  
8  
9  
10  
11  
12  
13  
14  
15  
16  
17  
18

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

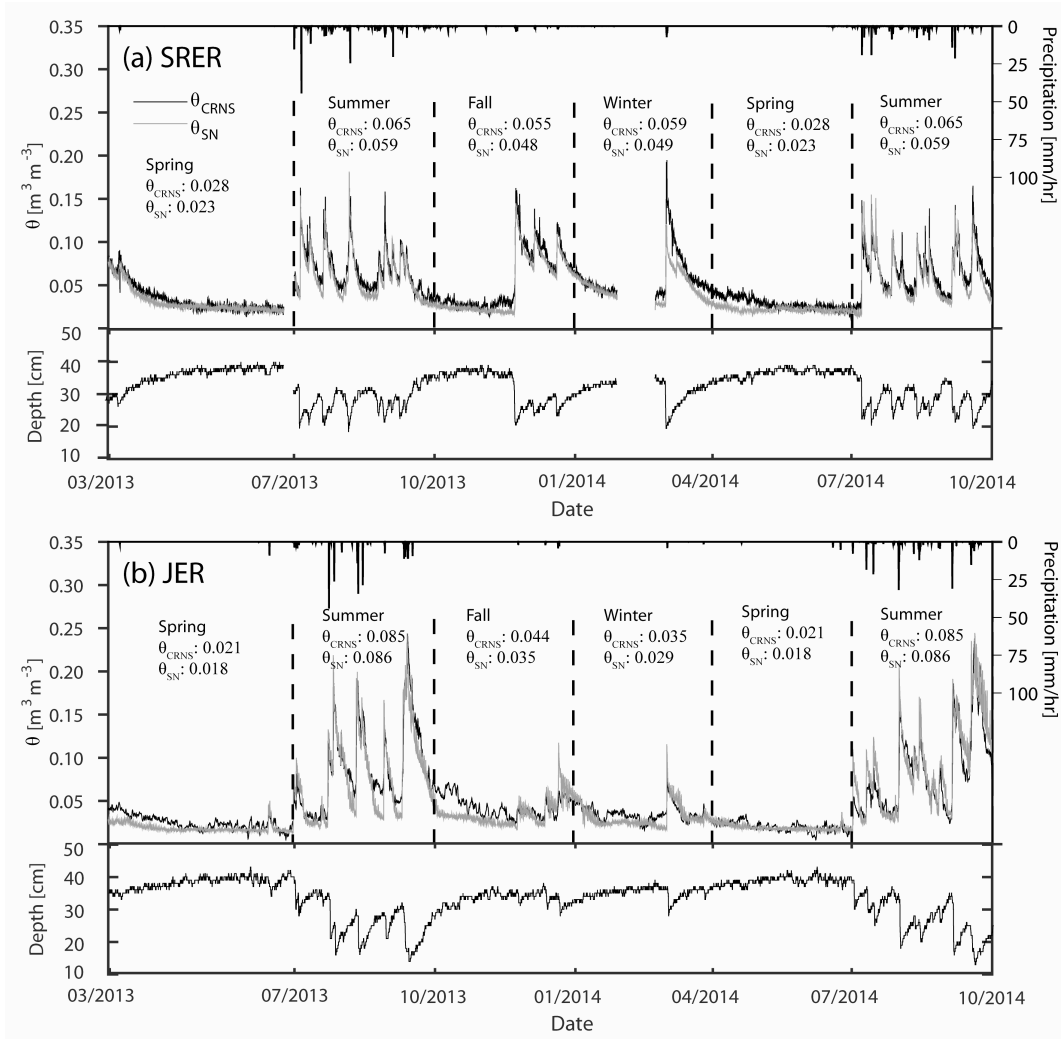




1  
2  
3  
4  
5  
6  
7  
8  
9  
10  
11  
12  
13  
14  
15  
16  
17  
18  
19  
20  
21  
22  
23  
24

