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ECOSYSTEM ECOLOGY - ORIGINAL PAPER

Spatial and temporal variability of plant-available water in calcium carbonate-cemented soils and consequences for arid ecosystem resilience

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Abstract Increased variability in precipitation, including frequency of drought, is predicted for many arid and semiarid regions globally. The ability of soils to retain water can increase resilience by buffering vegetation communities against precipitation extremes. Little is known, however, about water retention by carbonate-cemented soil horizons, which occur extensively in arid and semiarid ecosystems. It has been speculated that they may significantly modify vertical and temporal distribution of plant-available water (PAW). To investigate this hypothesis, PAW was monitored at three sites in a mixed shrub-grass community in southern New Mexico, USA, across soils with differing degrees of carbonate horizon development: no carbonate horizon, a horizon partially cemented with carbonates (calcic), and a horizon continuously cemented with carbonates (petrocalcic). Results are presented from 3 years that included extremely dry and wet periods. Both carbonate-cemented horizons absorbed and retained significantly greater amounts of PAW for several months following an extremely wet winter and summer compared to the non-carbonate soil. Following a wet summer, continuously cemented horizons retained very high PAW (16–18% volumetric or ∼72–80% of soil water holding capacity) through early spring of the following year, more than double the PAW retained by similar depths in the non-carbonate soil. Drying dynamics indicate both carbonate-cemented horizons release stored water into the grass rooting zone during growing seasons following extreme wet events. Water dynamics of these horizons during extreme events provide a mechanism to explain previous observations that perennial grasses exhibit greater resilience to drought when carbonate-cemented horizons occur at shallow depths (<50 cm). Water holding capacity of the entire profile, including horizons cemented with carbonates, should be considered when evaluating the potential resilience of vegetation communities to disturbance, including the increased variability in precipitation expected to occur as a result of global climate change.

Keywords Calcic · Petrocalcic · Chihuahuan Desert · Desert grassland · Climate change

Introduction

Both increases and decreases in precipitation are predicted for desert regions due to global climate change (Cubasch et al. 2001). In addition to changes in precipitation amount, increased variability of precipitation timing and intensity is predicted. In some scenarios, droughts in southwestern North America may increase in frequency and intensity to result in similar conditions as occurred during the Dust Bowl (Seager et al. 2007).

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In arid and semiarid ecosystems, vegetation community composition is controlled by water availability (Noy-Meir 1973). Precipitation, measured as distinct pulses or as annual averages, is a good predictor of production in arid ecosystems at regional scales (Webb et al. 1978; Ogle and Reynolds 2004). At local scales, however, plant community composition and production is greatly influenced by soil water availability associated with landscape position, infiltration capacity, soil water holding capacity, and species composition (Walter 1973; McAuliffe 1994; Reynolds et al. 2004; Swemmer et al. 2007). The location of plant-available water (PAW) within the soil profile, either shallow and available to shallow-rooted plant species or deep and only accessible to species with deep rooting systems, has been used to explain both the distribution of existing plant communities and response of vegetation to climate and management in arid and semiarid ecosystems in both observational studies (Herbel et al. 1972; McAuliffe 1994) and modeling exercises (Breshears and Barnes 1999; Hamerlynck et al. 2002; Gao and Reynolds 2003; Gutierrez-Jurado et al. 2006). Deciphering the mechanisms and processes behind observed patterns requires detailed knowledge of plant physiology as well as extensive knowledge of both soil pedology and hydrology, especially in soils with extensive and complex pedogenic development.

Important pieces of knowledge are lacking, however, in our understanding of water dynamics in arid and semiarid soil systems that have strongly developed soil horizons. For example, modeling studies of soil water dynamics often rely on predictive relationships between easily measured soil properties (e.g., particle size distribution and organic matter) and difficult to measure soil hydrologic properties to generate the parameters necessary to simulate water infiltration (e.g., Gutierrez-Jurado et al. 2006). However, these predictive relationships are primarily designed for agricultural applications; thus model training datasets do not typically include soil types common in non-cultivated ecosystems, such as carbonate-cemented soil horizons (calcic and petrocalcic horizons, commonly referred to as "caliche"; Fig. 1) (Saxton and Rawls 2006).

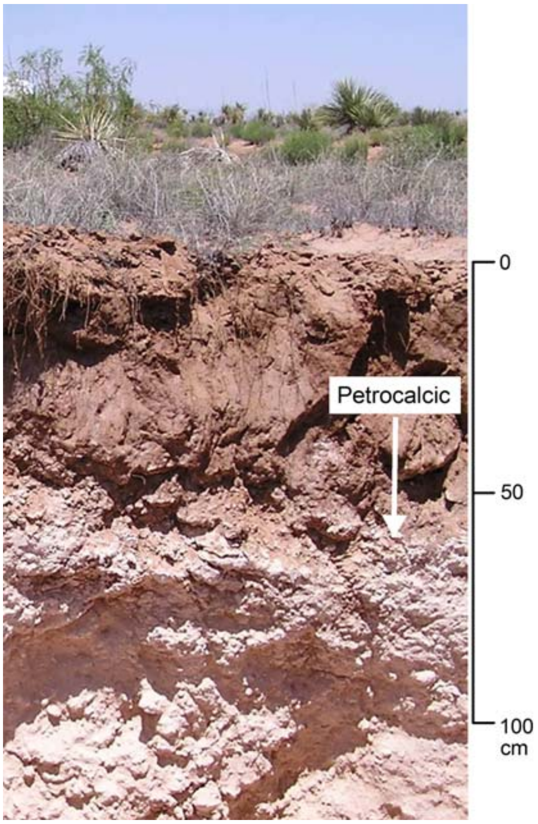

Fig. 1 Example of shrub-invaded black gram grassland growing in sandy soil shallow to a petrocalcic horizon (*top of petrocalcic horizon labeled*). Soil located very near the petrocalcic site

