Long-term research catchments to investigate shrub encroachment in the Sonoran and Chihuahuan deserts: Santa Rita and Jornada experimental ranges

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Abstract
Wood vegetation encroachment is a global phenomenon whereby shrubs or trees replace grasses. The hydrological consequences of this ecological shift are of broad interest in ecohydrology, yet little is known of how plant and intercanopy patch dynamics, distributions, and connectivity influence catchment-scale responses. To address this gap, we established research catchments in the Sonoran and Chihuahuan Deserts (near Green Valley, Arizona and near Las Cruces, New Mexico, respectively) that represent shrub encroachment in contrasting arid climates. Our main goals in the coordinated observations were to: (a) independently measure the components of the catchment water balance, (b) deploy sensors to quantify the spatial patterns of ecohydrological processes, (c) use novel methods for characterizing catchment properties, and (d) assess shrub encroachment impacts on ecohydrological processes through modelling studies. Datasets on meteorological variables; energy, radiation, and CO2 fluxes; evapotranspiration; soil moisture and temperature; and runoff at various scales now extend to nearly 10 years of observations at each site, including both wet and dry periods. Here, we provide a brief overview of data collection efforts and offer suggestions for how the coordinated datasets can be exploited for ecohydrological inferences and modelling studies. Given the representative nature of the catchments, the available databases can be used to generalize findings to other catchments in desert landscapes.

KEYWORDS
arid hydrology, ecohydrology, eddy covariance technique, hydrological modelling, instrument networks, water balance
1 | DATA SET NAME

Hydrologic data from long-term research catchments at the Santa Rita and Jornada Experimental Ranges.

2 | INTRODUCTION AND SITE DESCRIPTIONS

Woody plant encroachment is a global phenomenon whereby shrubs or trees replace grasses (Archer et al., 2017). The ecohydrological consequences of this vegetation change have been studied primarily in arid and semiarid sites where hydrological processes are dominated by vertical exchanges (e.g., Huxman et al., 2005). Catchment-scale perspectives are limited and typically confined to short periods that do not adequately capture the range of inter- to intra-annual hydrological variability. To address this gap, we established research catchments with similar instrument networks in the Sonoran and Chihuahuan Deserts to investigate hydrological processes resulting from long-term increases in the amount and distribution of shrubs in areas historically dominated by perennial grasses (Gibbens et al., 2005; McClaran, 2003). Figure 1 shows the location of the research catchments in the southwestern United States – Santa Rita Experimental Range (SRER, 31.817°N, −110.851°W, ~1200 m) in southern Arizona and Jornada Experimental Range (JER, 32.585°N, −106.603°W, ~1500 m) in southern New Mexico.

Figure 1 shows the location of the research catchments in the southwestern United States – Santa Rita Experimental Range (SRER, Arizona) and Jornada Experimental Range (JER, New Mexico) in the Sonoran and Chihuahuan Deserts, respectively. Watershed boundaries (black polygons), drainage networks (blue lines labelled streams), and instrument locations at: (b) SRER (2.18 ha total, 31.817°N, −110.851°W, 1169 m) and (c) JER (4.67 ha, 32.585°N, −106.603°W, 1469 m) on the ESRI World Imagery basemap (sources: ESRI, DigitalGlobe, GeoEye, i-cubed, USDA FSA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community)
slope extending from the Santa Rita mountains, the climate conditions are considered as Köppen classification BSh (hot, semiarid, Beck et al., 2018). While Sonoran Desert grasses were previously dominant (McClaran, 2003), the area is now a savanna of velvet mesquite (Prosopis velutina) arborescents in a matrix of perennial C4 bunchgrasses (e.g., black grama, Bouteloua eriopoda) and succulents (e.g., prickly pear, Opuntia engelmannii). Drainage on the active alluvial fan terrace occurs in small ephemeral channels (<0.5 m width) with sandy bottoms, while hillslope soils are deep and with sandy clay and sandy clay loam textures.

The JER is a single watershed (Figure 1c) of 4.67 hectares in area upstream of a similar Santa Rita-type outlet flume installed in 1977 (Tromble, 1988). The catchment is on a piedmont slope emanating from the San Andres mountains (Schreiner-McGraw & Vivoni, 2018). Climate at the site has a Köppen classification of BWk (cold, desert) typical of the Chihuahuan Desert. Gibbens et al. (2005) described the area as a grassland from 1860, whereas a mixed shrubland composed of creosotebush (Larrea tridentata), honey mesquite (Prosopis glandulosa), and mariola (Parthenium incanum) is present today (Templeton et al., 2014). Drainage in the remnant alluvial fan flows into a main channel (0.5–1 m width) from hillslopes whose soils are shallow (<0.5 m) due to a CaCO₃ horizon and sandy loam in texture. Bare soils occupy 65% of the catchment and contain large amounts of surface rock.

