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SPECIAL FEATURE: DYNAMIC DESERTS

Soil water dynamics at 15 locations distributed across a desert landscape: insights from a 27-yr dataset

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Abstract. Desert ecosystems are primarily limited by water availability. Within a climatic regime, topography, soil characteristics, and vegetation are expected to determine how the combined effects of precipitation, temperature, and evaporative demand of the atmosphere shape the spatial and temporal patterns of water within the soil profile and across a landscape. To forecast how desert landscapes may respond to future climatic conditions, it is imperative to improve our understanding of these ecohydrologic processes. Here, we report on 27 yr of monthly soil volumetric water content (VWC) measurements and associated soils data from a site in the northern Chihuahuan Desert of North America. The dataset includes VWC and soil properties measured to 3 m in depth across 15 locations that encompass a range of Chihuahuan Desert vegetation types. We use this unique dataset (1) to generate insights into general temporal and depth patterns in VWC, (2) to analyze how VWC corresponds to measures of climatic conditions, and (3) to qualitatively evaluate the relative importance of soils, topographic setting, and vegetation type in mediating temporal patterns in VWC. Analyses of this unique dataset emphasize the importance of soil and topographic setting in determining depth and temporal patterns in VWC across time. Results emphasize the episodic nature of deep wetting events in our study system—essentially limited to three large events over the 27-yr record driven primarily by wetter than normal winters. Comparison of soil water dynamics between mesquite shrub coppice dunes and interspace soils suggests the "island of fertility" concept does not extend to soil water. Median VWC was strongly coupled to climatic conditions over surprisingly long windows at most locations (6–18 months), suggesting that soil water at depth is decoupled from short climatic pulses. However, VWC dynamics and VWC–climate relationships varied among locations, depths, and seasons, with unexpected similarities in ecohydrologic dynamics observed among very different vegetation types (e.g., an eroded creosote shrubland and a playa grassland). These results further underscore the importance of ecohydrological investigations in these ecosystems, given forecasts for a warmer and more variable climate in deserts globally.

Key words: Chihuahuan Desert; coppice dunes; critical zone; deep recharge; desertification; ecohydrology; grassland; landscape context; neutron moisture meter; shrubland; soil water; Special Feature: Dynamic Deserts; vadose zone.

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Introduction

Ecosystem processes in arid and semiarid environments (deserts hereafter) are primarily limited by water availability (Noy-Meir 1973). Plant growth and community composition at broad scales is coupled to climatological measures of water availability (Webb et al. 1978, Ogle and Reynolds 2004) that vary in time and space, but these couplings are often mediated by soil and landscape attributes that influence ecohydrologic processes at fine scales within a climate regime (Sala et al. 1988, Gremer et al. 2015). Surface soil texture, subsoil horizon development, and other aspects of the soil-geomorphic template (Monger and Bestelmeyer 2006) determine how the combined effects of precipitation, temperature, and evaporative demand shape soil water availability to plants (magnitude, temporal pattern, and depth within the soil profile; Duniway et al. 2010*a*). In desert grasslands, precipitation amount is most often selected as the driver of primary productivity because of its relative ease of measurement (Webb et al. 1978, Sala et al. 1988, Robertson et al. 2009). However, the relationship between precipitation and productivity is typically weak (<0.85 r^2, forced through zero) in these ecosystems (Muldavin et al. 2008, Peters et al. 2014, Petrie et al. 2018), suggesting that other variables are important modifiers of precipitation that determine water available to plants. Long-term data collected across a range of vegetation and soil types can begin to tease apart the relative roles of soil properties, landform, and vegetation in modifying precipitation to result in soil water availability. Understanding the relationship between these different factors (soils, landform, vegetation) with precipitation and soil water is a critical first step in forecasting how deserts dominated by different functional types (grasslands vs. shrublands) may respond to a changing climate. Given that deserts cover ca. 41% of terrestrial ecosystems (Millennium Ecosystem Assessment 2005), and a more variable climate is forecast for many deserts globally and for the American Southwest in particular (Seager et al. 2007, Cook and Seager 2013, Cook et al. 2015), long-term soil water data could improve understanding and prediction of ecosystem processes, including primary productivity.

Topography, soil, and climatic characteristics are primary abiotic components shaping soil water dynamics in desert ecosystems. Many desert ecosystems are characterized by high spatial heterogeneity in vegetation composition and structure that reflect heterogeneity in near-surface hydrology and other factors that are imposed by variation in soil parent material, soil age, and other soil forming factors (Jenny 1941, Birkland 1999, Monger 2006). Landscape patterning in soil formation and resulting soil profile properties combined with climate play a primary role in regulating soil water availability both spatially and temporally (Duniway et al. 2010*b*). For example, soils with high sand and rock content tend to store a greater proportion of water at depth (>~50 cm) than finer textured soils (Dodd and Lauenroth 1997). Accumulation of clay (e.g., argillic horizons) increases the capacity of the soil to retain infiltrated moisture for longer periods of time and possibly maintain higher levels of plant-available moisture (e.g., at plant extractable tensions, typically > -1.5 to -3 MPa) during extended dry periods (Hamerlynck et al. 2000). Similarly, accumulation of pedogenic carbonates in an otherwise sandy soil has been demonstrated to greatly increase water-holding capacity (Duniway et al. 2007) and increase retention of winter and summer precipitation within the plant rooting zone (Duniway et al. 2010*a*). Relative topographic position and other features mediate ecohydrological processes, including run-off/run-on dynamics, subsurface flow, and evapotranspiration (Gutierrez-Jurado et al. 2006, Duniway et al. 2010*b*). A review of long-term soil water studies highlights variability among and within dominant Chihuahuan Desert ecosystem types, the importance of landscape setting and soil type in mediating soil water dynamics, and the low temporal variability in deep soil water (Snyder et al. 2006).

Variability in water availability imparted by soils has been linked to important plant community characteristics in water-limited systems, including productivity, composition, and response to and recovery following disturbance. For example, desert soils with higher surface sand content have been shown to have higher productivity than soils with finer textures, and conservation of sandy, surface horizons is a critical component of limiting degradation following fire and drought in desert grasslands (Sala et al. 1988, Buxbaum and Vanderbilt 2007, Bestelmeyer et al.

2011). Soil age and pedogenic development strongly control plant species composition on Sonoran Desert alluvial fans (McAuliffe 1994) through influences on plant water availability in space and time (Hamerlynck et al. 2002). During extended droughts of the 1950s, perennial grass species growing on sandy soils with shallow petrocalcic horizons in the northern Chihuahuan Desert demonstrated lower mortality than those on sandy soils with little subsurface development (Herbel et al. 1972), likely due to water perched above or retained within petrocalcic horizons (Duniway et al. 2010*a*). In this region, deep sandy soils tend to be more susceptible to woody shrub dominance and grass decline than sandy soils with greater horizon development (clay and/or carbonate accumulation with depth; Browning et al. 2012). In addition, sustained soil water at shallow soil depths may play an important role in desert grassland recovery following drought (Peters et al. 2012), and there is growing focus on how fine spatial-scale patterns of soil water support regeneration and other processes across semiarid ecosystems (Schlaepfer et al. 2012, Petrie et al. 2017). These studies reinforce the important linkages between soil water pattern and ecological processes across dryland landscapes and suggest that heterogeneity in soil properties may often underlie observed variation in ecological conditions and dynamics in these systems.

Although it has long been acknowledged that soils and soil water influence ecological processes and dynamics (Noy-Meir 1973, McAuliffe 1994), the role of soil heterogeneity in mediating soil water availability across a landscape has not often been evaluated (but see Singh et al. 1998, Snyder et al. 2006, Duniway et al. 2010*a*). Modeling approaches have been used to improve understanding of the relationships among soil properties, water availability, and ecological processes in arid and semiarid plant communities at multiple spatial and temporal scales (Gao and Reynolds 2003, Gremer et al. 2015). Soil water models can provide a process-based understanding of how moisture dynamics govern plant species niche space (Peters et al. 2010, Schlaepfer et al. 2011) and, through coupling to global climate circulation models, forecast plant vulnerabilities to future soil water conditions (Schlaepfer et al. 2012, Gremer et al. 2015). However, modeling approaches for understanding soil water dynamics have limitations due to uncertainty in parameterization (e.g., lack of accurate or sufficient soils data) and in inclusion of dominant processes (e.g., preferential flow paths; Simunek et al. 2003). These modeling challenges are especially acute in complex, and often deep, desert vadose zones marked by high spatial variability (Monger and Bestelmeyer 2006), strong horizon development important for soil water dynamics (Duniway et al. 2007, 2010*a*), and limited data that are required for accurate parameterization.

Our goal was to use a long-term dataset (27 yr at depths to 3 m) of soil water measurements from 15 locations spatially distributed across a Chihuahuan Desert landscape to provide insight into potential future patterns in soil water as related to variability in soils, landform, or ecosystem type. Because this time period included both multi-year drought and wet periods, and our locations include the major grassland (uplands, playas) and shrubland ecosystem types (mesquite, creosotebush, tarbush) of the Chihuahuan Desert, we are able to infer responses of soil water dynamics to either directional increases or decreases in precipitation across complex landscapes. We use this unique dataset to examine for each ecosystem type: (1) the general relationship between temporal and depth patterns in soil water content with patterns in soil horizon development and soil properties; (2) the relationships between water content and a potential evapotranspiration-derived climate index over temporal windows from 1 to 18 months. Finally, (3) we use analyses of time-integrated soil water metrics to evaluate similarities and differences in soil water dynamics among the ecosystem types.

Materials and Methods

Study location

The Jornada Basin Long Term Ecological Research (LTER) site is located in the northern Chihuahuan Desert near Las Cruces, New Mexico, USA (32°33′ N, 106°47′ W; Fig. 1). The Jornada Basin is positioned at the eastern edge of the Basin and Range physiographic province and contains landforms and associated soils typical of such regions globally. Average annual precipitation over 80 yr is 24 cm with most occurring in

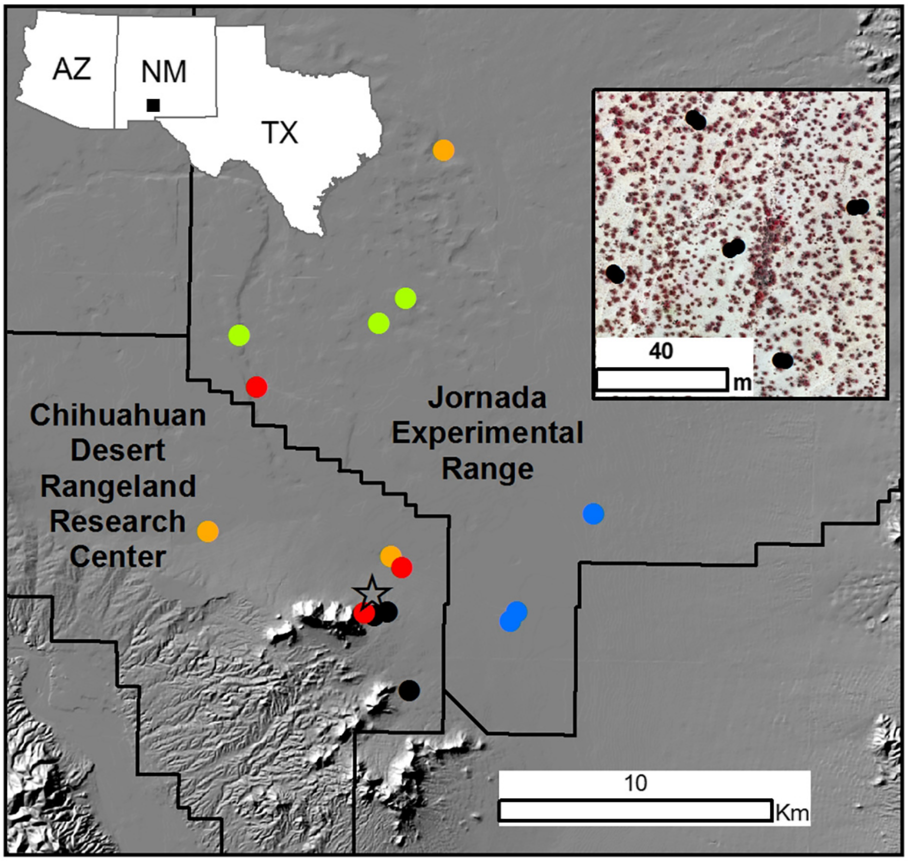

Fig. 1. Location of the Jornada Basin Long Term Ecological Research (LTER) within the southwestern United States (inset), the distribution of the 15 soil moisture monitoring locations in the USDA Jornada Experimental Range and NMSU Chihuahuan Desert Rangeland Research Center (creosotebush shrublands, black; upland grasslands, red; playa grasslands, orange; tarbush shrublands, blue; and mesquite shrublands, green), and example of Neutron Moisture Meter monitoring layout (location C-GRAV; color map inset). Star indicates the location of the Jornada LTER weather station.

July through October as monsoonal convective storms. Average summer temperature for the same time period is 24.9°C, and average winter temperature is 4.7°C (Wainwright 2006; updated with current precipitation and temperature data from https://jornada.nmsu.edu).

The soil moisture studies described here are located within the LTER Net Primary Productivity (NPP) study locations described in Huenneke et al. (2002) and Peters et al. (2014). These 15 NPP locations are distributed among five Chihuahuan Desert ecosystem types (Table 1, Fig. 1), with three locations in each type selected to span the range in productivity exhibited by that type in the Jornada Basin. The ecosystem types include shrublands (three) dominated by *Larrea tridentata* (creosotebush), *Flourensia cernua* (tarbush), or *Prosopis glandulosa* (mesquite); an upland grasslands dominated by *Bouteloua eriopoda* (black grama); and a playa grasslands dominated by *Panicum obtusum* (vine mesquite; P-COLL and P-SMAL) or *Pleuraphis mutica* (tobosagrass; P-TOBO). Because soils, geomorphology, and plant communities are often coupled in arid ecosystems (McAuliffe 1994, Wondzell et al. 1996), the NPP study also captured a wide range in soil types (Table 1).

Soil moisture measurements

At each NPP location, livestock were excluded from the 70 × 70 m plot beginning in 1989, and measurements of soil profile VWC were

Table 1. Study ecosystem type, locations, soil classification (US Soil Taxonomy), geomorphic landform, and long-term annual average Net Primary Productivity (NPP; 1990–2015, mean ± standard deviation).

Ecosystem type	Location	Soil taxonomy†	Geomorphic landform‡	NPP ($g \cdot m^{-2} \cdot yr^{-1}$)§
Creosotebush shrubland	C-GRAV	Loamy-skeletal, mixed, superactive, thermic; Ustic Haplocalcid	Fan Piedmont	94.2 ± 31.4
	C-SAND	Coarse-loamy, mixed, superactive, thermic; Ustic Calciargid	Fan Piedmont	127.1 ± 42.3
	C-CALI	Coarse-loamy, mixed, superactive, thermic; Sodic Haplocalcid	Fan Piedmont	39.1 ± 15.6
Upland grassland	G-SUMM	Coarse-loamy, mixed, superactive, thermic; Ustic Haplocambid	Alluvial Fan Collar and pediments	151.5 ± 109.7
	G-BASN	Fine-loamy, mixed, superactive, thermic; Ustic Calciargid	Fan Piedmont	137.1 ± 58.1
	G-IBPE	Coarse-loamy, mixed, superactive, thermic; Ustalfic Petrocalcid	Alluvial Plain Wind, worked	120.8 ± 66.8
Playa grassland	P-SMAL	Coarse-loamy, mixed, superactive, thermic; Aridic Argiustoll	Playas	263.6 ± 252.0
	P-COLL	Fine, smectitic, thermic; Chromic Haplotorrert	Playas	228.3 ± 205.6
	P-TOBO	Very fine, smectitic, thermic; Chromic Gypsitorrert	Lake-Plain Playas	93.9 ± 105.0
Tarbush shrubland	T-TAYL	Coarse-loamy, mixed, active, thermic; Ustic Haplocalcid	Fan Piedmont	70.8 ± 37.2
	T-EAST	Fine-loamy, mixed, superactive, thermic; Ustic Calciargid	Alluvial Flat	89.1 ± 36.1
	T-WEST	Fine-loamy, mixed, superactive, thermic; Ustic Calciargid	Alluvial Flat	67.2 ± 34.1
Mesquite shrubland	M-NORT	Mixed, thermic; Ustic Torripsamment¶	Alluvial Plain Wind, worked	106.3 ± 82.9
	M-RABB	Mixed, thermic; Ustic Torripsamment¶	Alluvial Plain Wind, worked	129.4 ± 99.9
	M-WELL	Coarse-loamy, mixed, superactive, thermic; Ustalfic Petrocalcid#	Alluvial Plain Wind, worked	112.7 ± 71.5

† Based on soil pedons excavated adjacent to each location and classified by the Natural Resource Conservation Service Soil Survey (Appendix S2).
‡ Monger et al. (2006).
§ Huenneke et al. (2002), Peters et al. (2012).
¶ Pedon excavated in coppice dune microsite (Appendix S2: Figs. S13, S14).
# The soil pedon does not match soils observed in plot. Based on within plot soil cores, we have assigned M-WELL the same taxonomic class as G-IBPE.

conducted using a neutron moisture meter (NMM) at 10 measurement stations (access tubes) in each location monthly at 30-cm intervals from 1989 to present. Access tubes were installed in 1989 in pairs: one tube under the canopy of the dominant perennial plant type at that location (Table 1) and the other in an adjacent area without perennial vegetation. Pairs were located along the outside of plot edges on each of the four sides and one pair in the middle (see Fig. 1 inset). Aluminum access tubes (50 mm in diameter with a wall thickness of 1.6 mm) were installed to a maximum depth of 3 m. Installation was completed by boring shafts using a manual bucket auger, inserting access tube into the resulting excavation, and carefully filling gaps around the access tube. In several locations or measurement stations within locations, it was not possible to measure to a depth of 3 m because a petrocalcic or other auger-limiting soil horizon was encountered. Additionally, over the long study period, several access tubes filled in were inadvertently lifted up, or otherwise shortened, thus reducing maximum measurement depths.

