THE FUNCTIONAL ROLE OF PETROCALCIC HORIZONS IN DESERT ECOSYSTEMS: SPATIAL AND TEMPORAL DYNAMICS OF PLANT WATER AVAILABILITY

BY

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DEDICATION

To Conor and Genevieve, the two most important results of my graduate work

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ABSTRACT

THE FUNCTIONAL ROLE OF PETROCALCIC HORIZONS

IN DESERT ECOSYSTEMS: SPATIAL

AND TEMPORAL DYNAMICS

OF PLANT WATER

AVAILABILITY

BY

MICHAEL C. DUNIWAY, B.S.

Doctor of Philosophy

New Mexico State University

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Petrocalcic horizons occur in most desert soils around the world, often within the plant rooting zone. Little is known, however, about water holding characteristics or water availability in horizons indurated with carbonates. Soil profile characteristics can control plant community composition and production by altering spatial and temporal patterns of plant available water, patterns that are important for understanding the causes and consequences of woody shrub encroachment into historic desert grasslands. A series of replicated experiments at multiple spatial scales were conducted to investigate petrocalcic horizon water retention and dynamics. Sampling and field studies were conducted in a mixed shrub-grass community in southern New Mexico, USA. A laboratory study was conducted to define the soil-water release curve for a variety of petrocalcic material from field capacity to <-10 MPa. To evaluate high carbonate horizon temporal water availability and dynamics, two multiyear field studies were conducted: a pasture scale study comparing water availability across a chronosequence of carbonate horizon development and a companion patch-interspace scale study investigating soil-water dynamics associated with woody shrub encroachment in a petrocalcic soil. Petrocalcic horizon plant available water holding capacity for desert species ranged from 0.26 m3m'3 in plugged to 0.06 m3m'3 in some laminar horizons. Calcic and petrocalcic horizons retained much greater amounts of available soil water during a winter with above-normal precipitation than similar depths in the non-carbonate sand (0.12 to 0.14 m3 m'3 versus 0.08 m3 m‘3) and retained soil water at plant available tensions a greater number of days during the following spring and summer. The companion study in the petrocalcic soil showed that unvegetated interspaces absorbed significantly more soil water during a wet winter and retained more available soil water into the spring than soils under shrubs. In contrast, soils under shrubs absorbed greater quantities of water following summer rains. Wetting and drying dynamics indicate petrocalcic horizons release stored water but it is unclear if plants access

petrocalcic water directly. Patterns of water availability, however, indicate soils with shallow petrocalcic horizons are potentially less susceptible to dominance by deep rooted woody shrubs and beneficial to establishment and persistence of grasses.

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THE HIGH WATER HOLDING CAPACITY OF PETROCALCIC HORIZONS

ABSTRACT

Petrocalcic soil horizons occur in most arid and semi-arid ecosystems around the world, often within the plant rooting zone. Little is known, however, about the water holding characteristic of soils indurated with calcium carbonate. We conducted a replicated experiment to define the soil-water release curve (SWRC) for a range of petrocalcic horizon materials. Samples from both plugged and laminar horizons of two stage V petrocalcic horizons in southern New Mexico were characterized. Wetter soil-water potentials were measured using a pressure plate; more negative potentials (down to < -10 MPa) were measured using a chilled mirror water activity meter. Measured SWRC data were fit to the van Genuchten equation. SWRC methods employed were found to be reliable and repeatable. Plant available water holding capacity (AWHC) for desert species (with permanent wilting point set at -4.0 MPa) ranged from 0.26 m^3m^{-3} in plugged horizons to 0.06 m^3m^{-3} in some laminar horizons in contrast to approximately 0.07 m^3m^{-3} in the loamy sand parent material. Correlation analyses across morphologies of AWHC and soil properties resulted in significant relationships only with bulk density and porosity. AWHC and calcium carbonate content, however, were significantly negatively correlated within the laminar and positively correlated within the plugged petrocalcic horizon

morphologies. Cementation by calcium carbonate dramatically alters the water holding characteristics of soils and understanding these horizons is crucial for understanding patterns of soil water in desert systems throughout the world.

INTRODUCTION

Petrocalcic horizons occur extensively in arid and semi-arid ecosystems of the United States and world (Reeves, 1976; Machette, 1985; Monger et al., 2005). In many soils, these horizons occur within the rooting depths of deep rooted shrubs and in some areas within the rooting zone of grasses and row crops. Soil volume occupied by petrocalcic material, however, is almost always excluded when quantifying soil profile available water and soil water holding capacity (Soil Survey Staff, 1996).

Calcic horizons are formed through accumulation of calcium carbonate (Soil Survey Staff, 1999). Although many carbonate minerals occur, calcite (calcium carbonate) accounts for the vast majority of carbonates in soils (Birkland, 1999; Monger and Wilding, 2002). Petrocalcic horizons occur in later development when a calcic horizon is continuously indurated with precipitated carbonates (Soil Survey Staff, 1999). Carbonates precipitate where the soil solution dries and reactants are concentrated (Gile et al., 1966). Fine carbonate crystals (~2 to 10 pm) initially precipitate along roots, fungal hyphae, soil particle surfaces and progressively fill soil pores (Gile et al., 1966; Monger et al., 1991b). With sufficient time, carbonates can completely plug soil pores, producing an indurated plugged horizon and a distinct laminar carbonate cap (Gile et al., 1966). Formation of laminar cap horizons is attributed to restriction of downward soil water movement and precipitation of carbonates in the accumulated soil water (Gile et al., 1966). Petrocalcic horizons are characterized by high bulk densities (1.6 to 2.3 Mg m^{-3}) and carbonate contents (30 to 95 %) (Gile, 1961; Gile and Grossman, 1979). Based on micromorphology, plugging of pores with carbonates changes a coarse textured soil from a matrix of large pores to one dominated by fine pores (Monger et al., 1991a).

Although petrocalcic horizons appear to be both root and water restricting (Shreve and Mallery, 1932; Ruellan, 2002), there is evidence that these horizons both absorb soil moisture and are potential water sources for plants. Manipulative field experiments by Hennessy et al. (1983) indicate petrocalcic horizons have the potential to rapidly absorb and retain large volumes of soil water with a measured field capacity of 0.36 $m^3\ m^{-3}$. Work by Gile et al. (1981) indicates that at times water penetrated the laminar horizons, giving the underlying plugged horizon carbonates a younger ^{14}C date than the overlying laminar horizons. Additionally, soil water tracers (bomb pulse ^{36}Cl) provide evidence of water absorption by petrocalcic horizons in recent decades (Gifford, 1987). Most shrubs and perennial forbs excavated by Gibbens and Lenz (2001) had roots that penetrated calcic or petrocalcic horizons. Mesquite *(Prosopis glandulosa)* roots were observed growing laterally across continuous petrocalcic horizons and then descending through cracks and holes (Gile et al., 1997). Additionally, fungal hyphae have been observed throughout petrocalcic horizons (Monger et al., 1991b).

Xylem and leaf water potentials of < -10 MPa have been measured in desert adapted shrubs and grasses (Senock et al., 1994; Reynolds et al., 1999; Pockman and Sperry, 2000). Therefore, it is important to understand the water holding characteristics in desert soils across a wide range of water potentials and at multiple depths, including petrocalcic horizons.

Soil-water release curves (SWRCs) previously measured for a non-indurated, high carbonate calcic horizon resembled those of soils with higher clay contents than the non-carbonate horizon texture (sandy clay loam) (Baumhardt and Lascano, 1993). Conversely, Stakman and Bishay (1976) concluded that soil carbonates reduced the water held across all potentials, except in very coarse textured soils. Although water contained in rock and rock-like material has been shown to be significant (e.g., Flint and Childs, 1984; Jones and Graham, 1993; Tokunaga et al., 2003) and important for some vegetation communities (Witty et al., 2003; Bomyasz et al., 2005), we are aware of only one published study characterizing the SWRC for petrocalcic horizons. Hennessy et al. (1983) measured soil-water release at four potentials between -0.03 MPa and -1.5 MPa for four size classes of petrocalcic mbble. Morphology of these horizons, however, is extremely diverse. Morphology of the “caliche rock” samples studied was not described but was likely laminar material. The SWRCs generated were highly variable and fit the data poorly. Thus, more work is needed to accurately evaluate the SWRC of different morphologies of petrocalcic horizons.

The primary goal of this study was to evaluate the water holding capacity of two morphologies of petrocalcic horizon material at potentials relevant to arid

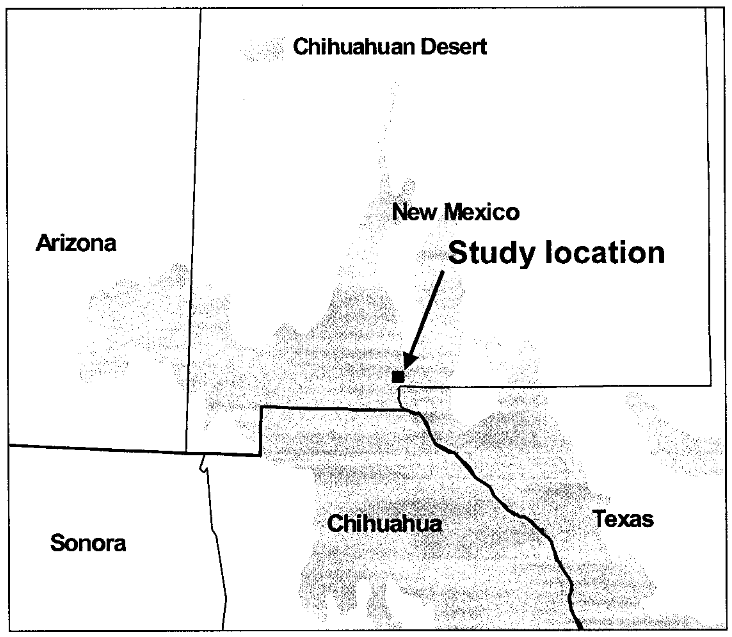

Fig. 1.1. Samples were collected from two locations in the Chihuahuan Desert (Schmidt, 1979) near Las Cruces, New Mexico, USA.

ecosystems and explore soil properties potentially responsible for petrocalcic horizon water retention. To address these objectives, it was necessary to modify existing SWRC methods. Therefore, an additional objective was to develop a reliable, repeatable method for determining SWRCs of petrocalcic materials.

MATERIALS AND METHODS

Study Locations and Profile Characteristics

Samples were obtained from two locations in the Chihuahuan Desert near Las Cruces, New Mexico (Fig. 1.1). Both sites have sandy and pebbly sandy parent material that was deposited by the ancestral Rio Grande River. Sediments at Site 1 are part of the upper La Mesa formation and estimated to be 1.5 million years old; sediments at Site 2 are part of the Jornada La Mesa formation and estimated to be 1.6

millions years old (Gile et al., 1981; Mack et al., 1996). Depth to the petrocalcic horizon varies between sites with the petrocalcic at Site 1 slightly shallower than at Site 2 resulting in different soil series. Site 1 is the Cruces series (loamy, mixed, superactive, thermic, shallow Argic Petrocalcid) while Site 2 is the Hueco series (coarse-loamy, mixed, superactive, thermic Argic Petrocalcid). Petrocalcic horizons sampled at Site 2 (Fig. 1.2) have wavy and in places irregular topography (Schoeneberger et al., 2002) with more frequent pipes and a more complex morphology than areas sampled at Site 1 (Gile et al., 1981; Gile, 2002; Gile et al., 2003). Additionally, based on previous sampling (Gile et al., 1981; 2003), both the laminar and plugged petrocalcic horizons at Site 2 contain more calcium carbonate by mass than their equivalents at Site 1. Together, the four horizons sampled represent much of the range of variability found in petrocalcic horizons formed in sandy parent material in arid ecosystems.

Sampling

Multiple samples were collected from a ~5 m horizontal section of the petrocalcic horizons at each site via preexisting soil trenches (Gile et al., 1981; 2003). We excavated back from the pit face before obtaining twelve samples from the plugged and laminar horizons at each site (n = 48). The indurated plugged horizons occur directly below the laminar horizons. From these larger samples, sub-samples were obtained and prepared for analysis. Samples were broken and gently filed to fit into sample cups (39 mm diameter, 11 mm deep) such that each cup contained 3 to 8 pieces of petrocalcic material that covered the sample cup bottom.

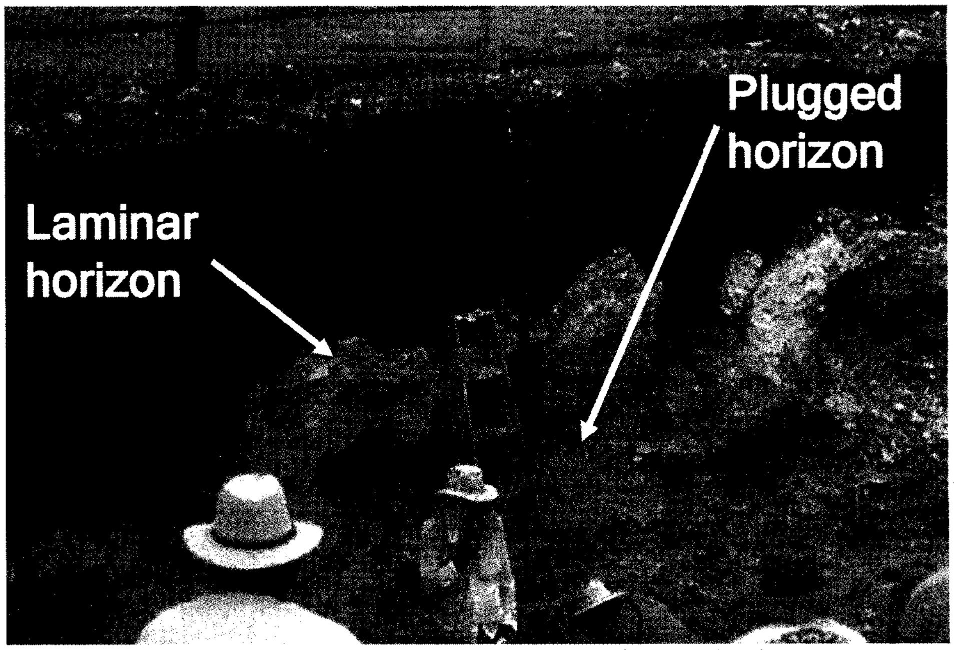

Fig. 1.2. Site 2 sampling trench showing laminar and plugged horizons.

Sample Characterization

Sample porosity was measured while obtaining bulk densities using Archimedes' Principle (Flint and Flint, 2002). Percent calcium carbonate was determined by dissolution of the each entire sample with 1 M HCl and back titration with 0.5 M NaOH (U.S. Salinity Lab Staff, 1954; Soil Survey Staff, 1996). The non-carbonate soil was saved, titrated solution decanted and soil rinsed twice with 800 ml of de-ionized water. Each sample was then oven-dried, weighed and dispersed by soaking in approximately 200 ml of a 12.5 g/L sodium hexametaphosphate solution (HMP). The mixture was agitated on a shaker table overnight. Sample sand content was determined by wet-sieving with a 53 μm sieve. Because sample non-carbonate mass was very small (most < 2 g), traditional particle size analysis methods were not appropriate. Therefore, estimates of sample clay versus silt were obtained using a modified version of methods described by Kettler et al. (2001) that allows for direct measurement of an entire sample particle size class. Sample passing through a 53 μm sieve was saved in large mason jars. De-ionized water was added to jars such that all had volumes of ~ 800 ml. Each jar was then closed and shaken vigorously for 1 minute. After samples settled undisturbed for 4 h, the top 12 cm of supernatant was siphoned off. The remaining solution was oven-dried to obtain the silt mass. Estimated mass of HMP in the silt sample was subtracted from the oven-dry weight. Clay mass was then calculated by difference.