The two settings have well established differences that offer novel insights into the ecohydrological processes of arid and semiarid regions. At the lower elevation SRER, the warmer and wetter Sonoran Desert conditions are linked to a more pronounced North American monsoon (Adams & Comrie, 1997) which brings summer precipitation to the region. At the higher elevation JER, the colder and drier Chihuahuan Desert conditions lead to lower vegetation cover with shorter statured shrub species and greater amounts of bare soil. Important differences also are present in soils with shallower and rockier areas of higher slope at JER.

At the two sites, long-term precipitation and outlet streamflow data are available from the USDA-ARS (SRER: http://www.tucson.ars.ag.gov/dap/; JER: http://iter.jornada.nmsu.edu/data-catalog/) at daily or greater resolution since the late 1970s, with some missing periods. This data availability and the supporting infrastructure at SRER and JER motivated the expansion of the instrument network, as described in the following section, to establish two coordinated research catchments. Each site now includes an eddy covariance (EC) tower whose sub-daily data products are distributed separately through AmeriFlux at http://ameriflux.lbl.gov/sites/siteinfo/US-SRS (SRER) and http://ameriflux.lbl.gov/sites/siteinfo/US-Jo2 (JER). The locations also afforded the opportunity to establish instrument test beds, where traditional sensors are compared to novel methods, for instance, to estimate soil moisture (cosmic ray neutron sensor, CRNS, Schreiner-McGraw et al., 2016) and precipitation (disdrometer, Tokay et al., 2014). To date, cross-site instrument networks have been compared in terms of their soil moisture and temperature distributions (Mascaro & Vivoni, 2016), the link between soil conditions and turbulent fluxes (Anderson & Vivoni, 2016), and the water balance closure (Schreiner-McGraw et al., 2016).

3 | METHODS AND DATA DESCRIPTION

The instrument networks shown in Figure 1 were deployed in May 2010 (JER) and May 2011 (SRER) using a coordinated approach to measure water, energy, and CO₂ states and fluxes. The water balance approach \( \frac{dSM}{dt} = P - ET - Q \), where \( SM \) is soil moisture, \( P \) is precipitation, \( ET \) is evapotranspiration, and \( Q \) is outlet streamflow was emphasized in the instrument network design (Templeton et al., 2014). Tipping-bucket rain gauges (TE525, Texas Electronics, Dallas, TX; resolution 0.2 mm, accuracy of ±1%) and line transducers of dielectric impedance soil moisture sensors (Hydra Probe II, Stevens Water, Portland, OR, USA; accuracy of 0.01 m³/m³) arranged over depth profiles (5, 15, and 30 cm) were deployed to obtain spatially-averaged estimates of SM and P (Figure 1b,c). The Santa Rita-type outlet flumes were equipped with pressure transducers (CS450, Campbell Scientific, Logan, UT; resolution of 0.0035% full scale, accuracy of ±0.1% full scale) to estimate water depths through a linear relation after which \( Q \) values were obtained following Smith et al. (1981). The EC method (Baldocchi et al., 1998) was implemented to obtain ET through the installation of a 10-m meteorological flux tower at each site. Tower sensors included a net radiometer (CNR2, Kipp & Zonen, Delft, the Netherlands; accuracy of ±10% daily value), a three-dimensional sonic anemometer (CSAT3, Campbell Scientific, Logan, UT; resolution of 0.5–1 mm/s; accuracy of ±4 to 8 cm/s offset error), an open-path infrared gas analyser (LI7500, LI-COR, Lincoln, NE; accuracy of ±1% for CO₂ and ±2% for H₂O), and soil heat flux plates (HPF01, Hukseflux, Delft, The Netherlands; accuracy of ±3%). ET is obtained as the covariance between high-frequency turbulent fluctuations in vertical wind velocity and H₂O concentration. Energy balance closure errors for ET estimates range from 10 to 15% of the available energy at the two sites. Analyses of the EC footprint indicate that spatial scales similar to that of the instrument networks are achieved (Vivoni et al., 2014). Pierini et al. (2014) and Templeton et al. (2014) provide a full description of the instrument network at SRER and JER, respectively, as summarized in Table 1, including the spatial patterns obtained from the distributed measurements of \( P \) and \( SM \).