Carbonate-cemented soil horizons occur extensively throughout arid and semiarid regions globally (Fig. 2). Unlike other soil horizons of arid and semiarid regions with distinct mineralogy, such as gypsic horizons, the occurrence of high carbonate horizons is not confined by parent material mineralogy. In these dry regions, carbonates accumulate where the soil solution dries and the reactants (typically calcium and bicarbonate ions) are concentrated, usually within the plant rooting zone (<1 m; Gile et al. 1966; Birkland 1999). Fine carbonate crystals initially precipitate along roots, fungal hyphae, and soil particle surfaces and progressively fill soil pores (Monger et al. 1991). Through time, the accumulation of carbonate precipitates can completely plug soil pores, often resulting in distinct soil horizons that are partially (calcic) to continuously cemented (petrocalcic; Soil Survey Staff 1999). Our understanding of the mechanisms of carbonate horizon genesis provides insight into long-term average soil moisture conditions; however, it is not understood how these horizons affect plant water availability during unusually wet and dry years. This knowledge is necessary to predict how soil variability will affect plant community response to disturbance, management and climate.

The importance of carbonate-cemented soil horizons for vegetation patterns and dynamics in arid and semiarid systems has long been hypothesized, but mechanisms have never been clearly established. Horizons that are continuously cemented with carbonates (petrocalcics) are traditionally viewed as barriers to both root penetration and vertical water movement (Shreve and Mallery 1932; Ruellan 2002). A manipulative field experiment by Hennessy et al. (1983), though limited in scope, indicates petrocalcic horizons have the potential to rapidly absorb and retain large

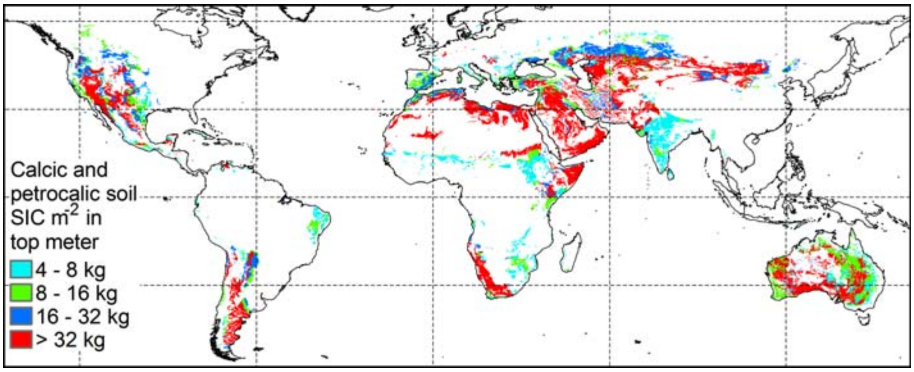

Fig. 2 Global distribution of soil inorganic carbon (SIC) within areas where calcic or petrocalcic horizons likely occur. The influence of carbonates on soil water dynamics in the top meter will increase with increasing amounts of SIC. Map produced by intersecting global maps of soil taxonomy (including only suborders that contain petrocalcic and calcic soils) and SIC (Soil Survey Staff 1999; Monger et al. 2005; USDA-NRCS 2008)

volumes of soil water. Carbonate ^{14}C dating and soil water tracers (bomb pulse ^{36}Cl) provide evidence of water absorption by these horizons during formation and in recent decades (Gile et al. 1981; Gifford 1987). Soil water measurements taken at a bedrock-petrocalcic interface indicate that water movement through these horizons in a semiarid karst landscape is common (Wilcox et al. 2007). Observations of plant roots in horizons partially and continuously cemented with carbonates suggest that water may be available to plants (Gibbens and Lenz 2001). Additionally, perennial grasses exhibit greater resilience to drought when petrocalcic horizons occur at shallow depths (Herbel et al. 1972). Furthermore, recent laboratory studies investigating the relationship between volumetric water content and soil water potential indicate petrocalcic horizons are capable of retaining large volumes of water (0.06–0.26 m^3 m^{-3}) at plant-available water potentials (Duniway et al. 2007). Although non-cemented or weakly cemented carbonate horizons (calcics) are not viewed to be a substantial barrier to roots or water, the few studies of which we are aware investigating plant water availability or utilization from these horizons are limited to agronomic settings (Georgen et al. 1991; Baumhardt and Lascano 1993; Mengel 1994).

Soils capable of retaining large amounts of PAW within the rooting zone for extended periods can increase vegetation resilience by buffering communities against extremes in precipitation and extending the period plants can survive between precipitation events (Gunderson 2000). Differences in PAW are likely less important during wet periods. However, the ability of soils with high water holding capacities to retain water long after the rains have stopped may facilitate plant persistence during drought (e.g., Herbel et al. 1972) but these processes are poorly understood. Despite the widespread occurrence of carbonate-cemented soil horizons and their perceived importance for plant community structure and dynamics, little is known about patterns of soil moisture in these horizons and less about the availability of the contained water.

This study was designed to determine if PAW is affected by soil horizon cementation by carbonates and if PAW dynamics can help explain the observed resilience of vegetation to extreme events. The approach used was to monitor daily patterns of soil water recharge, availability, and depletion across three coarse-textured soils on the same landform with differing degrees of carbonate cementation. We report results for a 3-year period including an unusually wet winter (2004–2005), extremely dry winter and spring (2005–2006), and very wet summer (2006). Specifically, we hypothesize that during these extreme events, the increased water holding capacity of the shallow (50–60 cm) carbonate-cemented horizons will result in higher soil water contents as well as greater amounts and frequencies of PAW than similar soils lacking carbonates.

Materials and methods

Study location

Study sites were located on the USDA-ARS Jornada Experimental Range in the northern Chihuahuan Desert of southern New Mexico, USA (Supplementary 1: Fig. S1). The historic climate is characterized by a warm dry spring, hot wet summer, and cold dry winter. Long-term (1915–2006) average annual rainfall is 248 mm of which more than half usually falls from July up to and including October. The rainfall record is characterized by seasons and years of drought and above-average rainfall with an annual rainfall coefficient of variation of 35% (1915–2006).

