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ORIGINAL ARTICLE

Soil Moisture Partitioning Between Under Canopy and Interspace Environments in Shrublands of the Northern Chihuahuan Desert

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Abstract

Soil moisture is a key link between hydrologic and ecologic processes in desert shrublands. Understanding how soil moisture is spatially distributed in desert shrublands provides valuable insights into how shrubs use and impact limiting water resources, and how shrublands may respond to future meteorological and climate change. Our goals were to determine how soil moisture is partitioned between soil volumes under canopies and in the bare soil interspaces across multiple desert shrublands, and to evaluate the roles of physical soil properties, shrub-type characteristics, meteorology, and measurement resolution in influencing and observing variation in soil moisture partitioning. Utilizing two long-term soil moisture datasets (monthly resolution, 30 years, whole soil profile measurements; and 30 min resolution, 10 years, 10–30 cm measurements), we compared soil moisture partitioning across nine northern Chihuahuan Desert shrubland sites (three sites dominated by creosotebush [*Larrea tridentata*], three by honey mesquite [*Prosopis glandulosa*], and three by tarbush [*Flourensia cernua*]) in the Jornada Basin, southern New Mexico, USA. Over 30 years, monthly, whole profile data showed that soil moisture in mesquite shrublands was consistently higher in bare soil interspaces compared to under canopies, whereas soil moisture under and between shrubs was more similar in creosotebush and tarbush shrublands. Physical soil properties were linked as explanatory variables of long-term soil moisture partitioning (monthly whole profile dataset), whereas 30-minute data showed that shorter-term periods of higher precipitation promoted greater near surface soil moisture (10–30 cm) in bare soil interspaces that was not captured at monthly time steps. Thus, although the long-term average partitioning of soil moisture in these shrublands is strongly controlled by soil physical properties, soil moisture partitioning varies at

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shorter timescales (daily to weekly) in response to precipitation events. Moreover, shrub-type characteristics influenced soil moisture partitioning, with dense and tall mesquite shrubs having lower under canopy soil moisture than tarbush, and root architecture potentially influencing partitioning across creosotebush sites. These results illustrate diversity in soil moisture partitioning both between and within shrublands of the northern Chihuahuan Desert, and elucidate how physical soil properties, shrub-type characteristics, and meteorological variation interact to shape their soil moisture dynamics.

Key words: Plant canopies; Fertility islands; Desert shrubs; Soil water; Stemflow; Semiarid ecosystems; Soil moisture dynamics.

Highlights

- Soil moisture partitioning shows variability across three shrubland ecosystems.
- Soil properties, shrub-type characteristics, and meteorological factors influence moisture partitioning.
- The ''fertility islands'' concept is challenged regarding soil moisture.

Introduction

Drylands comprise approximately 45% of the Earth's land surface (Prăvălie 2016) and are a pivotal component of terrestrial ecosystems, providing considerable ecosystem services to natural and human communities (Poulter and others 2014; Lal 2019). The most abundant land cover types in drylands are grasslands, barren areas, and shrublands (Maestre and others 2021). The ecological state transition of native grassland to shrubland, known as shrub encroachment, is occurring across global drylands. This phenomenon has received considerable research attention due to the ecological, economic, and ecosystem service disruptions associated with these transitions (Eldridge and others 2011; Naito and Cairns 2011; Sala and Maestre 2014). Although better adapted to moisture stress than dry grasslands, desert shrublands in North America have been found to be vulnerable to drought (Miriti and others 2007) and may exhibit slow post-disturbance recovery (Abella 2010). Further, variation in function among different types of dryland shrublands has received less attention (that is, different dominant species and variation in climate and edaphic setting; Gibbens and others 2005). Recent studies have found that shrub functional traits can shape the response of multiple ecosystem services (for example, Hanisch and others 2020; Pan and others 2022), and the direction of their trade-offs can be influenced by management actions (Archer and Predick 2014). Therefore, due to their diversity, ecological importance, and potential vulnerability to climate change, there is a need to better understand the function of desert shrublands as an important part of global dryland ecosystems.

Desert shrublands are often spatially heterogeneous and comprised of areas vegetated by one or more shrub species (under canopy, hereafter), herbaceous and/or succulent species, and bare soil interspaces between vegetated areas (interspaces, hereafter). Under canopy environments often have enriched soil and more favorable, sheltered microclimates (known as ''fertility islands'') compared to interspaces (Schlesinger and others 1990). Through reduced radiation, milder temperatures and subsequently lower evaporation (Kidron 2009, 2010), under canopy environments, may benefit the establishment and persistence of biocrusts (Garcia and others 2015; Gutiérrez and others 2018) and both shrub species and herbaceous vegetation, although the spatial arrangement of vegetation varies among desert shrublands and may be species specific (Tielbörger and Kadmon 1995, 1997). However, Li and others (2017), in a long-term experiment excluding litter production and soil nutrient uptake, demonstrated that soils captured by shrub canopies are not necessarily fertile; rather, soil enrichment appears to result from water–shrub–soil interactions (Schlesinger and others 2006; An and others 2023). Spatial heterogeneity and connectivity of under canopy and interspace environments is a key component of desert shrubland resilience (Okin and others 2009; Kéfi and others 2024). For example, Okin and others (2006) found that wind in drylands transport soil resources (for example, litter and coarse material) from interspaces to adjacent areas under canopies. Kéfi and others (2024) found that increasing aridity strengthens vegetation spatial structure, which was associated with the maintenance of a high level of soil multifunctionality. However, it is not clear how soil moisture is partitioned between under canopies and interspaces in desert shrublands, and to what degree the fertility island concept can also be applied to variation in soil water resources. Understanding how sequences of wet and dry periods influence shrubland structure and functioning through their effects on soil moisture dynamics will also aid in predicting future changes to shrub-dominated landscapes. Reduced soil water availability under canopy can lead to diminished transpiration, impaired growth, and increased heat stress. These changes may contribute to a shift toward desert shrub species adapted to more arid conditions, slower growth rates, and a potential progression toward desertification. This underscores the importance of understanding how moisture dynamics influence shrubland ecosystems and their resilience to changing environmental conditions.

Previous studies differ in their reports of soil moisture partitioning between under canopy and interspace environments in desert shrublands. Some studies report higher soil moisture under canopies compared to interspaces (for example, Pariente 2002; Bhark and Small 2003; D'Odorico and others 2007; Bachar and others 2012; Kidron and Gutschick 2013; Hao and others 2016). D'Odorico and others (2007) hypothesize that the increased soil moisture under canopies is created by positive feedbacks between canopy cover and rainfall infiltration, thus explaining the stability of woody vegetation distribution patterns. In contrast, other studies have reported higher soil moisture in interspaces (Hennessy and others 1985; Breshears and others 1997; Dong and others 2003; Moran and others 2010; Duniway and others 2010), presumably associated with less rainfall interception, and lower root density and thus reduced plant water uptake. We postulate that these mixed findings likely stem from differences in study location and shrubland type, local meteorology, and edaphic properties of the study sites. Additionally, they may be further complicated by shrub–water interactions (for example, interception, stemflow, preferential infiltration, water uptake, and evapotranspiration) that differ in their influence on soil moisture in ways that are not fully understood. Breshears and others (1998) observed that during the warm season, soil moisture in interspaces of a semiarid woodland declined at a higher rate than areas under the canopy, which was attributed to higher direct solar radiation and soil evaporation (Breshears and others 1997). Many desert shrub species exhibit physiological, phenological, and morphological variations that reflect and may even influence spatial and temporal patterns of soil moisture availability. For example, many desert shrub species develop lateral roots that enable them to access interspace soil moisture in addition to soil moisture under the canopy (Wilcox and others 2004). Dense, tall shrubs generally have higher canopy interception of precipitation, lower stemflow efficiency, and greater water requirements compared to low-stature shrubs (Zhang and others 2020), which can lead to reduced soil moisture under the canopy relative to interspaces. Deciduous shrubs, by adjusting their physiological activity in response to seasonal changes in water availability, may avoid periods of low moisture availability (Reynolds and others 1999). In contrast, evergreen shrubs that remain active year-round may be able to better capitalize on increases in soil moisture (Reynolds and others 1999; Petrie and others 2015). Given the important influence of spatial and temporal soil moisture variation for desert shrubs, we postulate that there remains an opportunity to improve understanding of desert shrublands at the ecosystem-level through better understanding of how soil moisture is partitioned between under canopy and interspace environments, and how meteorological variation shapes and alters partitioning patterns through time.

The goal of this research was to determine whether the fertility island concept—which predicts higher nutrient availability and greater microclimate favorability under canopies compared to interspaces—may also include greater soil moisture under canopies in desert shrublands. We evaluated soil moisture partitioning between under canopies and interspaces for three species across nine shrubland sites in the northern Chihuahuan Desert. A previous study by Duniway and others (2018) investigated the dynamics of soil moisture within these shrubland ecosystems, but did not evaluate soil moisture partitioning between under canopies and interspaces, leaving an important knowledge gap in our understanding of these ecosystems. Our analysis used two long-term soil moisture datasets: a monthly resolution, 30 year, whole soil profile measurements (Virginia and others 2025); and 30 min resolution, 10 year, 10 to 30 cm depth measurements (Pinos and others 2025a). We sought to determine to what degree moisture was partitioned differently between under canopies and interspaces in these desert shrublands, and to determine the primary factors controlling partitioning over long, multidecade time periods. We hypothesized that soil physical properties would exert the strongest control on soil moisture partitioning due to their influence on water retention, infiltration, and movement within the soil. Other influential factors including shrub morphology and precipitation patterns would have lesser effects, or effects that were limited to a smaller number of shrubland types. As an additional component, we assessed the influence of temporal resolution by contrasting coarse-resolution measurements, which capture broad trends (but may miss short-term moisture fluctuations), against fine-resolution measurements that may better capture short-term moisture fluctuations (but include fewer depths in the soil profile). In making these determinations, our study provides foundational information on the factors controlling soil moisture partitioning in desert shrublands and evaluates to what degree the islands of fertility concept may also include higher soil moisture availability. By understanding the factors that affect soil moisture, we can better predict the impacts of climate shifts on shrubland productivity, plant diversity, and water availability, thereby guiding conservation efforts to maintain ecosystem stability and mitigate desertification. Therefore, our findings improve insight on the diversity of desert shrubland functioning, and improve assessment of climate change impacts to these ecosystems through effects to soil moisture.