Soil Water Release Curve

Measurement of soil-water release was done at -0.03 MPa and -0.10 MPa using pressure plate techniques (Dane and Hopmans, 2002) and from -0.10 MPa to < -10 MPa using a Dewpoint Potentiameter (Scanlon et al., 2002; WP4 Dewpoint Potentiameter, Decagon Devices, Pullman, WA). Samples were initially saturated individually in de-aired de-ionized water for 24 h under vacuum. A 0.1 MPa pressure plate was pre-moistened and ~ 0.5 cm of fine sandy loam soil was placed within a containment ring on the pressure plate and moistened to saturation. Each saturated sub-sample was gently pressed into the soil to maximize connectivity and the pressure plate placed inside the pressure chamber. Pressure of 0.03 MPa was applied and samples allowed to equilibrate. Wet weights were obtained and samples oven-dried to constant weight. To assure good contact and capillary continuity between samples, contact material, and porous pressure plate, samples were re-saturated and plates prepared as described above and soil-water release under 0.10 MPa of pressure measured. It was necessary to obtain within SWRC oven-dry weights for use in calculating the water retained under 0.03 MPa pressure prior to re-saturation because small grains of sample were often lost during saturation. After samples equilibrated with the applied pressure, samples were placed in the sample cups, covered, and weighed. Covered sample cups were sealed with parafilm wax and placed in an incubator set at 25 °C overnight with the Potentiameter.

The -0.10 to < -10 MPa measurements were completed with the Potentiameter connected to a computer which continuously recorded the output. Soil-water potential readings were saved when both sample temperature and water potential came to equilibrium. After wet weights were obtained, samples were allowed to dry for a few minutes, covered, sealed, and placed back in the incubator overnight. Most readings took < 10 minutes. The process of measurements, drying, and equilibration was repeated for all samples until the desired range of soil water potentials were measured. Oven-dry weights were obtained. Samples were again saturated and a 0.03 MPa pressure plate and a complete range of the Potentiameter readings obtained. SWRC volumetric water contents were calculated by multiplying the gravimetric water contents obtained by the measured sample bulk density.

Statistical Analysis

Soil-water release points were fit for each sample separately ($n = 48$ samples, 10 to 20 points for each sample) using non-linear regression techniques (PROC NLIN, SAS, 2001) to the equation:

$$\theta = \theta_r + \frac{(\theta_s - \theta_r)}{[1 + (a|\psi|)^n]^m}$$

where θ is the observed volumetric water content, θ_r is the residual water content, θ_s is the water content at saturation, a is a scaling parameter, and n and m are shape parameters with $m = 1 - 1/n$, and ψ is the observed soil-water potential (van Genuchten, 1980). Fitting was performed with θ_s as a fitted parameter ($\theta_s \leq$ porosity) and with θ_r fitted ($\theta_r \geq 0$) and assumed to be zero. Available water holding capacity (AWHC) was calculated as water retained at field capacity (θ_{FC}) minus water retained at permanent wilting point (θ_{PWP}). Sample θ_{FC} was estimated based on water retained at -0.03 MPa, the value recommended for medium textured soils (Romano and Santini, 2002). Sample θ_{PWP} was determined both for water retained at the traditional PWP of -1.5 MPa (Romano and Santini, 2002) and a PWP of -4.0 MPa, more appropriate for desert adapted plant species (e.g., Senock et al., 1994; Pockman and Sperry, 2000).

Analysis of variance was used to test for significant differences ($\alpha = 0.05$) in average horizon sample properties, estimated SWRC parameters, θ_{FC}, θ_{PWP}, and AWHC (PROC GLM, SAS, 2001). Pearson's correlation coefficients were calculated between soil properties (bulk density, porosity, percent calcium carbonate, percent sand, percent silt, and percent clay) and θ_{FC}, θ_{PWP}, and AWHC (PROC CORR, SAS, 2001) both overall and within petrocalcic morphology. For correlations, sample texture and carbonate contents were evaluated on a whole soil weight basis. Pearson's correlation coefficients were tested for significance using a null hypothesis of no linear relationship ($\rho = 0$, $\alpha = 0.05$).

Soil Water Release Curve Method Test

To test method repeatability and check for effects of within curve oven-drying, one clod of plugged material from Site 1 was broken and split into 4 sub-samples, SWRCs obtained from -0.10 MPa to -10 MPa and oven-dry weights obtained using the methods previously described. After oven-drying, SWRCs were generated using the same methodology. Pre- and post-oven drying curves were compared by curve fitting the compiled SWRC data from the four sub samples and evaluating for significant differences in the fitted van Genuchten (1980) parameters ($\alpha = 0.5$, $n = 20$ points for pre-oven dry and $n = 15$ points for post-oven dry).

RESULTS & DISCUSSION

Sample Characterization

Horizon morphology and across site variability were reflected in the wide range and significant differences detected in average sample properties both within and across sites and horizon morphologies (Table 1.1). Laminar horizons had significantly higher average bulk densities and thus lower porosities than plugged horizons. Significant differences in bulk densities and porosities, however, were detected between the two laminar horizons studied with the Site 1 laminar horizon being the most dense. Average sample $CaCO_3$ content was significantly different for horizons within each site. The horizon with the higher carbonate content, however, was reversed at the two sites. Additionally, the standard deviation of sample

Table 1.1. Average petrocalcic horizon properties. Texture reported on a non-carbonate basis.†

Site	Horizon	N	Bulk density		Porosity		$CaCO_3$		Sand		Silt		Clay	
			Mg m^{-3}		m^3 m^{-3}		-------------------		-------------------	%	-------------------		-------------------	
1	Laminar	12	2.26*a*	(0.07)	0.16*c*	(0.02)	83.5*a*	(1.6)	57.8*c*	(4.3)	24.4*a*	(2.9)	17.8*ab*	(4.8)
	Plugged	12	1.63*c*	(0.04)	0.39*a*	(0.01)	48.0*c*	(21.2)	77.3*a*	(3.1)	18.5*b*	(2.1)	4.2*c*	(1.7)
2	Laminar	12	1.97*b*	(0.14)	0.26*b*	(0.06)	68.8*b*	(16.1)	79.9*a*	(12.3)	6.9*d*	(9.4)	13.3*b*	(7.6)
	Plugged	12	1.63*c*	(0.03)	0.40*a*	(0.02)	88.0*a*	(1.7)	66.5*b*	(8.7)	12.9*c*	(5.6)	20.6*a*	(9.8)

†Fisher's protected LSD ($\alpha = 0.05$) by letters, standard deviations in parentheses.

carbonate content was an order of magnitude larger for the two horizons with lower carbonate content. The trend in non-carbonate sand content was opposite of that measured in sample carbonate content with the highest sand contents occurring in the two lower carbonate horizons. Within study sites, estimated sample silt content followed the same trend as carbonate content. A decrease in sand and increase in silt content with pedogenic carbonate accumulation in petrocalcic horizons has been attributed to the dissolution of the parent material sand grains by the expansion of carbonate crystals during precipitation (Monger et al., 1991a). Additionally, relatively high clay contents in the Site 1 laminar horizon could be attributed to the shallow horizon occurrence and concomitant deposition of colloidal clay and carbonates during horizon formation (Gile et al., 1966).

Soil Water Release Curve Method

The two methods for measuring the SWRC were shown to be consistent to each other and there was no effect of oven-drying. Comparison of curves obtained before and after oven-drying revealed no significant change in curve shape or scale (Fig. 1.3) with fitted parameters not significantly different between curves ($p > 0.5$). There appeared to be no major breaks in curve continuity between the soil-water release points measured with the pressure plate and points measured with the Potentiameter, indicating that the two methods are comparable. However, due to the limited number of measurement points wetter than -0.5 MPa and the sensitivity of the fitted equation parameters to the wet end of the curve, the few wet measurement points carried large leverage on the curve fit. Additionally, the stated accuracy of the

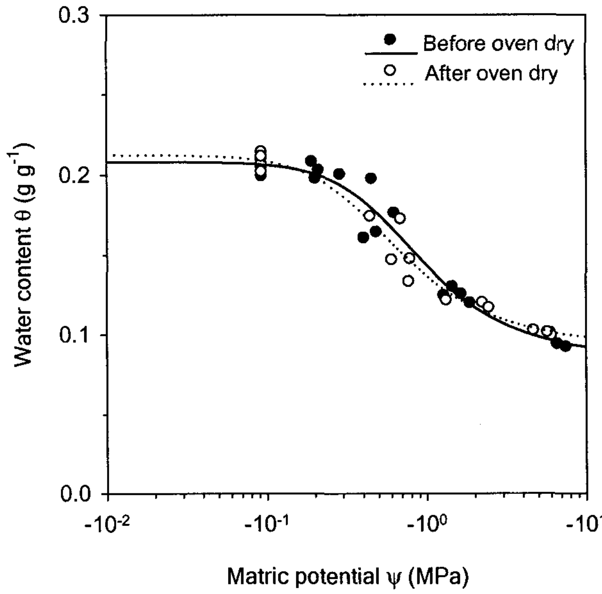

Fig. 1.3. Soil-water release curves measured before and after oven-drying samples. Observed points and fitted van Genuchten (1980) equation lines of gravimetric water content as a function of soil water potential in testing soil water release curve method repeatability.

Potentiameter is ± 0.1 MPa, which can generate relatively large errors for readings > -0.5 MPa. Therefore, in final analysis the Potentiameter readings > -0.5 MPa were not used if they appeared to significantly impact the overall curve fit. Also, the -0.10 MPa pressure plate measurements from Site 2 samples appeared to be suspiciously low outliers when compared to the rest of the curve and were therefore not used. Good agreement, however, was obtained between the -0.03 MPa replicate pressure plate readings. Although additional sample points, especially at the wet end of the SWRC, are desired to more precisely evaluate the van Genuchten (1980) equation parameters, methods used produced reliable values of θ_{FC} and θ_{PWP}, thereby meeting the goals of this study.

Table 1.2. Average horizon van Genuchten equation parameters and curve fitting root mean square error (RMSE) from each site.†

Site	Horizon	N	θ_s		a‡		n		RMSE§
			$m^3\ m^{-3}$		MPa^{-1}				$m^3\ m^{-3}$
1	Laminar	12	0.14*d*	(0.02)	1.16*c*	(2.12)	1.37*b*	(0.10)	0.0047
	Plugged	12	0.36*a*	(0.03)	16.24*a*	(4.44)	1.22*c*	(0.06)	0.0149
2	Laminar	12	0.23*c*	(0.04)	4.31*b*	(3.66)	1.36*b*	(0.08)	0.0075
	Plugged	12	0.34*b*	(0.02)	7.27*ab*	(1.35)	1.50*a*	(0.06)	0.0149

† Fisher's protected LSD ($\alpha = 0.05$) by letters, standard deviations in parentheses.
‡ Parameter log transformed for analysis.
§ Averaged over equations for all samples from each horizon at each site.

Soil Water Release Curves

Fitting of the measured SWRC points to the van Genuchten (1980) equation was successful for all samples with average root mean square error (RMSE) from each horizon < 0.015 $m^3\ m^{-3}$ (Table 1.2). Average RMSE values, however, were higher in both plugged horizons than the laminar horizons indicating either lower precision in SWRC measurements, or the model or model assumptions used were less appropriate for the plugged horizon samples. Curve fitting with θ_r as a fitted variable decreased the RMSE for only a few samples. Additionally, for almost all samples the optimization procedure estimated θ_r as < 0.01 $m^3\ m^{-3}$. Therefore, θ_r was set to zero in final fitting procedures for all samples.

The SWRCs generated compared favorably at drier water contents (< -0.8 MPa) to the calcic horizon curve from Baumhart and Lascano (1993) (Fig. 1.4). However, the curves diverge at wetter water contents, likely due to lower bulk density (1.44 Mg m^{-3}) and higher θ_s (0.45 $m^3\ m^{-3}$) of Baumhardt and Lascano's (1993) calcic horizon than those measured for our petrocalcic horizons (Fig. 1.4). Petrocalcic

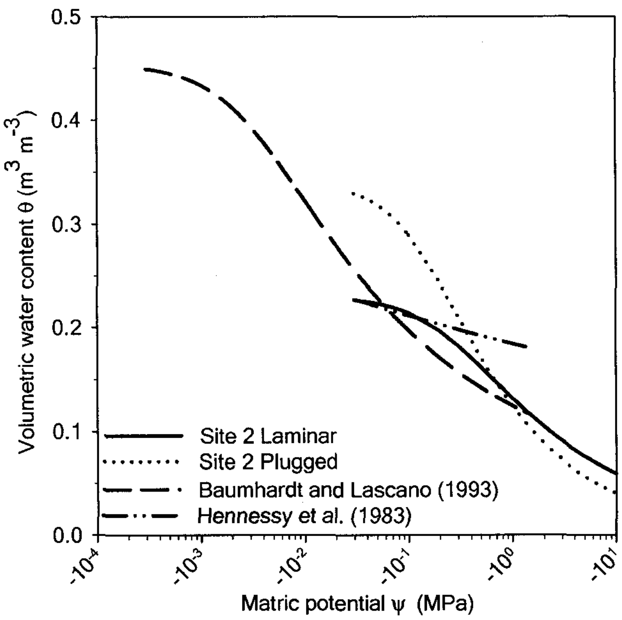

Fig. 1.4. Comparison of petrocalcic horizon soil-water release curves from this study to previous work. Average fitted curves from Site 2 laminar and plugged plotted against a calcic horizon curve (Baumhardt and Lascano, 1993) and petrocalcic material curve (Hennessy et al., 1983). Ranges plotted represent the range of soil water potential measured in each study.

horizon material curve estimated from Hennessy et al. (1983) is very similar at higher water contents (> -0.10 MPa) to the average Site 2 laminar horizon curve but quickly diverge at drier soil water potentials (Fig. 1.4). This is likely due to a poor fit and few measurement points in the previous study. However, laminar horizon SWRCs generated were very similar to those of calcareous rock fragments of similar bulk densities (Cousin et al., 2003).

The variability in sample morphology and site profiles was evident in the measured SWRCs (Fig. 1.5) and the fitted van Genuchten (1980) equation parameters (Table 1.2). The two plugged horizon average curves were similar but both quite

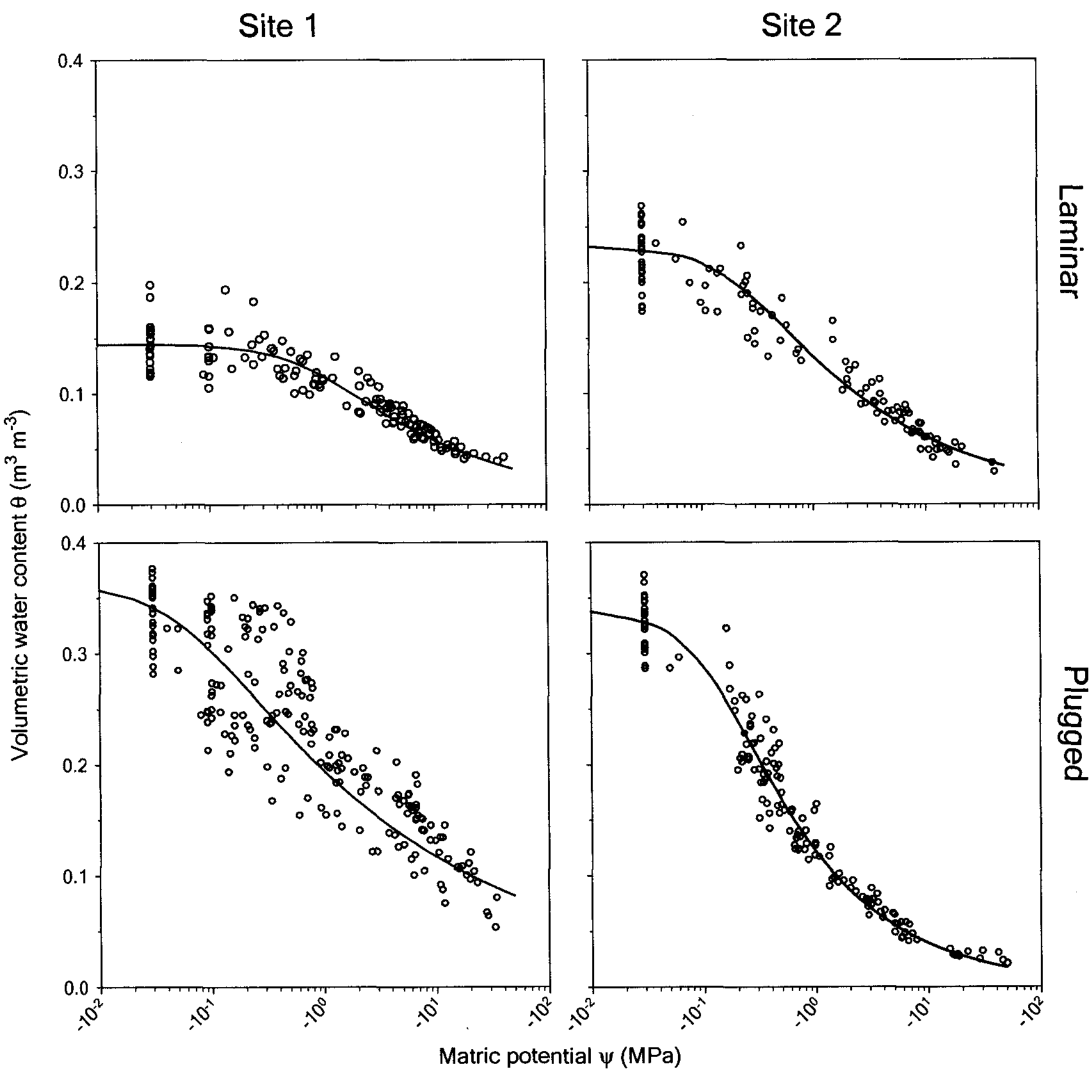

Fig. 1.5. Soil-water release observed points and the average fitted curve from both sites and horizons.

different than those of the laminar horizons as indicated by significant differences in fitted parameters. The log-transformed scaling parameter *a* was shown to be significantly higher for the plugged horizons than the laminar horizons ($p < 0.001$).