The study period was marked by extremes that exceed even the normally high variability in seasonal precipitation (Fig. 3). Rainfall for the winter of 2004–2005 was extremely high with study sites receiving 271% of the long-term average rainfall. Summer 2005 was dry with study sites receiving only slightly more than half of the average amount. This dry summer was followed by an extremely dry winter and spring for a total of 7 months with virtually no precipitation. This was the second driest November up to and including April since records began in 1914. This extremely dry winter and spring was followed by the wettest August up to and including October recorded on the Jornada.

To understand the effects of soil carbonate accumulation, cementation, and the resultant soil morphology on water dynamics, we selected a chronosequence of soils on the broad alluvial plain of the ancestral Rio Grande; time of soil development varied while topography, parent material, and climate were similar (Supplementary 1: Fig. S1). We selected sites that included a young sandy soil (sand), a moderately old soil with a horizon partially cemented with carbonates (calcic) and an ancient sandy soil with a horizon continuously cemented with carbonates (petrocalcic).

The youngest site (sand) served as a reference, an example of how soils at calcic and petrocalcic sites might behave without carbonate horizon development. Sand is located in an area that has very limited carbonate accumulation in the top 150 cm of soil (Pintura series; mixed, thermic Typic Torripsamments; Bulloch and Neher 1980; Supplementary 1: Fig. S2). The calcic site soil has a calcic horizon that is continuously plugged and partially cemented by carbonates with a stage III + morphology (Yucca series; coarse-loamy, mixed, superactive, thermic Typic Calciargids; stages following Birkland 1999). The petrocalcic site has a petrocalcic horizon with a stage V morphology as indicated by a laminar layer and pisoliths (Hueco series; coarse-loamy, mixed, superactive, thermic Argic Petrocalcids; Fig. 1). Additionally, as is common in older petrocalcic horizons that have undergone some degradation, there is a 1- to 10-cm-thick horizon of coarse petrocalcic rubble above the laminar layer (Hirmas and Allen 2007). Soil textures in the non-carbonate horizons are fairly coarse, ranging from loamy sands to sandy loams (Supplementary 1: Fig. S2). Vegetation at all sites is a mesquite (*Prosopis glandulosa* Torr.) shrub-invaded black grama (*Bouteloua eriopoda* Torr.) grassland. Shrub cover was <12% at all three sites and perennial grass cover averaged 30% across sites and years but was significantly higher at the calcic site (38%) than at the other two sites (27%; Duniway 2006; unpublished data). Taken together the three selected study sites allow for the comparisons of soil water dynamics among sites that are very similar in all aspects except the degree of carbonate accumulation.

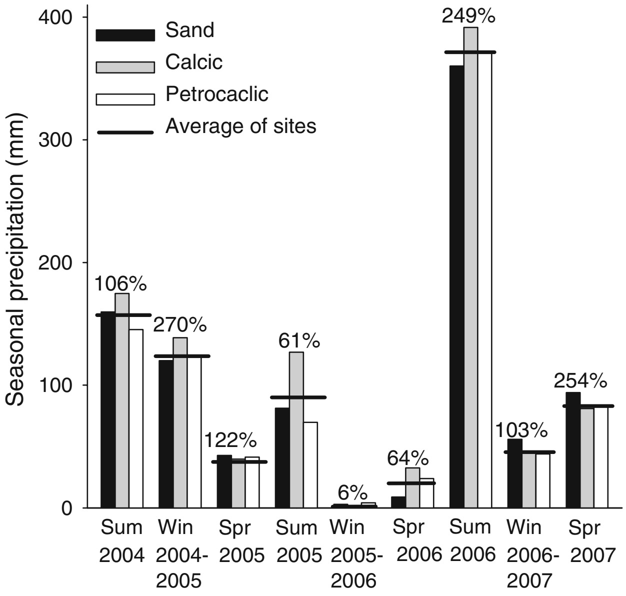

Fig. 3 Seasonal precipitation totals at the three soil moisture sites and percentage of long-term (1915–2006) average as recorded at the USDA-ARS Jornada Experimental Range headquarters (Supplementary 1: Fig. S1). Precipitation was recorded daily by a weighing bucket rain gauge located approximately 50 m from the petrocalcic site and monthly with manual rain gauges located 0.6 km from the sand site, and the average of two gauges located 1.8 km south and 2.5 km north of the calcic site. Additionally, manual rain gauges located at the sandy and calcic sites were checked periodically to confirm estimated monthly rain totals

Soil water content

We installed time domain reflectometry (TDR) soil moisture sensors in a split plot design with three whole plot treatment levels of soil carbonate horizon development, six replicate profiles per whole plot treatment, and three subplot treatment levels of soil depth (shallow, intermediate, and deep; Fig. 4). Each TDR profile (approximately 50 cm by 75 cm by 85 cm deep) was installed in a gap between perennial grass canopies such that each profile was $\sim$60 cm from the closest *B. eriopoda* basal. TDR profiles were located at calcic and petrocalcic sites such that depths to the carbonate-cemented horizons were similarly shallow (50–60 cm). The lateral extent of each site was limited to approximately 20 m due to allowable sensor cable lengths. Soil was saved by depth and horizon and replaced and packed to approximately field bulk density following probe installation. TDR soil moisture sensors at each site were connected to multiplexers and a wave propagator to generate probe wave forms (SDMX50, TDR100, CR10X; Campbell Scientific, Logan, Utah). Duplicate TDR measurements were taken every 8 h and saved wave forms analyzed for sensor travel time using TACQ (Evett 2000). Travel time was converted to volumetric water content using Topp et al.'s (1980) equation in non-carbonate soil and soil-specific calibration curves for carbonate horizons (see Duniway 2006 for detailed TDR methods).