Material and Methods

Study Area

This study was conducted at the Jornada Basin Long Term Ecological Research (LTER) station located in the northern Chihuahuan Desert, New Mexico, USA. The Jornada LTER includes both the Jornada Experimental Range (784 km^2) and the Chihuahuan Desert Rangeland Research Center (250 km^2; Figure 1). The Jornada Basin represents the transition from once-abundant grassland ecosystems to shrub-dominated habitat, which is widespread in the region. The climate is classified as hot arid (Köppen–Geiger classification BWk; Beck and others 2023), with a mean annual rainfall of 240 mm, more than 80% of which occurs during the monsoon season from July through September. The mean summer temperature is 26 °C, and the mean winter temperature is 6 °C (Peters and Savoy 2023).

Our study focuses on three shrubland ecosystems: creosotebush (*Larrea tridentata*), mesquite (*Prosopis glandulosa*), and tarbush (*Flourensia cernua*), studied at three long-term experimental plots (70 × 70 m) per ecosystem, located to capture diversity in vegetation and edaphic characteristics exhibited by these shrublands (Figure 1, Table 1). Our study therefore includes three different shrubland sites for each shrubland ecosystem, totaling nine sites.

Creosotebush is an evergreen shrub that comprises 28–45% of total canopy cover in our three creosotebush shrubland sites, and occurs in soils from well-drained sands to shallow stony soils underlain by cemented calcium carbonate at shallow or deep depths. In the creosotebush interspaces, there may be a short-lived biennial bunchgrass (for example, fluff grass [*Dasyochloa pulchella*]). When present, grass cover is very low (< 1%). Mesquite is a deciduous shrub that accumulates blowing sand, forming a coppice dune mound around plant bases. Mesquite comprises 30–55% of the total canopy cover in our three mesquite shrubland sites, occurring across most soil types, but is particularly prevalent on deep sandy soils with a calcium carbonate layer at variable depths. In the mesquite interspaces, there may be some bunchgrasses (*Aristida* spp. and *Sporobolus* spp.), but covers are < 1% with the exception of a large *Sporobolus* spp. establishment that was observed after a series of wet years (Peters and Savoy 2023). Tarbush is a deciduous shrub that makes up 2–15% of total canopy cover in our three tarbush shrubland sites and is often found on finer-textured soils. In the tarbush interspaces, the shallow-rooted bunchgrass burro grass (*Scleropogon brevifolius*) is common, along with infrequent patches of tobosa grass (*Pleuraphis mutica*; Peters and Gibbens 2006). Both grasses are mainly confined to small depressions but have also been observed under tarbush canopies (Kidron and Gutschick 2013). It is important to highlight that annual plant cover in the interspaces of the studied sites exhibits significant interannual variation, with some years showing virtually no annuals and others reaching 1–2% cover.

All nine study sites investigated here were likely predominantly grasslands with scattered shrubs in the early twentieth century (Gibbens and others 2005). Despite sites having domestic grazing excluded since 1989 (or earlier; Huenneke and others 2002), perennial grass cover has not generally recovered, likely as a result of reduced summer water availability linked to global warming (Kidron and Gutschick 2017) or historical overgrazing coupled with drought (Schlesinger and others 1990; Gibbens and others 2005; Peters and Savoy 2023). There is no evidence of pillaring in these shrublands (J. Anderson, personal communication). Overland flow during the monsoon season (July–September) occurs at creosotebush sites, which are located on piedmont slopes and are particularly susceptible to water erosion from overland flow (Wondzell and others 1987). At mesquite sites, local overland flow may occur be-

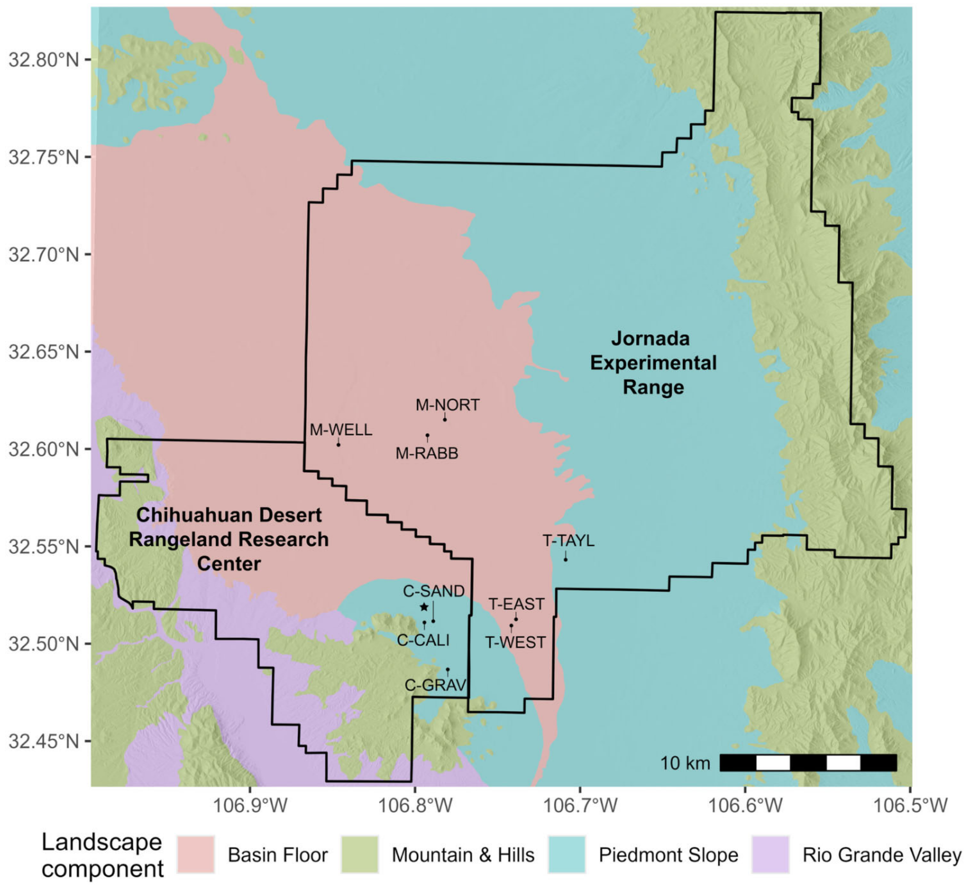

Figure 1. Map of the Jornada Basin Long Term Ecological Research (LTER) station and shrubland sites selected for this study (adapted from Hansen and others 2023). The star indicates the location of the Jornada LTER weather station.

tween mesquite dunes but does not physically affect the shrubs. The primary abiotic driver at mesquite sites is wind, which causes soil erosion and dune formation, especially where topsoil has been lost (Wondzell and others 1987). Tarbush sites, on level calcareous clay and clay loam soils, experience brief periods of standing water during heavy rain but are not prone to erosion due to their well-developed soil biocrusts that resist both wind and water erosion (Wondzell and others 1987; Hartley and Schlesinger 2002). Both tarbush and mesquite are dormant during the cold season, with leaf emergence occurring in January and April, respectively (Browning and others 2018). In contrast, creosotebush is an evergreen, is not drought deciduous, and will leaf out following spring, summer and fall rains (Ackermam and others 1980; Browning and others 2018). Gibbens and Lenz (2001) noted that the creosotebush, mesquite, and tarbush shrub species studied developed extensive horizontal root systems, with few roots penetrating the calcic and petrocalcic horizons. These shallow, dense root networks are capable of rapidly depleting soil moisture both under canopies and in the adjacent interspaces, subsequently drawing on deeper water reserves when available (Reynolds and others 1999). Typical shrub heights and canopy diameters of the studied shrubland sites are presented in Table 1.