After installation of the instrument networks, in-situ calibrations were carried out for all sensors following manufacturer guidelines (Pierini et al., 2014; Templeton et al., 2014). Site maintenance was performed on a nearly monthly basis in the research catchments over the study periods (2011–2018 at SRER; 2010–2019 at JER). Frequent visits allowed for troubleshooting and quality control of measurement techniques, with annual sensor re-calibrations performed for the EC method sensors. All measurements were obtained at high temporal resolutions (e.g., 1-min for \( Q \) and \( P \); 20 Hz for EC sensors) and aggregated to a common resolution of 30-min for quality control purposes. Data processing included the removal of values exceeding specified ranges and use of standard filtering techniques for EC measurements (Pérez-Ruiz et al., 2020). Data gaps due to instrument failures, power issues, or values removed due to poor quality were identified at the 30-min resolution for each sensor. Where possible, we used information from nearby sensors to fill gaps, thus obtaining daily values.
aggregated to the catchment scale with valid measurements only; otherwise, a No Data value (−9999) was reported.

The dataset released here consists of water, energy, and CO₂ fluxes aggregated to a daily resolution and commensurate with a spatial scale similar to the research catchments. These observations allow cross-site comparisons at inter- to intra-annual time scales. The EC method is also used to obtain the energy balance (Rᵢ − G = H + ĴET), where Rᵢ is net radiation, G is ground heat flux, H is sensible heat flux, and ĴET is latent heat flux), using ancillary measurements, as described in Templeton et al. (2014). Similarly, the EC method quantifies CO₂ fluxes between ecosystems and the atmosphere (NEE = Rᵣₑₑ − GPP, where NEE is net ecosystem exchange, Rᵣₑₑ is ecosystem respiration, and GPP is gross primary productivity), as described in Pérez-Ruiz et al. (2020). Temporal aggregations were performed through daily totals for P, ET, and Q in units of mm/day and daily averages for SM (m³/m³); Rᵢ, H, and ĴET (W/m²); and NEE, GPP, and Rᵣₑₑ (g CO₂/m²/day). Spatial aggregations consisted of Thiessen polygon averaging of P data and arithmetic averaging of depth-averaged SM measurements available each day. Aggregations to the daily resolution at the scale of the research catchments during the study periods allow assessments and comparisons to remotely-sensed observations, as well as support hydrological modelling efforts (e.g., Pierini et al., 2014; Schreiner-McGraw & Vivoni, 2018).

### TABLE 1

Annual average and ±1 annual standard deviation of water and energy components at SRER and JER for complete years in the period of record using consistent instrument packages

<table>
<thead>
<tr>
<th></th>
<th>Complete years</th>
<th>Sensors</th>
<th>Annual average and standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SRER</strong></td>
<td></td>
<td></td>
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<tr>
<td><strong>Water components</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Precipitation (P)</td>
<td>2012–2018</td>
<td>TE-525, Texas Instruments</td>
<td>406 ± 78</td>
</tr>
<tr>
<td>Evapotranspiration (ET)</td>
<td>2012–2018</td>
<td>LI-7500, LI-COR; CSAT3, Campbell Sci.</td>
<td>421 ± 39</td>
</tr>
<tr>
<td>Streamflow (Q)</td>
<td>2012–2018</td>
<td>Outlet flume; CS450 pressure, Campbell Sci.</td>
<td>30 ± 27</td>
</tr>
<tr>
<td>Soil Moisture (SM) Change</td>
<td>2012–2018</td>
<td>Hydra Probe II, Stevens</td>
<td>2 ± 26</td>
</tr>
<tr>
<td><strong>Energy components</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Net Radiation (Rᵢ)</td>
<td>2012–2018</td>
<td>CNR2, Kipp &amp; Zonen</td>
<td>105 ± 23</td>
</tr>
<tr>
<td>Latent Heat Flux (ĴET)</td>
<td>2012–2018</td>
<td>LI-7500, LI-COR; CSAT3, Campbell Sci.</td>
<td>34 ± 4</td>
</tr>
<tr>
<td>Sensible Heat Flux (H)</td>
<td>2012–2018</td>
<td>CSAT3, Campbell Sci.</td>
<td>61 ± 5</td>
</tr>
<tr>
<td>Ground Heat Flux (G)</td>
<td>2012–2018</td>
<td>HFP01, Hukseflux</td>
<td>1 ± 2</td>
</tr>
<tr>
<td><strong>JER</strong></td>
<td></td>
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<td></td>
</tr>
<tr>
<td><strong>Water components</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Precipitation (P)</td>
<td>2011–2019</td>
<td>TE-525, Texas Instruments</td>
<td>285 ± 51</td>
</tr>
<tr>
<td>Evapotranspiration (ET)</td>
<td>2011–2019</td>
<td>LI-7500, LI-COR; CSAT3, Campbell Sci.</td>
<td>280 ± 55</td>
</tr>
<tr>
<td>Streamflow (Q)</td>
<td>2011–2019</td>
<td>Outlet flume; CS450 pressure, Campbell Sci.</td>
<td>9 ± 6</td>
</tr>
<tr>
<td><strong>Energy components</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Net Radiation (Rᵢ)</td>
<td>2011–2019</td>
<td>CNR2, Kipp &amp; Zonen</td>
<td>114 ± 10</td>
</tr>
<tr>
<td>Sensible Heat Flux (H)</td>
<td>2011–2019</td>
<td>CSAT3, Campbell Sci.</td>
<td>65 ± 2</td>
</tr>
<tr>
<td>Ground Heat Flux (G)</td>
<td>2011–2019</td>
<td>HFP01, Hukseflux</td>
<td>6 ± 13</td>
</tr>
</tbody>
</table>