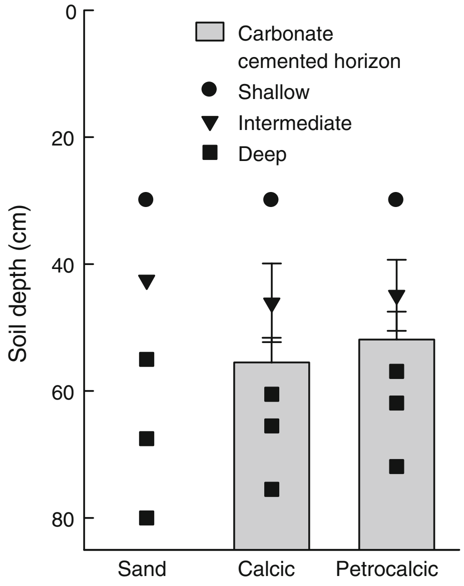

Fig. 4 Site soil moisture probe placement and carbonate-cemented horizon depths. Trifilar time domain reflectometry soil moisture probes were inserted horizontally. At the sand site, all probes were placed relative to the soil surface. At the calcic and petrocalcic sites, only shallow depth probes were placed relative to the soil surface; intermediate and deep depth probes were inserted relative to the upper carbonate-cemented horizon boundary. Intermediate probe and carbonate-cemented horizon depths are site means + SD ($n = 6$)

Soil characterization

To allow for comparisons of water contents across soils and horizons with contrasting pore sizes, permanent wilting point (PWP) volumetric water content (θ_{PWP}) representative of the specific soil properties at each soil moisture sensor was determined (Supplementary 1: Table S1). We used the conventional soil–water potential plant permanent wilting point of −1.5 MPa to make the results broadly applicable (Romano and Santini 2002). Estimates of θ_{PWP} were determined for non-carbonate soil using a predictive relationship (pedotransfer function) based on measured soil texture and bulk density (Schaap et al. 2001). Due to their unique physical and chemical characteristics, pedotransfer functions were not used to determine θ_{PWP} in the high carbonate horizons. Instead, we measured the characteristic soil water release curve for the soils at each probe located in a high carbonate horizon from approximately −0.5 to <−5.0 MPa ($n = 3$ subsamples, three to six points for each subsample) using a chilled mirror psychrometer (WP4 potentiometer; Decagon Devices, Pullman, WA; Scanlon et al. 2002). We extrapolated to obtain θ_{PWP} using the van Genuchten (1980) equation modified for gravimetric water content and bulk densities estimated based on a multiple regression relationship from data in Duniway et al. (2007; Duniway 2006). Bulk density values were validated with values for calcic and petrocalcic horizons from nearby soil pits (Soil Survey Staff 2006). To address hypotheses regarding soil water availability, we subtracted the soil-specific θ_{PWP} from measured soil water contents.

Statistical analysis

We used an ANOVA approach to test hypotheses regarding soil water content and dynamics. Diurnal variability of TDR soil water contents was generally less than 0.01 $\mathrm{m}^3\ \mathrm{m}^{-3}$, so we used daily average water contents for each TDR probe. Subsamples within the deep depths were then weighted by their representative soil depth and averaged (Fig. 4). For deep depths with a missing subsample (see Duniway 2006), we used the two remaining probes within each replicate. Mean deep measurement depths did not differ significantly between sites ($P = 0.717$). Variability within sites did exist, so we included average deep replicate depth as a covariate for cross-site hypotheses tests. To test hypotheses addressing amount of available water through time, ANOVA (PROC GLM; SAS Institute 2001) with deep mean depth included as a covariate was completed for each day of measurement and contrasts used to test for significant differences in available water between sites ($\alpha = 0.05$). While this approach can cause a high experiment-wise type I error rate, for this exploratory study we were more concerned with minimizing the type II error rate and increasing power to detect under what conditions significant differences were most likely to exist.

To test available water dynamics hypotheses, we determined the percent of days within a season where shallow and deep soil water contents were significantly greater than the permanent wilting point [$P < 0.05$; PROC MEANS, PROC FREQ (SAS Institute 2001); Fig. 4]. To evaluate differences in deep depth horizon drying rates, repeated measures analysis with a heterogeneous autoregressive covariance structure and Satterthwaite *df* (PROC MIXED; SAS Institute 2001) was completed for April drying events in the spring 2005 and 2007. Again, we used the mean deep measurement depth as a covariate.

For analysis, the calendar year was divided into three seasons that capture much of the variability in the study area climate: summer (July up to and including October), winter (November up to and including February) and spring (March up to and including June).

Results

Soil water content

During dry periods, horizons partially (calcic) and continuously (petrocalcic) cemented with carbonates contained approximately 0.10 $\mathrm{m}^3\ \mathrm{m}^{-3}$ more soil water than the non-carbonate depths and profiles (Fig. 5). Minimum average water contents ranged from 0.12 to 0.16 $m^3\ m^{-3}$ in the carbonate-cemented horizons compared to 0.05–0.06 $m^3\ m^{-3}$ in the corresponding depths (deep) at the sand site and 0.03 $m^3\ m^{-3}$ in shallow and intermediate depths (Figs. 4, 5). In the sand site, deep water contents were similar to the shallow, retaining only 0.01–0.02 $m^3\ m^{-3}$ more water during dry periods.

All depths at all sites recorded large increases in soil water content in response to rains in the wet winter of 2004–2005 and wet summer of 2006 (Fig. 5). Carbonate-cemented horizons had larger increases and maximum soil water contents than the sand site during the wet winter of 2004–2005 and wet summer of 2006. Following the winter of 2004–2005, deep water contents at the calcic and petrocalcic sites did not dry to pre-winter levels until August 2005, whereas the sand deep depths lost all winter moisture by June. After the initial wetting by rains in August 2006, the petrocalcic horizon retained 0.28–0.33 $m^3\ m^{-3}$ and the calcic horizon 0.20–0.23 $m^3\ m^{-3}$ soil water until April 2007.