**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.

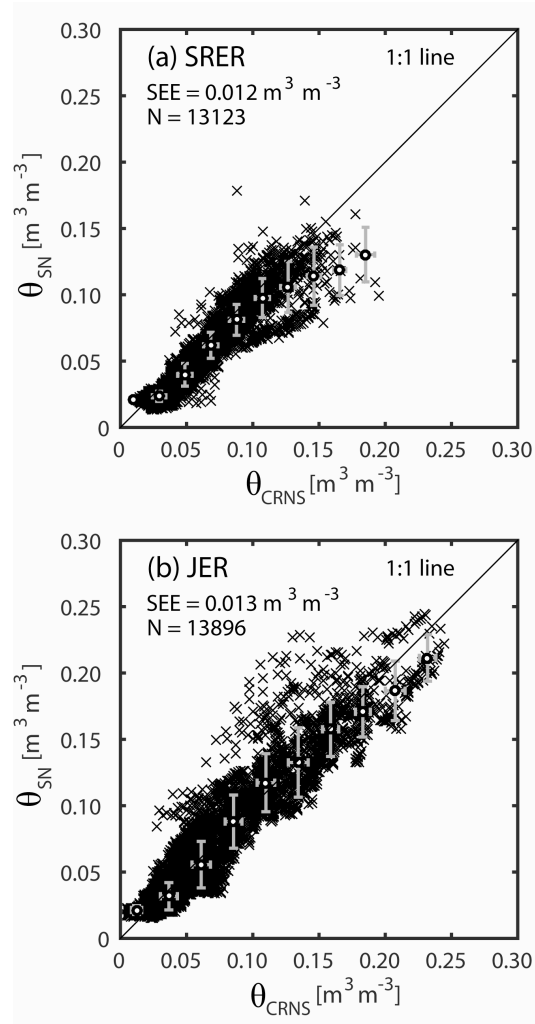
(Schreiner-McGraw et al., 2015, Fig. 3)



1  
2  
3  
4  
5  
6  
7  
8  
9  
10  
11  
12  
13  
14  
15  
16  
17  
18  
19  
20

**Fig. 4:** Comparison of the spatially-averaged, hourly soil moisture ( $\text{m}^3/\text{m}^3$ ) from CRNS method ( $\theta_{\text{CRNS}}$ , black lines) and distributed sensor network ( $\theta_{\text{SN}}$ , 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  $\theta_{\text{CRNS}}$  and  $\theta_{\text{SN}}$  in  $\text{m}^3/\text{m}^3$ . Also shown are the time-varying measurement depths ( $z^*$ ).

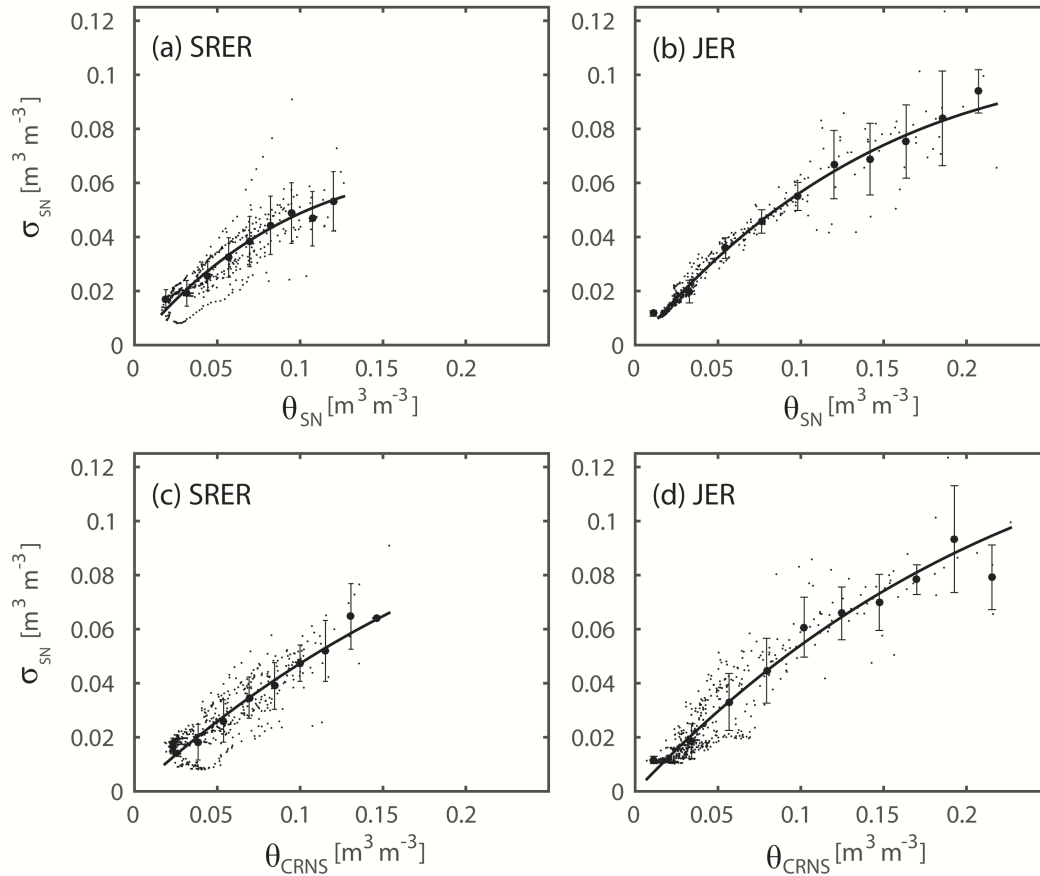
(Schreiner-McGraw et al., 2015, Fig. 4)