To measure profile VWC with an NMM, a fast neutron source and detector is lowered into an access tube and cable stops are used to place the center of the neutron source at selected soil depths (Hignett and Evett 2002). Fast neutrons are emitted into the soil matrix where they are thermalized (reduced to a lower energy state) through collisions primarily with soil hydrogen (Hignett and Evett 2002). Because dynamic hydrogen in soil is mainly in the form of H_2O, a linear relationship exists between thermalized neutron counts and soil water for a given soil type (Evett et al. 2007). The Jornada LTER uses two NMMs, both are Campbell Pacific Nuclear Corporation (Concord, California, USA) model 503DR with 50mci Americium-241/Beryllium neutron source. Most measurements are done using the primary NMM (Serial # H32073900). The LTER maintains a backup NMM (Serial # H36097085) for use when the primary NMM is unavailable. Readings from all 15 locations occur over ~3 d each month within 5 d of the first of the month. We report here NMM data from July 1989 through December 2015.

Soil-specific calibration equations that relate thermalized neutron counts to volumetric soil water content (VWC) were developed using data from each location, following Hignett and Evett (2002) and described in detail by Crossland (2012) and in Appendix S1.

Location characterization

We obtained daily meteorological data from the Jornada LTER weather station (Fig. 1), and gap filled daily precipitation (PPT: mm) data collected at each location from 1989 to 2015 (http://jornada.nmsu.edu/lter/data/climate). Additional data from the Jornada LTER weather station were used to estimate monthly potential evapotranspiration (Ep: mm/month). Because the data required for this calculation were not available at each location, we applied the same monthly Ep to our analyses for these locations, compared to location-measured PPT.

Soil descriptions and data are based on three separate samplings. First, in 2005, we excavated soil pits adjacent to each location in collaboration with the Natural Resource Conservation Service (NRCS) who performed full soil pedon characterizations (http://ncsslabdatamart.sc.egov.usda.gov/; Lab Pedon Numbers 04N0942 through 04N0957). Second, soil profile texture and calcium carbonate were determined from samples collected during NMM calibration activities (every 15 cm from 15 to 120 cm, and every 30 cm from 150 to 300 cm; Crossland 2012). Third, we collected soils data from nearby locations (within 2–3 m) at six NMM sampling access tubes at 10 locations (not sampled in this manner were C-GRAV, G-SUMM, and all playa locations). This deep sampling was achieved using a PN425 JMC Environmentalist's Sub-Soil Probe (Clements Associates, Newton, Iowa, USA), collecting 2–3 intact cores per location (3.5 cm in diameter, ~3 m long), which were then divided into depth segments (30 cm segments from 15 to 300 cm, where possible). Particle size analysis was determined by the Crossland (2012) and deep core samples by the hydrometer method (Gee and Or 2002). $CaCO_3$ was measured by the digital manometer method (Horváth et al. 2005).

Data analysis

Adjustments due to NMM probe differences, NMM source decay, and soil-specific calibration were applied using SAS (version 9.4; Appendix S1). Due to concerns in proximity of soil at the bottom of the NMM access tube affecting the deepest readings (see Hignett and Evett 2002), we excluded the deepest reading from each measurement date at each location (maximum depth then reported here is 270 cm). To limit spurious conclusions regarding variation in moisture with depth, we averaged VWC under vegetation and in bare interspaces for dates and depths with ≥2 corresponding tube pairs (4 + total measurements out of 10 possible). The exception was mesquite shrubland locations where data are presented from under vegetation (coppice dunes) and in inter-dune microsites separately where soil profiles often have large differences in soil chemical and physical properties (Gile 1966).

Objective 1: Patterns in soil water for each ecosystem type as related to soil properties.—Evaluation of patterns in soil water and soil properties were done qualitatively through comparisons of depth distributions of key soil properties and depth and time dynamics of soil water. Statistics associated with the distribution of VWC measurements by depth (5th, 25th, 50th, 75th, and 95th quantile) were generated using SAS (PROC SUMMARY). For data visualization (and not data analysis), we estimated VWC linearly in 10-cm increments between measurement depths for each access tube for each date, but did not gap fill missing measurement dates using The R Project for Statistical Computing software (R Core Team 2016).

Objective 2: Soil water dynamics and seasonal variability in climate.—To evaluate the interaction of our soil water measurements with climate, we elected to use a climate index, the Standardized Precipitation Evapotranspiration Index (SPEI;

Vicente-Serrano et al. 2010). The SPEI integrates incoming precipitation (i.e., system moisture) and atmospheric demand for moisture (potential evaporation; includes temperature, radiation, wind speed, and humidity effects), thus producing a more detailed approximation of the moisture state of the system over our monthly time interval.

To estimate monthly Ep from Jornada LTER weather station data, we gap filled daily measurements up to 10 d in length for net radiation (Rn: $mJ \cdot m^{-2} \cdot d^{-1}$), air temperature (Ta: °C), relative humidity (RH: %), and wind speed (u: m/s) using MicroMet preprocessor and moving average time series model methodologies (Walton 1996, Liston and Elder 2006, Henn et al. 2013). For months with ≥20 d of measurements, we calculated monthly potential evapotranspiration (PET) using the FAO-56 Penman-Monteith equation from average daily values (Suleiman and Hoogenboom 2007). We calculated the Standardized Precipitation Evapotranspiration Index (SPEI: PPT–Ep: mm) monthly for each location from 1989 to 2015 and calculated normalized SPEI values as deviation from monthly mean, scaled by standard deviation. We organized and gap filled data and made VWC and SPEI figures using The R Project for Statistical Computing software (R Core Team 2016).

Assessment of SPEI controls on measured VWC was conducted using quantile regression (PROC QUANT; SAS version 9.4, SAS Institute, Cary, North Carolina, USA). We elected to not use ordinary least-squares correlation for the following reasons. First, although SPEI accounts for both the effects of precipitation and temperature on water balance, preliminary examination of the SPEI–VWC association reveals many outliers, likely due to the monthly measurement interval as well as unaccounted for processes (such as storm intensity, transpiration water losses, and run-off). Second, the VWC data for each depth were generally not normally distributed (right skewed with many dry readings and a few wet readings). Quantile regression provides a good approach for examining relationships in datasets with incomplete information, outliers, non-normal distributions, and other issues (Cade and Noon 2003). We examined the relationship between median soil moisture conditions using location average VWC by depth (30–180 cm) and location SPEI data. Given potential lags and legacies in soil moisture (Monger et al. 2015), we examined quantile associations of VWC with SPEI averaged over the previous 1–18 months (PROC EXPAND). Analyses were conducted by season (winter, November–February; spring, March–June; and summer, July–October), resulting in ~85–95 observations in each regression (4 months for each of 27 yr minus missing dates).

Objective 3: Comparisons of soil water dynamics among ecosystem types.—To evaluate similarities and differences in temporal and depth VWC among the 15 locations and quantitatively compare water dynamics within and among the five ecosystem types, we compared VWC quantiles and interquantile ranges using both univariate and multivariate methods. First, for each measurement station (n = 10 per location) and each depth (n = 2–9 per station), we calculated soil quantiles across the study period. We then calculated location-level averages and 95% confidence intervals (CIs) by depth for the median and wet interquartile ranges (95th minus 50th quantile). Second, we used nonmetric multidimensional scaling (NMDS) to analyze VWC quantiles across depths. The vegan package (Oksanen et al. 2017) and Bray-Curtis distance dissimilarity matrix were used to perform NMDS with two-dimensional ordinations using random starting configurations and iterated 100 times or until a stable solution was reached. Location centroids were calculated using mean axis scores. Because ordinations cannot include observations with missing data, we limited the NMDS analysis to observations from the top 90 cm to include as many NMM measurement stations as possible. We examined similarities in VWC temporal and depth patterns among ecosystem types (and mesquite shrubland coppice dune and inter-dune microsites) using scatter plots of univariate and multivariate VWC statistics.

Study period climate

The 27-yr study period had an SPEI mean of approximately −200 mm; mean PPT of 245 mm and mean temperature of 14.9°C, which is similar to the long-term averages. To guide the qualitative comparisons of relationships between soil water and PPT among ecosystem types, we grouped the time series into four periods based on a 5-month sliding mean SPEI and deviation in the long-term mean (Fig. 2a). The first period (four years from 1989 to 1993) experienced average to above-average rainfall (Fig. 2b) and associated high SPEI (Fig. 2a), punctuated by a wet sequence of months in 1992. The second was an 11-yr period from 1994 to 2004 that experienced warmer and somewhat drier conditions with the 5-month mean temperature reaching normal

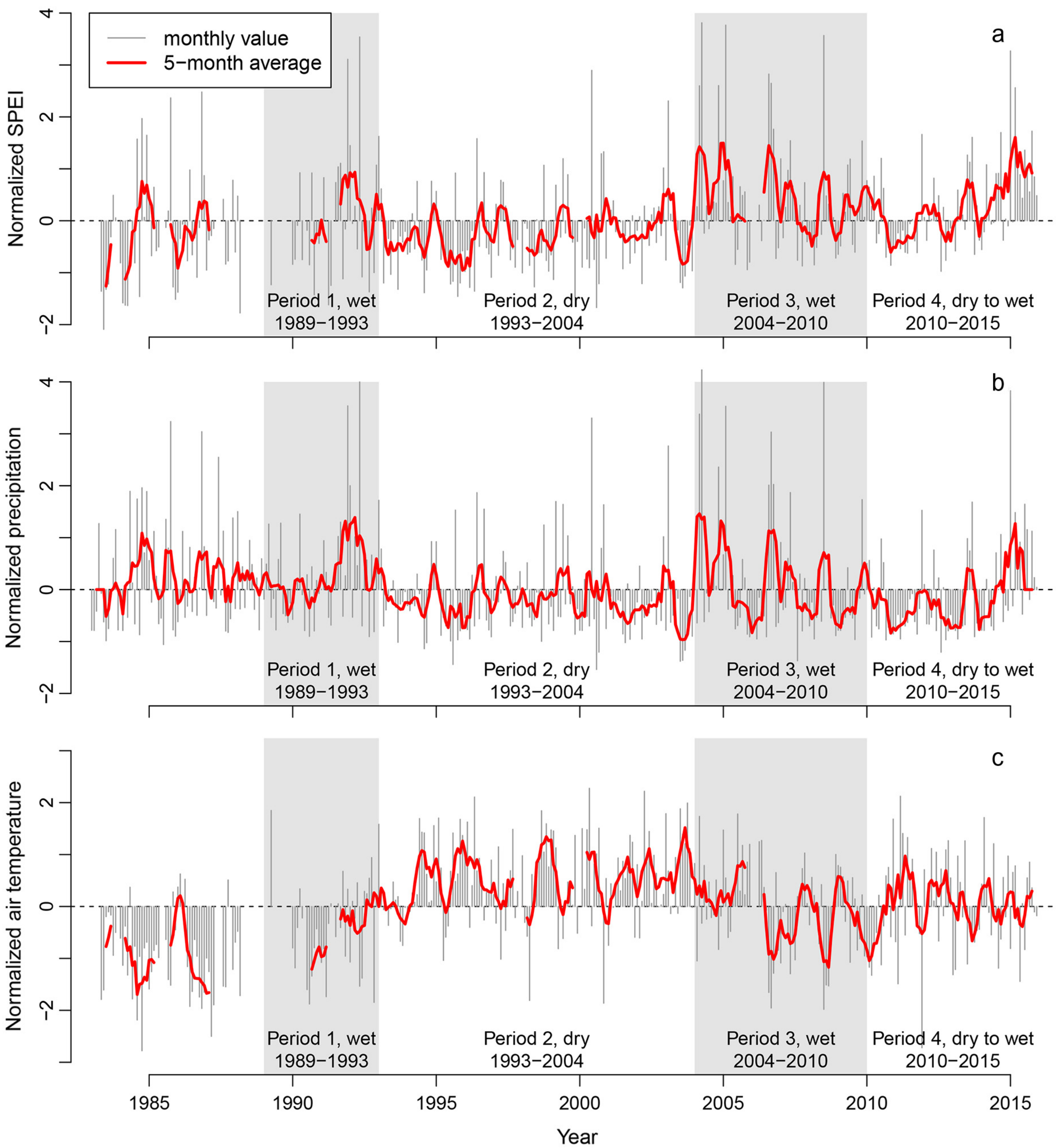

Fig. 2. Time series of normalized [(observed − mean)/standard deviation] monthly Standardized Precipitation and Evapotranspiration Index (SPEI; a), monthly precipitation (b), and monthly air temperature (c) at the Jornada Basin Long Term Ecological Research weather station from 1983 to 2015. Values greater than zero are above average, and values below zero are below average. Gray lines illustrate observed monthly values, and the red line illustrates the 5-month floating mean.

only sporadically (Fig. 2c). The third period experienced a sequence of wet years from 2005 through 2010 and also contained a dry sequence of months in early 2006. The final period begins with a dry 2011, followed by increasingly above-average conditions from 2012 to 2016.