Soil Moisture Data

Individual shrubs and adjacent bare soil interspaces between shrubs were selected in each site for continuous monitoring of soil moisture. All sites were designed to monitor the natural system, with neutron probe access tubes and soil moisture sensors all installed by hand, minimizing disturbances. The first soil moisture dataset spans 1989–2023, with monthly measurements collected using neutron moisture meter probes (NP, hereafter) at 30-cm intervals down to three meters (data available in Virginia and others 2025). In each of the nine shrubland sites, 10 aluminum access tubes (50 mm internal diameter and 1.6 mm wall thickness) were installed as five tube pairs. For each pair, one tube

Table 1. Description of Shrubland Study Sites in the Jornada Basin LTER

Shrubland ecosystem	Site	Latitude	Longitude	US soil taxonomy	Geomorphic landform	Shrub height (cm)	Canopy diameter (cm)
Creosotebush	C-CALI	32.5136	−106.7961	Fine loamy, mixed, superactive, thermic Typic Haplocalcids	Fan Piedmont	25.6 ± 10.9	94.8 ± 35.0
	C-GRAV	32.4892	−106.7817	Loamy skeletal, mixed, superactive, thermic Ustic Haplocalcids	Fan Piedmont	27.6 ± 12.6	134.4 ± 42.1
	C-SAND	32.5144	−106.7906	Fine loamy, mixed, superactive, thermic Ustic Haplargids	Fan Piedmont	26.4 ± 11.3	141.6 ± 64.6
Mesquite	M-NORT	32.6186	−106.7858	Sandy, mixed, thermic Ustic Haplocambids	*Alluvial Plain*	30.3 ± 12.7	508 ± 65.7
	M-RABB	32.6103	−106.7964	Coarse loamy, mixed, superactive, thermic Ustic Petroargids	*Alluvial Plain*	29.7 ± 13.4	499.2 ± 172.1
	M-WELL	32.6047	−106.8508	Mixed, thermic Ustic Torripsamments	*Alluvial Plain*	29.9 ± 12.6	165.8 ± 116.8
Tarbush	T-EAST	32.5157	−106.7402	Fine loamy, mixed, superactive, thermic Ustic Calciargids	*Alluvial Plain*	28.1 ± 9.9	50.6 ± 35.3
	T-TAYL	32.5469	−106.7106	Fine loamy, mixed, superactive, thermic Ustic Haplocalcids	Fan Piedmont	25.4 ± 9.7	48.8 ± 23.2
	T-WEST	32.5128	−106.7431	Fine loamy, mixed, superactive, thermic Ustic Haplargids	*Alluvial Plain*	24.8 ± 11.6	82.4 ± 48.3

For site location, see Figure 1. Soil taxonomy from Duniway and others (2018), geomorphic landform from Monger and Bestelmeyer (2006), shrub height (mean ± standard deviation) represents measurements taken in September 2022 by Peters and Huenneke (2023), and canopy diameter (mean ± standard deviation) of the shrubs associated with the soil water monitoring access tubes (n = 10) was estimated assuming a circular shape and one radius per shrub in February 2024.

was located midway under a shrub canopy, and the other was located in an adjacent interspace 3–4 m from the shrub stem. Access tubes were installed with a hand auger to a maximum depth of three meters, although installation depth differed between sites and tube pairs due to the presence or absence of belowground restrictive features (that is, petrocalcic or bedrock soil horizon).

The second soil moisture dataset spans 2013–2023, with continuous 30-minute measurements collected using time domain reflectometry (TDR) sensors (CS650 and CS655, Campbell Scientific) at 10-cm intervals from 10 to 30 cm depth (data available in Pinos and others 2025a). Two TDR sensor profiles were installed at each of the nine shrubland sites. For each pair, one profile was located midway under a shrub canopy, and the other was located in an adjacent bare soil interspace 3–4 m from the shrub stem. The TDR sensor readings were logged at 30-minute intervals by a datalogger (CR1000, Campbell Scientific).

Both the NP and TDR methods were calibrated and validated according to standard protocols to ensure high data quality and accurate soil moisture measurements. NP calibration is described in Duniway and others (2018), and TDR follows a factory calibration. The two methods differ in their temporal resolution due to the inherent configurations of the sensors. While both methods were deployed within the same plot, NP and TDR measurements were taken at approximately 15 cm distance from each other, and were therefore not positioned at identical locations. This may have introduced some spatial variability in the VWC data, but was necessary to minimize the impacts of soil disruption from access tubes and sensor installation on NP and TDR measurements.

To maintain the integrity of the data and avoid introducing bias, we chose not to gapfill the soil moisture time series from NP and TDR datasets. To account for soil moisture spatial variability measured by the NP, we calculated monthly averages for each environment (that is, under canopy and interspace) based on a minimum of three out of five valid measurements. Data points with fewer than three valid measurements were excluded from the analyses. The deepest soil moisture NP readings at each site were excluded from our analyses due to concerns that they might be influenced by the proximity of soil at the bottom of the NP access tubes. For the TDR dataset, we calculated 30-minute averages of soil moisture for each environment (10–30 cm depth range) based on a minimum of two valid observations.

Meteorological Data

We obtained gap-filled daily precipitation data for the nine shrubland sites from 1989 to 2023 from Yao and others (2023), and daily meteorological data from Jornada LTER weather station from 1989 to 2023 (Figure 1; Anderson 2024). Additionally, we obtained daily meteorological data from site-specific weather stations located in each of the nine shrubland sites from 2013 to 2023 (data available in Pinos and others 2025b).

We used multiple linear regression and artificial neural networks techniques to gapfill daily meteorological datasets between nearby stations. When the R^2 value in a multiple linear regression model, constructed using data from at least two nearby stations, exceeded 0.8, it was used to predict missing values. If the R^2 was below 0.8, a neural network model was employed, following the methodology outlined by Pinos and others (2020). Then, we estimated daily reference evapotranspiration (ET_o) for each site from 1989 to 2023 using the FAO-56 Penman–Monteith equation (Allen and others 1998). We used site-specific meteorological data to calculate ET_o from 2013 to 2023, and we used ET_o data from the Jornada LTER weather station to fill the time series back to 1989 for each site.

Physical Soil Property Data

Soil descriptions and data are based on the three samplings described in Duniway and others (2018). Briefly, these are composed of: (1) soil pits adjacent to each location in 2005 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); (2) soil samples collected during NP calibration activities in 2007 and 2008 (every 15 cm from 15 to 120 cm, and every 30 cm from 150 to 300 cm); and (3) deep soil cores collected from near (within 2–3 m) of six NP sampling access tubes at 10 locations (C-GRAV was not sampled in this matter). NP calibration and deep core samples analyzed for particle size analysis by the hydrometer method (Gee and Or 2002) and $CaCO_3$ was measured by the digital manometer method (Horváth and others 2005). The soil texture and bulk density were used to calculate saturated hydraulic conductivity by the Rosetta v.3 pedotransfer functions model (Zhang and Schaap 2017).

This section provides a concise overview of soil types within the shrubland ecosystems, based on the findings of Duniway and others (2018):

Creosotebush

C-CALI soils were characterized as moderately gravelly and calcareous with finer textures. In contrast, C-GRAV soils were shallow and stony, overlying a cemented calcium carbonate layer at 20 cm depth. C-SAND soils were relatively homogeneous, deep, and sandy with moderate gravel content. The soil physical properties of under canopy and interspace soils were not significantly distinct.

Mesquite

M-NORT soils were deep, sandy textured with less than 10% gravel content, transitioning abruptly to clay- and carbonate-rich soil at 180 cm depth. M-RABB soils were also deep with sandy texture; however, it is important to note that interspace soils presented a higher concentration of fine particles compared to the soils under shrubs. Moreover, M-NORT and M-RABB showed abrupt increases in soil carbonates in the soils under shrubs at ~ 100 cm and ~ 200 cm, respectively. These increases were also observed in interspace soils, though at half the depth of those under the shrubs. M-WELL soils were shallower, sandy textured with moderate gravel and carbonates content from ~ 30 cm depth.

Tarbush

Soils in the three tarbush sites were clay-rich with carbonate accumulation. All soils include moderate gravel content, which typically corresponds to the depths of high carbonates. T-EAST soils differ only in their higher sand content (profile mean 60%) compared to T-TAYL (45%) and T-WEST (35%). The soil physical properties of under canopy and interspace soils were not significantly distinct.

Analysis of Soil Moisture Partitioning

We evaluated soil moisture partitioning in all our analyses as the difference between interspace and under canopy volumetric water content (VWC; $\Delta VWC = VWC_{interspace} – VWC_{canopy}$). Positive ΔVWC values (> 0) indicate higher interspace VWC, whereas negative values (< 0) indicate higher VWC under canopy. We presented ΔVWC as the difference in VWC instead of a ratio between interspace and under canopy VWC values to show the absolute magnitude of difference between these environments.

To investigate the meteorological drought control over the ΔVWC, we computed the monthly aridity index as monthly total precipitation divided by monthly potential evapotranspiration. To evaluate the impact of the monsoon on ΔVWC, we classified monsoons as dry or wet. Dry monsoon seasons were defined as those with a monsoon precipitation 20% below the median monsoon precipitation for the study period (1989–2023), and wet monsoon seasons were those with monsoon precipitation 20% above the median. In the northern Chihuahuan Desert, wet monsoon seasons are most frequently produced by a small number of large rainfall events, and therefore, many wet monsoon seasons contain months with below average precipitation (Petrie and others 2014). In contrast, a dry monsoon season in this region is less likely to contain a month with above average precipitation (Petrie and others 2014).

Differences in VWC between under canopies and interspaces in the NP dataset and TDR dataset were assessed using descriptive statistics, including the mean, standard deviation, quartiles, and frequency distribution (FD). An exploratory analysis was conducted to identify the soil properties contributing to the highest mean square error in predicting ΔVWC for creosotebush, mesquite, and tarbush shrubland ecosystems, using the ''randomForest'' package (Liaw and Wiener 2002) in the R environment (R Core Team 2021).

Results

Soil Moisture Partitioning Between Shrubland Ecosystems from Monthly Data

Creosotebush

In the monthly NP dataset, VWC values were similar between under canopy and interspace environments in the creosotebush shrublands (C-CALI Pearson's R = 0.83, C-GRAV = 0.85, C-SAND = 0.89; Figure 2a–c). At shallow soil depths (30 cm), monthly observations of ΔVWC between interspace and under canopy environments suggest VWC were nearly equal (that is, ~ 50% of observations had higher under canopy VWC, and 50% had higher interspace VWC; Figure 3; Figure S1). Below 30 cm depth, VWC was more frequently higher in interspaces, with the exception of deeper soil depths at C-CALI (120 cm) and C-SAND (210 cm; Figure 3; Figure S1). Across all soil depths at the creosotebush sites, the absolute values of ΔVWC were consistently < 0.03 $m^3 m^{-3}$ (Figure 3).