1  
 2  
 3  
 4  
 5  
 6  
 7  
 8  
 9  
 10  
 11  
 12  
 13  
 14  
 15  
 16  
 17  
 18  
 19

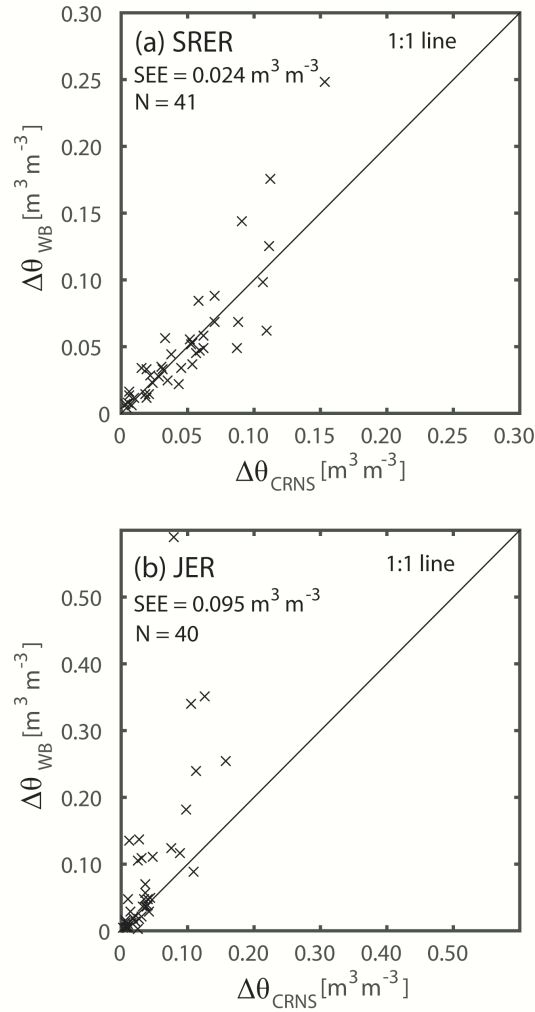
**Fig. 5:** Scatterplots of the spatially-averaged, hourly soil moisture ( $\text{m}^3/\text{m}^3$ ) from CRNS method ( $\theta_{CRNS}$ ) and distributed sensor network ( $\theta_{SN}$ ) at (a) SRER and (b) JER. The SEE and the number of hourly samples (N) are shown for each site. Bin averages and  $\pm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

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



1  
2  
3  
4  
5 **Fig. 6:** Soil moisture spatial variability as a function of the spatially-averaged distributed sensor  
6 network ( $\theta_{SN}$ , top) and the CRNS method ( $\theta_{CRNS}$ , bottom) for (a, c) SRER and (b, d) JER. Bin  
7 averages and  $\pm 1$  standard deviation are shown (circles and error bars) for bin widths of 0.015  
8  $m^3/m^3$  at SRER and 0.025  $m^3/m^3$  at JER. Regressions for the relations of  $\sigma$  with  $\langle \theta \rangle$   
9 are valid for the entire dataset.