Results

Objective 1: Patterns in soil water for each ecosystem type as related to soil properties

Water dynamics in creosotebush shrublands.—The three creosotebush locations exhibited a wide range in soil depths, textures, and resulting water dynamics (Table 1, Fig. 3). The very gravelly to skeletal soils at C-GRAV, along with a discontinuous petrocalcic horizon at ~20 cm, severely limit plant-available rooting volume and pore space for soil water retention (Appendix S2: Fig. S1). The very low median water contents (~1%; Fig. 3c) are likely driven by the large amount of coarse fragments (Fig. 3b). The relatively high (~9%) 95th quantile at 30 cm is evidence that surface soils at C-GRAV occasionally get very wet (especially considering the high coarse fragment content), but these conditions quickly fade with depth with

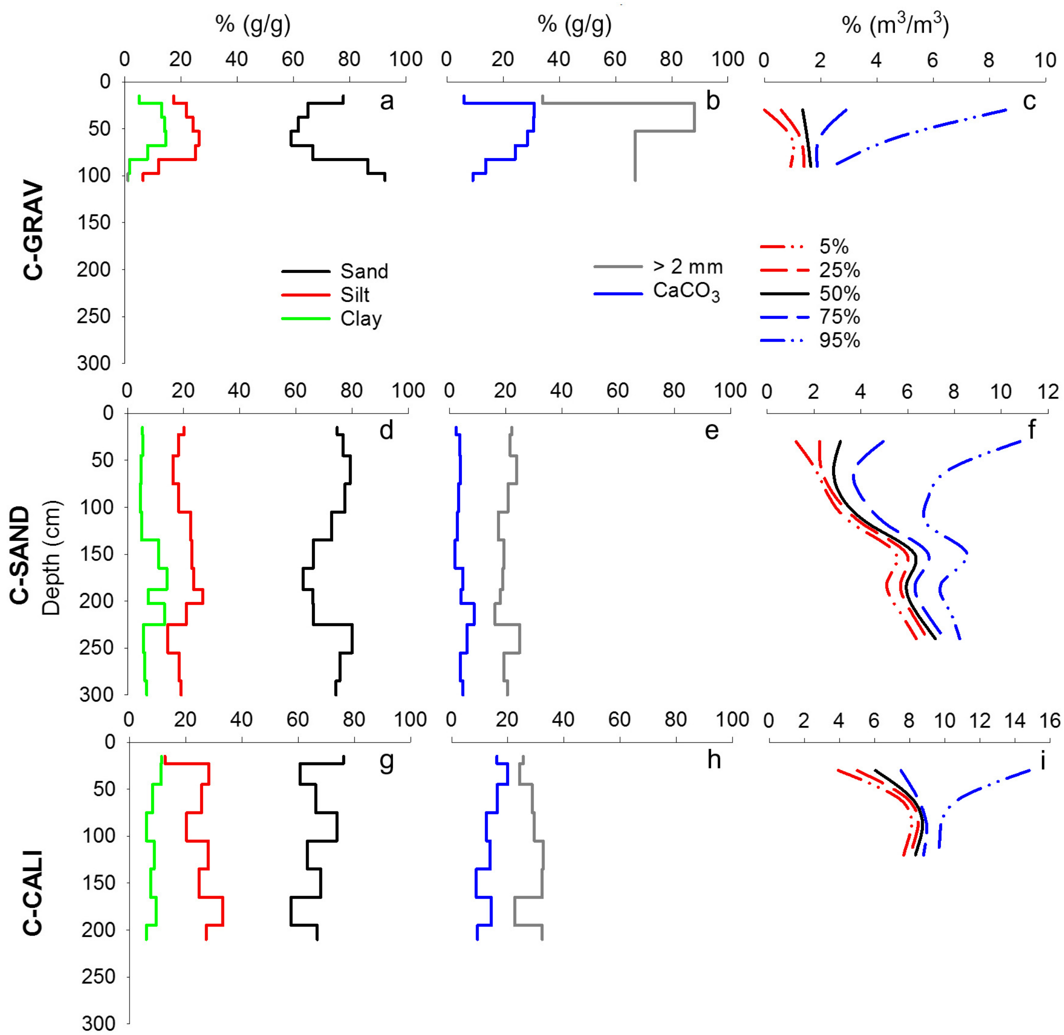

Fig. 3. Creosotebush shrubland location (Fig. 1) soil profile percent sand, silt, and clay (left column; a, d, and g); percent coarse fragment (>2 mm) and percent calcium carbonate ($CaCO_3$; middle column; b, e, and h); and location soil profile temporal quantiles (based on the entire study period; right column; c, f, and i). C-GRAV soil property data from Crossland (2012).

the 95th quantile being only ~1% wetter than the median by a depth of 90 cm (Fig. 3c). C-SAND, in contrast, is a relatively homogeneous, deep soil with moderate amounts of coarse fragments (~20%), limited clay or carbonate accumulation with depth, and no limit on rooting or water with depth (Fig. 3d–f; Appendix S2: Fig. S2). Examination of the 95th quantile relative to the median at C-SAND suggests that more extreme wetting events percolate to relative deep depths (~120 cm; Fig. 3f). The variability from 150 to 270 cm in all quantiles is likely in response to subtle variations in soil texture (clay and sand; Fig. 3d). C-CALI soil profile properties and water dynamics are intermediate between C-SAND and C-GRAV. Higher soil carbonates and finer textures (Fig. 3g, h; Appendix S2: Fig. S3) at C-CALI limit downward percolation of wetting fronts (95th percentile line) and increase the volumetric water retained during dry periods (5th quantile; Fig. 3i).

Temporal trends in soil water contents at these creosote shrubland locations show these soils are typically dry, with a limited number of wetting events with appreciable increase in VWC (increases of >~0.05 m^3/m^3 VWC; Fig. 4). Appreciable wetting below 60 cm was only observed approximately three times during the 27-yr record and only once below 90 cm (a very wet winter in 1991–92; Fig. 4a, b). At C-GRAV and C-CALI, soil rockiness and occurrence of calcic/petrocalcic horizons severely limited depths of measurements (Fig. 4c, e). Soil water results at C-SAND extend to 240 cm over most of the study period; however, wetting at this coarse-textured location below 90 cm was also relatively uncommon outside of an extremely wet winter in 1991–1992. During the relatively dry period from spring of 1994 through fall of 2004 (Fig. 2), wetting was restricted to the shallowest depths (Fig. 4d). The dominance of dry conditions through time (Fig. 4) and the very narrow range between the 5th and 50th quantile at most depths (Fig. 3) in the three creosotebush shrubland locations suggest soil water potentials are at or near the limit of plant extractable tensions much of the time.

Water dynamics in upland grassland locations.— The upland grassland locations also exhibited a wide range of soil classes (Table 1), properties, and resulting water dynamics (Fig. 5). G-SUMM is a deep, coarse-textured soil with little variation in soil properties with depth (Fig. 5a, b; Appendix S2: Fig. S4). The result is a relatively homogenous soil water profile, with a slight linearly increasing trend in the lower and decreasing trend in the upper quantiles. The relatively wide range between the median and 95th quantile at the deeper depths measured (~3% at 200 cm) suggests deep wetting is relatively common at G-SUMM (Fig. 5c). In contrast, the soil profile at G-BASN is marked by strong horizon development (Fig. 5d, e; Appendix S2: Fig. S5), resulting in high depth variation in water contents (Fig. 5f). There are pronounced increases in all quantiles of soil water corresponding to increases in clay and carbonates start at ~60 cm and again at ~200 cm. However, the interquantile ranges are relatively narrow starting at ~150 cm, suggesting very infrequent significant wetting or drying at deeper depths of G-BASN. Soils at G-IBPE are also marked by strong horizon development, primarily development of petrocalcic and calcic horizons starting at ~60 cm (Fig. 5g, h; Appendix S2: Fig. S6), which are correlated with an increase in VWC across all quantiles (Fig. 5i). There is another increase in VWC at 180 cm that is likely also associated with carbonates, though we lack soil data at that depth. An unusual aspect of the quantile profiles at G-IBPE is the relatively depth-consistent range between the median and 95th quantile (and to a lesser extent the 75th quantile; Fig. 5i), which suggests there is episodic deep percolation that is retained for long periods.

Temporal and depth patterns in soil water contents at the upland grasslands provide further evidence for the importance of soil horizon development on temporal and depth patterns in soil water contents (Fig. 6). The deep, coarse-textured soils at G-SUMM allow for very deep wetting during wet climate periods (winter 1991–1992, 2004–2005, and others Fig. 6a, b) but also result in very low water contents during dry periods (e.g., 1994–2004; Fig. 6c). Evidence of whole-profile wetting was not observed in the finer textured soils at G-BASN, with most wetting events concentrated in the upper 60 cm (Fig. 6d). The influence of the fine-textured, buried calcic and argillic horizon at depth (starting 180 cm; Appendix S2: Fig. S5 “2Btk5” horizon) is very apparent, showing consistently high (~10%) VWC through time (Fig. 6d). The temporal sequence of soil moisture measurements at

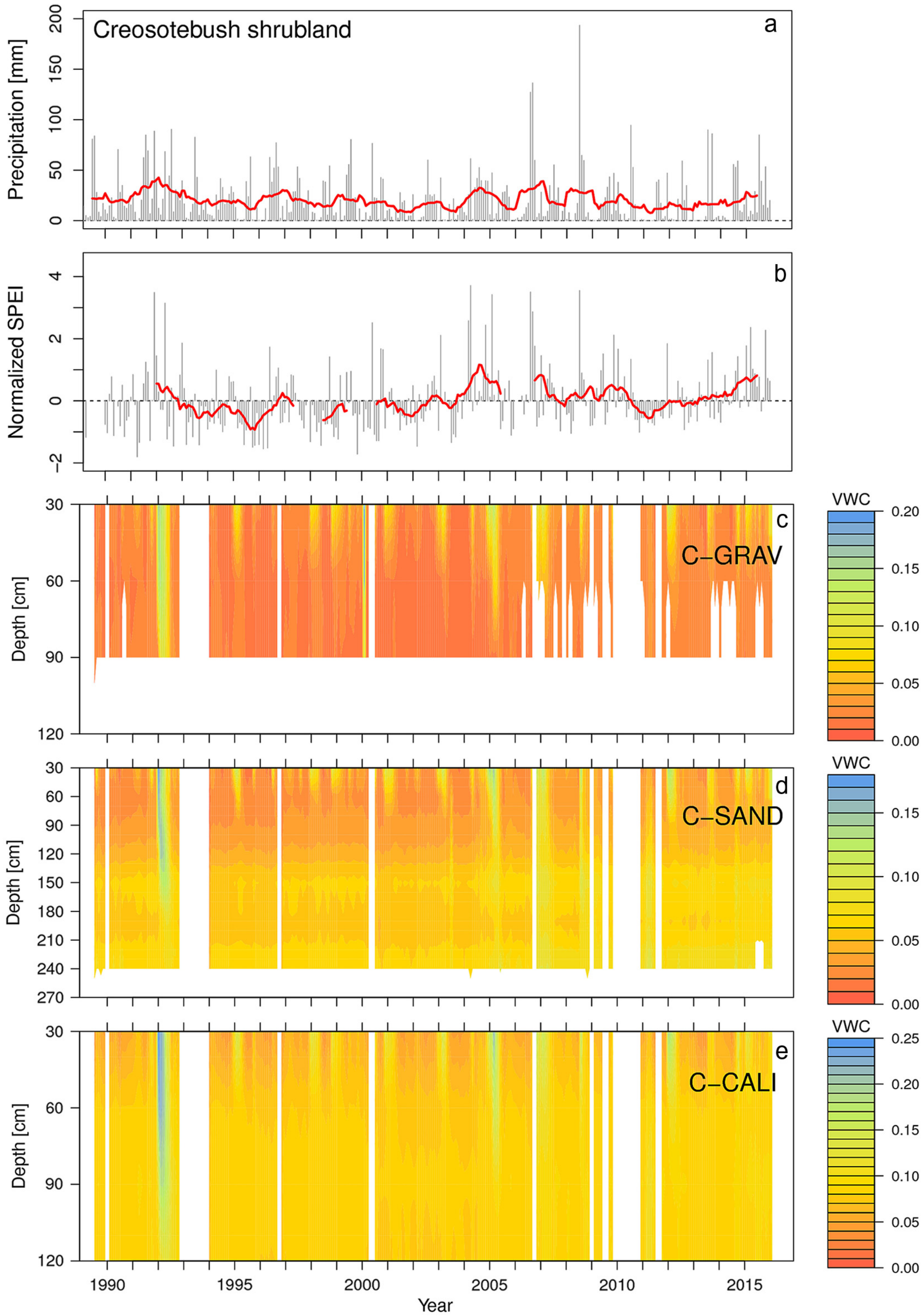

Fig. 4. Creosotebush shrubland location (Fig. 1) average monthly precipitation (a) and Standardized Precipitation Evapotranspiration Index (SPEI; b) and location mean volumetric water content (VWC; b, c, d). Red lines are 13-month mean precipitation (a) and 5-month mean SPEI (b). Color ramp scales of VWC vary for each location from zero to the maximum location mean value observed.

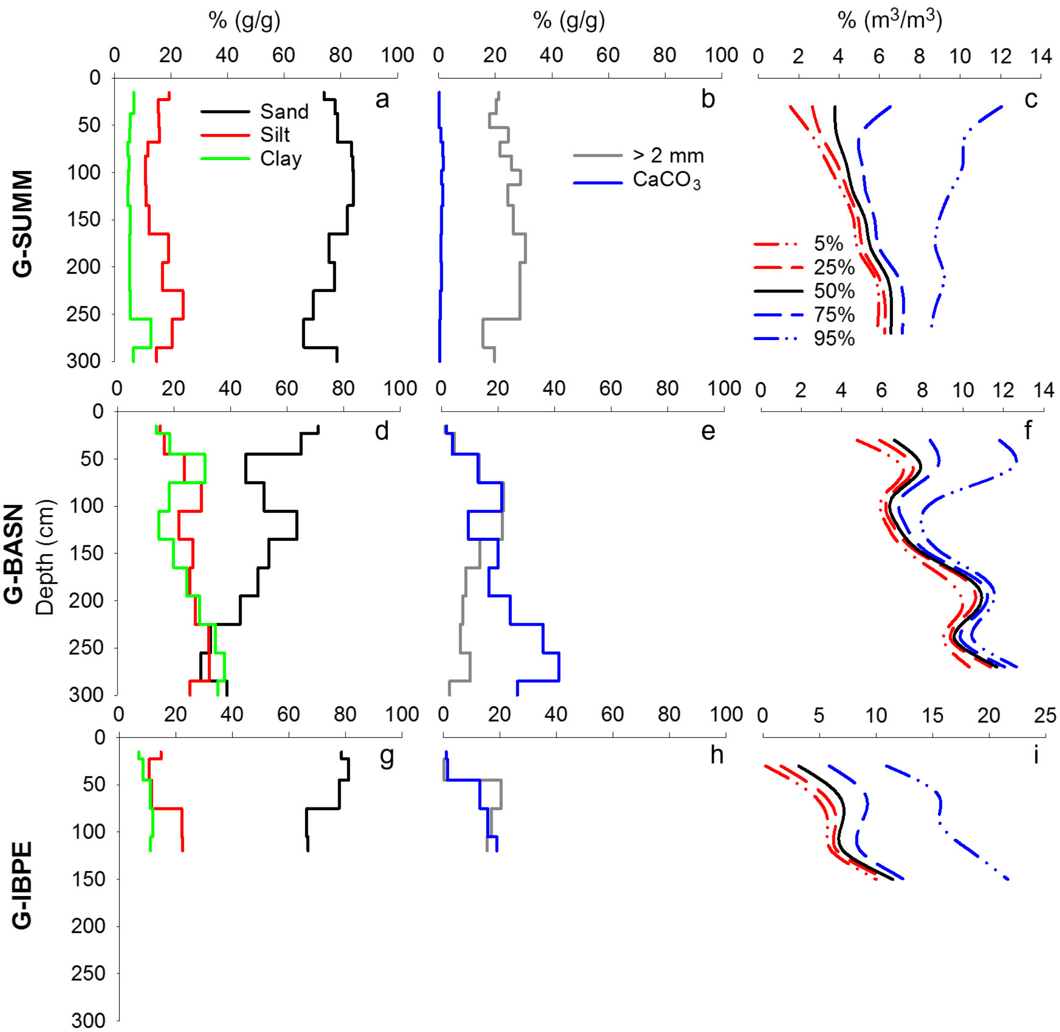

Fig. 5. Upland grassland location (Fig. 1) soil profile percent sand, silt, and clay (left column; a, d, and g); percent coarse fragment (>2 mm) and percent calcium carbonate ($CaCO_3$; middle column; b, e, and h); and location soil profile temporal quantiles (based on the entire study period; right column; c, f, and i). G-SUMM soil property data from Crossland (2012).

G-IBPE also suggests the calcic/petrocalcic horizon (Appendix S2: Fig. S6) is not limiting downward movement of moisture, with evidence of deep (150 cm) wetting events during both wet winters (e.g., 1991–1992, 2004–2005; Fig. 6a, b) and wet summer events (2006; Fig. 6e).