Mesquite

We found strong dissimilarities in monthly VWC values between under canopy and interspace environments in two mesquite shrublands (M-NORT Pearson's R = 0.55, M-RABB = 0.65; Figure 2d, e), while moderate similarities were observed in a third mesquite shrubland (M-WELL = 0.88; Figure 2f). At the whole soil profile, monthly observations of ΔVWC between interspace and under canopy environments were higher in the interspaces (that is, ~ 90–100% of observations had higher interspace VWC compared to under canopy; Figure 4; Figure S2). Across all soil depths at the mesquite sites, the absolute values of ΔVWC were consistently < 0.1 $m^3 m^{-3}$ (Figure 4).

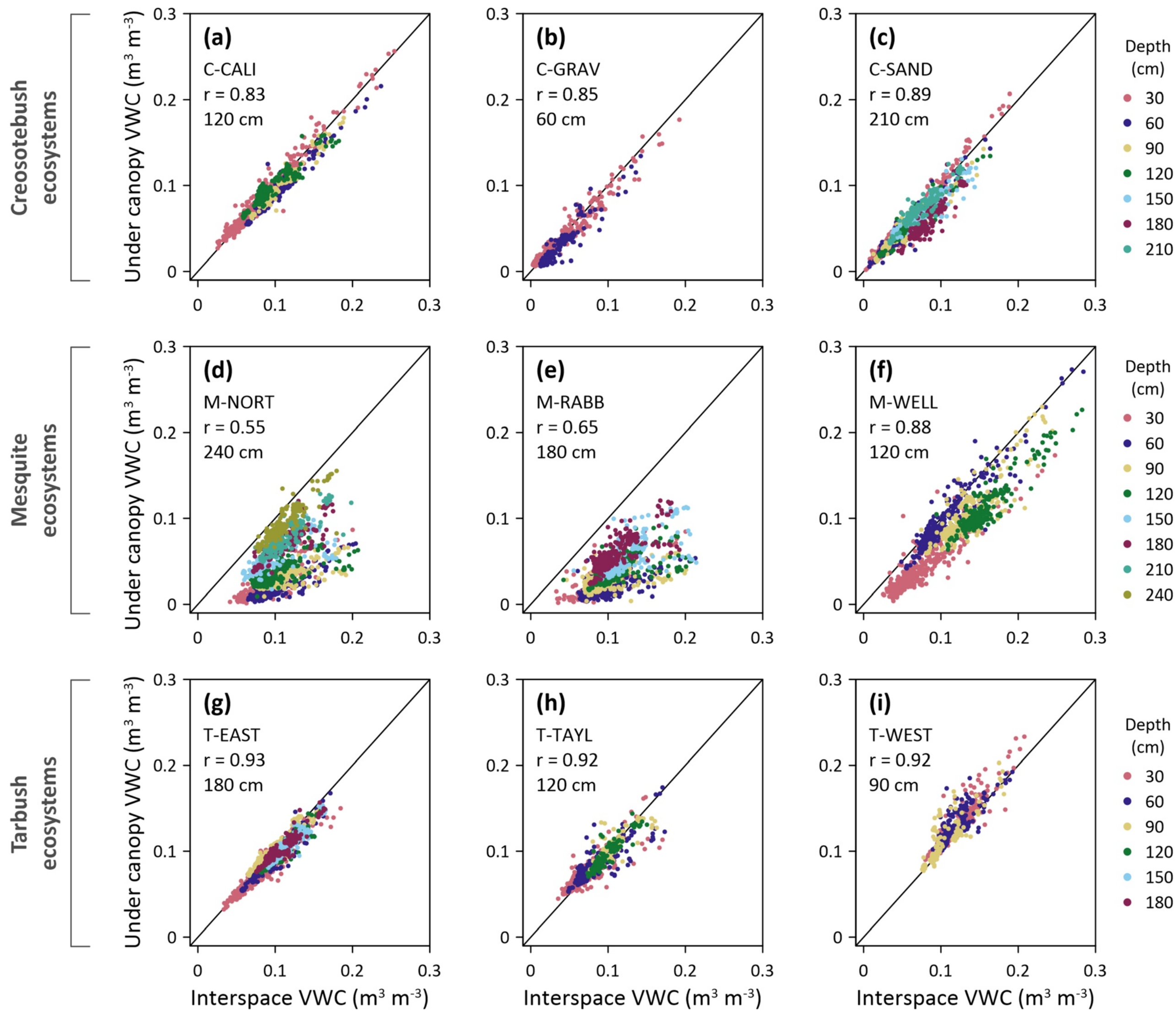

Figure 2. Scatterplots of under canopy and interspace volumetric water content (VWC: $m^3\ m^{-3}$) for the nine shrubland sites from 1989 to 2023, measured monthly with neutron moisture meter probes. Creosotebush ecosystems are shown in the upper panels, mesquite ecosystems in the middle panels, and tarbush ecosystems in the bottom panels. The legend illustrates VWC measurements at different depths in the soil profile, with each panel indicating the site's maximum depth. The Pearson correlation coefficient (r) was calculated from VWC measurements at all soil depths. The 1:1 line is provided for reference.

Tarbush

We found similar monthly VWC values between under canopy and interspace environments in the three tarbush shrublands (T-EAST Pearson's R = 0.93, T-TAYL = 0.92, T-WEST = 0.92; Figure 2g–i). Monthly observations of ΔVWC between interspace and under canopy environments were highly variable among tarbush sites (Figure 5; Figure S3). At the whole soil profile, VWC in T-EAST was higher in the interspaces compared to under canopies, except at 90 cm depth (Figure 5). In T-TAYL, VWC in the upper soil layers (that is, at 30 cm and 60 cm depth) was higher under canopies compared to the interspaces and the trend is reversed for the deeper soil layers (90 cm and 120 cm depth; Figure 5). At the whole soil profile, VWC in T-WEST was higher under canopies compared to the interspaces. Across all soil depths at the tarbush sites, the absolute values of ΔVWC were consistently $< 0.02\ m^3\ m^{-3}$ (Figure 5).

An exploratory analysis to identify significant soil predictors of soil moisture partitioning between under canopy and interspace environments, conducted using random forest models, is presented in

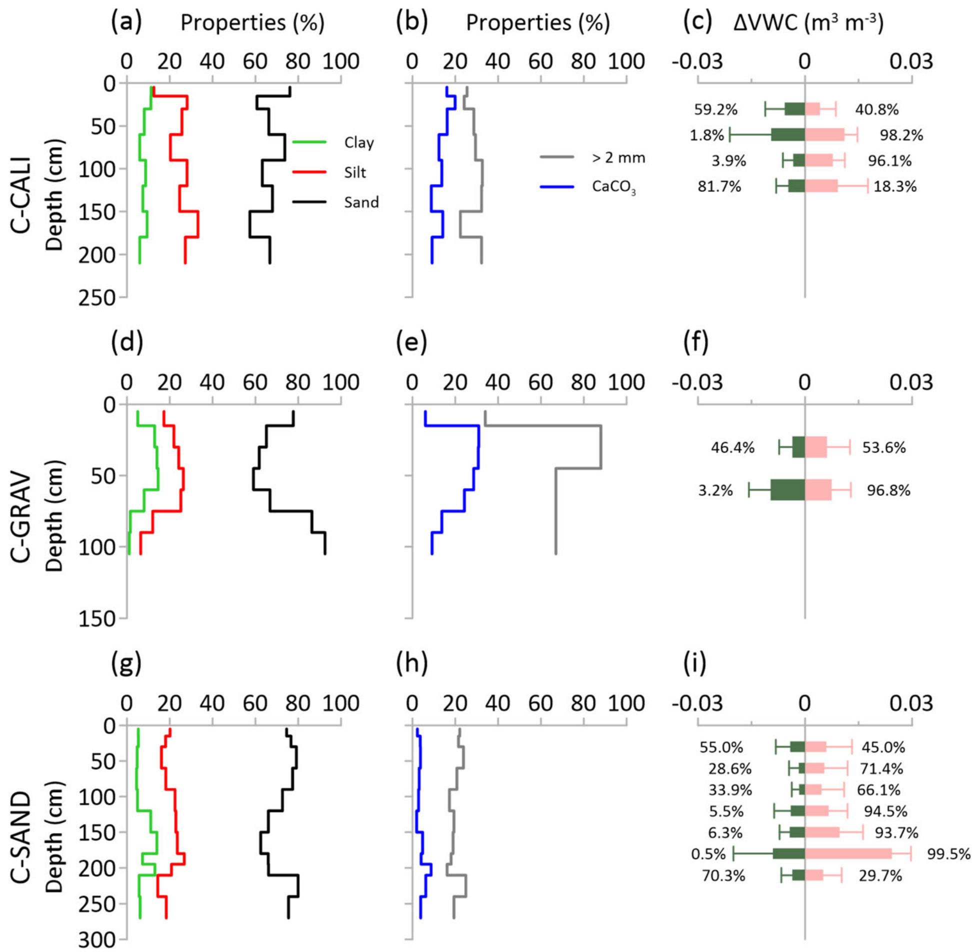

Figure 3. Creosotebush shrubland site (C-CALI, C-GRAV, C-SAND) profile soil properties and VWC measurements from monthly neutron moisture meter probe data. For each site, soil properties include percent sand, silt, and clay (left panels), percent coarse fragments (> 2 mm) and percent calcium carbonate ($CaCO_3$; center panels). The horizontal bars illustrate ΔVWC (mean ± standard deviation; right panels), where green bars illustrate the average magnitude of ΔVWC when it is higher under canopies compared to interspaces, and pink bars illustrate the average magnitude of ΔVWC when it is higher in interspaces. The percentage values adjacent to the green and pink bars illustrate the percentage of monthly observations from 1989 to 2023 for each condition. Using C-CALI as an example, 59.2% of monthly observations of ΔVWC had higher soil VWC under shrub canopies compared to interspaces at 30 cm depth, and VWC was on average ~ 0.008 higher under shrub canopies when these observations were made. Soil property data from Duniway and others (2018).