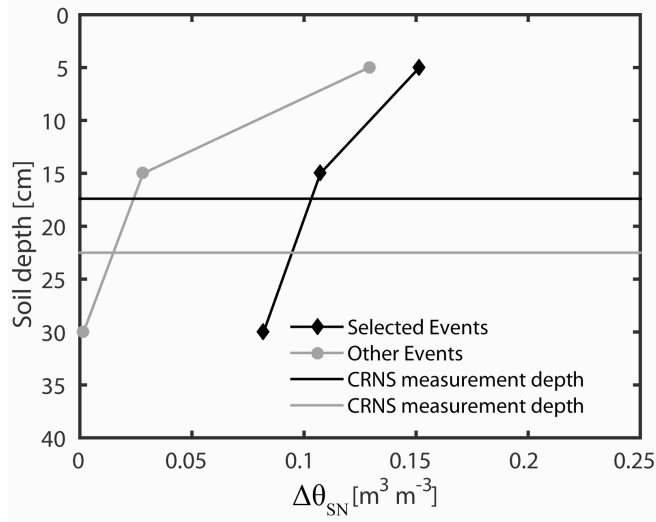
10  
11  
12  
13  
14  
15  
16  
17  
18  
19  
20  
21  
22  
23 **(Schreiner-McGraw et al., 2015, Fig. 6)**



**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.

1  
2  
3  
4  
5  
6  
7  
8  
9  
10  
11  
12  
13  
14  
15  
16  
17  
18  
19  
20

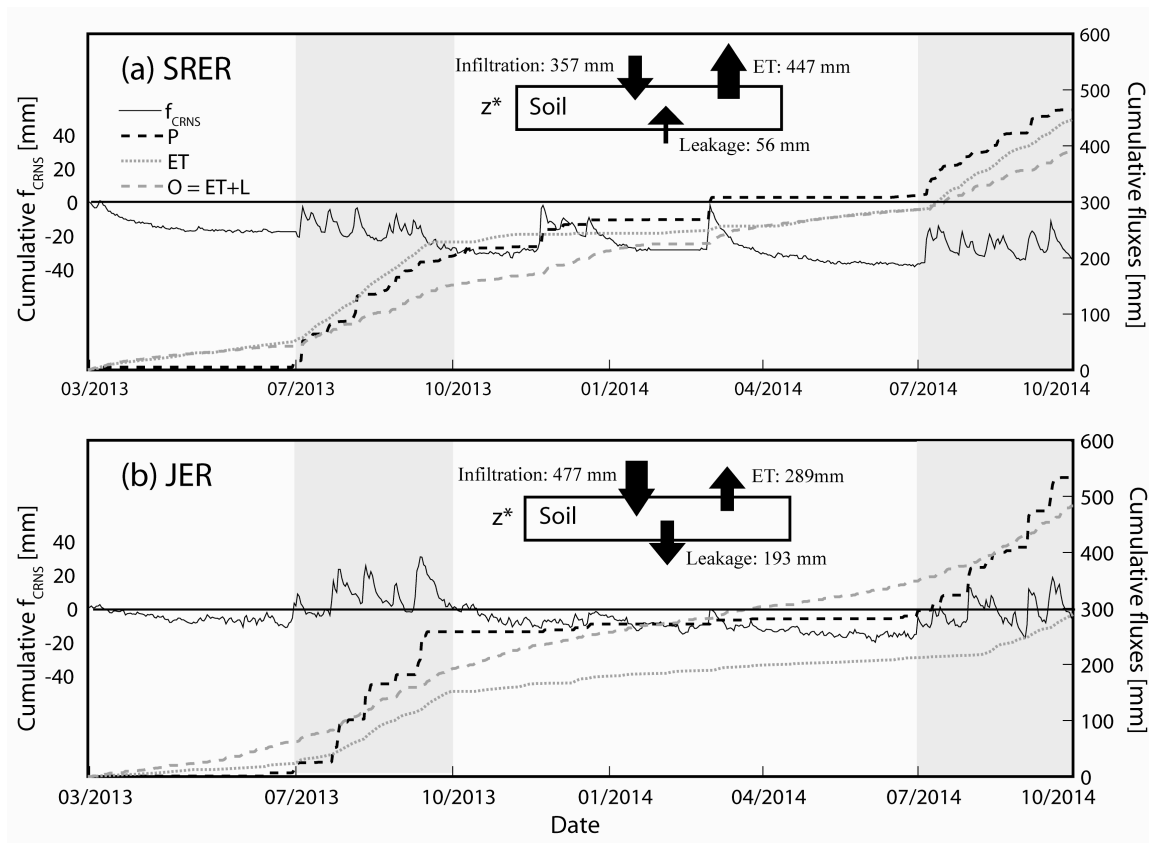
(Schreiner-McGraw et al., 2015, Fig. 7)