PAW content

Carbonate-cemented horizon PAW was higher on average in wet periods and in some dry periods than similar depths (deep) in the sand (Fig. 6). In contrast, the shallow depth PAW was similar across sites throughout the study. Deep PAW was initially fairly similar across sites. After peak moisture in mid to late winter 2004–2005 PAW in carbonate-cemented horizons was significantly greater than in corresponding (deep) depths in the sand for several months. The calcic horizon retained significantly more PAW than the petrocalcic horizon from early April until late May 2005, likely due to the slightly greater amounts of rainfall received by the calcic than the petrocalcic site during summer 2004 and winter 2004–2005 (Fig. 3).

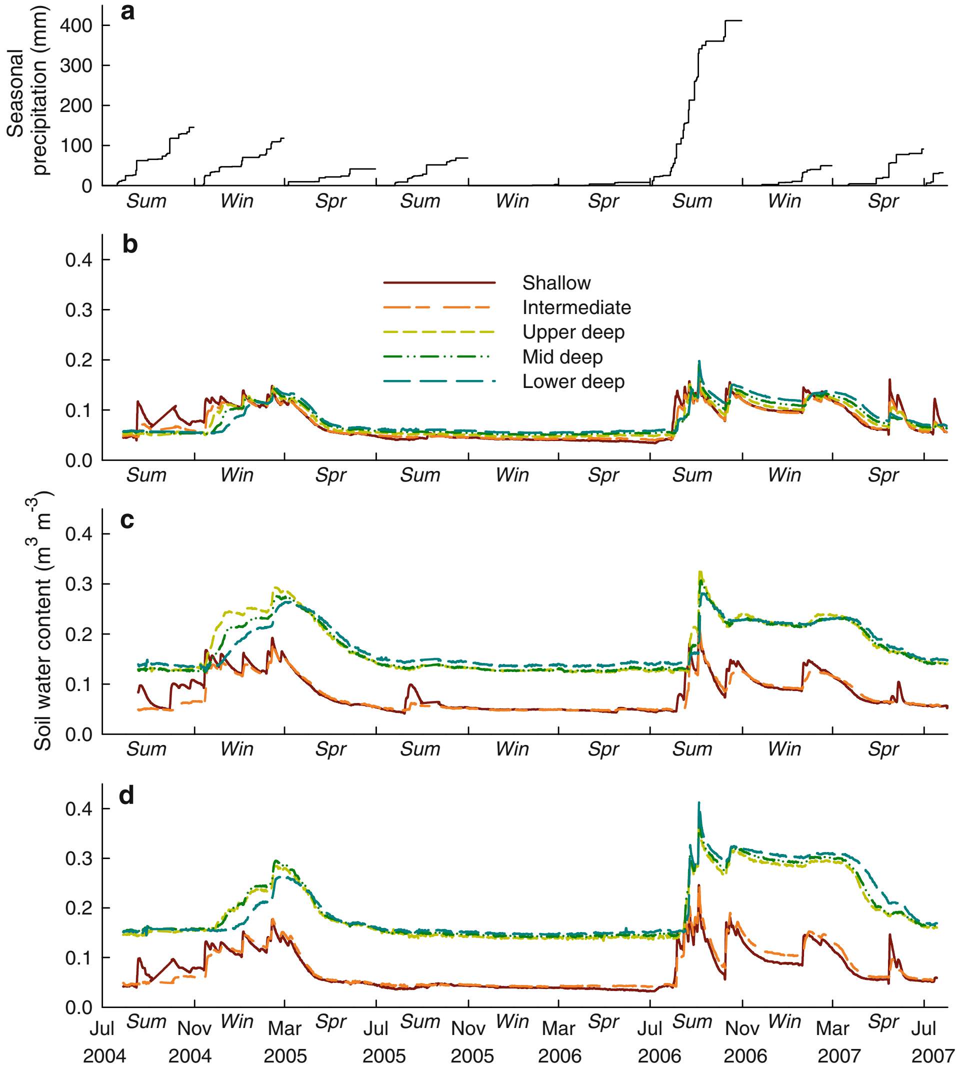

Fig. 5 Seasonal accumulated daily precipitation at the **a** petrocalcic site and average water content for all depths at the **b** sand, **c** calcic, and **d** petrocalcic sites. *Sum* Summer, *Win* winter, *Spr* spring, *Jul* July, *Nov* November, *Mar* March