Water dynamics in playa grasslands.—Soils in these grasslands generally experience higher minimum (5%) volumetric moisture than other ecosystem types because they are very fine in texture, and are without coarse fragments (Fig. 7; Appendix S2: Figs. S7–S9). This moisture retention advantage is compounded by supplemental run-on water, particularly at P-SMAL and P-COLL. P-SMAL (Fig. 7a, b) and P-TOBO (Fig. 7g, h) have greater depth variation in soil properties than P-COLL (Fig. 7d, e), with P-SMAL texture coarsening with depth and P-TOBO having increasing clay and carbonates with depth. The soil profile at P-COLL is very fine (>50% clay) and relatively homogeneous with depth. Additionally, P-COLL is dominated by shrink–swell (vertic) clays, resulting in large cracks when the soil is dry down to 2 m or more (Appendix S2: Fig. S8). Soil moisture conditions at all three playa locations are generally moist, with

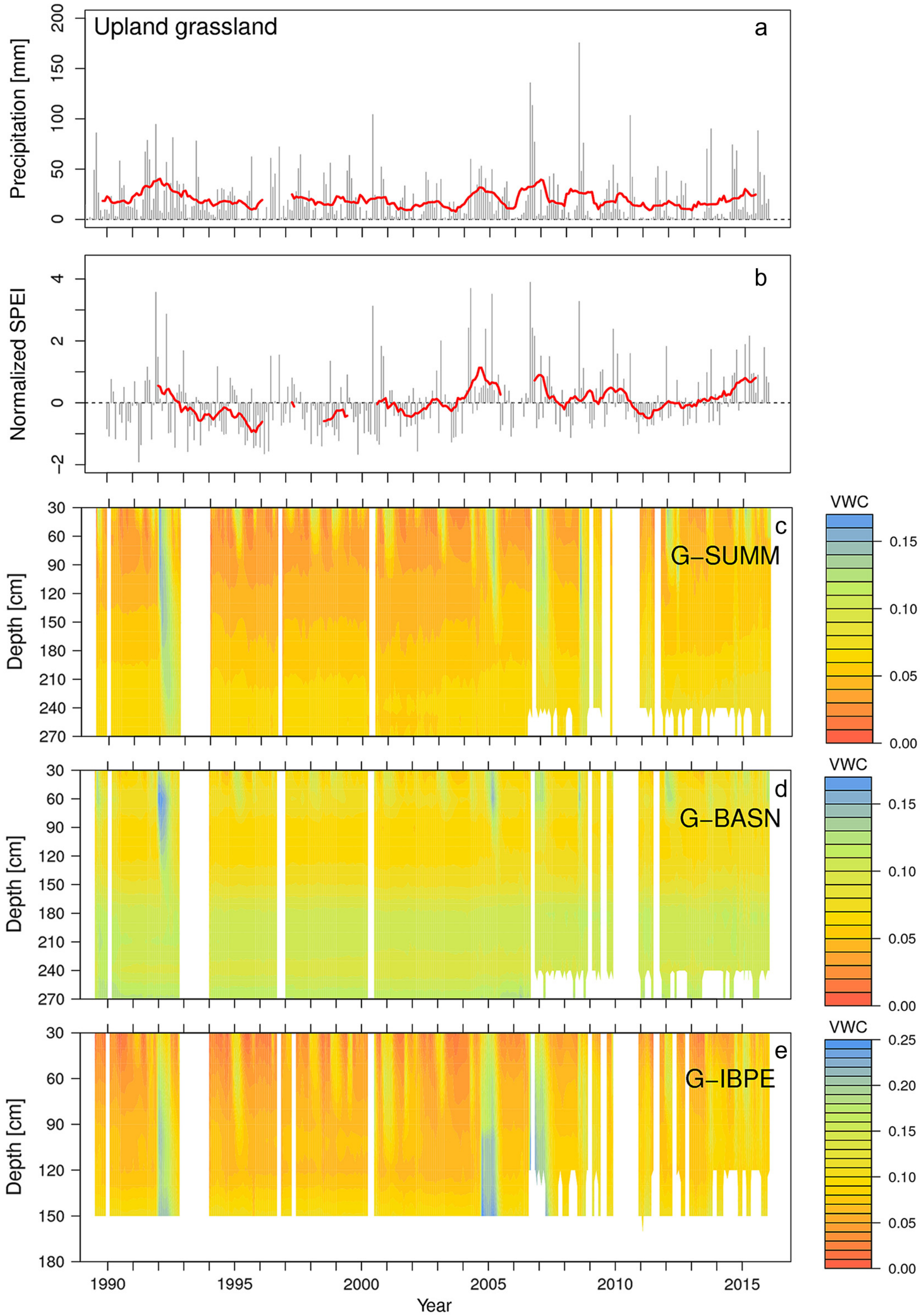

Fig. 6. Upland grassland location (Fig. 1) average monthly precipitation (a) and Standardized Precipitation Evapotranspiration Index (SPEI; b) and location mean volumetric water content (VWC; b, c, d). Red lines are 13-month mean precipitation (a) and 5-month mean SPEI (b). Color ramp scales of VWC vary for each location from zero to the maximum location mean value observed.

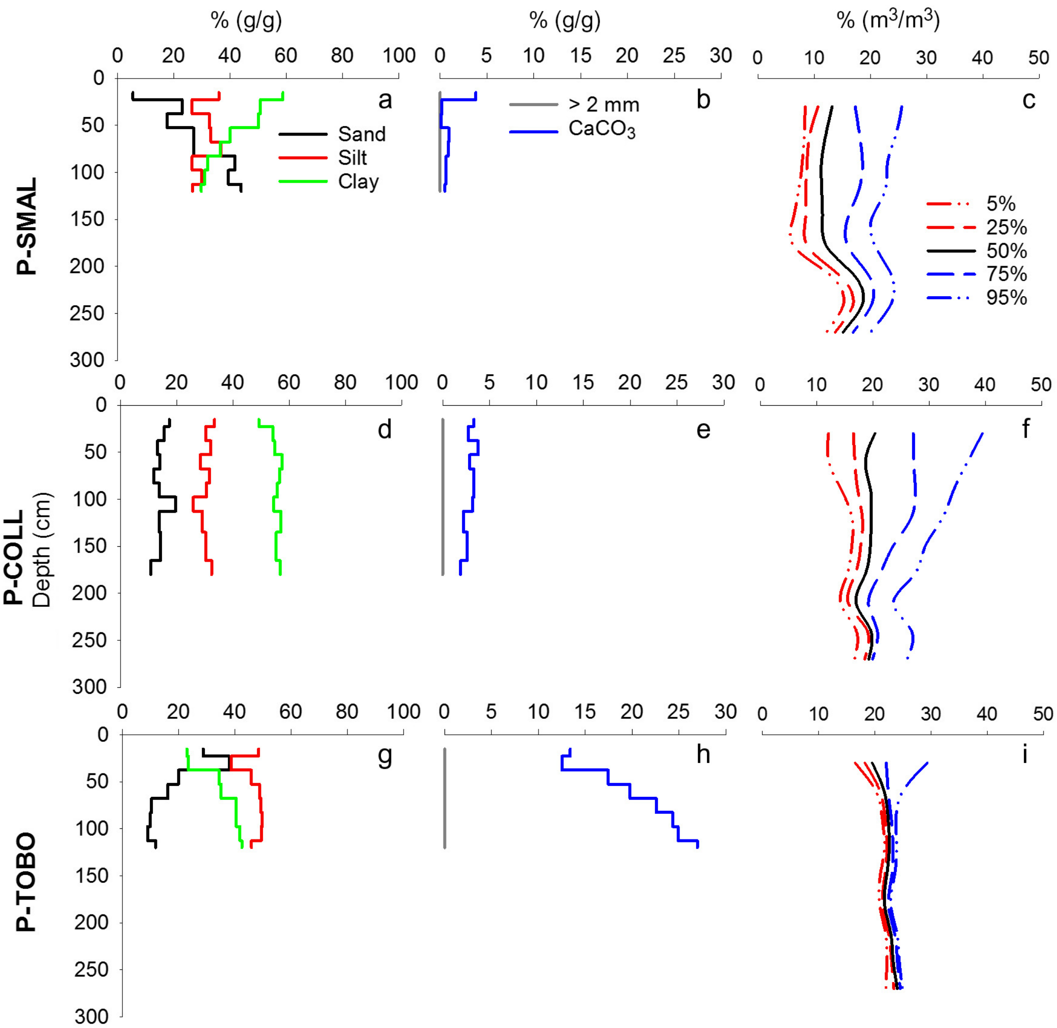

Fig. 7. Playa grassland location (Fig. 1) soil profile percent sand, silt, and clay (left column; a, d, and g); percent coarse fragment (>2 mm) and percent calcium carbonate ($CaCO_3$; middle column; b, e, and h); and location soil profile temporal quantiles (based on the entire study period; right column; c, f, and i). All soil property data from Crossland (2012).

median water contents ranging from 10% to greater than 20%. Both P-SMAL (Fig. 7c) and P-COLL (Fig. 7f) show a wide interquartile range for most of the measured depths, suggesting deep wetting and drying are fairly common. In contrast, P-TOBO has a very restricted interquartile range (Fig. 7i). P-SMAL soil water profile shows a marked increase in water content starting at about 200 cm, which is likely due to a change in soil properties (though below the depths characterized here; Fig. 7c; Appendix S2: Fig. S7).

Soil water patterns through time also show that deep wetting of greater than one meter is common at some playa grassland locations (Fig. 8). The wet periods, evident by the greater precipitation (Fig. 8a) and normalized SPEI (Fig. 8b), translate fairly predictably into wetter soil moisture conditions in P-SMAL (Fig. 8c) and P-COLL (Fig. 8d), often with moisture percolating to great depths (especially following 1991–1992, 2004–2005, 2006–2007, and 2014 wet events). Deep wetting is less common in P-TOBO, likely due to less run-on from the much smaller watershed of P-TOBO than the other playa grasslands. Indeed, flooding of P-COLL and to a lesser extent P-SMAL inhibited the

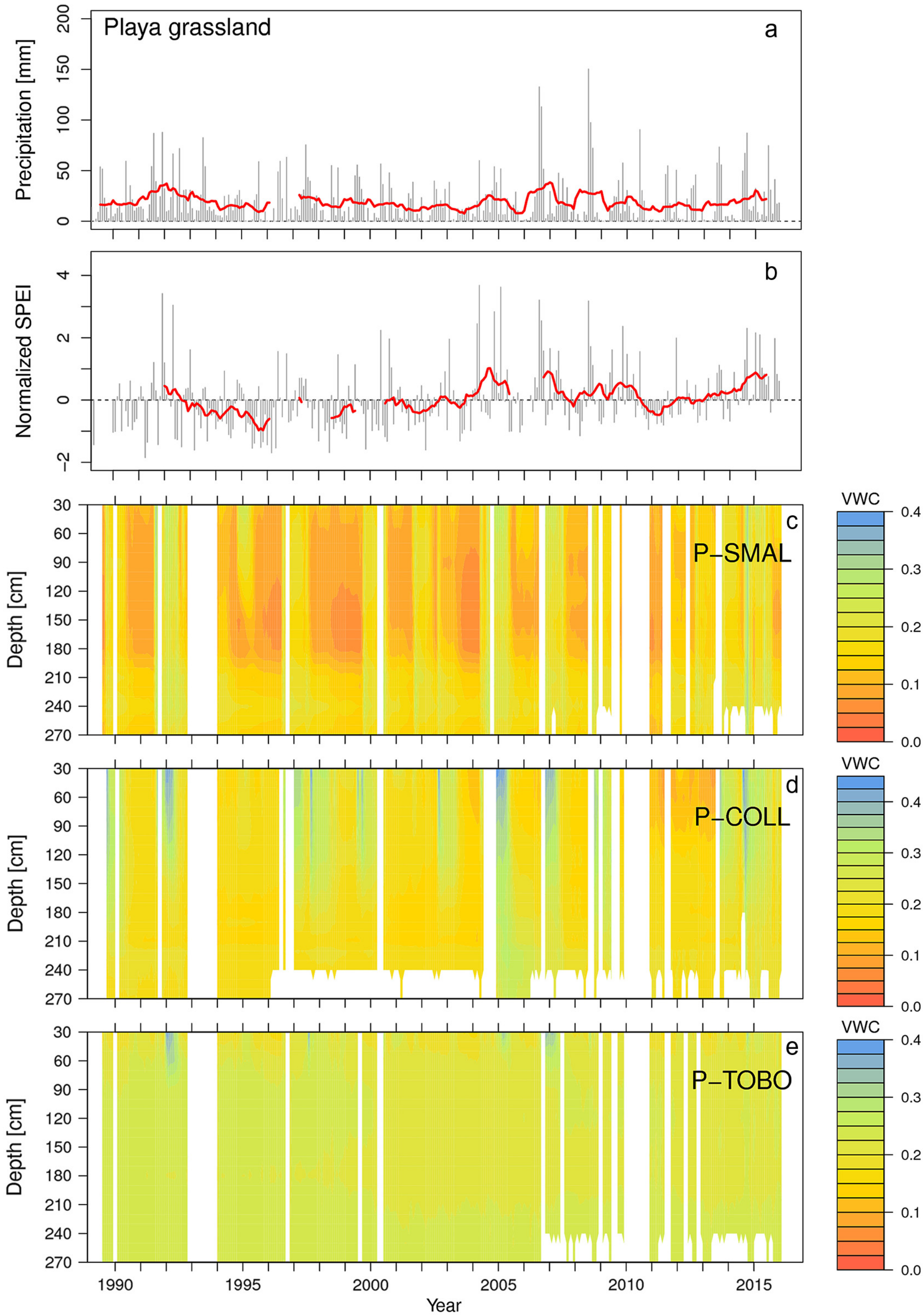

Fig. 8. Playa grassland location (Fig. 1) average monthly precipitation (a) and Standardized Precipitation Evapotranspiration Index (SPEI; b) and location mean volumetric water content (VWC; b, c, d). Red lines are 13-month mean precipitation (a) and 5-month mean SPEI (b). Color ramp scales of VWC vary for each location from zero to the maximum location mean value observed.

monthly measurements during several periods (e.g., 2004, 2006, 2008, and others) with standing water persisting for days to months. A notable feature of soil moisture at P-TOBO is very slow drying of the moisture at 90 and 120 cm following the wetting in 1992–1993 and again in the years following 2006 (Fig. 8e). Similarly, dry conditions at depth in P-SMAL were observed during the relatively dry periods in 1996, 1999, and 2004–2005 (Fig. 8c).

*Water dynamics in tarbush shrublands.—*The soil profiles in the tarbush shrublands are marked by clay and carbonate accumulation (Table 1, Fig. 9; Appendix S2: Figs. S10–S12). Maximum clay accumulation (argillic horizons) occurs generally between 50 and 100 cm depths which are closely followed by horizons with high calcium carbonate (calcic horizon). All soils include large amounts of subsurface coarse fragments (>2 mm), which typically correspond to the depths of high carbonates. Tarbush location soil water profiles are highly depth-variable, closely tracking soil properties. T-TAYL soil moisture (Fig. 9c; 75th quantile and drier) displays a marked increase between 30 and 90 cm followed by drier conditions at 120 and 150 cm, potentially due to high clay and