No difference, however, was detected between the two horizons at Site 2. The scaling parameter *a* is related to the inverse of the air entry potential (Brooks and Corey, 1964; van Genuchten, 1980; Kosugi et al., 2002). The small values of *a* in the laminar horizons is indicative of a soil with very few large pores and a large air entry potential. Additionally, the higher scatter within the Site 1 plugged horizon (Fig. 1.5) is reflected in the high variability in the *a* parameter (Table 1.2). Average values for the shape parameter *n* were very similar for both laminar horizons but significantly different than either plugged horizon. Plugged horizon shape parameter estimates were both significantly smaller and larger than those of the laminar horizons at Sites 1 or 2 respectively. The average value ($n = 1.22$) for the Site 1 plugged horizon (48% $CaCO_3$) is very similar to the estimated value ($n = 1.27$) from a finer textured and lower $CaCO_3$ (30%) calcic horizon (Baumhardt and Lascano, 1993).

Water holding capacity

Both plugged and laminar horizon AWHCs were higher than the 0.06 $m^3\ m^{-3}$ to 0.07 $m^3\ m^{-3}$ typically reported for loamy sands, which form the parent material at both sites (Gile and Grossman, 1979; Schaap et al., 2001). Increases in AWHC from lowering the PWP from -1.5 MPa to -4.0 MPa ranged from 0.025 $m^3\ m^{-3}$ to 0.039 $m^3\ m^{-3}$. This change is a substantial increase in estimated AWHC, especially for the lower porosity laminar horizons.

Sample morphology and site effects were also reflected in θ_{FC} and θ_{PWP} (Fig. 1.6a). Much of the sample pore space remained filled with water at -0.03 MPa (Table 1.1, Fig. 1.6a). Field capacities were on average 85% of measured porosities and

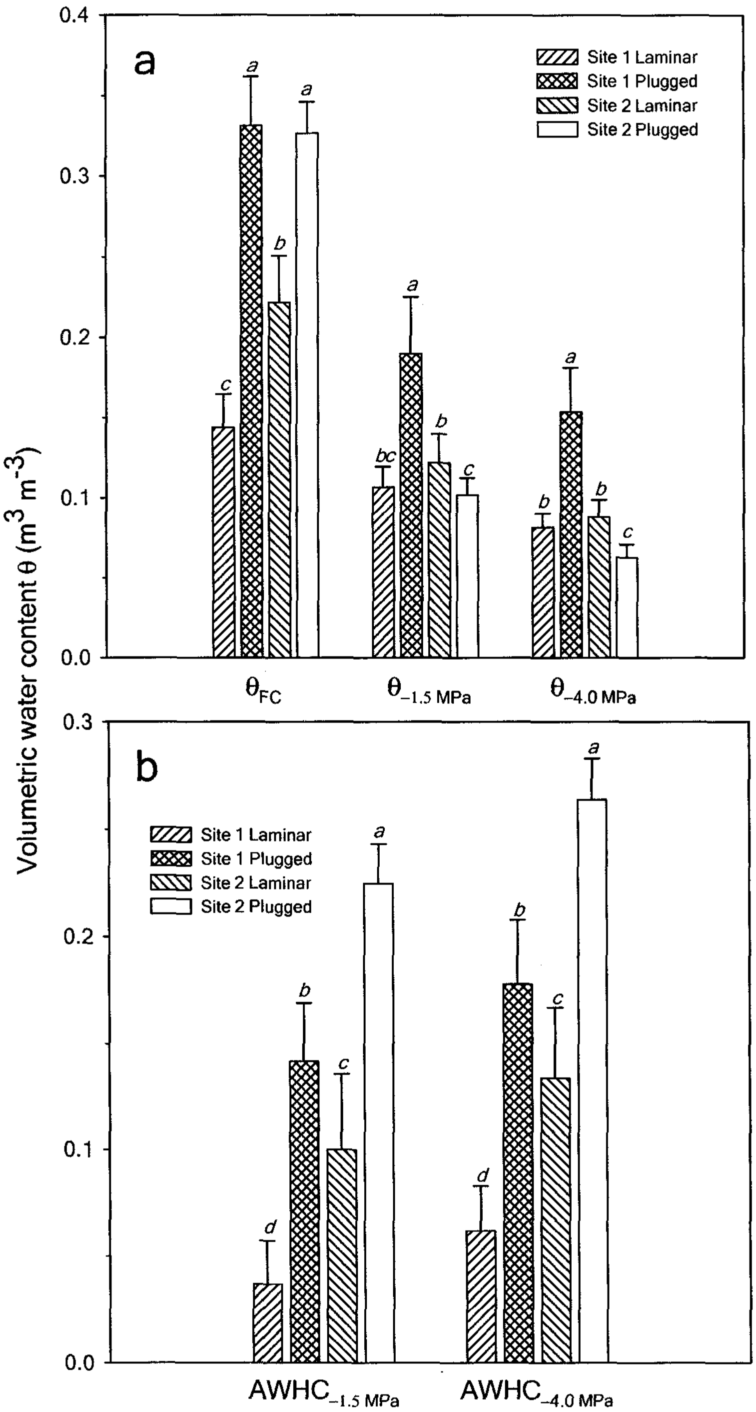

Fig. 1.6. Volumetric water retained by two morphologies of petrocalcic horizon at field capacity (θ_{FC}) and two permanent wilting points ($\theta_{-1.5\ MPa}$ and $\theta_{-4.0\ MPa}$) (a) and available water holding capacity (AWHC, based on $\theta_{-1.5\ MPa}$ and $\theta_{-4.0\ MPa}$) (b). Fisher's protected LSD ($\alpha = 0.05$) within measurement by letters, error bars represent sample standard deviations.

96% of estimated θ_s. The plugged horizons had significantly larger average field capacities than either of the laminar horizons with the laminar horizon from Site 1 retaining the least amount of water. The average Site 2 laminar horizon field capacity was very similar to the estimated water retained at -0.03 MPa for petrocalcic horizon material evaluated by Hennessy et al. (1983) and was comparable to that measured for a finer textured calcic horizon (Baumhardt and Lascano, 1993) (Fig. 1.5). The average field capacities of the plugged horizons (both were 0.33 $m^3\ m^{-3}$) were slightly less than the field capacity estimated by Hennessy et al. (1983) in a manipulative field study of water retention by a petrocalcic horizon (0.36 $m^3\ m^{-3}$). The Site 1 plugged horizon retained significantly more water on average at both -1.5 MPa and -4.0 MPa than any other horizon. Water release was similar in the laminar horizons with both retaining significantly more water at -4.0 MPa than the Site 2 plugged horizon.

Calculated AWHCs were highly variable both within and between sites (Fig. 1.6b). AWHC based on a PWP of -1.5 MPa ranged from 0.04 $m^3\ m^{-3}$ to 0.22 $m^3\ m^{-3}$ and was similar to the range reported for calcareous rock fragments (0.025 $m^3\ m^{-3}$ to 0.14 $m^3\ m^{-3}$) (Cousin et al., 2003). AWHC based on a PWP of -4.0 MPa ranged from 0.06 $m^3\ m^{-3}$ to 0.26 $m^3\ m^{-3}$. Plugged horizon AWHCs (both based on -1.5 MPa and -4.0 MPa) were significantly higher than those of the laminar horizons. When pooled by site, the planar petrocalcic horizon of Site 1 had a significantly lower AWHC ($p < 0.001$) than the irregular petrocalcic horizon at Site 2.

Correlations

Much of the variability in soil properties among samples was reflected in θ_{FC} and θ_{PWP} with many significant correlations detected. Strength and significance of the correlations with soil properties, however, changed when samples were grouped by horizon morphology (Table 1.3). Bulk density and porosity are strongly and significantly correlated with θ_{FC} compared both across all samples and within horizon morphology. Sample $CaCO_3$, sand, and silt content, however, were significantly correlated with field capacity within the laminar but not the plugged horizon. Morphological differences in water retention-soil property correlations are partially explained by the low or high horizon variability of some of the water retention measurements and soil properties, but are also likely a reflection of differences in horizon genesis. For example, the standard deviations of percent $CaCO_3$ are fairly similar if pooled by horizon morphology ($s = 13.46$ in the laminar and $s = 25.18$ in the plugged). Because the matrix of a laminar horizon is formed by the accumulation of precipitated $CaCO_3$ (Gile et al., 1966) and the grains of non-carbonate parent material unevenly distributed (Monger et al., 1991a), it would be expected that the amount of $CaCO_3$ is important for the horizon θ_{FC}. Plugged horizons are formed by the precipitation of calcium carbonates within the pore space of an existing soil matrix (Gile et al., 1966; Monger et al., 1991a), implying that the percent $CaCO_3$ might be less important for θ_{FC} than in the laminar horizon.

Sample $\theta_{-4.0\ MPa}$ was significantly correlated with sample bulk density, $CaCO_3$, and texture when comparisons were done across all samples. Because there is little

Table 1.3. Correlations of sample properties and field capacity (θ_{FC}), permanent wilting point (θ_{PWP}, based on -4.0 MPa), and available water holding capacity (AWHC). Within each cell, the first two rows contain the Pearsons' correlation coefficient and *p*-value for correlations across all samples ($n = 48$). The lower rows contain the Pearsons' correlation coefficients and *p*-values for correlations done within horizon morphology (n=24). *P*-values in bold are significant ($\alpha = 0.05$).

			θ_{FC}	θ_{PWP}	AWHC
Bulk density	All		-0.979	-0.312	-0.884
			<0.001	**0.031**	**<0.001**
		Laminar	-0.960	-0.151	-0.957
			<0.001	0.482	**<0.001**
		Plugged	-0.759	-0.302	-0.074
			<0.001	0.152	0.731
Porosity	All		0.978	0.275	0.902
			<0.001	0.058	**<0.001**
		Laminar	0.957	0.147	0.955
			<0.001	0.494	**<0.001**
		Plugged	0.684	-0.110	0.450
			<0.001	0.608	**0.028**
$CaCO_3$	All		-0.339	-0.777	0.017
			0.019	**<0.001**	0.907
		Laminar	-0.732	-0.014	-0.752
			<0.001	0.948	**<0.001**
		Plugged	-0.127	-0.885	0.823
			0.554	**<0.001**	**<0.001**
Sand	All		0.354	0.712	0.031
			0.014	**<0.001**	0.834
		Laminar	0.776	-0.015	0.803
			<0.001	0.943	**<0.001**
		Plugged	0.096	0.883	-0.837
			0.655	**<0.001**	**<0.001**
Silt	All		0.261	0.852	-0.135
			0.073	**<0.001**	0.360
		Laminar	-0.649	0.129	-0.697
			<0.001	0.547	**<0.001**
		Plugged	0.227	0.904	-0.793
			0.286	**<0.001**	**<0.001**
Clay	All		-0.244	0.019	-0.267
			0.095	0.897	0.066
		Laminar	0.019	0.122	-0.007
			0.931	0.570	0.973
		Plugged	0.119	0.153	-0.094
			0.579	0.476	0.662

variability in water release at the dry end in the laminar horizon, however, no significant correlations between $\theta_{-4.0\ MPa}$ and the soil properties were detected within the laminar horizons. Within the plugged horizons, sample percent $CaCO_3$, sand, and silt were all significantly correlated with $\theta_{-4.0\ MPa}$. Percent sand and silt were positively correlated with $\theta_{-4.0\ MPa}$ indicating that samples with more sand and/or silt on a whole soil weight basis retained more water that was unavailable to plants. In contrast, sample percent $CaCO_3$ was strongly negatively correlated with $\theta_{-4.0\ MPa}$. Soil-water retention under high suction values is attributed to adsorption on soil particles which is strongly dependent on soil surface area (Gardner, 1968). These results imply that accumulation of calcium carbonate within a soil will decrease the soil surface available to adsorb water. Trends and significance of correlations for $\theta_{-1.5\ MPa}$ and $\theta_{-4.0\ MPa}$ with sample properties were identical so only $\theta_{-4.0\ MPa}$ are reported.

Correlations across all samples between the $AWHC_{-4.0\ MPa}$ and soil properties revealed significant relationships only with sample bulk density and porosity. When grouped by morphology, however, many more statistically significant correlations were exposed. In the laminar horizons, all soil properties except percent clay content were significantly correlated. Similarly, all properties except sample bulk density and percent clay were significantly correlated in the plugged horizons. The reason for the high amount of correlation within morphologies but the lack of correlation across morphologies is that for many properties the relationship with $AWHC_{-4.0\ MPa}$ is reversed across morphologies. For example, percent $CaCO_3$ is strongly negatively correlated with $AWHC_{-4.0\ MPa}$ in laminar horizons but strongly positively correlated in the plugged horizon. Again, differences in the hydrologic function of differing morphologies are likely due to horizon genesis. Larger percent carbonate by mass in the laminar horizon appears to result in a much lower field capacity and thereby reduce the AWHC. In plugged horizons the filling of the soil pores by $CaCO_3$ appears to actually reduce the amount of water retained at PWP and thereby increasing the AWHC.

CONCLUSIONS

Petrocalcic horizons are common in arid and semi-arid regions around the world. Although water is regarded as the resource that most limits system productivity and community structure in these systems (Noy-Meir, 1973), little work has been done addressing how these horizons hold and release water. The petrocalcic horizon material SWRCs developed in this study indicate these horizons retain the majority of their porosity at field capacity and release much of the retained water at plant available potentials. Calculated AWHCs of the plugged horizons were up to four times that of the coarse textured parent material. Laminar horizon AWHC was one-half to one-third that of the plugged. The wide range of AWHCs observed indicate that petrocalcic horizons can behave both like calcareous soils (Baumhardt and Lascano, 1993) and calcareous rock fragments (Cousin et al., 2003). Reducing the PWP used in calculating AWHC from -1.5 MPa to -4.0 MPa increased the estimated AWHC by 20 to 50%.

The significance and strength of correlations between sample characteristics and θ_{FC} and θ_{PWP} changed when samples were separated by horizon morphology. These differences resulted in few significant correlations of soil properties and AWHC when both morphologies were included but there were many significant correlations within horizon morphology. Strong relationships detected present the potential for development of predictive relationships that can be used to extrapolate measured soil water retention to unmeasured soils for which basic soil characterization data are known. This is the first study to show that there are significant differences in soil water characteristics of different morphologies of petrocalcic horizons. It suggests that petrocalcic horizons should be stratified by horizon morphology (e.g., laminar and plugged) when other soil physical properties are measured.

The high water holding capacity of petrocalcic horizons measured in this study indicate their potential importance as a plant-water source, especially during drought. Because petrocalcic horizons underlie much of the world's desert regions, water dynamics in these horizons could play a significant role in ecological processes. Further work is needed to assess the occurrence of plant available water in petrocalcic horizons and the importance of petrocalcic water for current and potential plant communities.