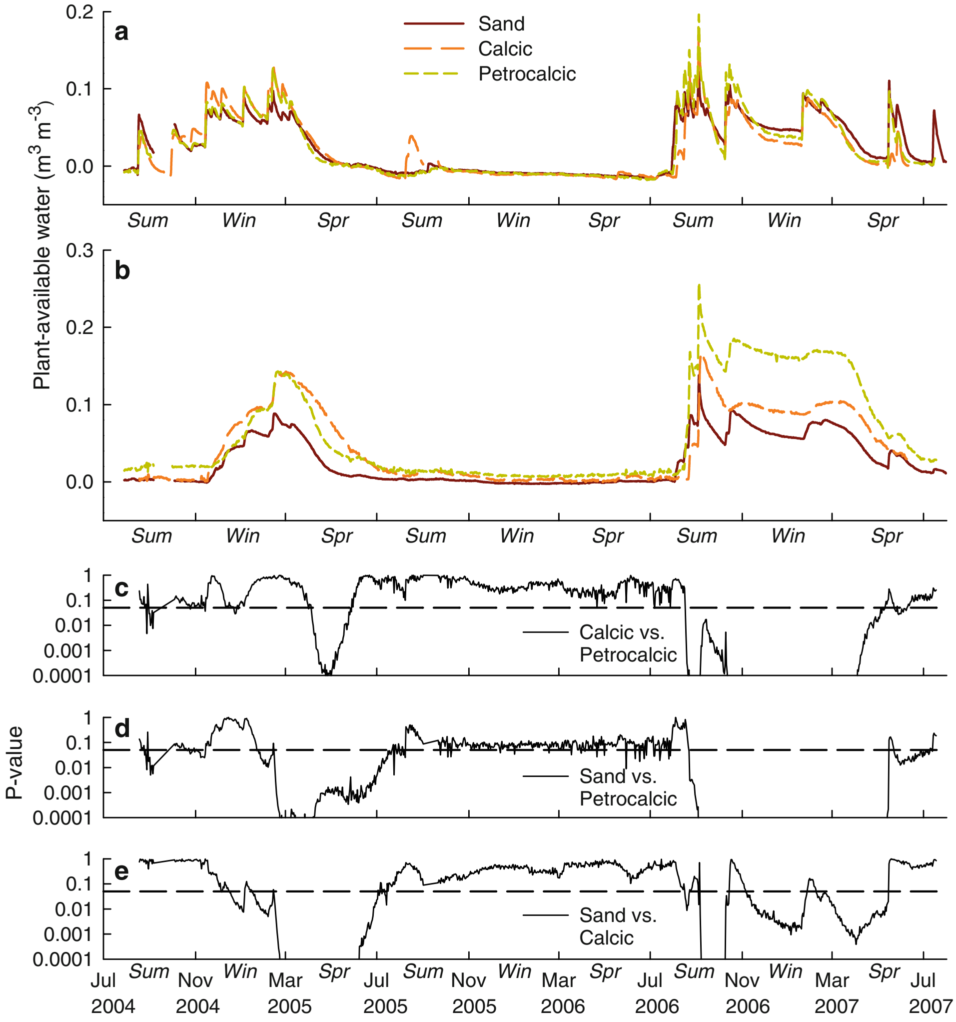

Fig. 6 Plant-available water (PAW) content of **a** shallow and **b** deep depths, and **c**, **d**, **e** deep depth contrast *P*-values from daily ANOVA pair-wise comparisons. For abbreviations, see Fig. 5

The rates of increase and maximum PAW at the petrocalcic site were much greater following the intense summer rains of 2006 than during 2005 (Fig. 6). Except for a 1-week period following a spring rain in May 2007, the petrocalcic horizon had significantly greater PAW than the deep depths in the sand from late August 2006 up to and including the end of June 2007 (10 months). Unlike the wet winter 2004–2005, however, the petrocalcic horizon had significantly greater PAW than the calcic horizon during the entire period (August 2006 up to and including early May 2007), even though the calcic site received slightly more rain than the petrocalcic site during the summer 2006. The calcic horizon retained significantly greater PAW than deep depths at the sand site for long periods during the summer 2006, winter 2006–2007 and spring 2007.

Frequency of PAW

Both carbonate-cemented horizons had a greater frequency of days with PAW than deep depths lacking carbonate accumulation (Fig. 7). Frequency of PAW in the shallow and deep depths of the sand closely mirrored rainfall patterns with virtually no available water during the long dry period beginning in the summer 2005 (Fig. 3). In contrast, frequency of PAW in the petrocalcic and calcic horizons was 100% during the spring 2005 and 20–30% during the following summer.

Spring 2005 and 2007 drying

In addition to the expected significant differences in April water contents due to the main effects of site (*S*) and day of the year (*D*), the repeated measures analysis results indicate a significant effect of site and site by year (*Y*) on drying rate ($S \times D$, $S \times D \times Y$ interaction effects; Supplementary 2; Fig. 8). Estimates of drying rates (Table 1) indicate the significant interaction effects were driven by faster rates of drying (more negative value) in the petrocalcic across years and the faster rate of drying in 2007 than in 2005 in the calcic. The covariate of mean deep depth was

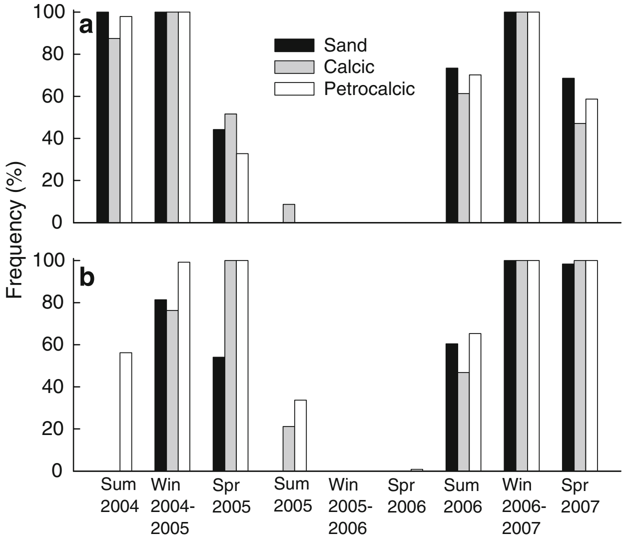

Fig. 7 Frequency of days within seasons with PAW contents greater than zero in the **a** shallow and **b** deep depths ($P < 0.05$). For abbreviations, see Figs. 5 and 6

significant in the model but the estimated effect was actually fairly small (0.0003 $m^3 m^{-3} cm^{-1}$).

Discussion

PAW dynamics

Presence of horizons both partially (calcic) and continuously (petrocalcic) cemented with carbonates greatly increased the near surface (upper 80 cm) soil water holding capacity, thus increasing the amount and duration of PAW during the extreme weather events captured by this study (Figs. 6, 7). Soil moisture availability is critical for plant survival during droughts. Carbonate-cemented horizons retained greater total water contents than similar depths in the deep sandy soil during the wet cool season, drought, and warm wet season included in the study period. During and following the extreme wet events, carbonate-cemented horizons retained more PAW and for a greater duration than in the deep sandy soil, a potentially important function for seedling establishment (Peters 2000).