Appendix A of the Supplement. Overall, the random forest model explained 53.7%, 64.2%, and 34.7% of the variance in ΔVWC for creosotebush, mesquite, and tarbush, respectively. For creosotebush, significant predictors included silt content, bulk density, and clay content, with increased silt and bulk density enhancing water retention (Figure A1a, Appendix A). In mesquite, the most influential variables were carbonate content, gravel content, and silt content, with higher carbonate and gravel reducing water infiltration but increasing water storage capacity (Figure A1b, Appendix A). For tarbush, sand content, saturated hydraulic conductivity, and carbonate content were key, where higher sand content improved water retention by enhancing hydraulic conductivity, while carbonate content had a smaller effect (Figure A1c, Appendix A).

Soil Moisture Partitioning: Meteorological Influence

For improved readability and clarity, values of ΔVWC in this section are expressed as percentages. It is important to note that while the differences may be small in magnitude, they hold significant importance given the context of soil moisture limitation in desert soils, and its effects on vegetation.

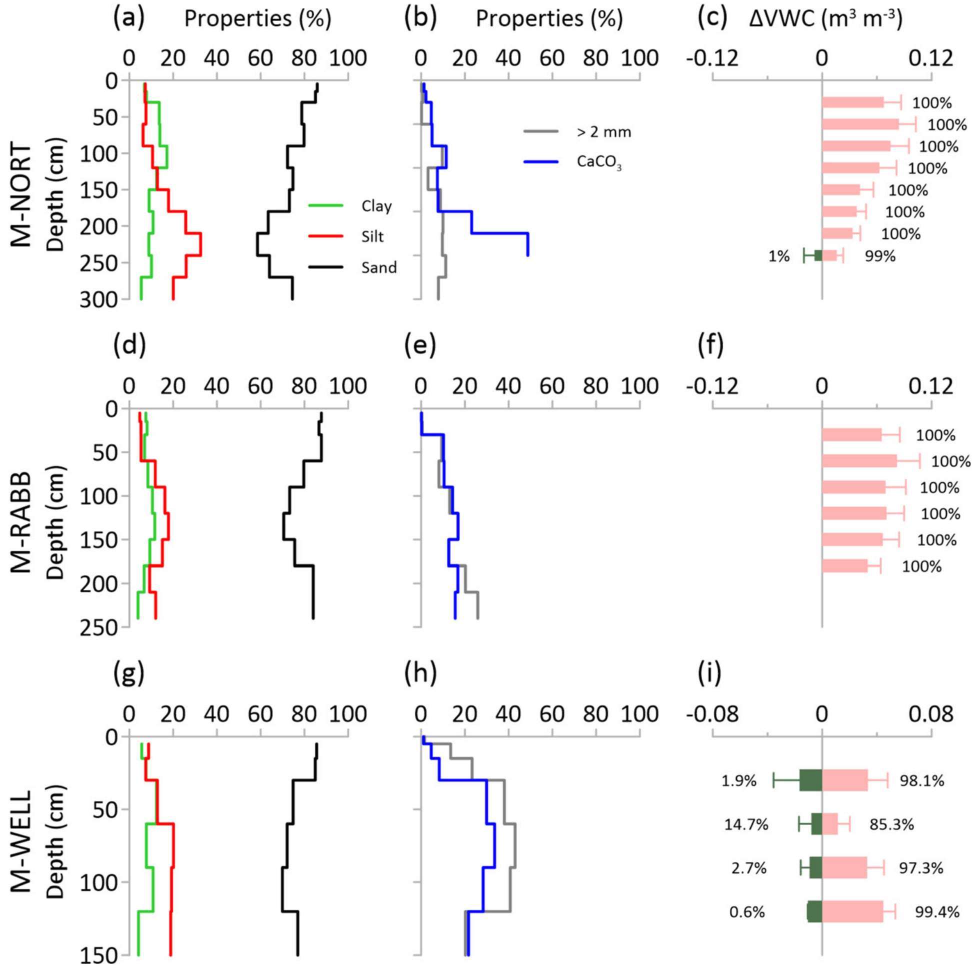

Figure 4. Mesquite shrubland site (M-NORT, M-RABB, M-WELL) profile soil properties and VWC measurements from monthly neutron moisture meter probe data. For each site, soil properties include percent sand, silt, and clay (left panels), percent coarse fragments (> 2 mm) and percent calcium carbonate ($CaCO_3$; center panels). The horizontal bars illustrate ΔVWC (mean ± standard deviation; right panels), where green bars illustrate the average magnitude of ΔVWC when it is higher under canopies compared to interspaces, and pink bars illustrate the average magnitude of ΔVWC when it is higher in interspaces. The percentage values adjacent to the green and pink bars illustrate the percentage of monthly observations from 1989 to 2023 for each condition. Using M-WELL as an example, 1.9% of monthly observations of ΔVWC had higher soil VWC under shrub canopies compared to interspaces at 30 cm depth, and VWC was on average ~ 0.02 higher under shrub canopies when these observations were made. Soil property data from Duniway and others (2018).

In the monthly NP dataset, differences in ΔVWC at a depth of 30 cm between wet and dry monsoons, as illustrated in Figure 6a, indicate that in C-CALI and C-GRAV, ΔVWC was slightly more negative during wet monsoons, with differences of 0.25% (mean values: − 0.57% vs. − 0.32% for C-CALI and − 0.19% vs. 0.05% for C-GRAV). In contrast, M-NORT, M-RABB, and M-WELL showed slightly more positive ΔVWC during wet monsoons, with differences of 0.49%, 0.35%, and 0.43%, respectively. T-EAST had a slightly more positive ΔVWC (difference of 0.22%), while T-WEST exhibited a slightly less negative ΔVWC (difference of 0.10%) during the wet monsoons. No significant differences were observed at the C-SAND and T-TAYL sites.

In the 30-minute TDR dataset, differences in ΔVWC at a depth of 30 cm between wet and dry monsoons depicted in Figure 6b indicate that C-CALI and C-SAND had slightly less negative ΔVWC with differences of 0.44% and 0.65%, respectively, while C-GRAV was slightly less positive with a difference of 0.55% during wet monsoons compared to dry monsoons. Differences in mean ΔVWC were substantially more positive in M-NORT (difference of 2.58%), slightly more positive in M-WELL (difference of 0.34%), and slightly less positive in M-RABB (difference of 0.24%) during wet

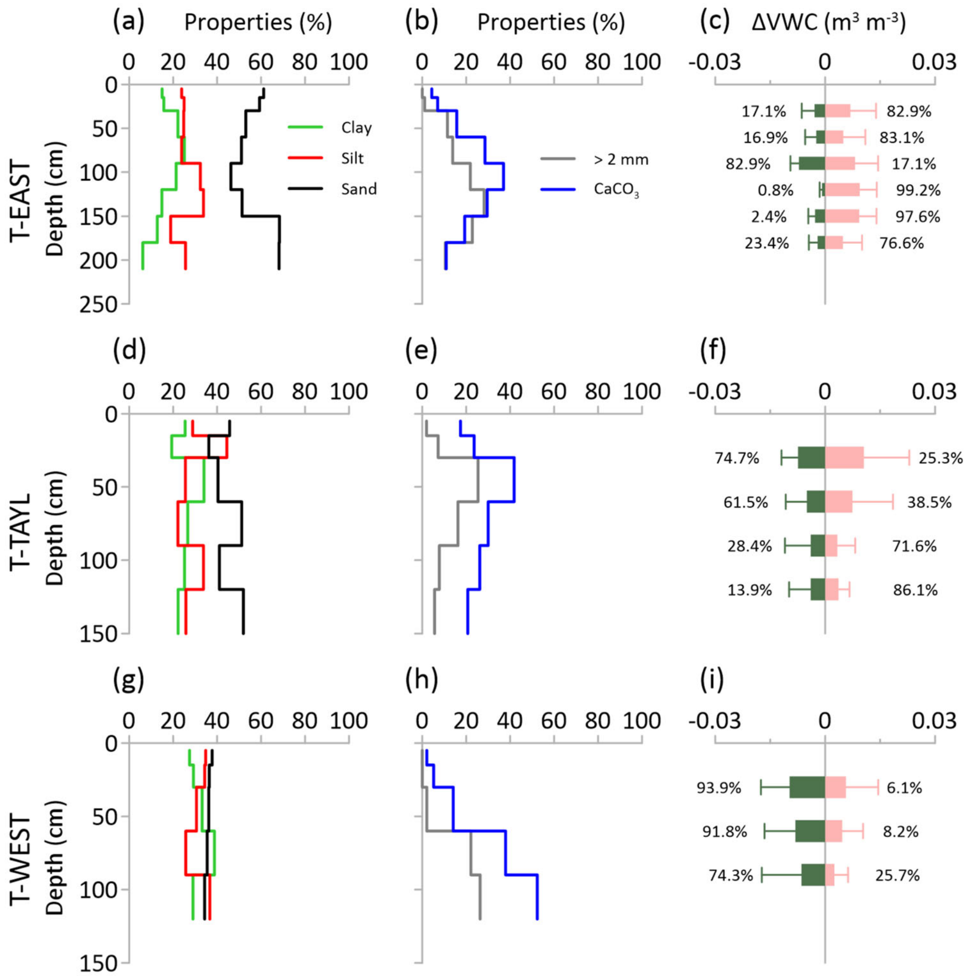

Figure 5. Tarbush shrubland site (T-EAST, T-TAYL, T-WEST) profile soil properties and VWC measurements from monthly neutron moisture meter probe data. For each site, soil properties include percent sand, silt, and clay (left panels), percent coarse fragments ($>$ 2 mm) and percent calcium carbonate ($CaCO_3$; center panels). The horizontal bars illustrate ΔVWC (mean ± standard deviation; right panels), where green bars illustrate the average magnitude of ΔVWC when it is higher under canopies compared to interspaces, and pink bars illustrate the average magnitude of ΔVWC when it is higher in interspaces. The percentage values adjacent to the green and pink bars illustrate the percentage of monthly observations from 1989 to 2023 for each condition. Using T-EAST as an example, 17.1% of monthly observations of ΔVWC had higher soil VWC under shrub canopies compared to interspaces at 30 cm depth, and VWC was on average ~ 0.004 higher under shrub canopies when these observations were made. Soil property data from Duniway and others (2018).

monsoons. Similarly, T-EAST and T-WEST sites displayed substantially more positive ΔVWC (difference of 1.79% and 3.33% respectively), while T-TAYL showed a slightly less negative ΔVWC (difference of 0.48%) during the wet monsoons.