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CHAPTER 2:

WATER AVAILABILITY AND DYNAMICS ACROSS A CHRONOSEQUENCE OF SOILS

ABSTRACT

Soil profile characteristics can control plant community composition and production through their effects on spatial and temporal patterns of plant-available water. Petrocalcic and calcic soil horizons develop ubiquitously in arid and semi-arid ecosystems around the world, often within the rooting zone of desert plant species. We report temporal variability in plant water availability for a two year period across a chronosequence of three soils in a mixed shrub-grass community in southern New Mexico, USA: (1) a deep sandy soil with little carbonate accumulation, (2) a soil with a strong calcic horizon, and (3) a soil with a highly developed petrocalcic horizon. Soil profiles were instrumented with a combination of TDR and gypsum block soil moisture probes, both above and within the 50 to 60 cm deep carbonate horizons. The calcic and petrocalcic horizons retained much higher amounts of soil water during a winter with above-normal precipitation than similar depths in the non-carbonate sand (0.12 to 0.14 m^3 m^{-3} versus 0.08 m^3 m^{-3}) and retained soil water at plant-available tensions a greater frequency of the days than the sand during the following spring and summer (100% versus 54% in the spring and 21-34% versus 0% in the summer). The petrocalcic horizon wet more slowly but dried more quickly in

the spring than the calcic horizon, due to both differing horizon properties and upper profile water dynamics. This study indicates that petrocalcic and calcic horizons can contain significant amounts of plant-available water and can be recharged by winter and summer rains. The retention of soil water through extended dry periods, however, indicates that the water within these soil horizons with high carbonate contents is not being directly accessed by the current vegetation.

INTRODUCTION

In arid and semi-arid ecosystems, vegetation community composition is controlled by water availability (Noy-Meir, 1973). While precipitation, measured as distinct pulses or as annual averages, is a good predictor of production in arid ecosystems at regional scales (Noy-Meir, 1973; Webb et al., 1978); it is a poor predictor of production at local scales. This is due to local variability in soil-water availability associated with landscape position, soil characteristics, and species composition (Walter, 1973; McAuliffe, 1994; Reynolds et al., 2004). Differences in soil hydrology have been used to explain both the distribution of existing plant communities and response of vegetation to climate and management in arid and semi-arid ecosystems in both observational studies (Herbel et al., 1972; McAuliffe, 1994) and modeling exercises (Hamerlynck et al., 2002; Gao and Reynolds, 2003). However, hydraulic properties of soils are often inferred from observed soil morphology, vegetation patterns, or modeling of homogeneous soil systems. Deciphering the mechanisms and processes behind observed patterns requires detailed knowledge of plant physiology as well as extensive information of both soil pedology and hydrology, especially in soils with extensive and complex pedogenic development. Our understanding, however, of many soil systems that occur in arid and semi-arid ecosystems is limited. This is particularly true in older soils that have strong horizon development, such as calcic and petrocalcic horizons.

Low precipitation and shallow depth of wetting in arid and semi-arid soils has led to sub-surface accumulation of secondary calcium carbonates and the subsequent formation of calcic and petrocalcic horizons (Gile, 1961; Gile and Grossman, 1979). Calcic and petrocalcic horizons can be over a meter thick and occur extensively in arid and semi-arid soils throughout the world (Reeves, 1976; Machette, 1985; Monger et al., 2005). The accumulation of carbonates is manifested in distinct morphological stages as described by Gile et al. (1966). Calcic horizons are a younger morphological stage of calcium carbonate accumulation while petrocalcic horizons occur in older soils when the horizon is continuously indurated with carbonates (Soil Survey Staff, 1999). With sufficient time, carbonates can completely plug soil pores, producing an indurated plugged horizon and a distinct laminar carbonate cap. Formation of laminar cap horizons is attributed to restriction of downward soil water movement and precipitation of carbonates in the accumulated soil water (Gile et al., 1966).

The importance of petrocalcic soil horizons for vegetation patterns and dynamics has long been hypothesized, but mechanisms have never been clearly established. Petrocalcic horizons are generally thought to be both root and water restrictive (Shreve and Mallery, 1932; Ruellan, 2002) causing plant roots to be concentrated between the soil surface and the top of the petrocalcic horizon (Bailey, 1967). McAuliffe (1994) attributed drought mortality and smaller stature of *Larrea tridentata* on soils shallow to petrocalcic horizons to low soil-water holding capacity and limited rooting depths. However, 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 volumes of soil water. Results from Chapter 1 show petrocalcic horizons can have high available water holding capacities, ranging from 0.06 to 0.26 $m^3 m^{-3}$. Additionally, most shrubs and perennial forbs excavated by Gibbens and Lenz (2001) had roots that penetrated calcic or petrocalcic horizons. Mesquite (*Prosopis glandulosa*) roots were observed growing laterally across continuous petrocalcic horizons and then descending through cracks and holes (Gile et al., 1997). Furthermore, fungal hyphae have been observed throughout petrocalcic horizons (Monger et al., 1991).

Smith et al. (1995) measured greater water stress in shrubs growing on soils shallow to a petrocalcic horizon than in soils lacking a petrocalcic horizon. Similarly, *Larrea tridentata* shrubs monitored by Cunningham and Burk (1973) growing on soils very shallow to petrocalcic horizons had greater water stress when compared to plants rooted in deep soils lacking subsurface development. However, the experimental design of both Smith et al. (1995) and Cunningham and Burk (1973) had confounding soil effects due to much finer surface soil textures in the petrocalcic sites than the contrasting deep soils. In contrast, Herbel et al. (1972) found that in sandy textured basin floor soils, the native perennial grass *Bouteloua eriopoda* had a lower mortality rate during drought in soils with shallow petrocalcic horizons than sandy soils without petrocalcic horizons. Additionally, sandy soils with a petrocalcic horizon at 50.8 cm or shallower have higher Ecological Site representative annual production values than those of sandy soils lacking shallow restrictive layers (Shallow Sandy Ecological Site, MLRA SD-2, USDA-NRCS, 2006). The apparent poor water relations of deep rooted evergreen shrubs, improved perennial grass water relations during drought, and increased annual production were all attributed to the restriction of downward soil water movement by shallow petrocalcic horizons.

Results from over 10 years of soil water potential measurements (gypsum blocks) across a variety of soil types in southern New Mexico indicate soil positions just above a petrocalcic horizon have water that is available to plants (>-1.5 MPa) a greater duration of time than in most other deep soil positions (Herbel and Gile, 1973). In a mesquite inter-dune area, Hennessy et al. (1985) found the soil water in depths below the petrocalcic horizon to be consistently high (0.23 g g^{-1}) over the duration of a two year study. They did not report the water contents in the petrocalcic horizon but concluded that the deeper water was an untapped resource. Work by Gile et al. (1981) indicates that at times water penetrated laminar horizons, giving underlying plugged horizon carbonates a younger ^{14}C date than the overlying laminar horizons. Additionally, soil water tracers (bomb pulse ^{36}Cl) provide evidence of water absorption by petrocalcic horizons in recent decades (Gifford, 1987). Despite the common occurrence of petrocalcic soils and their perceived importance for plant community structure and dynamics, little is known about patterns of soil moisture in petrocalcic horizons and less about the availability of the contained water. It is unclear how efficiently petrocalcic horizons block downward soil water movement, if petrocalcic horizons absorb soil water, or if water within petrocalcic horizons is available to plants.

This study was designed to address basic questions regarding the effect of high carbonate horizons on soil water dynamics and the functional role of these soils in system dynamics. We have addressed these general goals by testing specific hypotheses regarding the duration and dynamics of water in calcic and petrocalcic horizons. The approach used was to monitor patterns of soil water recharge and water availability across a chronosequence of carbonate accumulation in three coarse textured soils on the same geomorphic surface. We hypothesize that shallow calcic and petrocalcic horizons formed in coarse textured soils have (1) higher soil water contents as well as (2) greater amounts and (3) higher frequencies of available water than similar soils lacking carbonates. Additionally, we hypothesize that (4) rates of soil-water absorption and release will be slower in laminar capped petrocalcic horizons than in highly calcareous horizons lacking a laminar cap.

MATERIAL 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 (Fig 2.1). The climate is characterized by a warm dry spring, hot wet summer, and cold dry winter (Wainwright, 2006). Long term (1915 to 1995) average annual rainfall is 245.1 mm

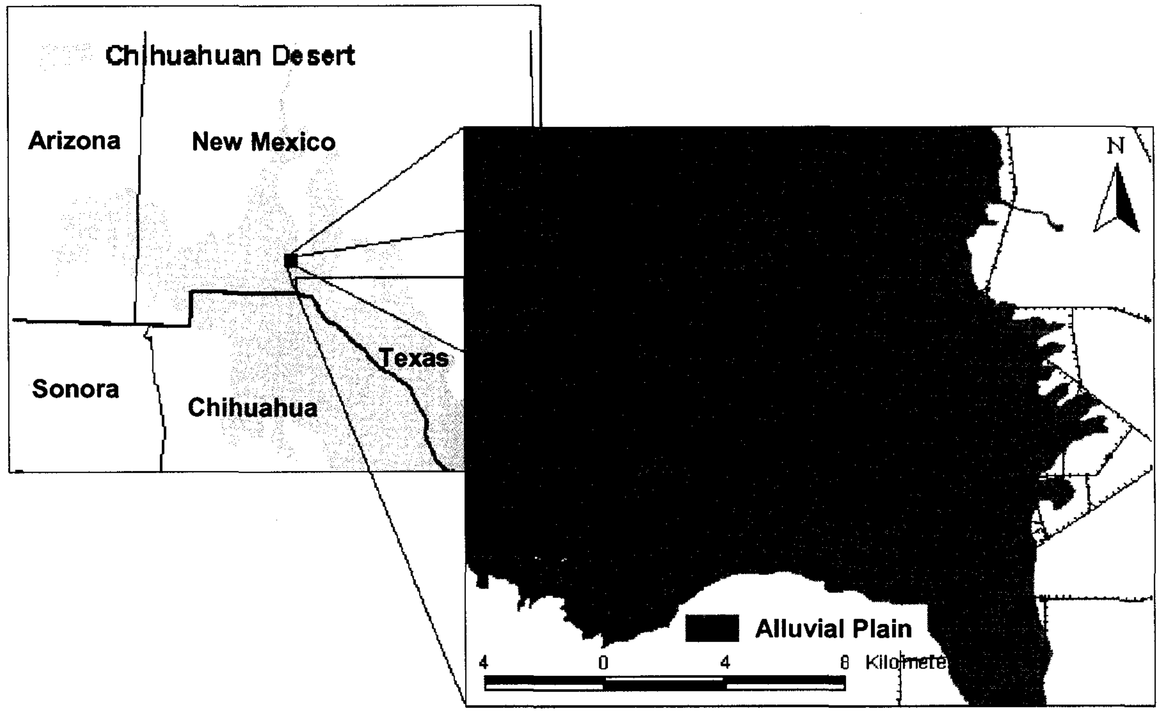

Fig. 2.1. Study sites were located in the northern Chihuahuan Desert in southern New Mexico USA. Study sites (black dots) were located on the broad alluvial plain of the ancient Rio Grande River within the USDA-ARS Jornada Experimental Range (black fence lines). Chihuahuan Desert boundary after Schmidt (1979); Alluvial Plain after Monger (2006).

of which more than half usually falls from July through October. The rainfall amount, timing, and intensity are highly variable within and between years. Summer rainfall totals are generally less variable between years but are dominated by intense, localized thunderstorms. Rainfall during the remainder of the year is generally of lower intensity but highly variable between years. The rainfall record at the study site is punctuated by seasons and years of drought and abundance with an annual rainfall coefficient of variation of 36% (1915 to 1995). Annual pan evaporation rates far exceed rainfall, with a measured annual average of 2204.1 mm (1953 to 1979) (Wainwright, 2006).

To understand the effects of soil carbonate accumulation and the resultant soil morphology on water dynamics, we selected a chronosequence of soils on the broad alluvial plane of the ancestral Rio Grande; time of pedogenesis varied while the other four soil forming factors of biota, topography, parent material, and climate were similar (Dokuchaev, 1883; Jenny, 1941). Deposition of sediments by the Rio Grande ended approximately 1.6 million years ago across the entire the study area (Mack et al., 1996). The alluvial plane is now a mosaic of varying aged soils due to geomorphic processes interrupting soil formation at different times and locations within the landform. We selected sites on a young sandy soil (Young Sand), a moderately old calcic (Medium Calcic) and an ancient petrocalcic soil (Old Petrocalcic) (Fig. 2.1) (Soil Survey Staff, 1999). Sites Young Sand and Old Petrocalcic are located approximately 1 km apart. The Medium Calcic site is located approximately 10 km to the east. The study sites have a mixed shrub-grass vegetation community dominated by mesquite (*Prosopis glandulosa*) and black grama (*Bouteloua eriopoda*).

The youngest site (Young Sand) is located in an area that received recent eolian deposition due to its position on the lower, leeward side of a fault uplift. These young sediments covered the previous soil surface such that there is very limited carbonate accumulation in the top 150 cm of soil (Fig. 2.2). The site is now fairly stable and of the Pintura series (mixed, thermic Typic Torripsamments) (Bulloch and Neher, 1980). The Medium Calcic site is located at the eastern edge of the geomorphic surface and of the Yucca series (coarse-loamy, mixed, superactive, thermic Typic Calciargids*)*. It is in an area that was periodically submerged under an ancient lake during mid-Pleistocene glacial periods, thereby interrupting pedogenesis and carbonate accumulation (Gile, 2002). The calcic horizon at the Medium Calcic site is continuously plugged and partially indurated with carbonates and is of stage III+ morphology (stages following Birkland, 1999). Soils at the Old Petrocalcic site have likely been undergoing pedogenesis since the original sediments were deposited and are of the Hueco series (coarse-loamy, mixed, superactive, thermic Argic Petrocalcids). The petrocalcic horizon is of a stage V morphology with a laminar layer and pisoliths evident. Additionally, there is a 1 to 10 cm thick horizon of coarse petrocalcic rubble above the laminar horizon. This is common in many petrocalcic horizons. Taken together the three selected study sites allow for the comparisons of soil water

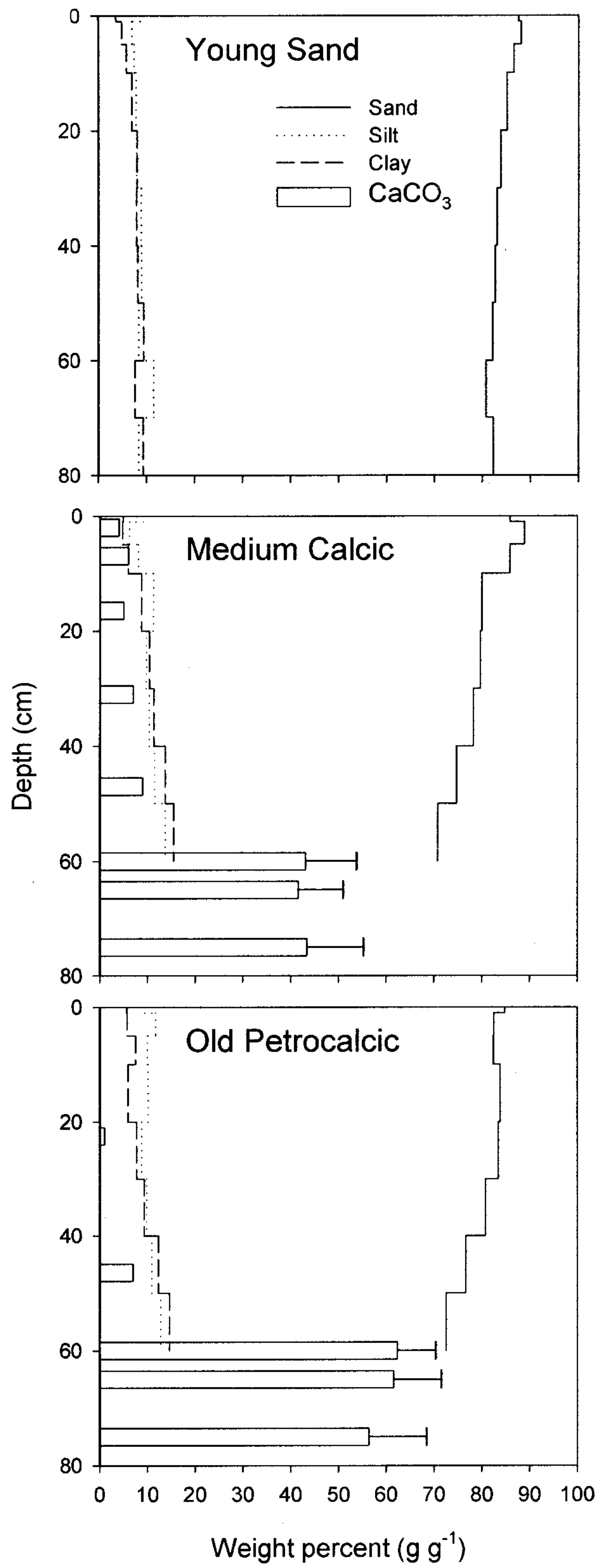

Fig. 2.2. Site average soil profile texture and carbonate content by depth. $CaCO_3$ values with error bars are average measurements from high carbonate horizon soil moisture sensor positions. Error bars are standard deviations. Other $CaCO_3$ values represent horizon values and are from similar soils in the same series.

dynamics among sites that are very similar in all aspects except the degree of carbonate accumulation.