**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).

1  
2  
3  
4  
5  
6  
7  
8  
9  
10  
11  
12  
13  
14  
15  
16  
17  
18  
19  
20  
21  
22  
23  
24  
25  
26  
27  
28  
29  
30  
31  
32  
33  
34

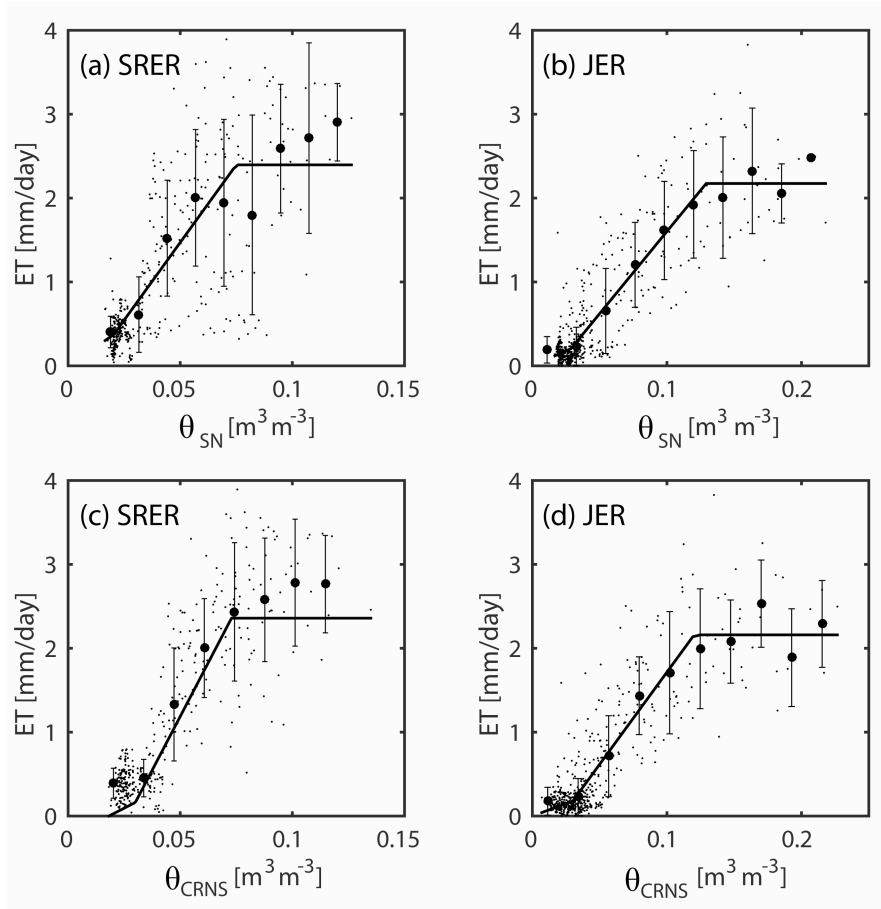
(Schreiner-McGraw et al., 2015, Fig. 8)