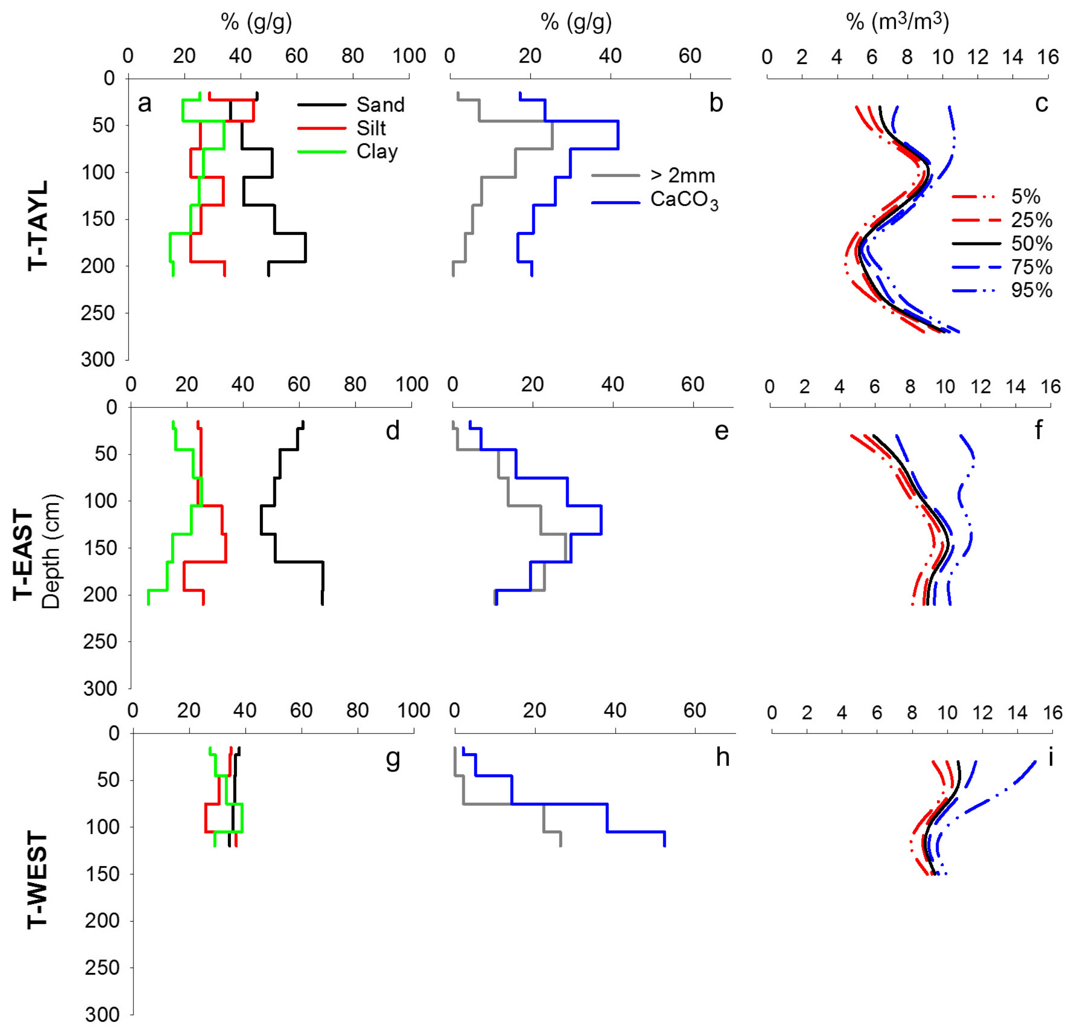

Fig. 9. Tarbush shrubland location (Fig. 1) soil profile percent sand, silt, and clay (left column; a, d, and g); percent coarse fragment (>2 mm) and percent calcium carbonate ($CaCO_3$; middle column; b, e, and h); and location soil profile temporal quantiles (based on the entire study period; right column; c, f, and i).

carbonates at 60 cm (Fig. 9a, b; Appendix S2: Fig. S10). Soil moisture at T-EAST follows a similar pattern (Fig. 9f), with most soil water quantiles (75th and drier) increasing down to a maximum slightly below the maximum clay and carbonate depths (~120 cm; Fig. 9d, e; Appendix S2: Fig. S11). The depth patterns in soil moisture at T-WEST are somewhat different, with water contents generally greater at the shallow (30 cm) depth than at other depths in the top 150 cm (Fig. 9i). The drier conditions at T-WEST between 90 and 150 cm are potentially attributable to the abrupt increase in coarse fragments and carbonates at 90 cm (Appendix S2: Fig. S12).

Depth patterns of soil water content through time at the tarbush shrublands show that appreciable wetting below about 60 cm occurred at all three locations only a few times (1991–1992, 2004–2005, and 2006–2007; Fig. 10) during periods with elevated precipitation (Fig. 10a) and SPEI (Fig. 10b). T-EAST and T-WEST recorded some additional deep wetting not observed at T-TAYL (in 2008, 2012, 2013, and 2014). T-EAST shows the clearest evidence for very deep wetting (>120 cm) at points over the period (Fig. 10d). During the relatively dry decade between 1994 and 2004 (Fig. 10a, b), no wetting events percolated below 60 cm and deep soil moisture decreased slightly.

*Water dynamics in mesquite shrublands.—*Profiles of soil properties and soil water statistics from the mesquite shrublands showed extreme contrasts between inter-dune and coppice dune microsites (Fig. 11; Appendix S2: Figs. S13, S14). The upper depths of the dune soils are generally sandier in texture and relatively free of carbonates and coarse fragments compared to inter-dune locations (left three columns Fig. 11). Inter-dune locations demonstrated strong depth variation in texture, coarse fragments, and soil carbonates beginning relatively near the surface (top 50 cm and deeper). In contrast, dune locations show less variation in these properties (right three columns Fig. 11). M-RABB shows the strongest dune to inter-dune contrast with the abrupt increase in soil carbonates occurring at ~200 cm in the dune (Fig. 11e) and beginning to show up at ca. 100 cm in the inter-dune (Fig. 11b). There is a similar pattern in M-NORT, with a clear carbonate increase at ca. 100 cm in the dune (Fig. 11k) and at 50 cm in the inter-dune (Fig. 11h). Soil property profiles in the inter-dune and dune at M-WELL are the most similar, with only minor differences in the depth profiles of texture and carbonates apparent.

Soil water profiles reflect differences in soil properties between dune and inter-dune locations (Fig. 11). Soil water contents in the well-developed coppice dunes of M-RABB (Fig. 11f; Appendix S2: Fig. S13) and M-NORT (Fig. 11I; Appendix S2: Fig. S14) are often very dry in the top 60 or 90 cm and at 30 cm at M-WELL (Fig. 11r; 75th percentile and drier). Dune soils at M-RABB and M-NORT also exhibit relatively small interquartile range (between 95th and drier quantiles), suggesting large wetting events in these very sandy soils are very brief and/or infrequent. Interquartile ranges for dune locations at M-WELL are much larger, particularly at 60 cm, which corresponds to an increase in clay, carbonates, and coarse fragments. Soil water contents in the top meter of inter-dune locations at M-RABB (Fig. 11c) and M-NORT (Fig. 11l) are wetter than similar depths in the dunes in all quantiles, while the dune and inter-dune locations at M-WELL are more similar. Inter-dune locations at M-RABB and M-NORT also exhibit a wider interquartile range between the wettest quartile (95th percentile) and drier quantiles than observed in the dunes, with a maximum range two to three times larger. As observed in other ecosystem types, these peak soil water contents (across quantiles) correspond to peaks in soil carbonates and soil fines that occur within the top 1–2 m.

Examination of temporal patterns in mesquite shrubland soil water dynamics reveals broad similarities in patterns of wetting and drying across locations and within inter-dune (Fig. 12) and dune locations (Fig. 13). In the inter-dune depths measured, all three locations showed pronounced wetting in response to the wet periods that occurred in 1991–1992, 2004–2005, and 2006–2007. Dune locations also recorded wetting in these periods, though the absolute increases in VWC are less in dune than inter-dunes, and evidence of these deep wetting events is gone within ~1 yr (Fig. 13). Across the study period, the 30 and 60 cm depths in both interspace and dune locations have high temporal variation in response to climate fluctuations. However, conditions are considerably drier in dunes (Fig. 13) than comparable depths in the inter-dunes, with

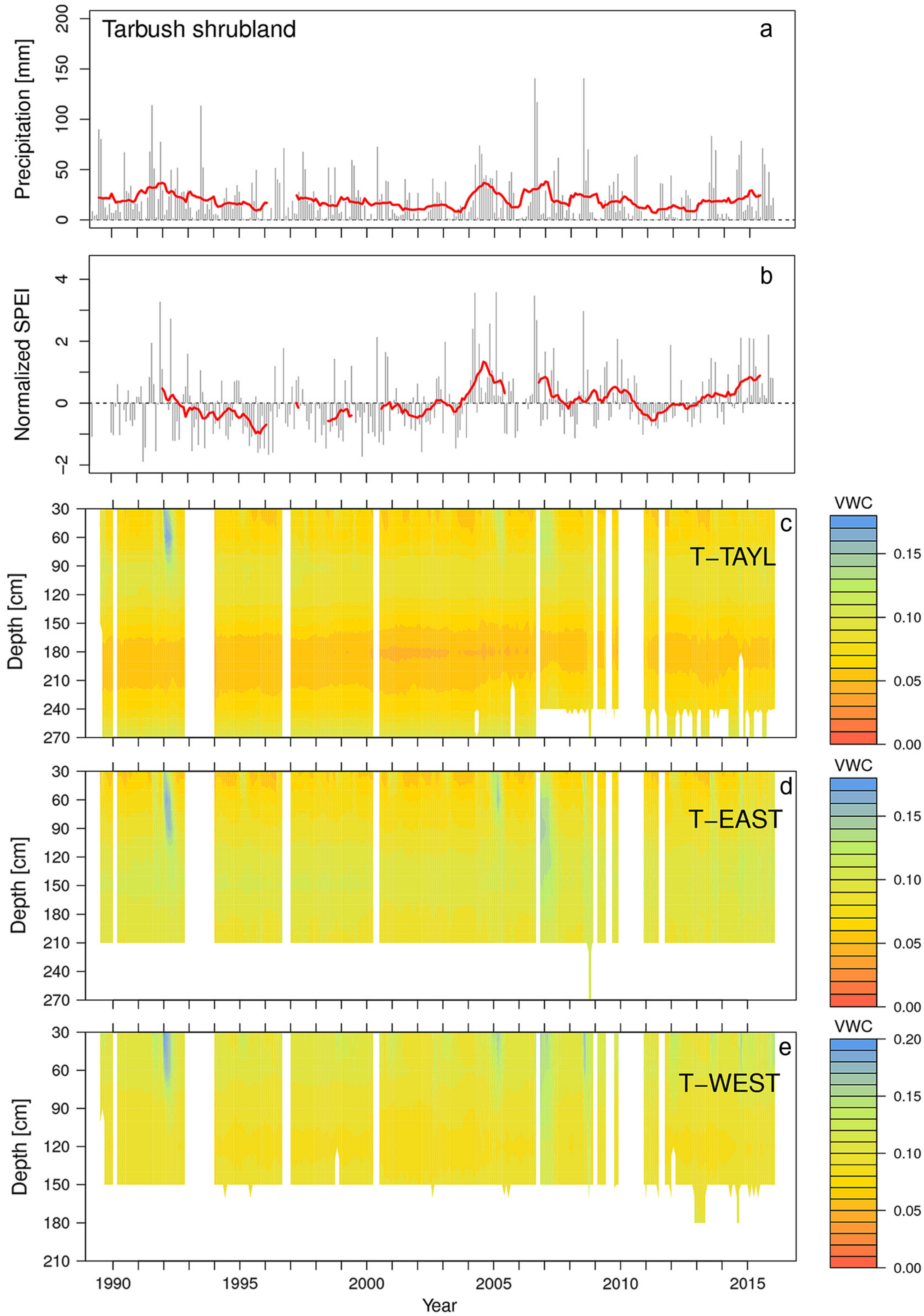

Fig. 10. Tarbush shrubland location (Fig. 1) average monthly precipitation (a) and Standardized Precipitation Evapotranspiration Index (SPEI; b) and location mean volumetric water content (VWC; b, c, d). Red lines are 13-month mean precipitation (a) and 5-month mean SPEI (b). Color ramp scales of VWC vary for each location from zero to the maximum location mean value observed.

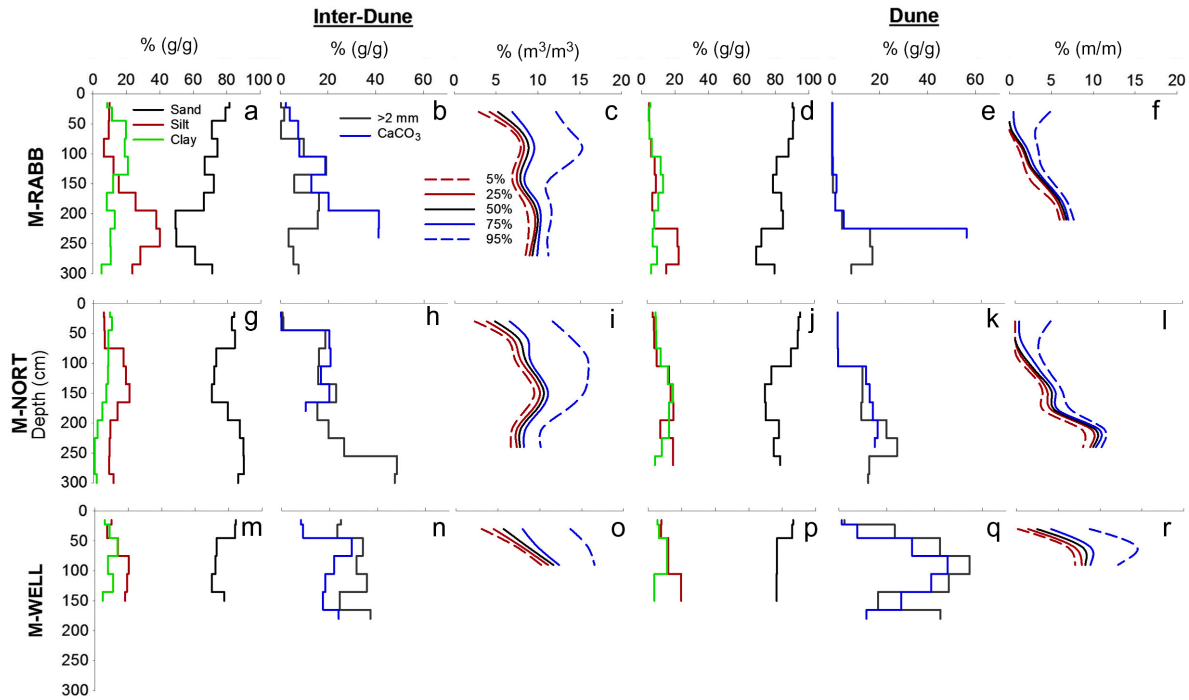

Fig. 11. Mesquite shrubland location soil profile percent sand, silt, and clay (a, d, g, j, m, and p); percent coarse fragment (>2 mm) and percent calcium carbonate ($CaCO_3$; b, e, h, k, m, and q); and soil water quantiles (over the whole study period; c, f, i, l, o, and r). Due to strong soil differences between coppice dunes and inter-dune locations, data are shown separately for measurement locations done in the inter-dune and dunes.

noticeable very dry conditions in the dunes during the warm dry decade from 1994 to 2004 (Fig. 12).

Objective 2: Soil water dynamics and seasonal variability in climate

Analysis of the association between VWC and 1- to 18-month time windows of SPEI for the creosotebush shrubland locations reveals the generally stronger association (steeper slope) during the spring across most depths (Fig. 14). Associations between SPEI and VWC in summer were generally weaker (lower slope) and the winter had few significant ($P < 0.01$) associations for SPEI periods of <6 months. At C-GRAV and C-CALI, strong associations were generally limited to the shallowest depths. C-SAND VWC–SPEI were generally higher than those at C-GRAV and C-CALI across depths, with even strong associations at a depth of 180 cm. Additionally, each location has a similar time-lag of associations, with significant and higher slope associations generally detected for winter moisture after averaging 8–10, 6–7 months in the spring, and 4–5 months in the summer.

In the upland grasslands, there is also a concentration of high association of VWC with SPEI in the spring (Fig. 15), but with high associations occurring at some depths in both winter and summer. At G-SUMM, the strongest associations (slopes) are for longer averages of SPEI (8–18 months) at shallow and moderate depths (30 and 90 cm) in the winter and spring. For G-BASN, the high associations are limited to the shallow (30 cm) depths, with some intermediate slope estimates for SPEI averaged over the previous 11–14 months prior to winter and spring measures. G-IBPE had the highest associations of VWC at all depths and SPEI, especially with SPEI averaged over 8–14 months in the winter and 6–18 months in the spring. In all upland grasslands, associations between median summer VWC and SPEI was generally weak (low slope), with the exception of longer SPEI windows at G-IBPE.