Vegetation characterization

We characterized site vegetation using the line-point method (Herrick et al., 2005) in September 2005. Ten 40 m transects were measured in a grid pattern centered on the sites with a line spacing of 10 m and reading interval of 1 m (40 points per transect).

Soil water content

We instrumented sites with time domain reflectometry (TDR) soil moisture sensors in a split plot design with three whole plot treatment levels of soil age and three subplot treatment levels of soil depth (Shallow, Intermediate, and Deep) (Fig. 2.3). We also instrumented the Medium Calcic and Old Petrocalcic sites with gypsum blocks at the Shallow depths and on top of the high carbonate horizons (Boundary) (Fig. 2.3). The Young Sand site served as a reference, an example of how soils at sites Medium Calcic and Old Petrocalcic might behave without pedogenic development. Six instrumented soil pits were located under bare soil, approximately 60 cm from the base of a black grama stand (Fig. 2.3). Soil pits were located at Medium Calcic and Old Petrocalcic sites such that the calcic and petrocalcic horizon depths were similarly shallow (50 to 60 cm). The lateral extent of each site was limited to approximately 20 m due to allowable sensor cable lengths.

We installed the Shallow depth TDR probes at a depth of 30 cm at all three sites. The Shallow depth measurement allowed us to evaluate the similarity of upper

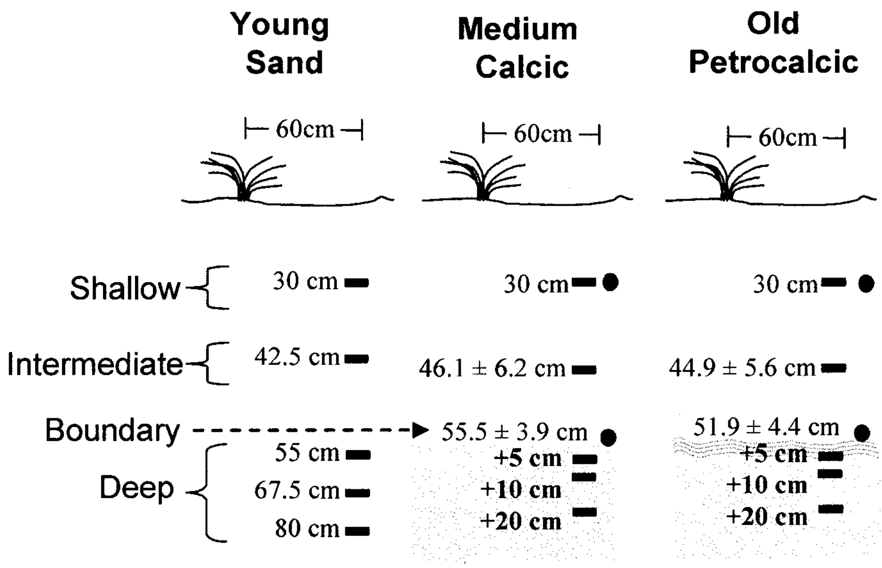

Fig. 2.3. Site soil moisture monitoring instrumentation schematic. TDR soil moisture probes (black rectangles) were placed by depth in the Young Sand site. At sites Medium Calcic and Old Petrocalcic probes were placed by depth for the Shallow measurements but in the Intermediate and Deep depths, probes were placed relative to the upper high carbonate horizon boundary. Additionally, gypsum block soil water potential sensors (black circles) were installed at the Medium Calcic and Old Petrocalcic sites paired with the Shallow depth TDR sensors and placed on top of the calcic and petrocalcic horizons (Boundary). The Intermediate and Boundary depths are site averages with standard deviations.

profile water dynamics across the chronosequence. We paired gypsum blocks with TDR sensors at the Medium Calcic and Old Petrocalcic site Shallow depths to assess whether water availability dynamics measured by the two methods were comparable. The Intermediate depth at the Young Sand site included one sensor at 42.5 cm while the Deep included three subsamples at 55, 67.5, and 80 cm depths. At sites with calcic or petrocalcic horizons, Intermediate and Deep soil moisture probes were placed relative to the upper high carbonate horizon boundary to capture horizon water dynamics. For the Intermediate depth, we installed one soil moisture sensor just above the calcic or petrocalcic horizon. However, the occurrence of carbonate nodules and/or fragments above the calcic and petrocalcic horizons interfered with our ability to install TDR probes, thus the Intermediate depths were on average 10.6 cm and 7.0 cm above the petrocalcic and calcic horizons, respectively. The Boundary gypsum blocks, placed on top of the calcic and petrocalcic horizons, allowed us to evaluate soil water dynamics at the horizon boundaries. The Deep depths at the Medium Calcic and Old Petrocalcic sites were comprised of three soil moisture sensors installed approximately 5, 10 and 20 cm into the horizon, relative to the upper horizon boundary. We concentrated the calcic and petrocalcic horizon measurements in the upper sections of the firm horizons because these locations were more likely to interact with the rhizosphere.

We fabricated the TDR soil moisture probes using a trifilar design with 3.175 mm diameter stainless steel welding rod and 3 cm center to center rod spacing (Evett and Ruthardt , 1999). The rods were soldered to 50 ohm coaxial cable and connections encased in an epoxy resin handle. Probe lengths of 20 cm were used in the non-carbonate, non-cemented soil horizons (Shallow and all of Young Sand depths). We used 15 cm probes for the Intermediate depths at the Medium Calcic and Old Petrocalcic sites to limit insertion interference due to carbonate nodules and fragments. Due to concerns over installation and signal attenuation, we limited probe lengths to 10 cm in the high carbonate soil horizon soils. The measured apparent dielectric constant was converted to volumetric water content using Topp's equation

(Topp et al., 1980) for Shallow and Intermediate depths at sites Medium Calcic and Old Petrocalcic and the entire profile at the Young Sand site. For high carbonate soil horizons, we developed a soil specific calibration equation in the laboratory using finely crushed petrocalcic horizon material from the Old Petrocalcic site. We packed the crushed material to near field bulk density (1.4 Mg m^{-3}) in a small wood box (15 by 20 cm) and obtained six calibration points from air dry to near saturation (0.02 to 0.43 m^3 m^{-3}) using a 10 cm TDR probe. A calibration equation was developed with a linear regression analysis of waveform travel time and directly measured volumetric water content.

We performed a laboratory calibration of the gypsum blocks (Bouyoucos brand) by allowing the sensors to equilibrate with soil of known water potential from Boundary depths at the Old Petrocalcic site (Scanlon et al., 2002). Gypsum blocks were initially saturated and then three calibration points obtained from approximately -0.10 to -1.0 MPa. A calibration equation was developed with a linear regression analysis of the natural log of sensor resistance and natural log of soil water potential. The calibration equations were adjusted for estimated field temperatures.

To install the TDR sensors and gypsum blocks, we excavated small individual mini-pits for each whole plot replicate (approximately 50 cm by 75 cm by 85 cm deep). The removed soil was saved by depth in covered containers for refilling pits (0-5, 5-10, 10-20, and then by 20 cm increments until the petrocalcic horizon or maximum depth was reached). At the Old Petrocalcic site, we saved the entire petrocalcic horizon as a unit. Prior to excavation, we hammered a 20 cm wide by 45 cm tall rigid sheet metal plate into the soil to brace the mini-pit face and limit evaporational loss from the upper profile. We installed the gypsum blocks by removing a small soil core approximately 8 cm deep at the desired depth, inserting the gypsum block sensor and repacking the hole. To allow insertion of TDR rods into indurated or firm horizons, we drilled undersized pilot holes (2.778 mm) using a cordless hammer drill guided by a metal jig. However, in some excessively hard material it was not possible to insert TDR rods into undersized holes and 3.175 mm diameter holes were used. With the jig in place as a guide, probes were inserted partially by hand and finished using a wood block and hammer. During drilling and installation, soil inevitably eroded around rod holes to a distance of 1 to 5% of sensor rod lengths. To assure continuous contact, eroded material was replaced and repacked as the last 0.5 cm of probe was inserted. The jig also served as a guide during probe installation when pre-drilling was not necessary. We instrumented mini-pits from the deepest depth up and replaced soil as probes were installed. Probe cables were routed to the back of the mini-pit to avoid creating water-flow channels by the pit face. We repacked each layer of replaced soil to approximate field bulk density using a steel plate and heavy iron pipe. In repacking the petrocalcic and calcic horizons, extra care was taken to tightly repack the removed material to original horizon density and depth. Completed pits were always flush with the soil surface.

TDR soil moisture sensors at each site were connected to multiplexers and a wave propagator to generate probe wave forms (SDMX50, TDR100, Campbell

Scientific, Logan, UT). Duplicate measurements were taken every eight hours, wave forms saved by data logger (CR10X, Campbell Scientific, Logan, UT) and later analyzed for sensor travel time using TACQ (Evett, 2000). Gypsum block electrical resistance was measured once every eight hours. At the Old Petrocalcic site, data from three TDR soil moisture sensors within the petrocalcic, two upper horizon and one Deep, were not collected due to equipment failure. Additionally, massive relay failure in the coaxial multiplexers in late summer of 2004 resulted in noisy data and finally 27 days of missing data from sites Medium Calcic and Old Petrocalcic (September 7 to October 3) while the faulty equipment was repaired. There were 19 days of missing data from the Medium Calcic site in late summer 2005 due to battery failure. During the course of the study, multiplexer relays continued to cause some trouble and produce occasional bad data points. Therefore it was necessary to remove outlier data, resulting in incomplete sets of readings. However, because average daily data were used in final analysis there were very few additional lost data days.

Precipitation

Precipitation was recorded daily by a weighing bucket rain gauge located approximately 50 m from the Old Petrocalcic site and monitored by the USDA-ARS Jornada Experimental Range staff. To assess differences in rainfall totals between sites, we installed manual graduated rain gauges at all three sites and measured rainfall totals approximately monthly.

Soil characterization

We obtained profile samples and limited horizon descriptions at soil mini-pits during excavation. We sampled bulk density using the core volume method (Grossman and Reinsch, 2002) for depths of 0 to 1, 1 to 5, 5 to 10, 10 to 20 and by 10 cm increments for the entire profile at the Young Sand and Medium Calcic sites. At the Old Petrocalcic site, we took core samples until the petrocalcic horizon was reached. Particle size analysis was done for core samples at the Young Sand site and for soil cores obtained above the high carbonate horizons at the Medium Calcic and Old Petrocalcic sites by the hydrometer method (Gee and Or, 2002). We measured $CaCO_3$ content by mass for soils at each probe placed within the calcic and petrocalcic horizons by the manometer method (Nelson, 1982).

We measured the characteristic soil water release curve (SWRC) for the soils at each probe in high carbonate horizons from approximately -0.5 MPa to < -5.0 MPa using a chilled mirror psycrometer (WP4 Potentiameter, Decagon Devices, Pullman, WA; Scanlon et al., 2002). Measured SWRC points of each calcic/petrocalcic replicate at each site (n = 3 subsamples, 3 to 6 points for each subsample) were fit using non-linear regression techniques (PROC NLIN, SAS Institute, 2001)to the equation:

$$w = \frac{w_s}{[1+(a|\psi|)^n]^m}$$

where w is the observed gravimetric water content, w_s is the water content at saturation, a is a scaling parameter, and n and m are shape parameters with

m = 1- 1/n, and ψ is the observed soil-water potential. The equation used was the van Genuchten (1980) equation modified for gravimetric water content and without the residual water content parameter. Fitting was performed with w_s as a fitted parameter. After we determined the shape parameters for the high carbonate soil horizon at each mini-pit, we repeated non-linear regressions for each sample to determine a and w_s using the horizon shape parameter. Calcic and petrocalcic horizon probe locations gravimetric water contents retained at -1.5 MPa were converted to volumetric water content using estimated bulk densities. Bulk densities at probe locations were estimated based on a multiple regression relationship of sampled $CaCO_3$ content and gravimetric soil water retention points developed from data in Chapter 1 (Duniway, *unpublished data*), and validated with clod method bulk density values for calcic and petrocalcic horizons from nearby soil pits (Soil Survey Staff, 2006). This approach allowed the permanent wilting point volumetric water content (θ_{PWP}) used to be representative of the specific soil properties at the soil moisture sensors in these heterogeneous horizons. Estimates of volumetric soil-water content retained at -1.5 MPa were calculated for the non-carbonate soil using the ROSETTA computer program based on measured soil texture and bulk density (Schaap et al., 2001). To address hypotheses regarding soil water availability, we subtracted the soil specific θ_{PWP} from measured soil water contents. 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).

Statistical analysis

Analysis of variance was used to test for significant differences ($\alpha = 0.05$) in average site vegetation cover, cover by functional group, and cover of dominant species (PROC GLM, SAS Institute, 2001). To allow for parametric analysis, we arcsine transformed the data for significance tests and calculating variances (Snedecor and Cochran, 1980). Reported data were back calculated to percent.

Diurnal variability of TDR soil water contents was generally less than 0.01 $m^3\ m^{-3}$, 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. For Deep depths with a missing subsample, we used the two remaining probes within each replicate. Mean Deep measurement depths did not differ significantly between sites ($p = 0.717$). Within site variability 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, analysis of variance (PROC GLM, SAS Institute, 2001) with Deep mean depth included as a covariate were done for each day of measurement and contrasts performed testing for significant differences in available water between sites ($\alpha = 0.05$). While this approach can cause a high experimentwise type I error rate, for this exploratory study we were more concerned with minimizing the type II error rate and increasing power to detect when significant differences were most likely to exist.

To evaluate differences in calcic and petrocalcic horizon wetting and drying rates, repeated measures analysis with a heterogeneous autoregressive covariance structure and Satterthwaite degrees of freedom (PROC MIXED, SAS Institute, 2001) was done for select wetting and drying events in the winter of 2004 and spring of 2005, respectively. Again, we used the mean Deep measurement depth as a covariate.

To test available soil water dynamics hypotheses, we determined the percent of days within a season where Shallow and Deep soil water contents were significantly greater than θ_{PWP} ($p < 0.05$) (PROC MEANS, PROC FREQ, SAS Institute, 2001). Additionally, we calculated the percent of days within a season where average Shallow and Boundary gypsum block soil water potentials (log transformed) were significantly greater than -1.5 MPa. To allow for comparison with the Boundary depth frequency results, we also performed frequency analysis on the Young Sand site 55 cm depth TDR probes. For this study, the calendar year was divided into three seasons: summer (July through October), winter (November through February) and spring (March through June).

RESULTS

Site characterization

Significant differences were detected between sites in total plant canopy cover, cover by functional group, and cover by species (Table 2.1, Table 2.2). The Medium Calcic site had significantly greater total cover, perennial grass cover, and perennial forb/sub-shrub cover and the Young Sand site had significantly more canopy cover of shrubs. *B. eriopoda* was the dominate perennial grass at all sites; however there was substantial cover of *Aristida purpurea* and *Sporobolus flexuosus* at

Table 2.1. Average canopy cover by functional group. Fisher's protected LSD (α = 0.05) by letters, standard deviations in parentheses.