1  
2  
3  
4  
5  
6  
7  
8  
9  
10  
11  
12  
13  
14  
15  
16  
17  
18  
19  
20  
21  
22  
23  
24  
25

**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)



1  
2  
3  
4  
5  
6  
7  
8  
9  
10  
11  
12  
13  
14  
15  
16  
17  
18  
19  
20  
21  
22

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

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



## 1 **Table Captions**

2 **Table 1:** Watershed and precipitation characteristics at the SRER and JER sites. Precipitation  
3 values are long-term averages (1923-2014 at SRER and 1915-2006 at JER) for annual and  
4 seasonal quantities, defined as fall (October-December), winter (January-March), spring (April-  
5 June) and summer (July-September). Note that individual vegetation species have been  
6 generalized into three functional types.

7  
8 **Table 2:** Energy balance closure at SRER and JER using 30-min net radiation ( $R_n$ ), ground ( $G$ ),  
9 latent ( $\lambda E$ ) and sensible ( $H$ ) heat fluxes. The parameters  $m$  and  $b$  are the slope and intercept in the  
10 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  
11 a measure of how much available energy is accounted for in the turbulent fluxes.

12  
13 **Table 3:** Soil properties at SRER and JER. Soil moisture values correspond to conditions during  
14 the CRNS calibration dates (February 13, 2013 at SRER and February 10, 2013 at JER) for the  
15 gravimetric sampling at 18 locations with six depths ( $\theta_G$ ), CRNS ( $\theta_{CRNS}$ ) and the sensor network  
16 ( $\theta_{SN}$ ), each expressed as volumetric soil moisture using the soil bulk density ( $\rho_b$ ) and soil  
17 porosity ( $\phi$ ) of the samples. Mean values of  $\theta_G$ ,  $\rho_b$  and  $\phi$  are shown along with the  $\pm 1$  standard  
18 deviations. Particle size distributions were obtained from soil auger sampling of the top 45 cm at  
19 20 locations at each site (Anderson, 2013). Mean values of percent clay, silt, sand and gravel are  
20 shown along with the  $\pm 1$  standard deviations.

21  
22 **Table 4:** Statistical comparisons of CRNS method with distributed sensor network and water  
23 balance estimates based on the Standard Error of Estimates (SEE), Root Mean Square Error  
24 (RMSE), Bias (B), and Correlation Coefficient (CC), described in Vivoni et al. (2008b). Values  
25 in parentheses for JER indicate metrics when large rainfall events are excluded.

1  
2 **Table 5:** Total water flux estimates from daily CRNS soil water balance method ( $f_{CRNS}$ ) and daily  
3 sensor measurements during study period at the SRER and JER sites.  $P$  is from rain gauge  
4 measurements in both cases.  $L$  in CRNS is computed as  $O - ET$  where  $ET$  is from EC method,  
5 while  $L$  in sensor estimates is calculated from solving the water balance.

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

1

| Characteristic (unit)            | Value     | SRER   | JER    |
|----------------------------------|-----------|--------|--------|
| Watershed area (m <sup>2</sup> ) |           | 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    |

2

3

4

5

6

7

8

9

10

11

12

13

14

15

16

17

18

19

20

**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). Note that individual vegetation species have been generalized into three functional types.

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

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                                      |

2

3

4

5

6

7

8

9

**Table 2:** Energy balance closure at SRER and JER using 30-min net radiation ( $R_n$ ), ground ( $G$ ), latent ( $\lambda E$ ) 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.