Playa grasslands had some of the highest VWC–SPEI slope estimates, while also displaying

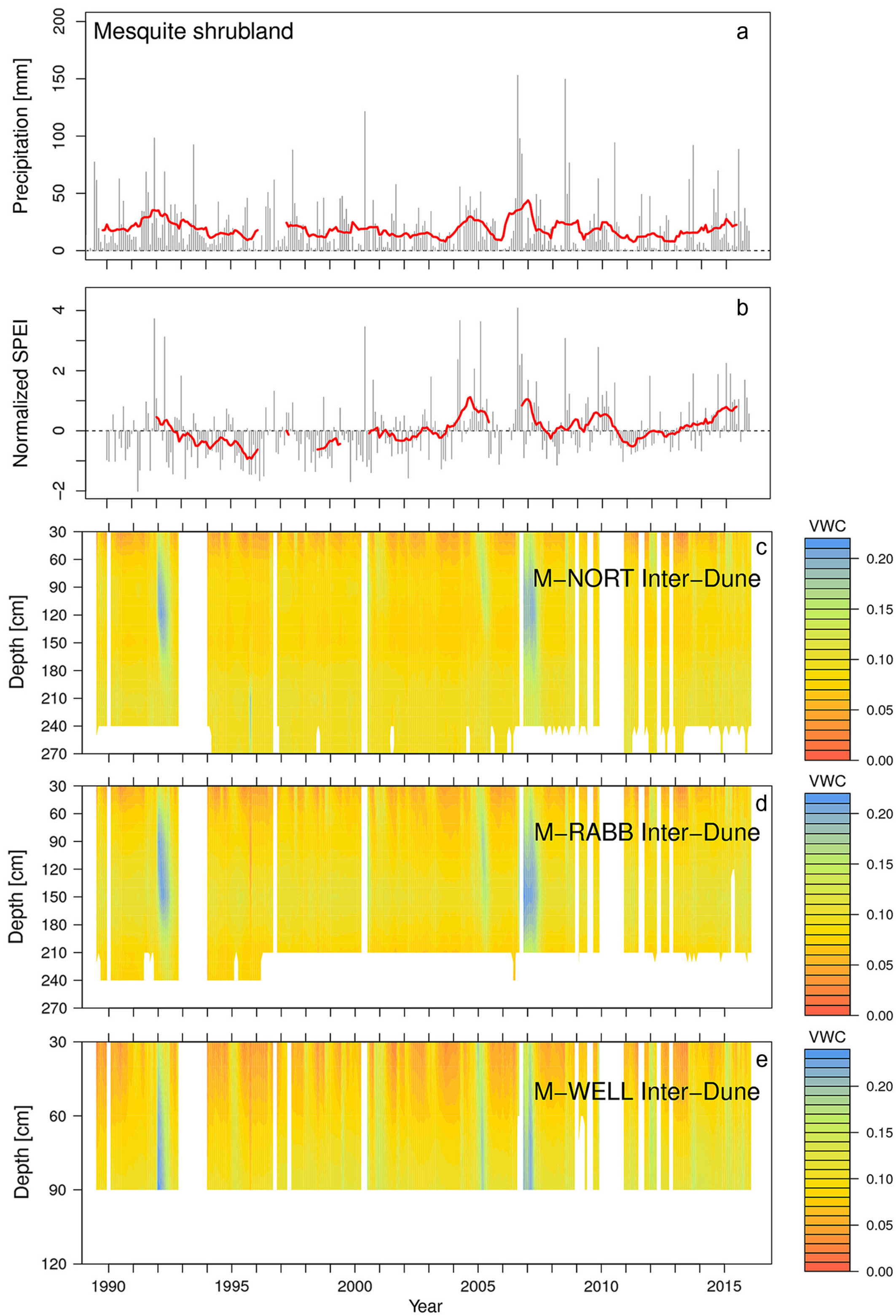

Fig. 12. Mesquite shrubland location (Fig. 1) average monthly precipitation (a) and Standardized Precipitation

(Fig. 12. *Continued*)
Evapotranspiration Index (SPEI; b) and inter-dune mean volumetric water content (VWC; b, c, d). Red lines are 13-month mean precipitation (a) and 5-month mean SPEI (b). Color ramp scales of VWC vary for each location from zero to the maximum microsite mean value observed. Due to strong soil differences between coppice dunes and inter-dune microsites (Fig. 11), data are shown separately for measurement stations in the inter-dune and dune microsites.

relatively few significant estimates overall (Fig. 16). At all three playa grasslands, there were fewer significant associations in the summer than other seasons and generally greater association in shallower than deeper depths. Median VWC–SPEI associations for P-SMAL and P-COLL were very similar across all depths in the winter and spring, with very high estimated slopes for winter VWC with SPEI averaged over previous 10–14 months. P-TOBO median VWC–SPEI associations were essentially limited to the 30 cm depth. At P-TOBO, soil water measured at depths of 90 cm and deeper had negative estimated slopes (ranging from −0.027 to −0.010).

Examination of relationships between median soil water conditions and SPEI in tarbush shrublands shows a strong association between winter and spring soil water and SPEI averaged over the previous 8–16 months (Fig. 17). At T-TAYL, significant median quantile regressions were limited to the 30 and 60 cm depths, while significant and higher slopes were detected at depths down to 90 and 120 cm at T-EAST and T-WEST. Relatively few significant associations between summer soil moisture and SPEI were detected. Patterns in soil water–climate associations are very similar in T-EAST and T-WEST and both also have fewer significant associations at intermediate and deep depths than shallow, particularly for shorter windows of SPEI (<6 months) with median and drier quantiles in the winter and spring.

Due to the extreme soil differences between dune and inter-dune sampling locations in the mesquite shrublands (Fig. 11), examination of the association of VWC and SPEI was done separately for these two strata (Fig. 18). In general, the inter-dune VWC had stronger association (higher slopes) with climate than dunes, which is attributable to the overall greater range in VWCs observed in the inter-dunes (Fig. 11). In the inter-dunes, the strongest associations (highest estimated slope over many SPEI windows) were between spring soil moisture in shallower depths and SPEI averaged over the previous 7–13 months. In contrast, in the dunes at M-NORT and M-RABB, there is much less season and depth variation in estimated VWC–SPEI slopes. M-RABB inter-dune soil moisture had the least association with climate in all seasons. The VWC–SPEI quantile associations are fairly similar in dune and inter-dune locations at M-WELL, likely due to the relatively similar soil properties of these two strata (Fig. 11).

Objective 3: Comparisons of soil water dynamics among ecosystem types

Plots of median VWC vs. the wet interquartile ranges by depth illuminate some of the interplay between soil properties and water dynamics (Fig. 19). Median VWC is strongly driven by soil pore size distribution, with locations and depths with finer textures having much higher median VWC (e.g., P-COLL and P-TOBO) and coarser textured lower median VWC (e.g., M-RABB and M-NORT dunes and C-GRAV). At the shallowest depth measured here (30 cm; Fig. 19a), wet interquartile ranges (p50–p95) are linearly associated with median VWC (likely driven by soil texture controls on soil water-holding capacity; Hillel 1998). However, with increasing depth, median and wet interquartile VWC become decoupled at many locations, particularly P-TOBO, G-BASN, tarbush shrublands, C-CALI, and M-WELL dunes (Fig. 19b–d).

The NMDS reached a stable solution in 35 iterations with a stress of 0.121, indicating that two axes explained 98.5% of the variance in the data. Plots of the two-dimensional ordination suggest soil water dynamics in the top meter are more organized around soil texture and geomorphic/topographic setting than ecosystem type (Table 1, Fig. 19e). The first axis is positively associated with dry and median quantiles (all depths; 5th, 25th, and 50th) and negatively associated with wet interquartile ranges at depth

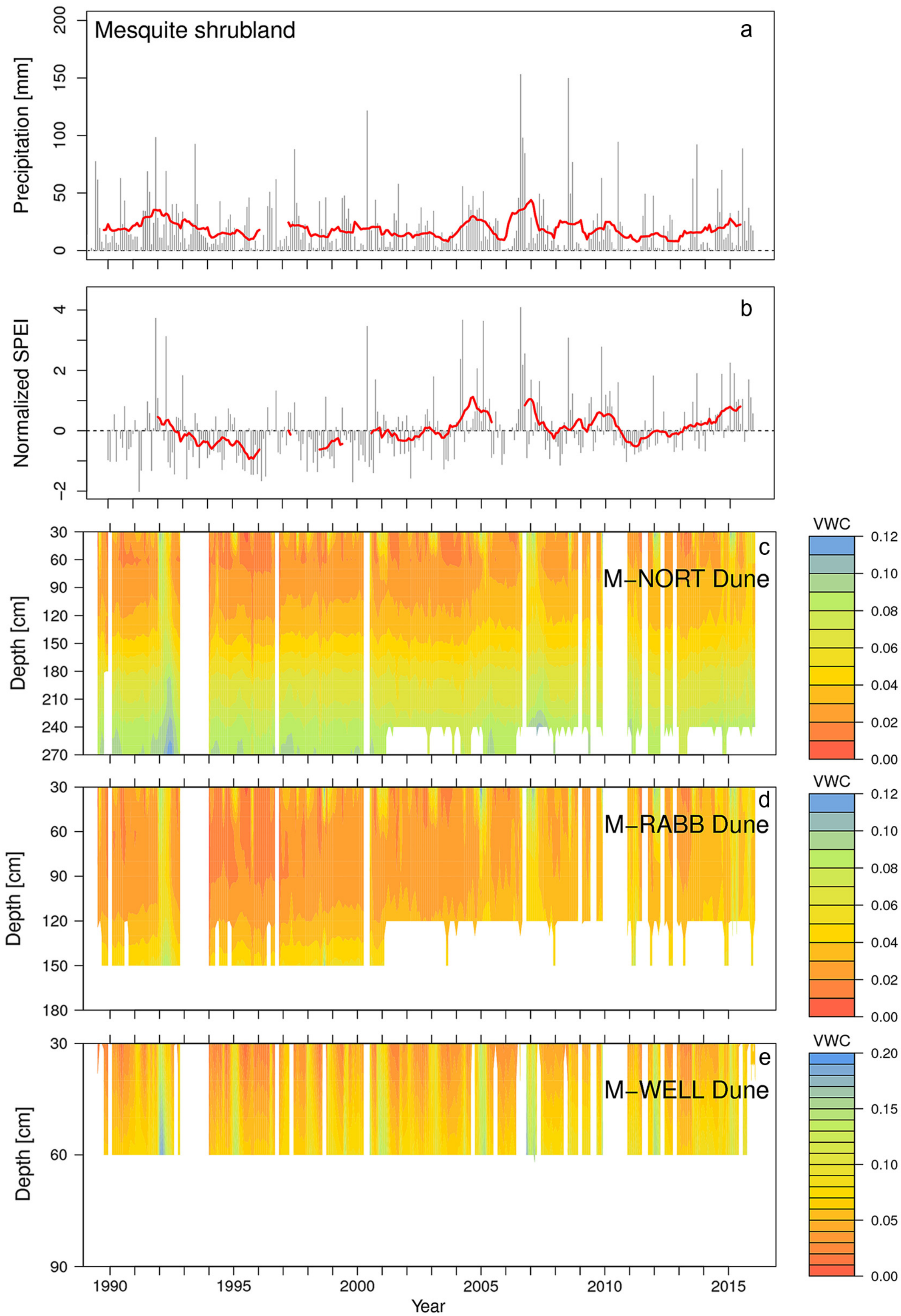

Fig. 13. Mesquite shrubland location (Fig. 1) average monthly precipitation (a) and Standardized Precipitation

(Fig. 13. *Continued*)
Evapotranspiration Index (SPEI; b) and coppice dune mean volumetric water content (VWC; b, c, d). Red lines are 13-month mean precipitation (a) and 5-month mean SPEI (b). Color ramp scales of VWC vary for each location from zero to the maximum microsite mean value observed. Due to strong soil differences between coppice dunes and inter-dune microsites (Fig. 11), data are shown separately for measurement stations in the inter-dune and dune microsites.

(primarily 90 cm). The second axis is positively associated with wet quantiles and interquartile ranges at 30 cm and negatively associated with interquartile ranges of 50th to 75th and 25th to 75th at 60 cm and 90 cm depths. This ordination effectively separates the study locations into those with large VWC dry quantile values and relatively small interquartile ranges (high axis 1 scores and near zero on axis 2), low median and drier water contents but large 30 cm interquartile ranges (low axis 1 score and high axis 2 score), and those locations with larger interquartile ranges at depth (low axis 2 scores; Fig. 19e). In general, this ordination based on the top meter places the very coarse-textured locations (and microsites) in the upper left quadrant (C-GRAV, C-SAND, G-SUMM, and the dune microsites of M-RABB and M-NORT), the fine-textured locations clustered on the right (and near zero on axis 2; tarbush shrublands, P-TOBO, and G-BASN), and then locations that have either coarse surface textures with finer subsurface horizons (G-IBPE, M-WELL, and inter-dune microsites at M-RABB and M-NORT) or playa grasslands characterized by high amounts of run-in water in the bottom left quadrant (Fig. 19).

Discussion

Water has long been recognized as a critical limiting resource shaping the structure and function of desert ecosystems. Questions regarding the patterns and controls of soil water dynamics in deep, heterogeneous desert vadose zones are an important aspect of ecological investigations

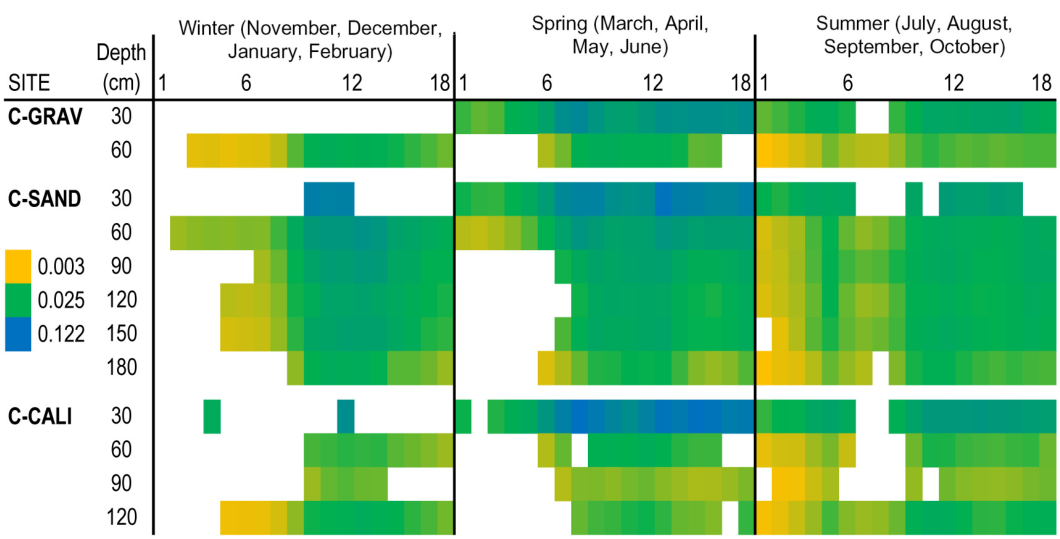

Fig. 14. Relationship between volumetric water content (VWC) in creosote shrublands and the Standardized Precipitation and Evapotranspiration Index (SPEI) over the previous 18 months, by season. Cells are colored by the estimated slope of the relationship ($P < 0.01$) between SPEI and median VWC (50th quantile; VWC in percent; color ramp values represent minimum, median, and maximum at each location). Columns represent the number of previous months' SPEI averaged (up to 18 months previous).