Site	N	Total canopy	Bare ground	Perennial grass	Shrubs	Perennial forbs/sub-shrubs	Annuals
		%					
Young Sand	10	35.3*b* (7.4)	50.0*a* (9.9)	13.3*b* (7.5)	10.3*a* (6.5)	6.8*b* (4.6)	11.3*a* (7.4)
Medium Calcic	10	48.8*a* (9.4)	44.5*a* (9.7)	27.0*a* (8.6)	2.3*b* (4.0)	17.0*a* (7.1)	10.0*a* (5.3)
Old Petrocalcic	10	32.3*b* (10.9)	45.0*a* (13.8)	12.5*b* (5.7)	3.5*b* (3.6)	6.3*b* (5.2)	13.8*a* (4.6)

Table 2.2. Canopy cover of dominant species within functional groups. Fisher's protected LSD (α = 0.05) by letters, standard deviations in parentheses.

		Perennial grasses			Shrubs			Perennial sub-shrubs/forbs		
Site	N	*Aristida purpurea*	*Bouteloua eriopoda*	*Sporobolus flexuosus*	*Ephedra trifurca*	*Prosopis glandulosa*	*Yucca elata*	*Caesalpinia jamesii*	*Croton pottsii*	*Gutierrezia sarothrae*
		%								
Young Sand	10	0.3*b* (0.8)	10.8*a* (7.0)	1.8*b* (2.1)	0.3*a* (0.8)	9.3*a* (6.0)	1.0*a* (1.7)	0.0*b* (0.0)	0.0*b* (0.0)	6.3*a* (4.0)
Medium Calcic	10	6.8*a* (5.0)	15.0*a* (10.2)	6.0*a* (4.9)	0.0*a* (0.0)	1.3*b* (3.2)	1.0*a* (1.7)	5.3*a* (4.0)	2.5*a* (3.1)	6.0*a* (3.2)
Old Petrocalcic	10	0.0*b* (0.0)	12.0*a* (5.6)	0.5*b* (1.1)	0.0*a* (0.0)	2.5*b* (3.1)	0.8*a* (1.7)	1.0*b* (1.7)	0.0*b* (0.0)	5.0*a* (4.2)

the Medium Calcic site. *P. glandulosa* and *Gutierrezia sarothrae* were the dominant shrubs and sub-shrubs respectively.

Upper profile textures at all sites were fairly coarse, with clay maximums of approximately 15% in sites Old Petrocalcic and Medium Calcic (Fig. 2.2). Clay accumulation with depth was less pronounced at the Young Sand site where profile clay content did not exceed 10%. Soil texture profiles above the high carbonate horizons at sites Medium Calcic and Old Petrocalcic were fairly similar and ranged from sands to sandy loams; the Young Sand site was slightly coarser with only sands and loamy sands present. Shallow depth bulk densities and estimated θ_{PWP} were fairly similar across sites (Table 2.3). However, the Shallow layer bulk density was slightly lower and estimated θ_{PWP} was somewhat higher on average at the Medium Calcic site likely due to the slightly higher clay contents at the 30 cm depth (Fig. 2.2).

Bulk density and θ_{PWP} were substantially higher in the Deep depths at sites Medium Calcic and Old Petrocalcic than Young Sand (Table 2.3). Bulk density and

Table 2.3. Average soil properties at TDR soil moisture sensor locations. Standard deviations in parentheses.

	θ_{PWP}			Bulk density		
Layer	Young Sand	Medium Calcic	Old Petrocalcic	Young Sand	Medium Calcic	Old Petrocalcic
	----------$m^3\ m^{-3}$----------			----------$g\ cm^{-3}$----------		
Shallow	0.053 (0.008)	0.059 (0.002)	0.051 (0.003)	1.46 (0.05)	1.38 (0.04)	1.45 (0.03)
Deep	0.054 (0.006)	0.138 (0.011)	0.135 (0.025)	1.46 (0.07)	1.73 (0.03)	1.76 (0.03)
	0.046 (0.002)	0.127 (0.007)	0.135 (0.020)	1.49 (0.05)	1.72 (0.04)	1.78 (0.11)
	0.053 (0.008)	0.127 (0.009)	0.136 (0.012)	1.45 (0.08)	1.67 (0.06)	1.68 (0.08)

θ_{PWP} varied little with depth in the Young Sand site. Average percent $CaCO_3$ was higher at the Old Petrocalcic site, with the upper horizon locations having the most carbonates (Fig. 2.2). There was little differentiation in $CaCO_3$ content with depth in the calcic horizon. Average θ_{PWP}'s by depth within the petrocalcic horizon were very similar; however the upper horizon locations had nearly twice the variability of the lowest location. Within the calcic horizon at the Medium Calcic site, average θ_{PWP} was less variable and smaller on average than at the Old Petrocalcic site but had greater differences with depth.

Precipitation

The study period was marked by extremes in rainfall (Fig. 2.4). During the summer of 2004, study sites received approximately 145 mm of precipitation, which is slightly below the long term average. However, rainfall for the winter of 2004-2005 was extremely high with a total of 123 mm or 261% of normal. Spring 2005 was also fairly wet with 41 mm of rain (122% of normal). Summer 2005 was dry with study sites receiving only 69 mm of rain, less than half of the normal season total. This dry summer was followed by an extremely dry winter and spring for a total of seven months with virtually no precipitation. Total rainfall recorded within the 2006 summer months was above average due to a succession of storms that dropped an unprecedented 106 mm of rain on the study sites between August 1st and 18th. Monthly and seasonal rainfall totals were fairly similar at all three sites. Old Petrocalcic and Young Sand sites had very similar rainfall totals throughout the study. However, summer 2005 totals were considerably higher at the Medium Calcic site due to an isolated storm in August that produced over 70 mm of precipitation that the other two sites did not receive.

Soil water content

Shallow and Intermediate depths retained less total soil water than any of the high carbonate horizons through almost the entire study period (Fig. 2.4). Minimum and maximum Shallow and Intermediate soil water contents were fairly similar across sites, ranging from 0.03 to 0.19 $m^3\ m^{-3}$. The Medium Calcic site had more Shallow and Intermediate soil water on average during both wet and dry periods than either the Old Petrocalcic or Young Sand sites. The Old Petrocalcic site, however, did register higher maximum average Shallow water contents than the Young Sand site. The Shallow depth measurements showed increases in soil water contents in response to summer rains in August, September, and October of 2004 (Fig. 2.4). However, the winter rains of 2004-2005, although less in total amount than the summer, resulted in increases in both Shallow and Intermediate water contents by 0.05 to 0.10 m^3m^{-3} over late summer water status. Rainfall received at the sites through winter 2004-2005 continued to register in the Shallow and Intermediate depths up through the first week of March 2005. During the spring of 2005, the Shallow and Intermediate soils dried down to pre-winter levels. Below average summer 2005 rainfall slightly increased Shallow and Intermediate soil water contents at the Old Petrocalcic and Young Sand sites. A localized thunderstorm at the Medium Calcic site produced an approximately 0.05 m^3m^{-3} increase at the Shallow depth. The Shallow and Intermediate soils at all sites remained very dry, with a slight downward trend, during the rainless winter of

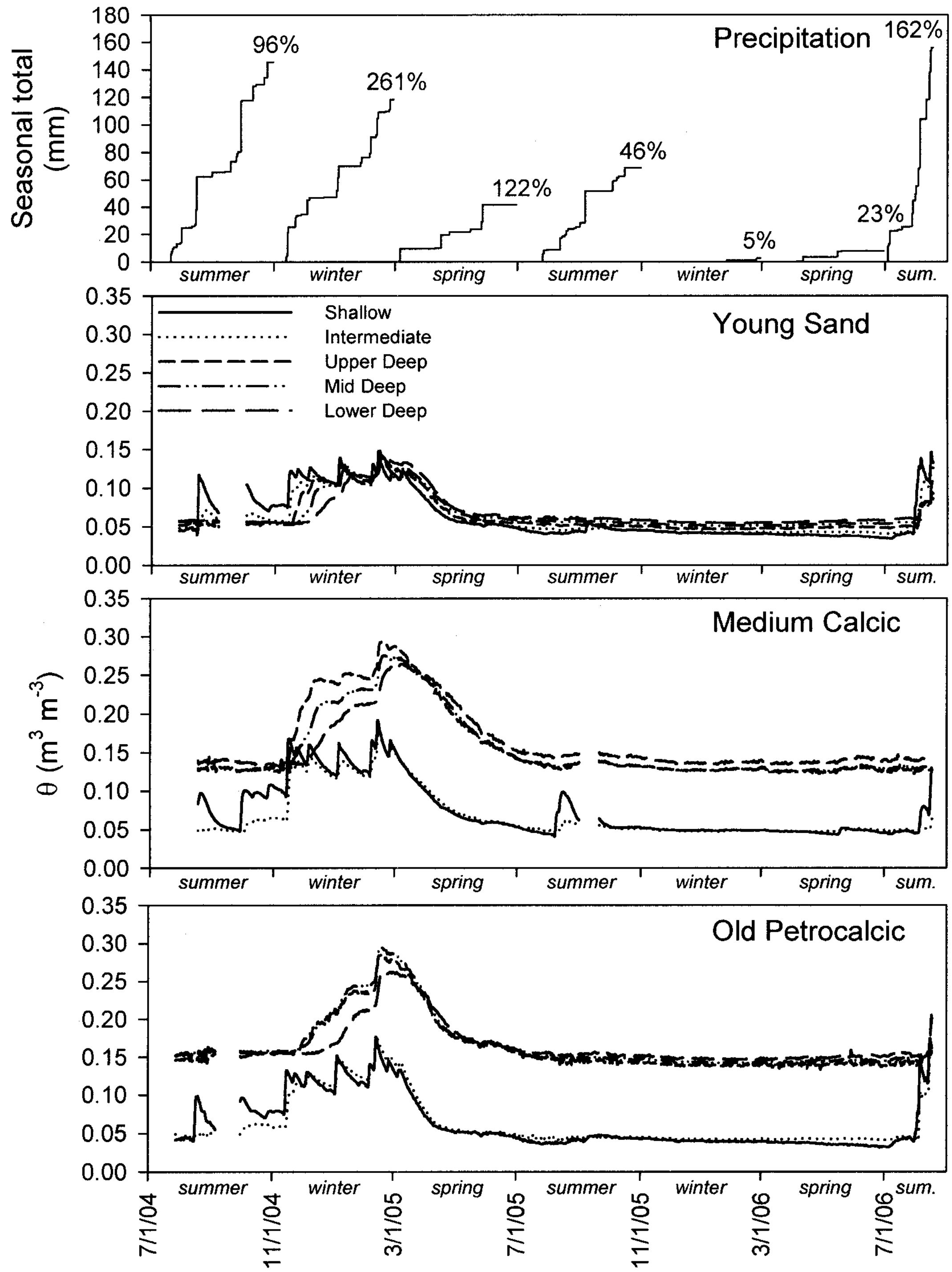

Fig. 2.4. Seasonal accumulated daily precipitation and percent of long term season average (upper panel) and average water content for all depths at each site (lower three panels). Summer 2006 rainfall total is through 18 August and percent is of long term average totals for July and August.

2005-2006 and spring of 2006 until the rains returned at the very end of the study period in the summer of 2006.

Calcic and petrocalcic horizons retained more water than equivalent depths at the Young Sand site throughout the study period (Fig. 2.4). High carbonate horizon minimum average water contents ranged from 0.12 to 0.16 $m^3 m^{-3}$, compared to 0.05 to 0.06 $m^3 m^{-3}$ in the Young Sand site. High carbonate horizons also contained approximately 0.10 $m^3 m^{-3}$ more soil water than the Shallow and Intermediate measurements. In the Young Sand site, Deep water contents were similar to the Shallow, retaining only 0.01 to 0.02 $m^3 m^{-3}$ more water during dry periods, a difference that can be explained by the slightly coarser texture and greater concentrations of roots in the Shallow. Deep water contents in all sites increased during the wet winter of 2004-2005, however high carbonate horizons had larger increases and maximum soil water contents than the Young Sand site. Additionally, Deep water contents at the Medium Calcic and Old Petrocalcic sites did not dry to pre-winter levels until August of 2005 whereas the Young Sand Deep depths lost all winter moisture by June. Deep water contents remained fairly steady during the summer of 2005 and the dry winter of 2005-2006. The Medium calcic site Deep measurements did register a slight increase in response to the isolated rainfall in August. The petrocalcic and the Young Sand Deep water contents abruptly increased in response to the large storms at the very end of the study period.

Available soil water content

At the Shallow and Intermediate depths, available water contents were similar and zero for the majority of the study (Fig. 2.5). In contrast, high carbonate horizon available water contents were higher on average in wet periods and in some dry periods than the Deep positions in the Young Sand (Fig. 2.5, Fig. 2.6). The petrocalcic horizon had significantly ($p < 0.05$) more available soil water than Deep points in the Young Sand prior to the winter 2004-2005 wetting event (Fig. 2.6). Higher average petrocalcic horizon water contents again became significant after peak moisture in mid February 2005. The Young Sand versus Old Petrocalcic Deep depth contrast p-value remained less than 0.05 until August, 2005. During the relatively dry summer of 2005 and following dry winter, spring and early summer of 2006, the petrocalcic horizon retained on average 0.01 $m^3 m^{-3}$ more available water than the Young Sand Deep, a difference that was marginally significant at the $\alpha =$ 0.05 level.

Calcic horizon available water dynamics were similar to those in both the Old Petrocalcic and Young Sand sites Deep depths. Available water was significantly less than Old Petrocalcic but not Young Sand at the beginning of the study and most of summer 2004 (Fig. 2.6). During wetting events of November and December 2004, the calcic horizon initially absorbed more water than either the petrocalcic or Young Sand Deep. However, mean available water contents in the high carbonate horizons were essentially equal by mid January 2005. The calcic and petrocalcic horizons responded similarly to the final wetting events in February 2005. The calcic horizon

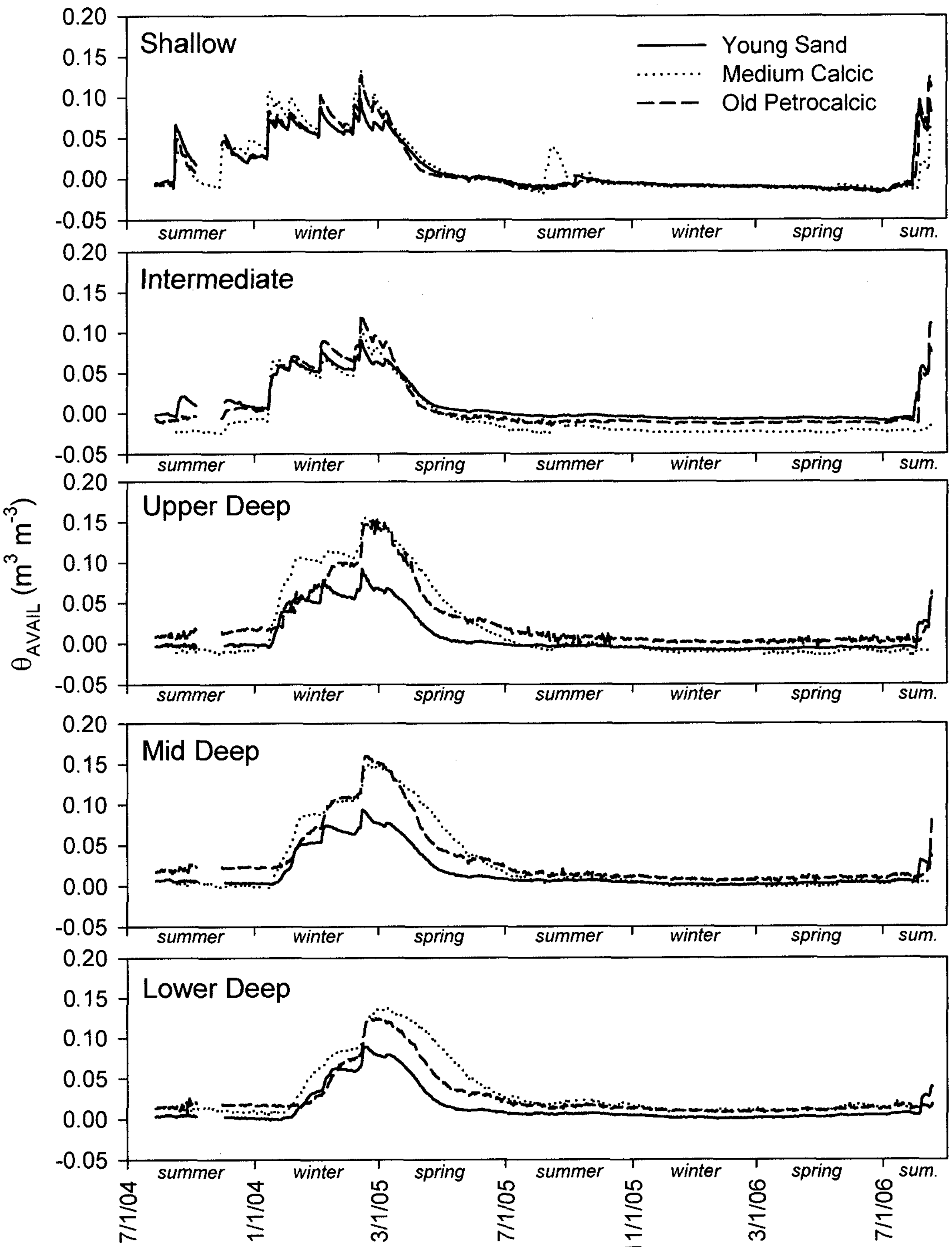

Fig. 2.5. Available soil water content at each measured depth for all sites.