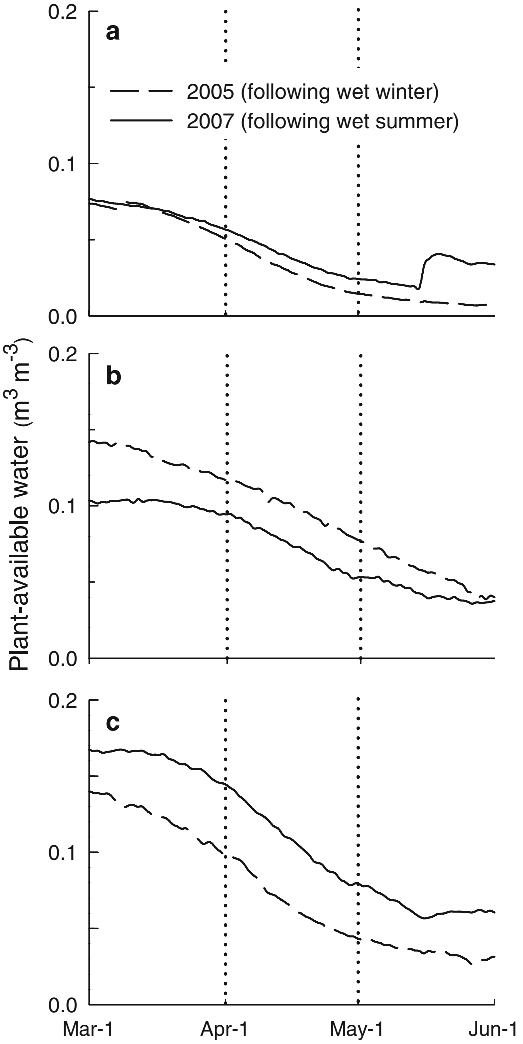

Fig. 8 PAW contents for deep depths during the spring 2005 and 2007 drying events at the **a** sand, **b** calcic, and **c** petrocalcic sites. *Dotted vertical lines* delineate month of April (*Apr*), the period analyzed with repeated measures. *Jun* June

Table 1 Estimated deep depth (Fig. 4) rate of drying for April 2005 and 2007. SEs *in parentheses*

Year	Site	*df*	Rate of water loss ($m^3 m^{-3} day^{-1} \times 10^{-2}$)[a]
2005	Sand	87	−0.15*** (0.01)
	Calcic	210	−0.12*** (0.01)
	Petrocalcic	181	−0.16*** (0.02)
2007	Sand	106	−0.13*** (0.01)
	Calcic	95	−0.19*** (0.01)
	Petrocalcic	176	−0.23*** (0.03)

*** $P < 0.001$ (rate of change significantly different than zero)

[a] Reported values are the actual values multiplied by 100

During the wet winter of 2004–2005, evapotranspiration losses from the sites were likely relatively low due to cooler temperatures and senescence of most plant species present. Although the total precipitation during winter 2004–2005 was less than the previous summer, shallow and intermediate soil water content at all sites exceeded field capacity and excess water continued down to the deep depths (Fig. 5). Beginning in mid February 2005, both carbonate-cemented horizons retained increases of 0.12–0.13 $m^3 m^{-3}$ over early winter levels and water contents of 0.26–0.28 $m^3 m^{-3}$ for a period of 3–4 weeks. These values are comparable to laboratory and field estimates of field capacity (Hennessy et al. 1983;

Duniway et al. 2007). In contrast, the sand site lower depth field capacities were only slightly larger than the shallow and excess moisture likely drained below the lowest monitored depth (80 cm). Thus, the sand soil with low water holding capacity lost more water to deeper depths, potentially providing a stable water source for the deep-rooted *P. glandulosa*.

Carbonate-cemented horizons continued to have available water well into the growing season with no or limited rainfall. In contrast, timing of PAW (both shallow and deep) in non-carbonate horizons more closely mirrored rainfall. The lack of more consistently available water in the unconsolidated soil at the carbonate-cemented horizon upper boundaries indicates the greater drought tolerance of *B. eriopoda* observed by Herbel et al. (1972) growing on soils shallow to petrocalcic horizons could be attributed to root contact with the upper parts of the horizon (Gibbens and Lenz 2001). It might also be the result of mycorrhizal networks within the horizon providing access to the contained stable water source, similar to the fungal-accessible water in weathered bedrock (Bornyasz et al. 2005).

During the extreme dry event (November 2005–April 2006), the carbonate-cemented horizons did not have greater amounts of PAW after drying to pre-winter levels (Fig. 6). This lack of difference in PAW is due to the large amount of water retained by the carbonate-cemented horizons at -1.5 MPa (Supplementary 1: Table S1). Many plant species present on the study sites have been shown to be photosynthetically active at xylem and/or leaf water potentials much drier than -1.5 MPa (Senock et al. 1994; Reynolds et al. 1999; de Soyza et al. 2004). If a drier permanent wilting point of -4.0 MPa were considered (instead of -1.5 MPa used here), the amount of water held at plant-available tensions in the carbonate-cemented horizons would further increase relative to the sand by 0.03–0.06 $m^3\ m^{-3}$ (Duniway et al. 2007).

Very high water contents (Fig. 5) and PAW (Fig. 6) were recorded for the carbonate-cemented horizons in response to the extremely large amounts of rainfall that the sites received in the summer 2006. The sequence of large rain events exceeded the water holding capacity of the upper profiles and the water quickly reached and was absorbed by the carbonate-cemented horizons. As was observed during the wet winter of 2004–2005, much of the infiltrated water at the sand site was likely lost to depths below those measured here. Peak water contents recorded were close to previously measured petrocalcic horizon porosities (Duniway et al. 2007). Following the initial pulse of water, the petrocalcic horizon quickly drained to water contents near field capacity ($\sim$0.30 $m^3\ m^{-3}$), which were maintained for nearly 8 months.

Carbonate-cemented horizon drying mechanisms

This study was designed to quantify patterns of water availability in carbonate-cemented horizons, thus mechanisms of horizon drying were not measured directly. However, the observed drying dynamics coupled with soil, plant and climate properties do allow us to make some inferences regarding likely mechanisms for how the water retained by these horizons was released.

The study area weather during the spring dry-down months is marked by low humidity and increasing temperatures and wind speeds, resulting in rapidly increasing potential evapotranspiration rates (Wainwright 2006). Both theory (Yamanaka and Yonetani 1999) and the small estimated deep depth covariate effect during the April dry-downs indicate very little of the water lost from these deep horizons can be attributed to evaporational losses from the sandy soil surface; thus the losses observed were likely due to transpirational losses. Roots were not observed within the small sections (<50 cm) of petrocalcic or calcic horizons exposed during soil moisture-probe installation; however, high densities of roots were often found matted on top of the upper horizon boundaries.