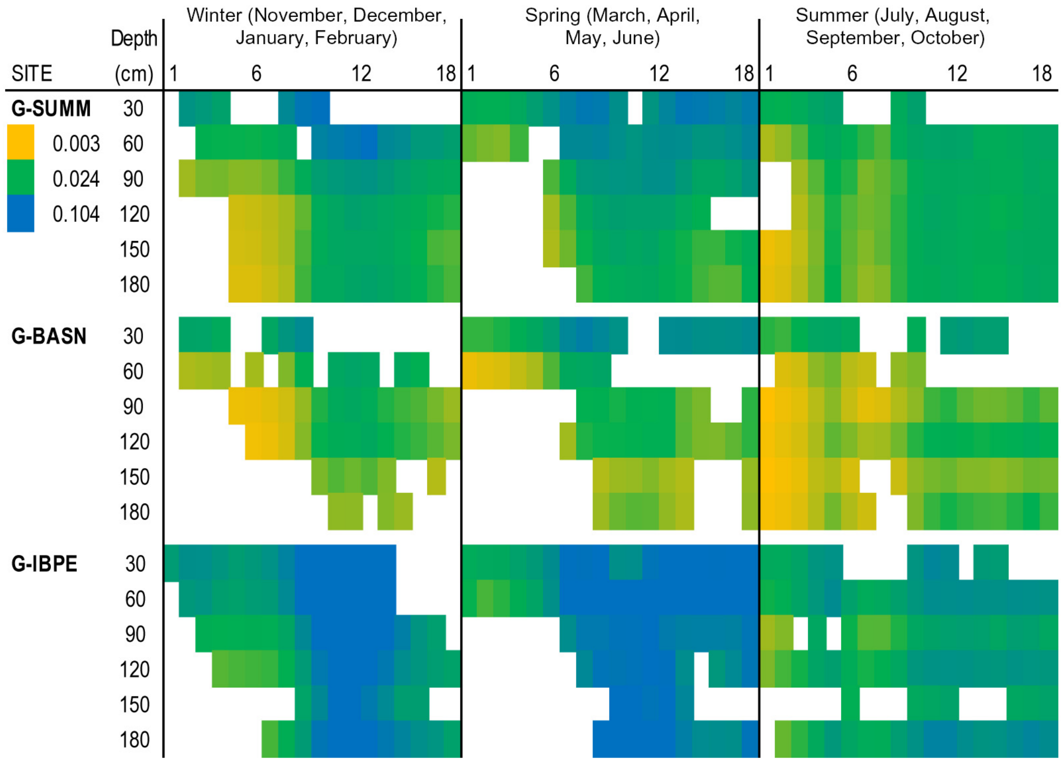

Fig. 15. Relationship between volumetric water content (VWC) at upland grasslands and Standardized Precipitation and Evapotranspiration Index (SPEI) over the previous 18 months, by season. Cells are colored by the estimated slope of the relationship ($P < 0.01$) between SPEI and median VWC (50th quantile; VWC in percent; color ramp values represent minimum, median, and maximum at each location). Columns represent the number of previous months' SPEI averaged (up to 18 months previous).

and theory in these ecosystems (Noy-Meir 1973, Walter 1973, McAuliffe 1994, Breshears and Barnes 1999, Snyder et al. 2006, Duniway et al. 2010*a*). The soil moisture data described here can be used to address some of the unknowns about ecohydrological processes through direct observation. The range of soil types, plant communities, years, and depths included in this work is unique in the to-date published desert ecohydrological literature. Previous to this study, knowledge of soil water dynamics in desert ecosystems was limited either to observation over shorter time scales, depths, or both (using direct or indirect measurements; Hamerlynck et al. 2002, Gutierrez-Jurado et al. 2006, Snyder et al. 2006, Duniway et al. 2010*a*); modeling exercises (Ogle and Reynolds 2004, Schlaepfer et al. 2011, 2012, Gremer et al. 2015); and use of naturally occurring or experimental tracers (Scanlon et al. 1999, 2005).

Importance of deep wetting events

An important insight from this study is that sustained, deep wetting events in drylands are episodic—essentially limited to three widespread, deep wetting events captured in the 27-yr record. Although climate regimes in deserts are generally characterized by low and variable amounts of precipitation, and there has been extensive research characterizing the pulse nature of ecosystem processes in these systems (Ogle and Reynolds 2004, Potts et al. 2006), there has been little observational documentation of deep wetting events over the decadal time scales shown here. The fall of 1991 through spring of 1992 was a particularly unique event in the Jornada record, with 12-month precipitation totals from June 1991 to May 1992 more than double long-term averages (554 mm; Fig. 2b). The importance of the 1991–1992 wet period on the Jornada was also noted by Reynolds et al. (1999), who observed deep

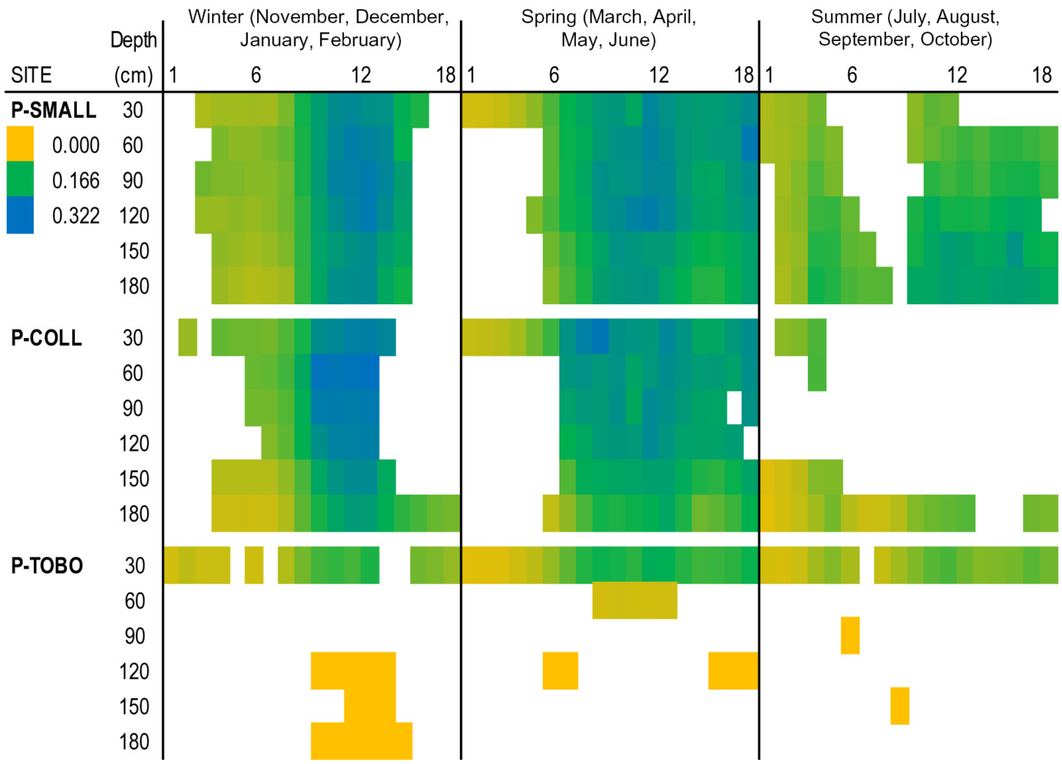

Fig. 16. Relationship between volumetric water content (VWC) at playa grasslands and Standardized Precipitation and Evapotranspiration Index (SPEI) over the previous 18 months, by season. Cells are colored by the estimated slope of the relationship ($P < 0.01$) between SPEI and median VWC (50th quantile; VWC in percent; color ramp values represent minimum, median, and maximum at each location). Columns represent the number of previous months' SPEI averaged (up to 18 months previous).

wetting occurred mostly in response to wet winters. The winter of 2004–2005 was also extremely wet, with approximately three times seasonal average precipitation falling during the winter months alone (156 mm; Fig. 2b). Although the Chihuahuan Desert is characterized as having hot, wet summers and dry winters and springs (Wainwright 2006), these two winter–spring season events translated into the most pronounced deep and widespread wetting events observed, with several study locations recording significant wetting to 270 cm. An extremely wet summer of 2006 (nearly double seasonal average precipitation of 372 mm; Fig. 2b) also resulted in significant wetting at many locations. However, unlike the wet–cool events, deep wetting during this summer event was not observed at all 15 locations, possibly due to fine-scale spatial heterogeneity in monsoon seasonal rainfall in this region (Petrie et al. 2014), high rates of evaporation during summer that limited deep percolation, or an inability to capture sustained wetting with monthly measurements (Fig. 2c; Wainwright 2006).

The importance of winter storms in the Chihuahuan Desert is surprising, given the low average precipitation in the winter (Wainwright 2006), especially compared to other warm deserts in North America (Sonoran and Mojave; Reynolds et al. 2004). Indeed, based on the intra-annual distribution of storms, it would be expected that winter recharge of deep soil depths is more important in the Sonoran and Mojave (Reynolds et al. 2004). These results support recent work highlighting the importance of winter precipitation for net carbon balance in the warm desert shrublands of North America (Biederman et al. 2018). However, more work is needed in our study sites to assess the degree these winter soil moisture recharge events may be influencing vegetation and ecosystem processes.

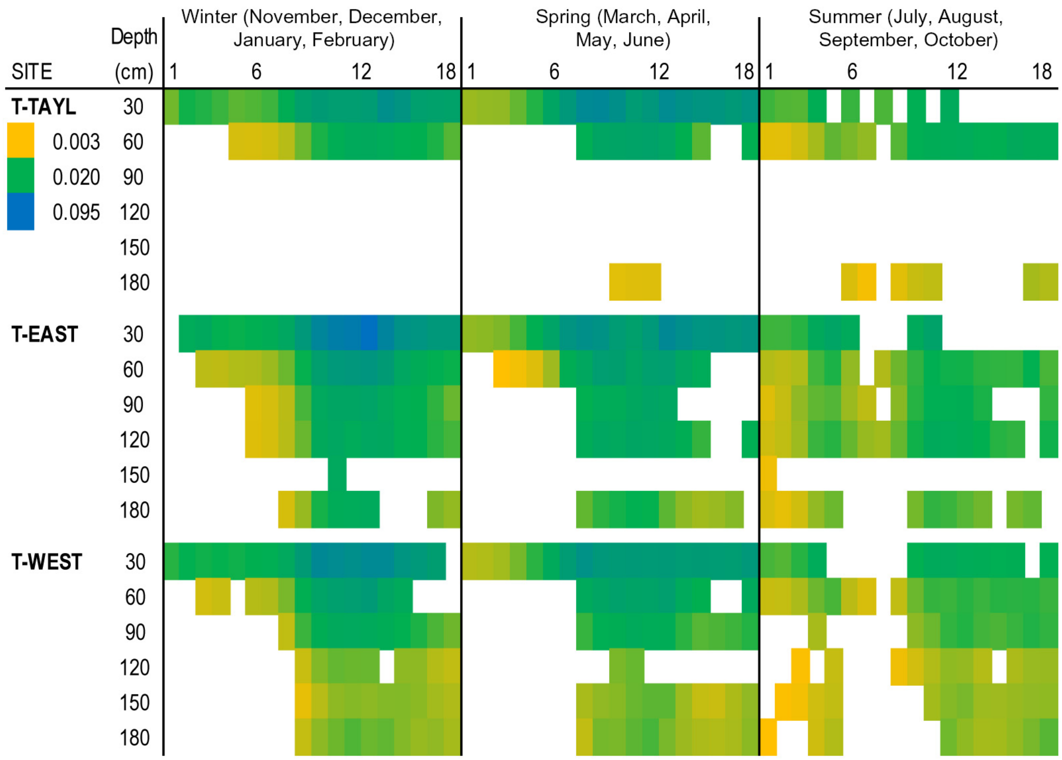

Fig. 17. Relationship between volumetric water content (VWC) at tarbush shrublands and Standardized Precipitation and Evapotranspiration Index (SPEI) over the previous 18 months, by season. Cells are colored by the estimated slope of the relationship ($P < 0.01$) between SPEI and median VWC (50th quantile; VWC in percent; color ramp values represent minimum, median, and maximum at each location). Columns represent the number of previous months' SPEI averaged (up to 18 months previous).

The occurrence of deep wetting (>100–200 cm) observed here could help clarify how the deep rooting systems of some desert shrubs have developed (Gile et al. 1997, Gibbens and Lenz 2001). The soil moisture residence times for deep wetting events varied widely, but generally ranged from 4 to 6 months in the creosotebush shrublands (e.g., 1991–1992; Fig. 4), from 10 to 12 months in the upland grasslands (e.g., 1991–1992; Fig. 6), and nearly 2 yr at the P-COLL playa grassland (e.g., 2004–2005; Fig. 8c; following several extensive flooding events in June, September, and October 2004). This finding corroborates past work in similar soils (Duniway et al. 2010*c*). These wet events were interspersed with dry periods with soil moisture levels at deep depths dropping to pre-event levels (and thus likely near the limit of plant extractable tensions). New shrub root growth occurred over the course of two weeks in response to water used to separate roots from soil (Gibbens and Lenz 2001). Thus, the relatively long soil moisture duration of several of these events may lead to the formation or expansion of deep root systems by shrubs during these infrequent, but widespread deep wetting events.

Grassland–shrubland comparisons

Over the previous 100–150 yr, shrub species have expanded into former perennial grasslands as a result of a combination of livestock overgrazing and severe drought, leading to declines in perennial grass cover on the Jornada and throughout the American Southwest (van Auken 2000, Gibbens et al. 2005). Changes from a more continuous cover of perennial herbaceous species to the patchy cover characteristic of shrublands has been shown to affect spatial patterns in soil nutrients, run-off and erosion processes, and other important shifts in ecosystem

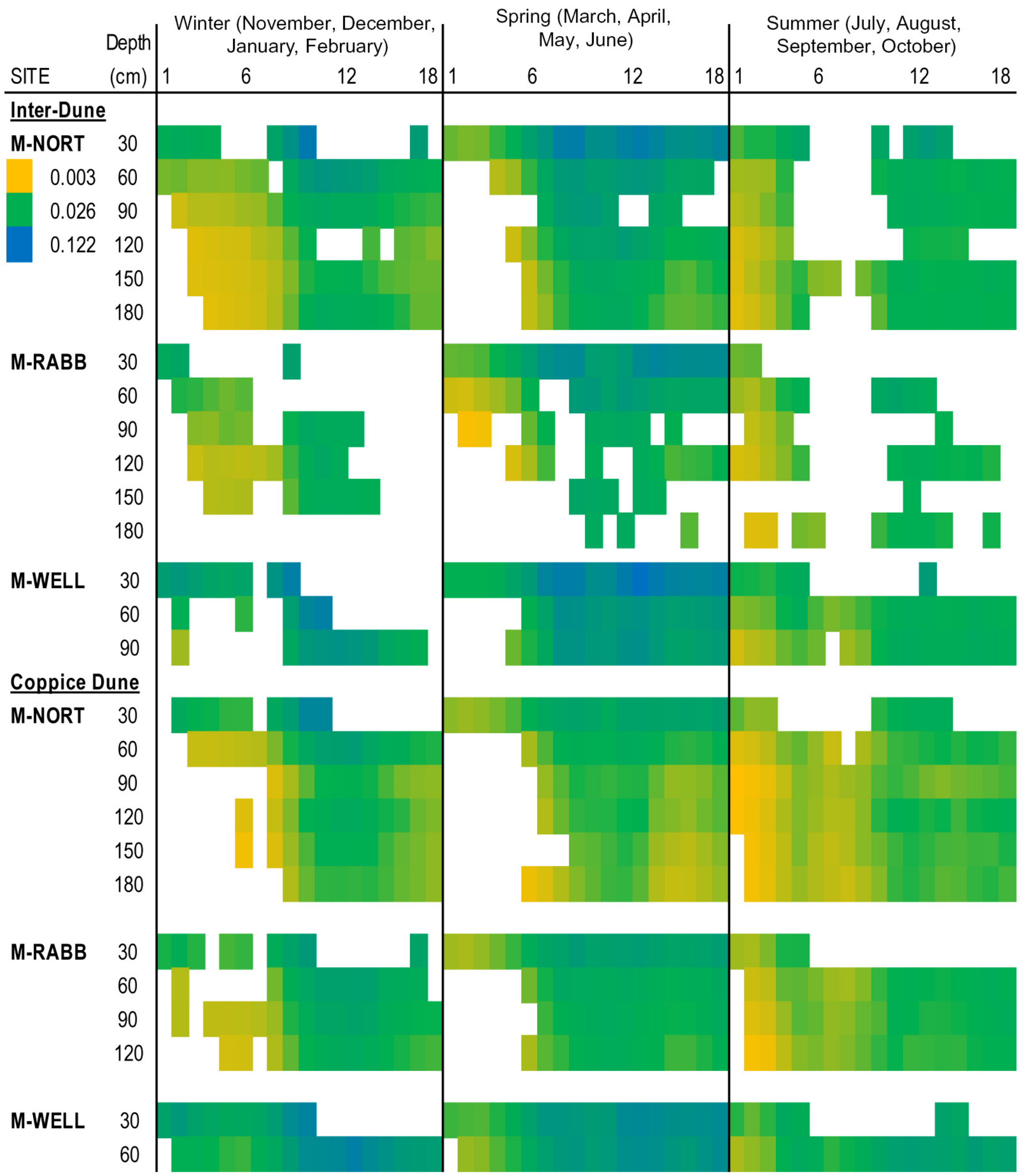

Fig. 18. Relationship between volumetric water content (VWC) at inter-dune and coppice dune locations at mesquite shrublands and Standardized Precipitation and Evapotranspiration Index (SPEI) over the previous 18 months, by season. Cells are colored by the estimated slope of the relationship ($P < 0.01$) between SPEI and median VWC (50th quantile; VWC in percent; color ramp values represent minimum, median, and maximum at each location). Columns represent the number of previous months' SPEI averaged (up to 18 months previous).

processes (Turnbull et al. 2010). The upland grasslands and associated shrublands in similar topographic and soil settings provide an opportunity to compare water dynamics between these alternative states.