10

11

12

13

14

15

16

17

18

19

20

21

22

23

24

25

26

27

28

29

30

31

32

33

34

35

36

37

38

39

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

| Property (unit)                                   | SRER          | JER           |
|---|---------------|---------------|
| <i>Soil Moisture Calibration</i>                  |               |               |
| $\theta_G$ (m <sup>3</sup> /m <sup>3</sup> )      | 0.114 ± 0.023 | 0.056 ± 0.013 |
| $\theta_{CRNS}$ (m <sup>3</sup> /m <sup>3</sup> ) | 0.114         | 0.056         |
| $\theta_{SN}$ (m <sup>3</sup> /m <sup>3</sup> )   | 0.105         | 0.016         |
| $\rho_b$ (g/cm <sup>3</sup> )                     | 1.54 ± 0.18   | 1.30 ± 0.15   |
| $\phi$ (m <sup>3</sup> /m <sup>3</sup> )          | 0.42 ± 0.07   | 0.51 ± 0.06   |
| <i>Particle Size Distribution</i>                 |               |               |
| 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 % |

1  
2  
3  
4  
5  
6  
7  
8  
9  
10  
11  
12  
13  
14  
15  
16  
17  
18  
19  
20  
21  
22  
23  
24  
25  
26  
27  
28  
29  
30

**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 ( $\theta_G$ ), CRNS ( $\theta_{CRNS}$ ) and the sensor network ( $\theta_{SN}$ ), each expressed as volumetric soil moisture using the soil bulk density ( $\rho_b$ ) and soil porosity ( $\phi$ ) of the samples. Mean values of  $\theta_G$ ,  $\rho_b$  and  $\phi$  are shown along with the  $\pm 1$  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  $\pm 1$  standard deviations.

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

1

| Metric (unit)                                    | SRER  | JER           |
|--|-------|---------------|
| $\theta_{CRNS}$ versus $\theta_{SN}$             |       |               |
| RMSE (m <sup>3</sup> /m <sup>3</sup> )           | 0.009 | 0.013         |
| CC   | 0.949 | 0.946         |
| B  | 1.117 | 1.019         |
| SEE (m <sup>3</sup> /m <sup>3</sup> )            | 0.012 | 0.013         |
| $\Delta\theta_{CRNS}$ versus $\Delta\theta_{WB}$ |       |               |
| RMSE (m <sup>3</sup> /m <sup>3</sup> )           | 0.001 | 0.082 (0.019) |
| CC   | 0.949 | 0.940 (0.945) |
| B  | 0.936 | 0.543 (0.903) |
| SEE (m <sup>3</sup> /m <sup>3</sup> )            | 0.024 | 0.095 (0.020) |

2

3

4

5

6

7

8

9

**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.

10

11

12

13

14

15

16

17

18

19

20

21

22

23

24

25

26

27

28

29

30

31

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

1

| Water Flux                            | SRER | JER  |
|---------------------------------------|------|------|
| <i>CRNS Estimates</i>                 |      |      |
| 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 |
| <i>Sensor Measurements</i>            |      |      |
| 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 |
| Streamflow ( $Q$ , mm)                | 64   | 5    |
| Runoff ratio ( $Q/P$ )                | 0.14 | 0.01 |

2

3

4

5

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

10

11

12

13

14

15

16

17

18

19

20

21

22

23

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

| Site        | Relation             | $ET_{max}$<br>(mm/day) | $E_w$<br>(mm/day) | $\theta_w$<br>(m <sup>3</sup> /m <sup>3</sup> ) | $\theta^*$<br>(m <sup>3</sup> /m <sup>3</sup> ) | RMSE<br>(mm/day) |
|-------------|----------------------|------------------------|-------------------|---|---|------------------|
| <b>SRER</b> | $ET - \theta_{SN}$   | 2.61                   | 0.41              | 0.03  | 0.07  | 1.15             |
|             | $ET - \theta_{CRNS}$ | 2.40                   | 0.36              | 0.02  | 0.08  | 0.55             |
| <b>JER</b>  | $ET - \theta_{SN}$   | 2.16                   | 0.18              | 0.03  | 0.12  | 0.34             |
|             | $ET - \theta_{CRNS}$ | 2.17                   | 0.21              | 0.03  | 0.13  | 0.34             |

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

1  
2  
3  
4  
5  
6  
7  
8  
9  
10  
11  
12  
13  
14  
15  
16  
17  
18  
19  
20  
21  
22  
23  
24  
25  
26  
27  
28  
29  
30  
31  
32  
33  
34  
35  
36

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