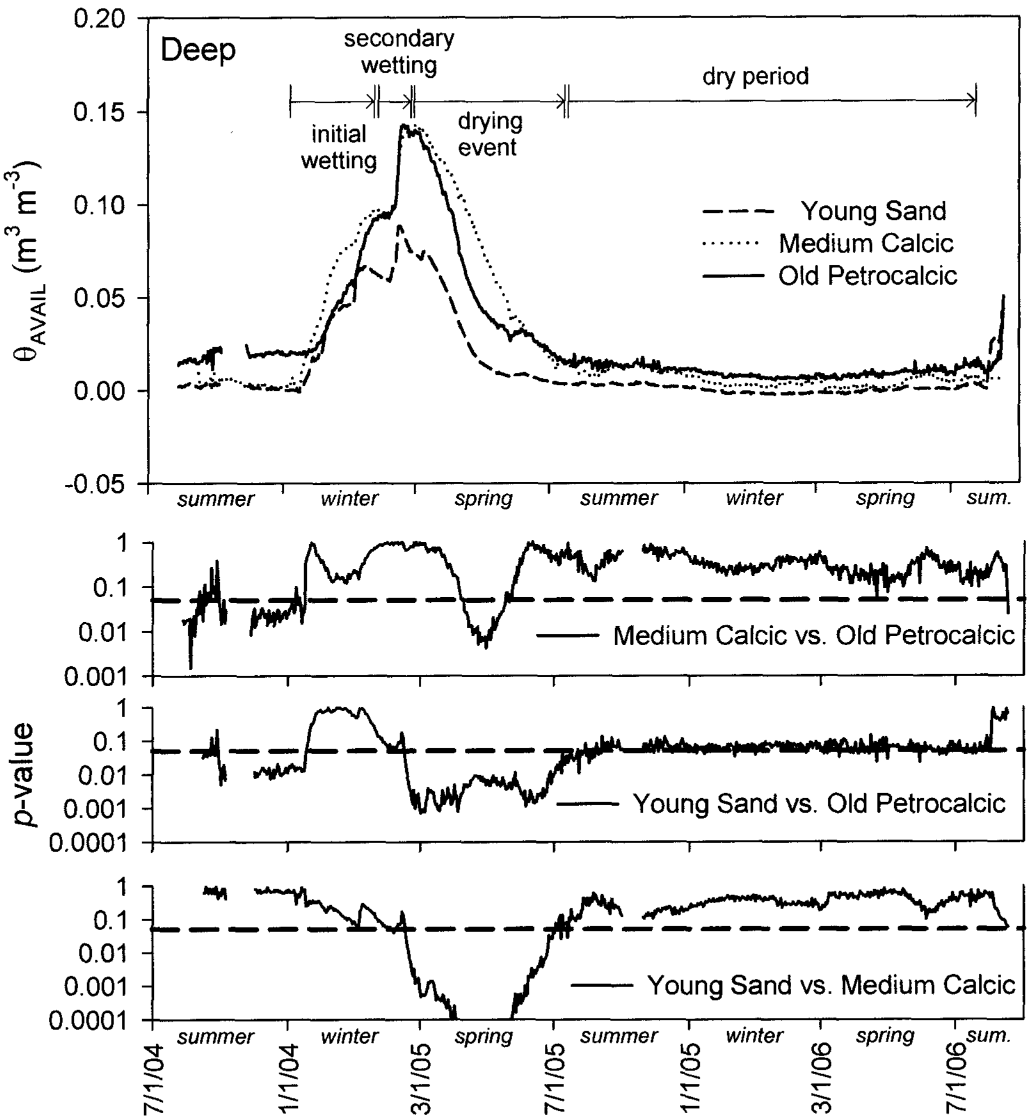

Fig. 2.6. Deep layer available water contents and contrast p-values from daily analysis of variance pairwise comparisons.

had significantly more available soil water than the Young Sand Deep from peak wetness in February until the beginning of July 2005. During the 2005 drying event, the calcic horizon retained significantly more available soil water than the petrocalcic horizon from early April to late May 2005 (Fig. 2.6). However, average available water in the calcic horizon was not significantly different than the petrocalcic horizon or Deep at the Young Sand site after May and June 2005, respectively.

Frequency of available water

Results addressing hypotheses regarding the stability of soil water availability indicate Deep depths with high carbonate horizons had a greater frequency of days with plant-available water than Deep depths lacking carbonate accumulation. Shallow depths had soil water contents significantly greater than θ_{PWP} for most days in summer 2004 and all days in winter 2004-2005 (Fig. 2.7). During the spring of 2005, the Shallow layers only had available water for 35 to 50% of the days, with the Old Petrocalcic having the lowest and Medium Calcic having the highest frequency. Except for a brief period in the summer, no Shallow layers had available water content that was significantly greater than zero from the summer 2005 through spring 2006. The increase in frequency of Shallow available water in summer 2006 was due to the rainstorms in August (Fig. 2.4).

Seasonal frequency of available water in the petrocalcic horizon was higher than or as high as the in calcic horizon and Young Sand Deep depths during all seasons of the study (Fig. 2.7). During summer 2004 measurement days, the petrocalcic horizon had available water more than 80% of the days. All Deep soils had available water for the majority of the winter of 2004-2005. In the spring of 2005, high carbonate horizons had available water 100% of the days as compared to only 54% in the Young Sand. In the following summer, the petrocalcic horizon

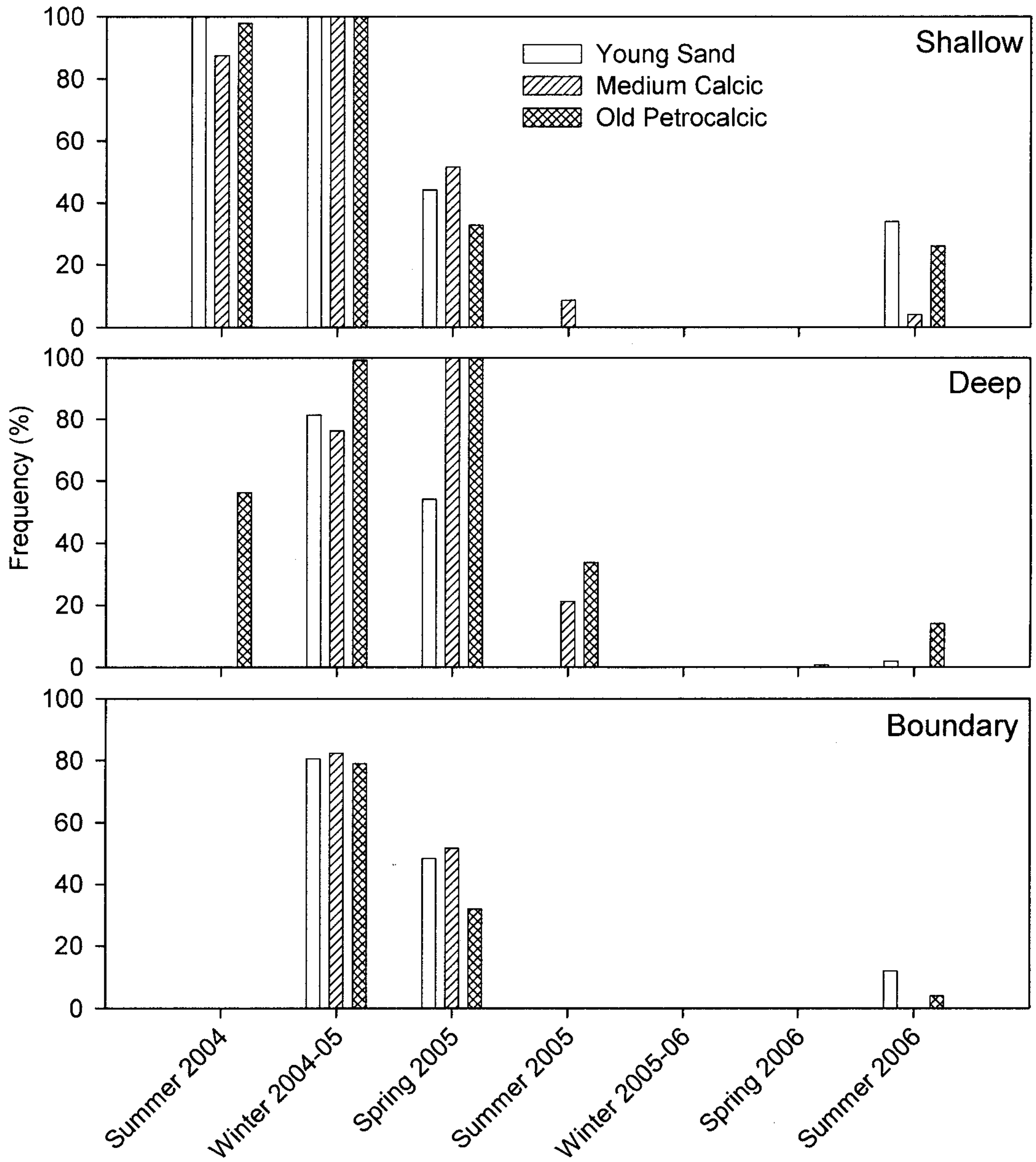

Fig. 2.7. Frequency of water availability. The upper two panels are within season frequency of daily average water contents significantly greater than θ_{PWP} (α = 0.05), measured with TDR sensors for Shallow and Deep from all three sites. The bottom panel is frequency of soil water potential significantly greater than PWP using gypsum block data from the Boundary position at the Medium Calcic and Old Petrocalcic sites and TDR data from similar depths at the Young Sand site.

retained available water for 44%, the calcic horizon for 21%, and the Young Sand Deep 0% of the days. In the dry winter of 2005-2006 and spring of 2006, all of the Deep layers had essentially no available water. The increase in frequency of available water during summer 2006 was attributed to the rainfall in August 2006. Frequency of the Shallow available water as measured by the gypsum blocks was virtually identical to that from the TDR (Pearson's correlation coefficient, $r = 0.995$), indicating the two methods are comparable for determining the duration of water availability. In contrast to the Deep depths, frequency of water availability in the Boundary position at the Medium Calcic and Old Petrocalcic sites resembled that of similar depths in the Young Sand (Fig. 2.7). The frequency of water availability in the Boundary depths was similar in all sites during the winter of 2004-2005 but was markedly less at the Old Petrocalcic site during the spring of 2005. During the following dry seasons, there were no days with available water in the Boundary depths.

Horizon wetting and drying rates

During wetting in the winter 2004-2005 and drying in the spring 2005, the calcic horizon absorbed soil water more rapidly and dried more slowly than the petrocalcic horizon (Fig. 2.8, Table 2.4). There was a significant time effect during all periods and a significant soil by time interaction between the Medium Calcic and Old Petrocalcic sites during the initial wetting event from November 16 to February 2 but not for the secondary wetting event from February 9 to 23. During the high carbonate horizon drying from March 1 to June 14 there was significant soil by time

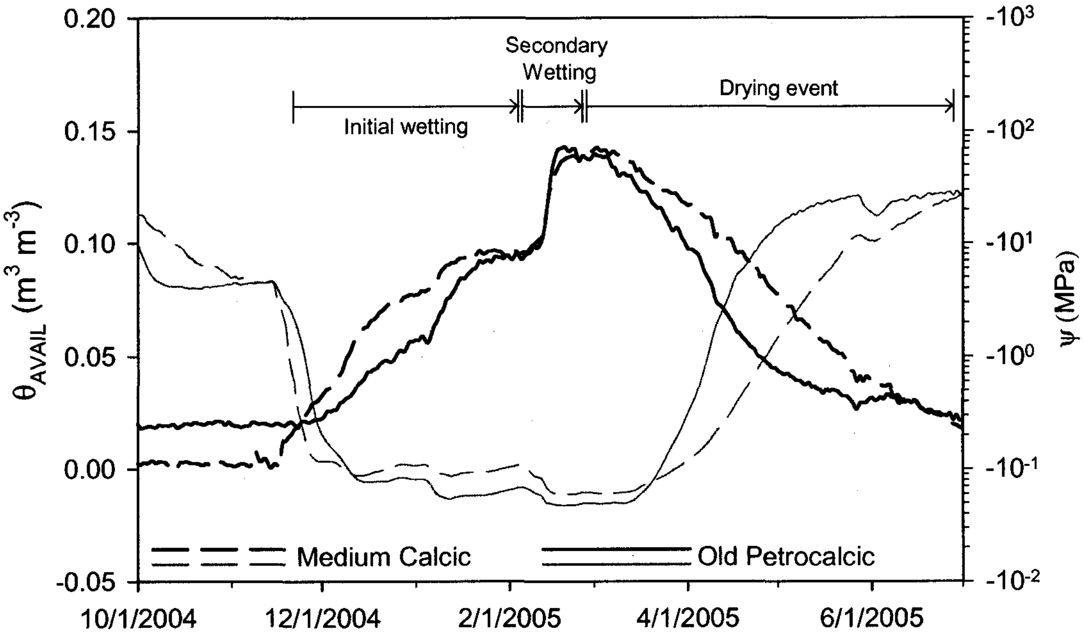

Fig. 2.8. Wetting and drying events of 2004-2005 for Deep depths at the Medium Calcic and Old Petrocalcic sites. Black lines are measured Deep available soil water contents. Grey lines are measured soil water potentials at the Boundary depths. Initial wetting, secondary wetting, and drying event are available soil water content periods analyzed with repeated measures for soil by time interaction.

interaction. However, unlike the initial wetting event, the rate of change of available soil water content was initially slower in the calcic than petrocalcic horizon. Interestingly, the Deep mean depth covariate effect was significant for both wetting events but not the drying event.

DISCUSSION

Total and available soil water contents

Presence of high carbonate horizons greatly increased the near surface soil water holding capacity. The unusually high variability in seasonal precipitation

Table 2.4. High carbonate horizon repeated measures analysis results of two wetting events during winter 2004-2005 and the spring 2005 drying event.