We observed that the range of ΔVWC values during monsoons was smaller in the monthly NP dataset compared to the 30-minute TDR dataset at the 30 cm depth (Figure 6a vs. b). In contrast, we did not find significant relationships between the monthly ΔVWC and the monthly aridity index for any of the shrubland sites (Figure S4–S6).

Comparison of Temporal Resolution of Soil Moisture Observations

Our analysis of the frequency distribution from the 30-minute TDR dataset showed that at the C-CALI site, VWC was higher in interspaces at 0–20 cm depth but higher under canopy at 30 cm depth. At the C-GRAV site, VWC was similar at 10 cm and 30 cm depths but higher under canopy at 20 cm depth. At the C-SAND site, VWC was higher under canopy at 10 cm and 30 cm depths, while interspaces had higher VWC at 20 cm depth (Figure 7). In three mesquite (M-NORT, M-RABB, M-WELL)

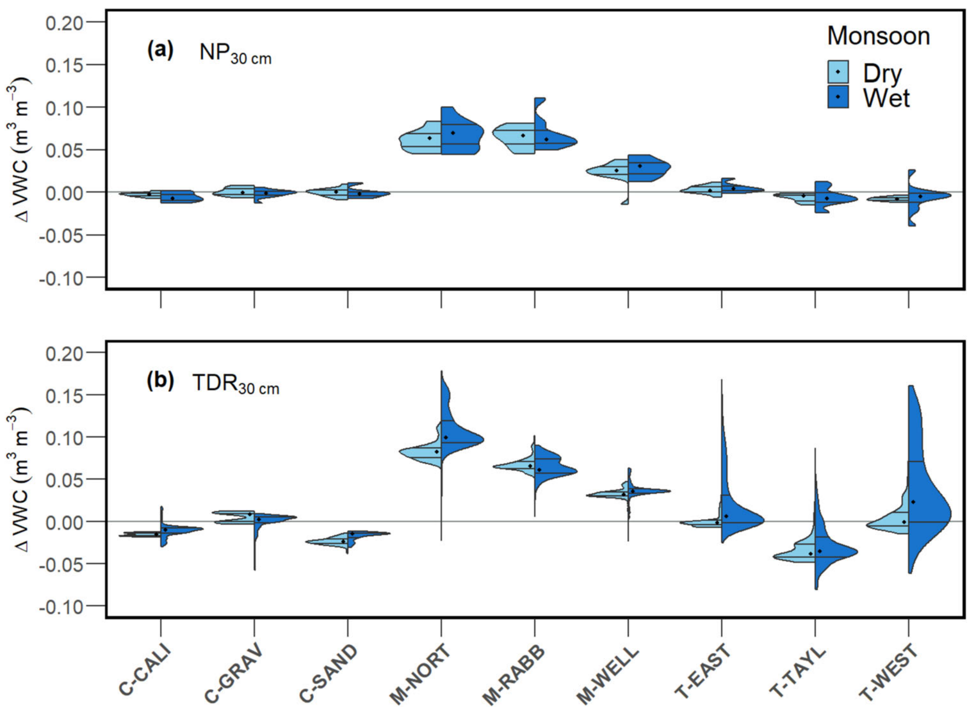

Figure 6. Violin plots illustrating the density of soil moisture partitioning (ΔVWC) between interspaces and under canopies during dry and wet monsoons for: **a** NP dataset at 30 cm depth, and **b** 30-minute TDR dataset at 30 cm depth. Dry monsoons are defined as those with monsoon (July–September) rainfall 80% or less than the median precipitation for the study period 1989–2023, and wet monsoons are defined as those with monsoon rainfall 120% or more than the median precipitation for the study period. Positive values represent higher VWC in the interspaces, whereas negative values indicate higher VWC under canopies. The gray line represents no difference between interspace and under canopy VWC. Black lines in the violin plots represent 25% and 75% quartiles, and the black dot is the median.

and two tarbush (T-EAST and T-WEST) sites, we observed higher VWC in interspaces compared to under canopies at the three depths measured (Figures 8 and 9). At the T-TAYL site, VWC was similar at 10 cm depth but diverged at 20 cm with higher values in interspaces, reversing at 30 cm where under canopy showed higher VWC (Figure 9). Soil moisture time series from the 30-minute TDR dataset are presented in Figures S7–S9.

In the 30-minute TDR data, we observed greater differences between under canopy and interspace VWC at 30 cm depth that were not capture by the monthly NP data (Figures 7, 8, 9). Accordingly, the monthly NP data showed lower VWC values at two creosotebush sites (C-GRAV and C-SAND) and three tarbush sites compared to the 30-minute TDR data (Figure 7 and 9). Similar VWC values were found in the three mesquite sites (M-NORT, M-RABB, M-WELL) between both datasets (Figure 8). Moreover, the frequency distribution of VWC in interspaces and under canopies differs in direction between the monthly NP data and the 30-minute TDR data for the C-SAND, T-TAYL, and T-WEST sites (Figures 7, 9).

Discussion

Soil Moisture Partitioning Between Under Canopy and Interspace Environments

Previous research has extensively documented the formation of nutrient-rich fertility islands under dryland shrub canopies compared to interspaces (for example, Schade and Hobbie 2005; Thompson and others 2005), including evidence from the Jornada Basin (Reynolds and others 1999; Schlesinger and others 2006). However, our findings in northern Chihuahuan Desert shrublands indicate that the fertility island effect does not consistently apply to soil moisture. Long-term VWC data reveal a generally negative relationship between soil moisture and woody vegetation in creosotebush and mesquite ecosystems (that is, greater VWC in the interspaces) but a relatively positive relationship in tarbush ecosystems (that is, wetter soils under canopies). These results differ from many findings of soil moisture partitioning between under canopy and interspace environments in desert shrublands, and show that these relationships are