During both 2005 and 2007, the most rapid carbonate-cemented horizon drying occurred during April (Fig. 8), a month when the resident warm season grasses and shrubs become active. Despite the differences in precipitation (warm season wet versus cold season wet) and differences among soils, few differences in the rate of deep depth drying, both within and among sites and years, were detected (Table 1). Although the petrocalcic horizon has a very fine porosity, no observable roots, and is continuously cemented, it was found to dry faster than deep depths in the sand and calcic sites when data were pooled across years (causing the significant site by day interaction; Supplementary 2). Though the faster rates were likely driven by a greater water potential gradient between the wet petrocalcic and dry upper layers than gradients present in the other sites, they indicate that the morphology and sparse roots within the horizon do not prevent release of the entrapped water from the previous season or seasons.

This long-term retention and subsequent spring-time release of moisture could help explain the close link between primary production of spring active C_3 plants and winter precipitation (e.g., Muldavin et al. 2008). The study by Muldavin et al. (2008) was done in low water holding capacity (sandy loam) soils with a very shallow petrocalcic horizon (15–50 cm deep). Although petrocalcic horizon water content was not monitored, it is highly likely that winter precipitation was absorbed by the petrocalcic and later released in response to water potential gradients established by the onset and growth of C_3 species. Critical experiments are still needed to confirm if water retained in these cemented horizons is utilized by plants, rates of utilization, and mechanisms for water extraction.

Implications for plant community resilience

During a 3-year period with extremes in precipitation, horizons partially (calcic) and continuously (petrocalcic) cemented with carbonates were recharged by winter and summer rains and contained large amounts of water at plant-available tensions for extended periods. Retention properties of these carbonate-cemented horizons do limit the downward loss of soil water; however, instead of posing a significant obstacle to soil water movement as previously believed, the horizons investigated appear to function as a soil water reservoir. Both calcic and petrocalcic horizons can contain soil water at tensions that are potentially available to plants for several months to a year. Cemented horizon drying was preceded by drying in the upper soil profile, with horizon water potentially lost via unsaturated flow through the horizon matrix to roots growing on top of or through fractures in the horizons (Gibbens and Lenz 2001). It is also possible petrocalcic and calcic water loss was facilitated by mycorrhizal fungal hyphae networks growing within the cemented soil (Monger et al. 1991).

There is evidence from the literature demonstrating that water in carbonate-cemented horizons is ecologically important to resident plant communities. First, extensive root excavations from the Jornada by Gibbens and Lenz (2001) found than nearly all shrubs species and most other perennial forb species had root systems that penetrated through calcic and petrocalcic horizons. Additionally, several perennial grass rooting systems, including *B. eriopoda*, also penetrated calcic and to a lesser extent petrocalcic horizons, though none extended completely through the horizons (Gibbens and Lenz 2001). Second, in a semiarid agricultural system, Georgen et al. (1991) found sunflower (*Helianthus annus* L.), kochia (*Bassia scoparia* L.) and cotton (*Gossypium hirsutum* L.) to readily extract water from a ~1.1-m-deep, partially cemented calcic horizon. Although there were fewer roots within the calcic than upper horizons, Georgen et al. (1991) calculated a higher water uptake rate (per root area) for roots in the calcic than in the upper soil layers and concluded that the upper calcic horizon held more water available to *H. annus* and *B. scoparia* than most upper soil layers (0.3–0.9 m). Third, Herbel et al. (1972) found that in sandy textured basin floor soils, *B. eriopoda* had a lower mortality rate during an extended drought in soils with shallow petrocalcic horizons than sandy soils without petrocalcic horizons. The presence of roots on top of and within calcic and petrocalcic horizons (Gibbens and Lenz 2001), evidence of water utilization from high carbonate horizons by other species (Georgen et al. 1991), and lower *B. eriopoda* mortality during drought in an otherwise low water holding capacity soil (Herbel et al. 1972), suggest that water within carbonate-cemented horizons is accessible to plants.

Although carbonate-cemented horizons are potentially an important water reservoir, the chemical and physical nature of these horizons do impose some important limitations on plant growth. In addition to causing alkaline conditions, calcium carbonate accumulation has been found to fix phosphorus, making in unavailable to plants (Lajtha and Bloomer 1988), and limit plant uptake of iron (Mengel 1994). The hardness of some soils cemented by carbonates can restrict root penetration to gaps and fractures (Gile 1961; Gibbens and Lenz 2001), thereby limiting available soil rooting volume. If carbonate-cemented horizons occur at extremely shallow depths such that very little unconsolidated material is present, the slow permeability of the horizon (Gile 1961) could result in increased water loss due to run-off or evaporation. Although carbonate-cemented horizons likely provide less resilience to drought than horizons of similar water holding capacity that are more easily penetrated by roots, in sandy semiarid and arid systems carbonate-cemented horizons are likely among the most common high water holding capacity horizons (Fig. 3) (Duniway et al. 2007). Therefore, species that are able to overcome the nutrient limitations imposed by high carbonate concentrations and have the ability to access water in carbonate-cemented soils are likely to benefit when these horizons are deep enough such that their low permeability does not increase water loss but shallow enough to be well within the species rooting zone.

Plant communities in arid and semiarid regions have changed dramatically in response to past climatic change and land-use patterns (van Auken 2000; Gibbens et al. 2005). Decreased precipitation and increased temperatures in these areas are predicted to produce more frequent, extreme droughts during the 21st century (Seager et al. 2007). The results of this study indicate that carbonate-cemented horizons can dramatically alter patterns and dynamics of soil profile water availability. As has been observed for grasses that survived the 1950s drought (Herbel et al. 1972) and in other systems with a thin soil layer over rock-like material (Witty et al. 2003), water holding capacity of carbonate-cemented horizons could provide a seldom recognized source of water potentially making resident plant communities more resilient to drought.

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