Widespread encroachment and dominance of creosote and tarbush shrubs into former grasslands has been documented on the Jornada (Gibbens et al. 2005). Among the tarbush and creosotebush shrublands, reasonable comparisons

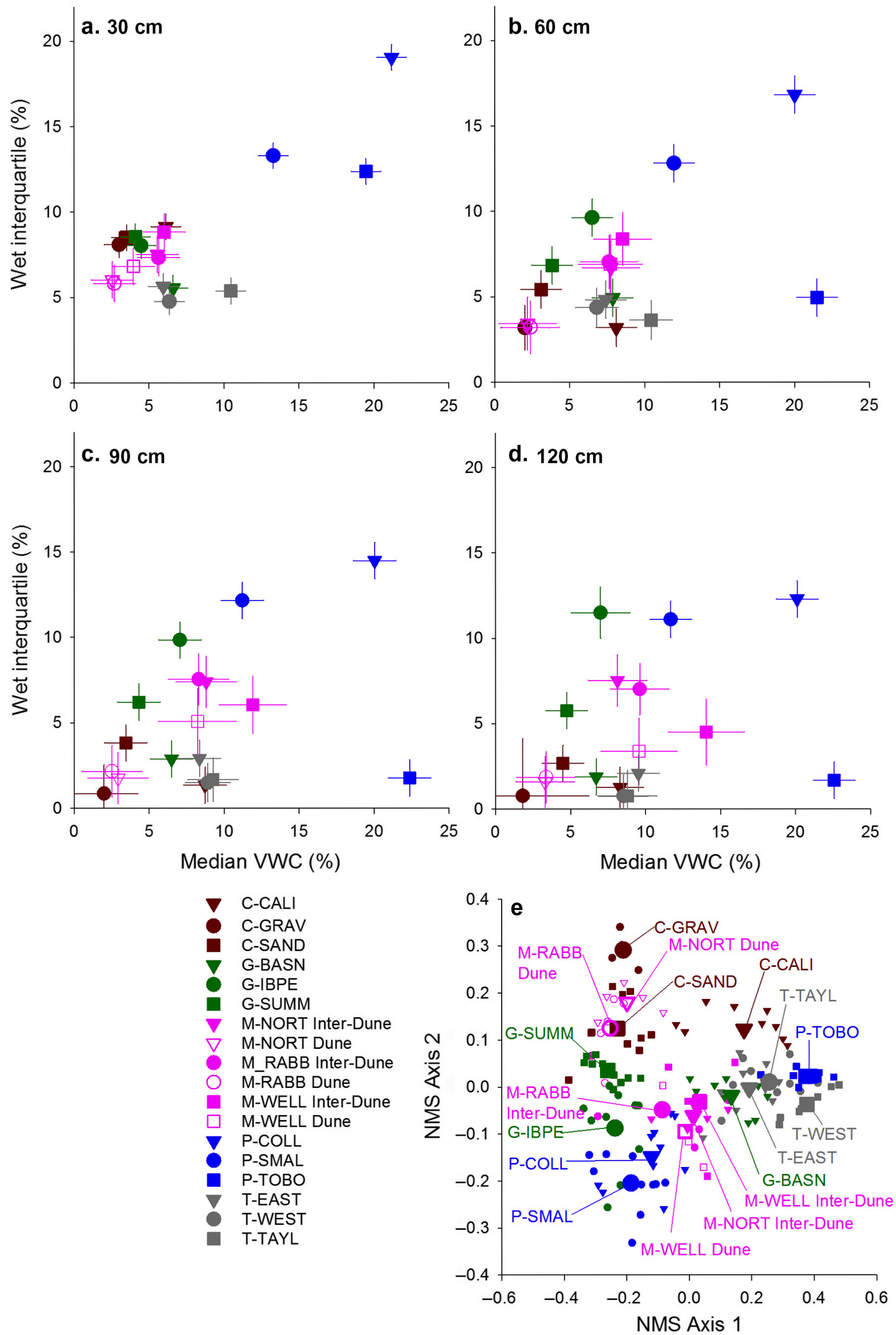

Fig. 19. Cross-location comparisons of volumetric water content (VWC) statistics. Plots of median VWC and

(Fig. 19. *Continued*)
wet interquartile ranges (50th to 95th) for depths of 30 cm to 120 cm (a, b, c, and d; error bars represent 95% confidence intervals of the mean) and an ordination of soil water statistics in the top meter of soil (30, 60, and 90 cm depths; e). In ordination panel, small symbols are axis scores of individual soil water measurement points (access tubes) and large symbols are mean axis scores for each location (or microsite for mesquite shrublands).

can be made between T-EAST vs. G-BASN and C-SAND vs. G-SUMM (based on soil profiles and landscape settings). In the 1858 Jornada vegetation maps recreated by Gibbens et al. (2005), the area where T-EAST is now located is classified as good grass, and although C-SAND is outside the mapped area, it is likely that C-SAND historically had much greater perennial grass cover as well (Stein and Ludwig 1979). Comparison of these paired shrubland–grassland depth profiles (Figs. 3f, 5c, f, 9f), temporal patterns (Figs. 4d, 6c, d, 10d), and VWC statistics (Fig. 19) provides little evidence that these locations in differing vegetative states systematically differ in soil water dynamics. G-BASN and T-EAST have similar median VWC and wet interquartile ranges (overlapping 95% CI; Fig. 19a–d) and similar ordination space (Fig. 19e). C-SAND and G-SUMM are also similar, but exhibit greater separation in wet quantile at depth (95% CI do not overlap at 90 and 120 cm depths; Fig. 19c, d) and do separate slightly along axis 2 in the ordination (Fig. 19e). Near-surface water dynamics were not documented here, and past work suggests that shallow moisture is likely to differ between shrublands and grasslands, both under vegetation and in interspaces (Ludwig and Tongway 1995, Bhark and Small 2003). It is possible that the greater wetting at depth observed in G-SUMM than C-SAND is attributable to plant–soil feedbacks, decreased connectivity of gaps between plant bases characteristic of grasslands (Schlesinger et al. 2000, Neave and Abrahams 2002).

One of the more dramatic grassland-to-shrubland transitions observed on the Jornada historically is that of black grama grasslands to mesquite coppice dunes (Hennessy et al. 1983, Gibbens et al. 2005), yet the impacts of grass loss and coppice dune formation on soil water dynamics have not been well documented (though see Hennessy et al. 1985). This loss of grass cover, increase in shrub cover, loss of soils in the intershrub areas, and deposition of soils under shrub canopies have resulted in dramatic changes in soil properties (Gile 1966), including soil fertility (Schlesinger et al. 1990). Excavations of mesquite coppice dunes revealed buried surface (A) horizons at depths of 60 cm at M-NORT (Appendix S2: Fig. S13), 40 cm at M-RABB (Appendix S2: Fig. S14), and deeper (Connin et al. 1997).

The soil water profiles from M-RABB and M-NORT (Fig. 11) suggest that the inter-dune locations are generally wetter, though the finer texture of the inter-dune soils restricts the availability of this moisture to vegetation (Hennessy et al. 1985, Hillel 1998). We also found a significantly larger wet interquartile range in M-RABB and M-NORT inter-dune than dune locations (95th and 50th percentile and 95% CI; Fig. 19), particularly at depths >30 cm. Desert soils are generally dry, lingering at or below typical wilting point (−1.5 MPa) for much of the year (Duniway et al. 2010*a*), suggesting that common water contents observed here are not readily plant available (e.g., 50th quantile). The spread between the 95th and 50th quantile in the coppice dunes at M-RABB and M-NORT is quite small, especially compared to the inter-dunes, suggesting the concept of islands of fertility may not extend to soil water availability (Schlesinger et al. 1990). Work by Duniway et al. (2010*c*) in a mesquite shrubland that has not developed significant coppice dunes suggests water dynamics under mesquite canopies is not different than those observed under grass patches. This is similar to observations here from M-WELL, which has minimal coppice dune development (though dunes have increased in size over the 27-yr study; J. Anderson, *personal observation*) and water dynamics between inter-dune and dune locations that are not different at most depths measured (overlapping 95% CI; Fig. 19a–d) and are similar in multivariate space (Fig. 19e). These results are similar to those of Hennessy et al. (1985), who found inter-dune locations to be wetter than mesquite coppice dune microsites but contrast the results of McAuliffe et al. (2007), who found that soil moisture stored in *L.*

tridentata coppice dunes enhanced shrub performance in the Sonoran. The importance of coppice dunes soil water for *L. tridentata* performance was partially attributed to low infiltration rates in the inter-dune soils, which is also likely an important attribute of the inter-dune soils described here (Hennessy et al. 1985).

Relationship between soil water dynamics and ecohydrological frameworks

Conceptual frameworks are an important tool for conveying complex biophysical relationships and interactions in ecological systems and have worked well in the field of ecohydrology (Walter 1973, Breshears and Barnes 1999, Turnbull et al. 2012). In an effort to relate the soil water profiles and VWC-SPEI associations in our study, we created broad groupings of locations based on spatio-temporal dynamics of soil water and climate linkages. Here, we summarize how these soils and locations fit with the two-layer hypothesis (Walter 1971). The two-layer hypotheses proposes that water resources in the soil profile can be roughly divided into two pools, shallow and available to species with dominantly shallow roots (herbaceous or woody species) or deep and potentially favoring deep rooted woody species over herbaceous (Browning et al. 2012).

First, a number of locations have water dynamics limited to the upper soil profile (e.g., primarily 30 cm depth) where we expect most plants will be competing for the same, shallow soil water resources that are typically closely coupled to recent climate events (Snyder et al. 2006, Monger et al. 2015) and potentially make these communities less resilient to prolonged droughts or delayed monsoons forecast under climate change (Cook and Seager 2013). These include the playa grassland P-TOBO, which has characteristics of a playa setting but does receive enough run-on moisture to overcome the fine surface textures that limit downward water movement. As the name implies, the three playa NPP locations are located in topographic lows within the basin and collect run-on water from surrounding lands. However, P-TOBO receives much less run-on water than the other two playas due to the size and topography of the contributing areas (P-SMAL and P-COLL flood fairly frequently, while P-TOBO rarely experiences standing water; J. Anderson, *personal observation*; Monger et al. 2006). Also in this group are the low productivity creosotebush shrublands, C-GRAV and C-CALI. These two locations are in a geomorphic erosional fan remnant where surface horizons have been stripped, leaving no to little soil on top of the calcic and petrocalcic horizons, which can limit downward soil water movement (Wondzell et al. 1987, Monger 2006). Furthermore, the networks of small rills and common pedestaled plants at these locations suggest high amounts of run-off which limits water penetration to deeper depths, and the high concentration of roots above the petrocalcic horizon at locations similar to C-GRAV reinforces the importance of shallow water for vegetation (Gibbens and Lenz 2001). The dune measurement locations in the mesquite shrublands of M-RABB and M-NORT also fall within this group. These coppice dunes have very sandy soils which limit water retention and facilitate rapid percolation of infiltrated precipitation, perhaps below the 270 cm depths of our study. However, the convex shape and steep side slopes of these coppice dunes (Appendix S2: Figs. S13, S14) likely result in quick initiation of run-off, evidenced by the lack of wetting at depth at these locations.

The second group of locations is characterized by highly dynamic soil profiles, with wetting events penetrating down to deep depths, and tight coupling of median soil water condition and climate. At these sites, plant species that are able to forage for deep water resources may have a competitive advantage when shallow soil moisture is unavailable, particularly during extended droughts (Cook et al. 2015). This group includes the very deep and coarse C-SAND and G-SUMM as well as the G-IBPE upland grassland and M-WELL mesquite shrubland. The two playa grasslands with larger contributing areas (P-SMAL and P-COLL) are also in this group. The more common deep penetration of wetting fronts in these locations suggests greater occurrence of high levels of soil moisture at depth, and some locations show strong association between this deep moisture and deviations in monthly SPEI (e.g., P-SMAL, P-COLL, and G-IBPE). We attribute deep water at C-SAND and G-SUMM to the very coarse textures (high sand and coarse fragment fraction), which leads to low water retention in the surface depths and high hydraulic conductivity (Hillel 1998). G-IBPE and M-WELL also have sandy surface textures but, unlike C-SAND and G-SUMM, have strong calcic/petrocalcic horizons starting at ~60 cm. The high water contents we found for depths that correspond to these horizons high in calcium carbonate support previous work that indicates percolating water can penetrate these cemented horizons and that absorbed water can be retained for long periods of time (Duniway et al. 2007, 2010*c*).

Finally, we identified an intermediate group of locations with both shallow and moderately deep soil water dynamics, where soil water does penetrate to some depth but not generally greater than 90 or 120 cm. This group includes locations with primarily fine surface and subsurface textures due to topographic position and age (e.g., Alluvial Fan and Fan Piedmont locations; Table 1; T-EAST, T-WEST, T-TAYL, G-BASN; Monger et al. 2006) or truncation of sandy surface horizons (wind worked inter-dune M-RABB and M-NORT; Table 1; Gile 1966, Monger 2006). At these locations, wetting fronts from larger events do percolate to depths greater than 30 cm but generally do not penetrate below 90 or 120 cm. The correspondence of the lower limit of wetting observed here and general concentration of tarbush roots in similar soil types (Gile et al. 1998, Gibbens and Lenz 2001) suggests a close matching of tarbush root distribution to the ecohydrologic characteristics of these soils. The greater water availability at depth in the M-RABB and M-NORT inter-dune than dune locations, coupled with the wide horizontal spread of mesquite dunes (Gile et al. 1997), suggests that deeper water within shrub interspaces is important (Breshears and Barnes 1999).

Future research

We view the new and updated (from a previous book chapter; Snyder et al. 2006) insights on soil moisture dynamics of these systems presented here as representing just a fraction of the possible ecological, hydrological, and ecohydrological research questions that can be addressed with this extensive dataset (Newman et al. 2006). The NPP location soil moisture monitoring design was strongly influenced by the recent islands of fertility concepts (Schlesinger et al. 1990). The results from the mesquite shrublands presented here suggest that coppice dunes are drier than the surrounding interspace and maybe viewed as desert islands where the shrubs are perhaps foraging for water in the surrounding interspaces (Gile et al. 1997), though more work is needed to test this hypothesis and other hypotheses regarding plant–soil feedbacks and plant–patch dynamics (Svejcar et al. 2014, Bestelmeyer et al. 2015).

Interpretation of soil moisture observations is often hampered by uncertainty regarding the bioavailability of measured soil water resources (when measured as volumetric water content; Romano and Santini 2002). We propose that the common (median or modal) volumetric water contents that we observed are likely at tensions that are not readily plant available. Future studies that couple measures of the characteristic soil moisture release curves with these long-term observation of soil moisture may reveal a statistically or simulation-driven approach for determining the lower limits of plant extractable water applicable to long-term field investigation.

A changing or non-stationary climate requires a modeling approach for forecasting the range of potential future conditions. It is unlikely that our current ability to parameterize and model soil water dynamics is sufficient to account for the extreme variability in soils observed here. Indeed, the complex soil-geomorphic template (Monger and Bestelmeyer 2006), the importance of uncommon but important processes such as preferential flow (Simunek et al. 2003), and associated impacts on ecohydrologic processes (Monger et al. 2015) suggest a completely process-based approach would be extremely difficult (e.g., independently parameterizing each process at each location at each depth). The development of models that can simulate future conditions in these complex soil systems, and can utilize statistical calibration to capitalize on long-term field data, remains a major component of both large- and small-scale land surface modeling initiatives in ecological systems (Keane et al. 2015, Revermann et al. 2016).

Conclusions

Long-term soil water data across 15 locations at one 100,000 ha research site in the Chihuahuan Desert provide an opportunity to examine in detail the properties and processes of the desert critical zone—the near-surface environment that supports life on the Earth's surface (Brantley et al. 2007). We provide further evidence for the episodic or pulse nature of soil moisture in desert environments (Schwinning et al. 2004) and demonstrate that the response of soil moisture in complex desert soils to pulses of moisture varies among soils, landscape settings, and ecosystem types. Multi-decadal, basin-scale studies are critical for understanding these strongly water-limited and spatially and temporally complex desert ecosystems. Forecasts for warmer and more variable climates in deserts globally and the high importance for ecosystem services provided by deserts over much of the globe further underscore the importance of ecohydrological investigations in these systems.

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Supporting Information

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