Note: Measurement uncertainty for the various components is discussed in Schreiner-McGraw and Vivoni (2017).

### 4 | CROSS-SITE COMPARISON AT INTER-TO INTRA-ANNUAL SCALES

Table 1 compares the annual water and energy balance components at the SRER and JER research catchments obtained over the complete years in the periods of record. The ET/P ratio is close to unity at both sites (1.04 ± 0.22 at SRER; 0.98 ± 0.26 at JER), indicating a majority of the P input is returned to the atmosphere during a year as ET, when averaged over the period of record. Inter-annual variability of the water fluxes, however, is particularly high. For example, coefficients of variations (CV = σ/μ, where σ is annual standard deviation and μ is the annual average) for outlet streamflow (Q) are 0.90 and 0.67 at SRER and JER, respectively. As expected at the annual scale, the change in SM is small, though inter-annual variability is high due to carry-over effects during wet years. Due to the arid and semiarid climate, the majority of net radiation input is partitioned into sensible heat flux, with H/Rᵢ values of 0.58 ± 0.14 at SRER and 0.57 ± 0.05 at JER, respectively. As a result of the climatic conditions, the Bowen Ratio (B = H/ĴET) is above unity (1.79 ± 0.25 and 2.95 ± 0.54 at SRER and JER, respectively), with higher CVs for ĴET due to high inter-annual variations in water availability.

The water, energy, and CO₂ fluxes in the research catchments are compared at the intra-annual (monthly) time scale in Figure 2. The
higher $P$ at SRER has a more marked seasonality during the North American monsoon (July to September), leading to a more pronounced seasonality in both $ET$ and $Q$. At both sites, the one-month delay in maximum seasonal $ET$ with respect to maximum $P$ reflects the time required for quiescent grasses and shrubs to green-up during the monsoon (Vivoni et al., 2008). While elevation-mediated differences are noted in $R_n$, the intra-annual variability of energy partitioning depends largely on water availability. Summer months at SRER have $\lambda ET$ that exceed $H$, but this is not observed at JER. Water and energy fluxes are strongly linked to the ecosystem CO$_2$ response, which exhibit stark differences in GPP and NEE during the monsoon and subsequent autumn season. Higher summer-time moisture and temperature conditions at SRER enhance its carbon uptake (more negative NEE) relative to JER, consistent with its higher aboveground biomass and less bare soil.

ACKNOWLEDGEMENTS


FIGURE 2  Long-term monthly values of water, energy, and CO$_2$ fluxes at the SRER (left) and JER (right) research catchments. (a, b) Precipitation ($P$, bars), evapotranspiration ($ET$, green symbols), and outlet streamflow ($Q$, blue symbols). (c, d) Net radiation ($R_n$), sensible heat flux ($H$), and latent heat flux ($\lambda ET$). (e, f) gross primary productivity (GPP), ecosystem respiration ($R_{eco}$), and net ecosystem exchange (NEE). Symbols represent monthly averages and error bars depict ±1 monthly standard deviation over the entire study periods: SRER (2011–2018) and JER (2010–2019). Due to low values (Table 1), $dSM/dt$ and $G$ have been omitted from (a, b) and (c, d), respectively.