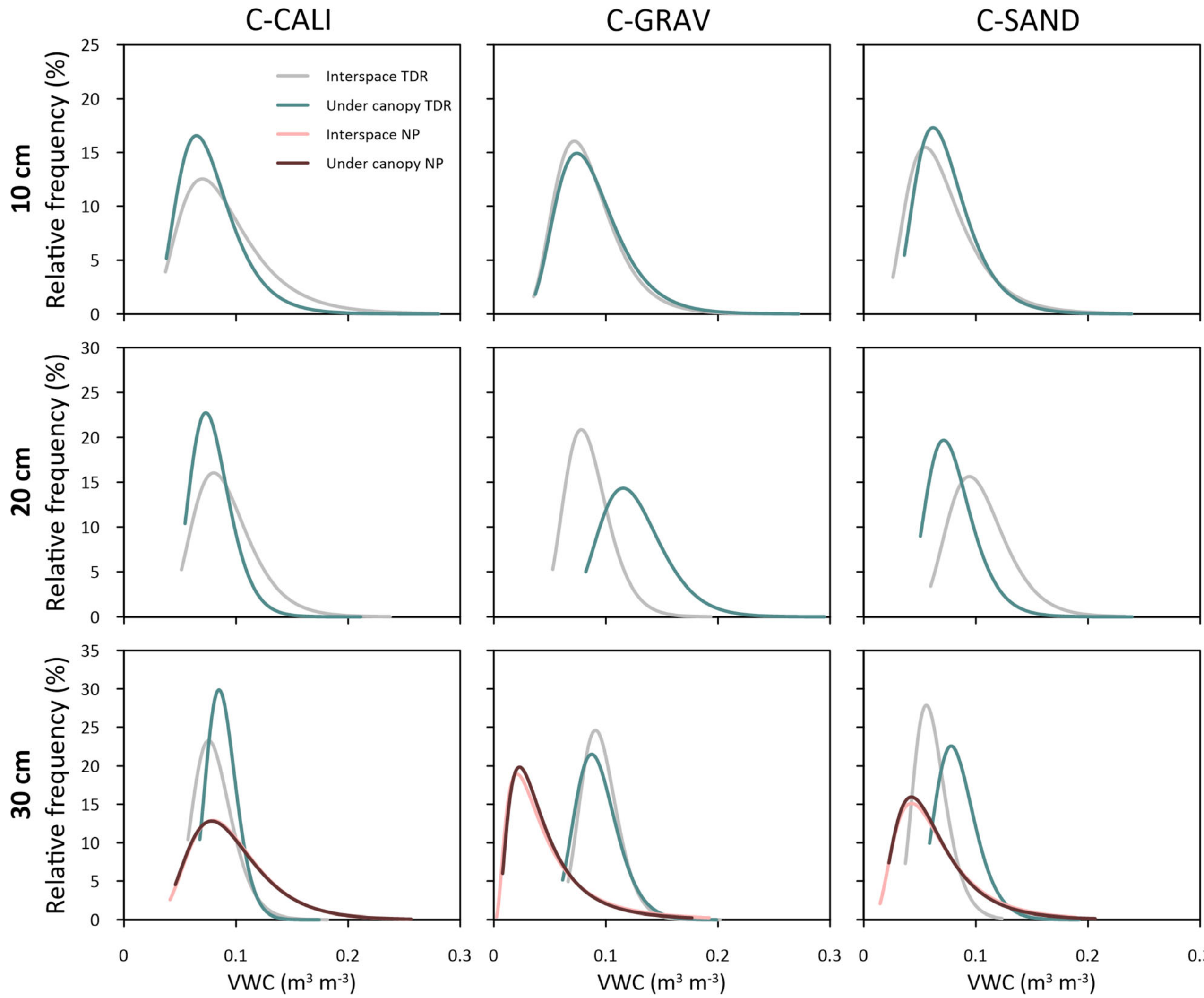

Figure 7. Frequency distribution of soil volumetric water content (VWC) measured by the TDR sensors from 2013 to 2023 at 10 cm, 20 cm, and 30 cm depths in the soil profile of the creosotebush sites. Additionally, the frequency distribution of VWC measured by neutron moisture meter probes at 30 cm depth for the same time period is included.

more complex than may have been previously attributed (Pariente 2002; Bhark and Small 2003; Cantón and others 2004; D'Odorico and others 2007; Bachar and others 2012; Kidron and Gutschick 2013; Hao and others 2016).

A modeling study by Dong and others (2003) reported that creosotebush interspaces had higher soil moisture than under canopies during the growing season due to active root water uptake, with soil moisture becoming spatially homogeneous during winter months. In our study, lower VWC observed under canopies at C-GRAV, which has shallow soils over a root-restrictive petrocalcic layer, is therefore likely attributable to active root water uptake constrained to the top ~ 60 cm of the soil profile. In the creosotebush sites lacking a restrictive soil horizon, we observed higher VWC under canopies at both shallow and deep soil layers, while intermediate layers exhibited higher VWC in interspaces. Canopy shade and stemflow infiltration around the shrub's base likely contributed to higher VWC in the shallow layer, whereas preferential flow processes—such as macropores created by roots and burrowing animals (Marquart and others 2020), stemflow belowground funneling (Li and others 2009), and inverse hydraulic redistribution (Prieto and others 2014)—resulted in elevated VWC in deeper soil layers.

In mesquite sites, we consistently observed higher VWC in interspaces compared to under canopies. These observations align with previous studies conducted in the Jornada Basin (Duniway and others 2010, 2018; Hennessy and others 1985;

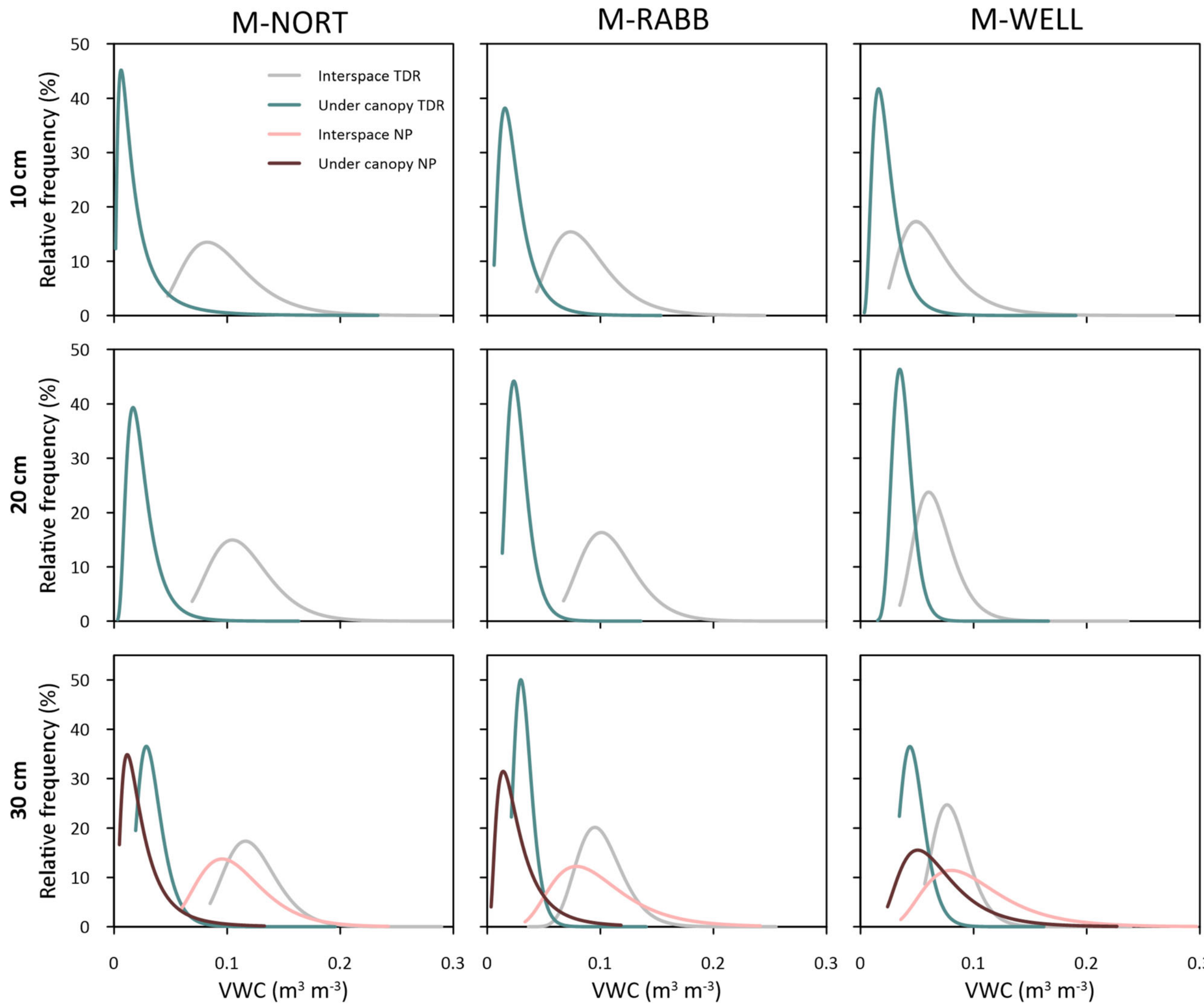

Figure 8. Frequency distribution of soil volumetric water content (VWC) measured by the TDR sensors from 2013 to 2023 at 10 cm, 20 cm, and 30 cm depths in the soil profile of the mesquite sites. Additionally, the frequency distribution of VWC measured by neutron moisture meter probes at 30 cm depth for the same time period is included.

Li and others 2013; Snyder and others 2006). Hennessy and others (1985) and Duniway and others (2018) noted that mesquite dune soils had higher sand content and lower water-holding capacity compared to interspaces. Conversely, Carrillo-Garcia and others (1999) found that mesquite canopies trap fine windborne soil particles, significantly increasing dune clay content. High clay content can lead to water repellency and runoff, which the dune topography then directs to interspaces. Moreover, other studies have found no significant differences in infiltration rates between mesquite canopies and interspaces (Mueller and others 2008; Ravi and others 2007). Mesquite shrubs, with their large, dense canopies, produce low stemflow (Martinez-Meza and Whitford 1996), and their substantial root water uptake can rapidly deplete soil moisture under their canopies. M-NORT and M-RABB, which have relatively large canopies, depleted under canopy moisture to a greater extent than M-WELL, which has smaller canopy cover (see Table 1 for differences). Although greater canopy shading in M-NORT and M-RABB is expected to reduce evaporation (Kidron 2009), the observed depletion likely reflects increased water demand associated with their higher biomass.

Soil moisture partitioning in tarbush shrublands varied across sites and soil depths. At two tarbush sites, we observed higher VWC in shallow soil horizons under canopies. The relatively shallow main root system of tarbush facilitates stemflow,

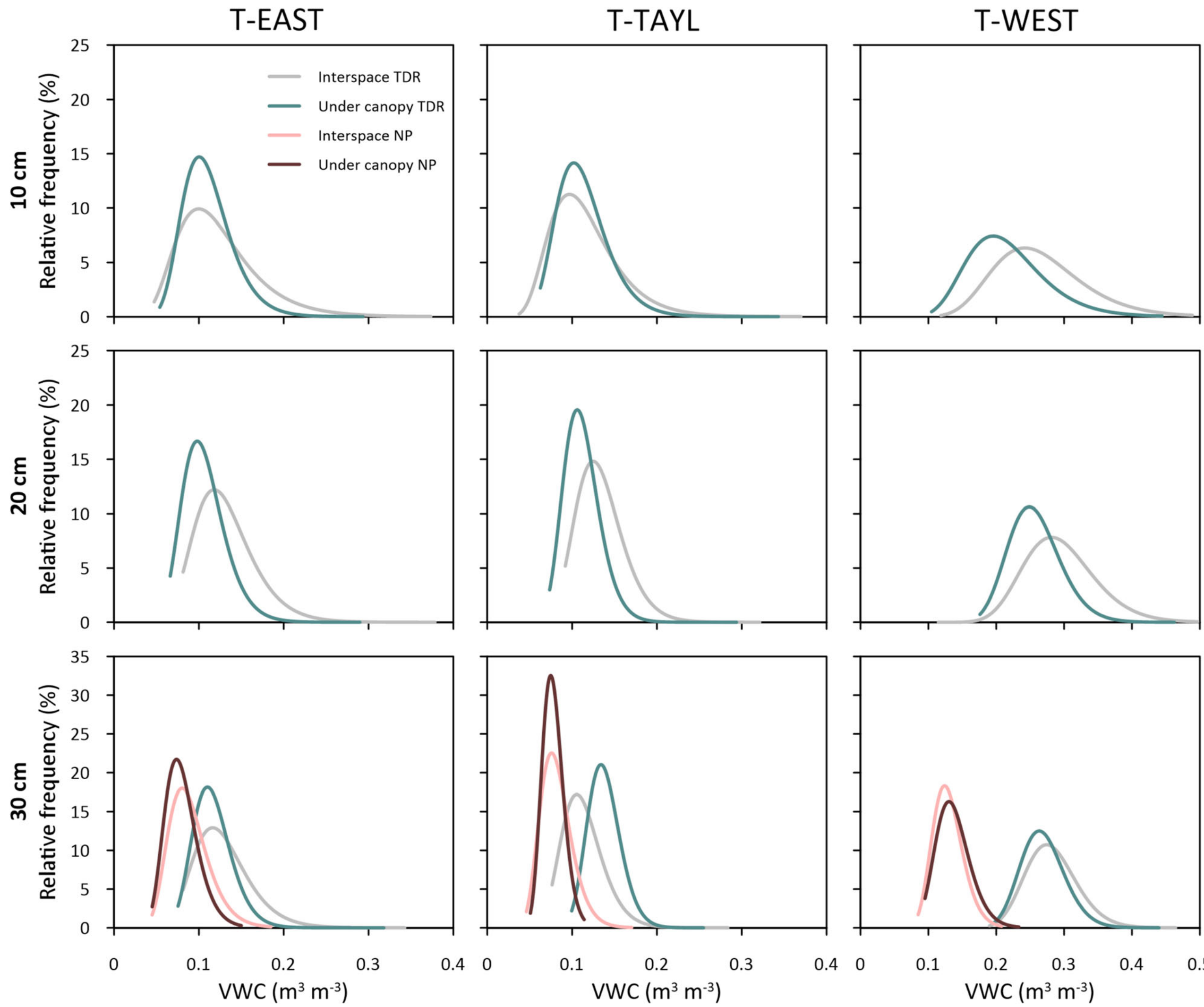

Figure 9. Frequency distribution of soil volumetric water content (VWC) measured by the TDR sensors from 2013 to 2023 at 10 cm, 20 cm, and 30 cm depths in the soil profile of the tarbush sites. Additionally, the frequency distribution of VWC measured by neutron moisture meter probes at 30 cm depth for the same time period is included.

enhancing soil moisture near root tips (Martinez-Meza and Whitford 1996). At the T-EAST site, the VWC was lower under canopies throughout the soil profile, except at a depth of 90 cm, where higher calcium carbonate content was observed. Despite fine-textured soil and strong calcic and petrocalcic horizons present at sites, which generally limit percolation of soil water to deeper depths (Duniway and others 2010), tarbush shrubs can alter soil structure to improve infiltration rates throughout the soil profile, as corroborated by Mueller and others (2008) and our study.

The spatial partitioning of soil moisture in desert shrublands is influenced by a complex interplay of soil properties (Duniway and others 2010, 2018), shrub–grass competitive interactions (Le Roux and others 1995), and shrub-type characteristics that modify various ecohydrological processes, including canopy interception (Martinez-Meza and Whitford 1996; An and others 2022), plant water uptake (Yoder and Nowak 1999), evaporative losses (Dong and others 2003), preferential flow (Marquart and others 2020), and hydraulic lift (Richards and Caldwell 1987). Collectively, these factors contribute to the spatial redistribution of soil moisture, both across the soil surface and with depth. For example, denser and taller shrubs, such as mesquite, are less efficient in redistributing rainwater under the canopy, due to higher interception loss and lower stemflow efficiency, while also having greater water demands than smaller shrubs like creosotebush and tarbush (Zhang and others 2020; see Table 1 for differences). In addition to differences in water-holding capacity between under canopy and finer-textured interspace soils, this may help to explain why lower VWC was found under the canopy of mesquite shrublands, whereas greater VWC was found under the canopy in tarbush shrublands. Additionally, the presence of shallow-rooted bunchgrasses in tarbush shrublands likely contributes to the depletion of soil moisture in the shallow soil layers of the interspaces. In contrast, the similar VWC partitioning found in evergreen creosotebush ecosystems could be attributed to the extensive lateral root systems of these shrubs, which allow them to simultaneously uptake water from both under canopy and interspace environments (Wilcox and others 2004). Furthermore, the ''double funneling of trees,'' the process whereby an aboveground funneling occurs when rainfall concentrates into stemflow, followed by a belowground funneling process in which stemflow infiltrates into the soil along tree roots and macropores (Johnson and Lehmann 2006; Pinos and others 2023), is a primary mechanism for soil moisture recharge in drylands (Li and others 2009), significantly shaping the distribution of soil moisture between under canopies and interspaces.

Influence of Climate on ΔVWC

Previous research by D'Odorico and others (2007) has found that soil moisture partitioning between under canopies and interspaces tends to increase as aridity increases in dryland regions. However, our study indicates that this pattern may not be exclusively driven by long-term aridity. Our findings suggest that overall levels of meteorological drought do not significantly influence soil moisture partitioning between under canopy and interspace environments. By employing a monthly aridity index, which captures variations in dry and wet periods, our approach offers a more nuanced understanding than the annual precipitation focus of D'Odorico and others (2007). This monthly resolution allows for a detailed examination of how aridity impacts soil moisture distribution over shorter timescales.

Monsoon rainfall provides critical soil moisture for ecosystems in the northern Chihuahuan Desert, yet the partitioning of soil moisture within these ecosystems has been less clear. Although our analysis of the monthly NP dataset revealed only small differences in soil moisture partitioning emanating from higher and lower monsoon precipitation, the 30-minute TDR dataset illustrated higher sensitivity of soil moisture partitioning in response to monsoon precipitation at shorter timescales. Overall, soil moisture differences between interspaces and under canopies (ΔVWC) were slightly more positive or less negative during wet monsoons. Notably, M-NORT, T-EAST, and T-WEST sites exhibited the greatest sensitivity to monsoon conditions, with increased VWC observed in interspace soils during wet monsoons. Overall, our study reveals small to moderate sensitivity of soil moisture partitioning to climate influences both between and among shrubland ecosystems in the northern Chihuahuan Desert. This finding aligns with Snyder and others (2006), who reported in the Jornada Basin that seasonal rainfall is an unreliable indicator of soil moisture due to variations in water availability for infiltration, which are contingent on landscape characteristics. These results underscore the critical role of soil texture, rather than rainfall alone, in determining the variability of soil moisture partitioning in desert shrublands. Although our study did find small to moderate sensitivity at the seasonal scale, we propose that precipitation inputs at the event scale may still significantly influence the magnitude and direction of soil moisture partitioning (Cantón and others 2004; Li and others 2013).

Impact of Fine vs Coarse Resolution on ΔVWC

The significance of temporal resolution in environmental monitoring is well documented. For instance, Walling and Webb (1981) demonstrate the importance of river water turbidity monitoring at fine temporal resolution rather than weekly or monthly sampling. Fine-resolution monitoring in the 30-minute TDR dataset captured the full spectrum of drying and wetting cycles after precipitation events (see frequency distributions at 30 cm depth in Figures 7, 8, 9), a detail obscured in the monthly NP dataset. For example, periods of high rainfall increased shallow soil moisture ($\leq$ 30 cm) in shrub interspaces in mesquite and tarbush ecosystems, but this response was less pronounced in creosotebush sites and largely missed in the monthly data. However, the fine-resolution TDR data were only conducted at shallow soil depths and therefore cannot inform fine-scale dynamics at deeper soil depths. These results demonstrate that coarser temporal resolutions underestimate the variability, and range of ΔVWC, reinforcing the importance of fine-resolution monitoring for understanding soil moisture dynamics, and promoting the potential value of employing TDR instruments at deeper soil depths.

Conclusions

This study shows distinct differences in soil moisture partitioning between under canopy and interspace environments across three shrubland ecosystems in the northern Chihuahuan Desert. Results underscore the influence of physical soil properties and shrub-type characteristics on long-term soil moisture distribution and highlights how meteorological variation influences short-term soil moisture dynamics. In general, mesquite shrublands had drier soil under the canopy, tarbush shrublands had higher soil moisture under the canopy, and creosotebush shrublands had heterogeneous soil moisture partitioning that differed among sites. These findings challenge the adoption of the ''island of fertility'' concept to soil moisture broadly across desert shrublands. In tarbush and creosotebush shrublands, higher soil moisture under canopies may be promoted by variation in soil moisture partitioning at different depths in the soil profile, by low precipitation periods, and/or by evaporation and plant water use in shrub interspaces. As shrub encroachment continues in dryland ecosystems, a deeper understanding of the interactions between soil moisture and shrub vegetation is crucial. This knowledge can help mitigate the adverse effects of woody plant encroachment and enhance land management strategies aimed at conservation and sustainable land use.

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DATA AVAILABILITY

All the data used in our study is available to readers through the Environmental Data Initiative (EDI) repository, and all citations have been included in the manuscript including DOI.

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