	18 Nov. to 2 Feb.				2 Feb. to 23 Feb.				1 Mar. to 14 June			
Source of variation	Num df	Den df	F-value	*p*-value	Num df	Den df	F-value	*p*-value	Num df	Den df	F-value	*p*-value
Main effects												
Soil (S)	1	10.4	0.37	0.554	1	9.9	0.01	0.907	1	10.6	2.04	0.182
Time (T)	78	281.0	4.66	<0.001	20	89.3	14.39	<0.001	103	308.0	9.40	<0.001
Interaction effects												
S x T	78	281.0	1.43	0.020	20	89.3	1.00	0.474	103	308.0	2.02	<0.001
Covariate												
Depth	1	171.0	5.14	0.025	1	129.0	67.26	<0.001	1	86.6	0.51	0.478

during the study period (Fig. 2.4) allowed us to document soil water dynamics under a wide variety of conditions. The high carbonate horizons retained significantly greater quantities of plant-available soil water during the approximately four month period after the winter rains of 2004-2005 (Fig. 2.5). 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. The Shallow and Intermediate soil water content at all sites exceeded the field capacity of the coarse textured soils and excess water continued down to the Deep depths. Calcic and petrocalcic horizons retained increases of 0.12 to 0.13 $m^3 m^{-3}$ over early winter levels and water contents of 0.26 to 0.28 $m^3 m^{-3}$ for a period of 2 to 3 weeks. These values are comparable to laboratory based field capacity estimates for plugged horizons (Chapter 1) and field estimates by Hennessy et al. (1983). In contrast, at the Young Sand site the lower depth field capacities were only slightly larger than the Shallow and the excess moisture likely drained below the lowest monitored depth. Thus, the low water holding capacity Young Sand soil lost more water to deeper depths, potentially providing a stable water source for the abundant deep rooted *P. glandulosa.*

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). The high carbonate horizons retained much more soil water at -1.5 MPa than the Young Sand site (Table 2.3). If a drier permanent wilting point of -4.0 MPa were considered, available water contents in the high carbonate horizons would increase by 0.03 to 0.06 $m^3 m^{-3}$. Due to the coarse texture of the Young Sand and already low water content at -1.5 MPa (0.05 m^3m^{-3}), lowering the permanent wilting point water potential would only result in a very minor increase (less than 0.01 m^3m^{-3}) in available water content. Thus, although high carbonate horizons do not appear to reflect a continuous, large water source at tensions wetter than -1.5 MPa, they do represent a source for species able to access soil moisture drier than -1.5 MPa during both wet and extended dry periods.

Aspects of the data suggest that the observed wetting and drying of the petrocalcic horizon were not influenced by the probe installation. The horizon wetted slowly in response to the winter rains and after wetting, petrocalcic horizon water content measurements did not dry below the initial water contents. Furthermore, un-calibrated neutron probe data gathered from a neighboring research site showed similar patterns (Jornada Basin LTER, 2006).

Frequency of water availability

Calcic and petrocalcic horizons continued to have frequent days with available water well into the growing season with no or limited rainfall. In contrast, the seasonal frequency of available water content (both Shallow and Deep) in non-carbonate horizons closely mirrored rainfall. Additionally, available water on top of a partially indurated calcic and indurated petrocalcic horizon measured in this study was not more frequent than at similar depths in the Young Sand. The lack of more consistently available water in the unconsolidated soil at the high carbonate horizon upper boundaries indicates the greater drought tolerance of black grama observed by Herbel et al. (1972) growing on soils shallow to petrocalcic horizons could be attributed to root contact with the top of the horizon. It might also be the result of mycorrhizal networks within the horizon providing access to the contained stable water source.

Implications of wetting and drying rates

The wetting of the horizon was notably slower within the petrocalcic than calcic horizon during the initial wetting event (Fig. 2.8). The slower wetting of the petrocalcic horizon than the calcic horizon can be partially attributed to slightly higher Medium Calcic site Shallow and Intermediate water contents (Fig. 2.4) and earlier wetting of the calcic horizon boundary (Fig. 2.5), however it was also probably a reflection of horizon properties. The laminar capped petrocalcic horizon had higher carbonate contents and bulk densities (Fig. 2.2, Table 2.3). The slower petrocalcic horizon water absorption rates provide evidence that laminar capped horizons can have lower hydraulic permeability and obstruct soil water percolation. However, the rate of change within the petrocalcic was similar to the calcic during the secondary wetting, indicating possible macropore flow occurring through cracks in the very wet petrocalcic laminar horizon (Fig. 2.8).

The timing and relative rate of the calcic and petrocalcic horizon drying during the spring of 2005 was mirrored by the soil water potentials at the upper horizon boundaries (Fig. 2.8). The study site climate during the dry-down months was 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 lack of a significant depth covariate effect indicate very little of the water lost from these Deep horizons can be attributed to evaporational losses from the soil surface. Faster upper profile drying at the Old Petrocalcic site, including at the Boundary depth, is probably due to larger transpirational losses. Most perennial vegetation was probably not transpiring in the spring but annuals were active. During spring 2005 site visits, it appeared that the Old Petrocalcic site had a much higher cover of annuals. Although the total cover of annuals in September was not significantly different between sites, the late winter and early spring active annual pinnate tansymustard (*Descurainia pinnata*) was much more prevalent at the Old Petrocalcic site. In September 2005 pinnate tansymustard had 6.75% cover at the Old Petrocalcic site compared to 0% at Medium Calcic and 0.5% at the Young Sand site. Roots were not observed within the petrocalcic or calcic horizons; however high densities of roots were often found matted on top of the upper horizon boundaries. The more rapid drying of the petrocalcic, coupled with the higher cover of spring active annuals and rapid Boundary and upper profile drying provide further evidence of petrocalcic horizons releasing stored water up to the zone with the greatest concentration of roots.

CONCLUSIONS

Petrocalcic and calcic horizons can contain significant amounts of plant-available water and can be recharged by winter and summer rains. Retention properties of these high carbonate horizons do limit the downward loss of soil water.

Instead of posing a significant obstacle to soil water movement as previously believed, they appear to function as a reservoir. Furthermore, study results show that despite morphological evidence, calcic and laminar capped petrocalcic horizons do not consistently differ in their hydraulic behavior. Both the calcic and petrocalcic horizons can contain soil water at tensions that are potentially available to desert plants throughout the year. Wet calcic and petrocalcic horizons dried in parallel to the upper soil profile, with horizon water potentially lost via bulk flow to roots growing on top of the horizons.

Plant communities in arid and semi-arid regions have changed dramatically in response to past climatic change and land-use patterns (Van Auken, 2000; Gibbens et al., 2005). These ecosystems are predicted to be some of the most sensitive to expected future climate changes and land-use pressures (Schlesinger et al., 1990; Briggs et al., 2005). The composition of plant communities in grasslands, mixed grass-shrub, and shrub communities has been attributed in large part to the spatio-temporal patterns of soil moisture (Walter, 1971; Breshears and Barnes, 1999). The results of this study indicate that petrocalcic and calcic horizons can dramatically alter patterns and dynamics of soil profile water availability.

Petrocalcic and partially indurated calcic horizons are often ignored when assessing soil profile available water. Shallow calcic and petrocalcic horizons could represent a near surface storage location of excess precipitation available to grasses and shrubs directly or via mycorrhizal relationships, potentially favoring more shallow rooted species. Further work is needed to evaluate soil water fluxes through calcic and petrocalcic horizons and potential links of the contained water to the plant community.

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CHAPTER 3:

EFFECTS OF MESQUITE ON WATER DYNAMICS IN SOILS SHALLOW TO PETROCALCIC HORIZONS

ABSTRACT

Widespread encroachment of woody shrubs into historic arid and semi-arid grasslands is a major problem throughout the world. Conversion of grasslands to shrub dominated systems can result in significant alteration of biogeochemical processes and lead to greater resource heterogeneity making grassland recovery difficult. Petrocalcic soil horizons have been shown to dramatically alter patterns of plant-available soil water. To assess how soil-water dynamics are affected by woody encroachment in soils with petrocalcic horizons, we conducted a two year replicated study in a mixed shrub-grass site monitoring soil water in unvegetated interspaces and under shrubs. Plots were instrumented with TDR soil moisture probes, both above and within the shallow (50 to 60 cm) petrocalcic horizon. Non-carbonate upper profiles and petrocalcic horizons of both strata had large increases in soil water contents during a wetter than normal winter and summer (increases of 0.08 to 0.14 m^3 m^{-3} and 0.04 to 0.13 m^3 m^{-3}, respectively). However, interspaces absorbed significantly greater quantities of available soil water during the winter and retained more available soil water into the spring than under shrubs. In contrast, soils under shrubs absorbed greater quantities of plant-available water following the summer

rains. These differing seasonal dynamics were attributed to canopy induced variability in hydrologic function and perennial and annual transpirational demands. Retention of winter moisture by the shallow petrocalcic horizon and apparent slow release of the stored water within the rooting zone of shallow rooted grasses and forbs indicates these soils are potentially less susceptible to dominance by deep-rooted woody shrubs.

INTRODUCTION

Invasion of historic grasslands by woody perennials is a persistent problem for arid and semi-arid land managers in the United States and throughout the world (Van Auken, 2000; Briggs et al., 2005; Gibbens et al., 2005). Potential local scale consequences of shrub encroachment in native grasslands include loss of economically important herbaceous forage, increased soil erosion, and habitat loss (Grover and Musick, 1990). At regional to global scales, shrub encroachment is a principle mechanism and result of desertification, which has been linked to atmospheric dust pollution, famine, and national and regional political upheaval (Schlesinger et al., 1990). The transition from a grassland to shrubland can be difficult to reverse due to changes in system water and nutrient cycling resulting from increased resource heterogeneity with concentration of water and nutrients under the shrubs (Schlesinger et al., 1996). The composition of plant communities in grasslands, mixed grass-shrub, and shrub communities has been attributed in large part to the spatio-temporal patterns of soil moisture (Walter, 1971; Breshears and Barnes, 1999; Schwinning and Ehleringer, 2001). Previous research, however, has not addressed how this concentration of resources, or "resource island", phenomenon is affected by soils with strong subsurface horizon development.

Canopy structure and soil-vegetation feedbacks can alter important hydrologic processes and soil properties under shrub canopies. Higher soil organic matter contents, due to increased inputs from leaf fall and root decomposition, can result in improved soil structure under vegetation when compared to bare interspaces (Bird et al., 2002). Shrub canopies help to protect the soil surface from erosion and physical crust formation associated with raindrop impacts but also reduce soil water inputs through canopy interception of small rain events (Abrahams et al., 2003; Loik et al., 2004). Soil surface plant litter can slow surface water flow and decrease losses due to runoff (Abrahams et al., 2006). Greater canopy shading of the soil surface and increased plant litter provides for a cooler soil surface and can decrease soil evaporation rates (Breshears et al., 1998). Additionally, a greater macropore density under shrubs has been attributed to increased macrofauna activity and woody root decomposition (Devitt and Smith, 2002).

Results from the literature documenting woody vegetation effects on temporal soil water dynamics in arid and semi-arid ecosystems are mixed. Several studies in arid and semi-arid mixed woody-grass ecosystems found consistently drier conditions under shrubs despite lower evaporation rates (Hennessy et al., 1985; Breshears et al., 1998; Breshears et al., 1999), while others observed wetter soil moisture conditions under shrubs immediately following summer rains (Bhark and Small, 2003). Soil water contents measured on the Jornada LTER were not consistently affected by the age of shrub islands, as estimated from the degree of development (Reynolds et al., 1999). In their preliminary analysis of a long term, landscape-level soil moisture data set from the Jornada LTER, Snyder et al. (2006) found little evidence that "shrub islands" have more stored water even though other studies have shown locations under shrubs can have higher infiltration rates (Bhark and Small, 2003). Furthermore, soil profiles under mesquite appeared to have lower water contents when compared to interspaces. These contradictory results can be partially explained by differing temporal resolution of the studies and variable storm characteristics. Most of the studies monitored soil water contents on a bi-weekly to monthly basis (Breshears et al., 1998; Reynolds et al., 1999; Snyder et al., 2006), potentially missing important but short periods following short-lived summer moisture like that observed by Bhark and Small (2003).

While canopy structure and vegetation-soil feedbacks can alter upper soil profile hydrologic properties, deeper soil profile horizon characteristics can also control vegetation community composition through their effects on spatio-temporal patterns of plant-available water (McAuliffe, 1994; Hamerlynck et al., 2000; Hamerlynck et al., 2002). One of the more striking and common subsurface horizons in older soils of arid and semi-arid regions are petrocalcic horizons. Petrocalcic horizons can be over a meter thick and occur extensively in arid and semi-arid soils across the world (Reeves, 1976; Machette, 1985; Monger et al., 2005). Petrocalcic horizons (commonly referred to as caliche) occur in older soils when a horizon is continuously indurated with carbonates (Soil Survey Staff, 1999), and have been shown to dramatically alter soil water availability and dynamics (Chapters 1 and 2) with potential implications for vegetation dynamics (Herbel et al., 1972). Little is known, however, about how soil-vegetation feedback dynamics associated with woody shrub encroachment function within the context of soils shallow to petrocalcic horizons.

The goal of this study was to improve our understanding of soil-water dynamics associated with woody shrub islands and associated interspaces in soils shallow to petrocalcic horizons. We addressed this general goal by testing specific soil water dynamic hypotheses in a mixed shrub-grass community located on a sandy soil shallow to a petrocalcic horizon. Our approach was to continuously monitor soil water contents above and within the petrocalcic horizon both under shrubs and in bare interspaces. We hypothesized that soils under shrubs will differ when compared to bare interspace positions in the (1) amount of soil water and (2) amount of available soil water above and within a shallow petrocalcic horizon. Additionally, we hypothesized that (3) wetting and drying dynamics will differ between the two strata. Finally, we explored potential soil-vegetation feedbacks with correlation analyses.

MATERIAL AND METHODS

Study location

The study was located on the USDA-ARS Jornada Experimental Range in the northern Chihuahuan Desert of southern New Mexico, USA (Fig. 3.1). The climate is characterized by a warm dry spring, hot wet summer, and cold dry winter (Wainwright, 2006). Long term (1915 to 1995) average annual rainfall is 245.1 mm

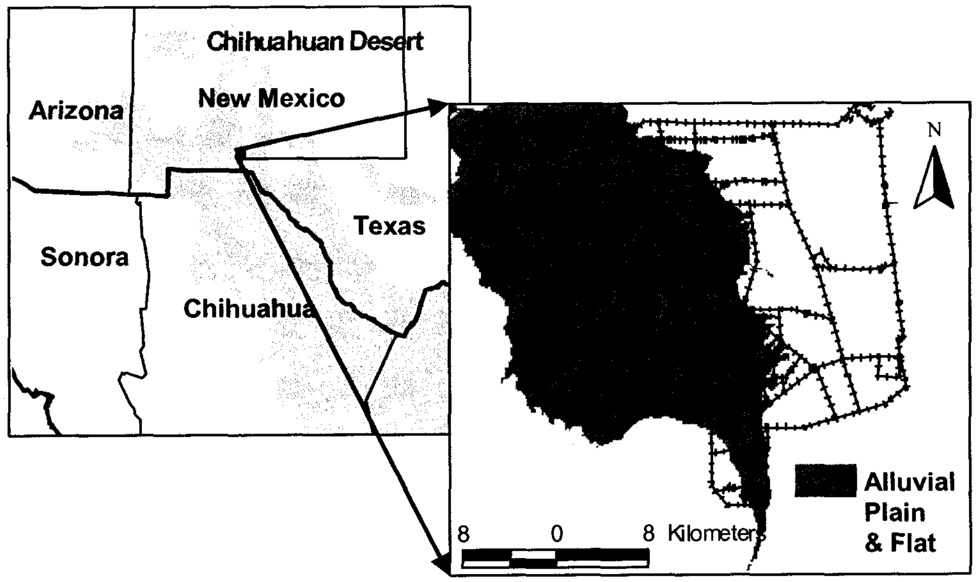

Fig. 3.1. The study was located in the northern Chihuahuan Desert in southern New Mexico USA. The study site (black asterisk) was located within the USDA-ARS Jornada Experimental Range (black fence lines).

of which more than half usually falls from July through October. Rainfall amount, timing, and intensity are highly variable within and between years. Summer rainfall totals are generally less variable between years but are dominated by intense, localized thunderstorms. Rainfall during the remainder of the year is generally of lower intensity and highly variable between years. The annual rainfall coefficient of variation is 36% (1915 to 1995). Annual pan evaporation rates far exceed rainfall, with a measured annual average of 2204.1 mm (1953 to 1979) (Wainwright, 2006). During the study, precipitation was recorded daily by a weighing bucket rain gauge located approximately 50 m from the site.

The study was carried out in a sandy soil shallow to a petrocalcic horizon (50 to 60 cm) of the Hueco series (coarse-loamy, mixed, superactive, thermic Argic

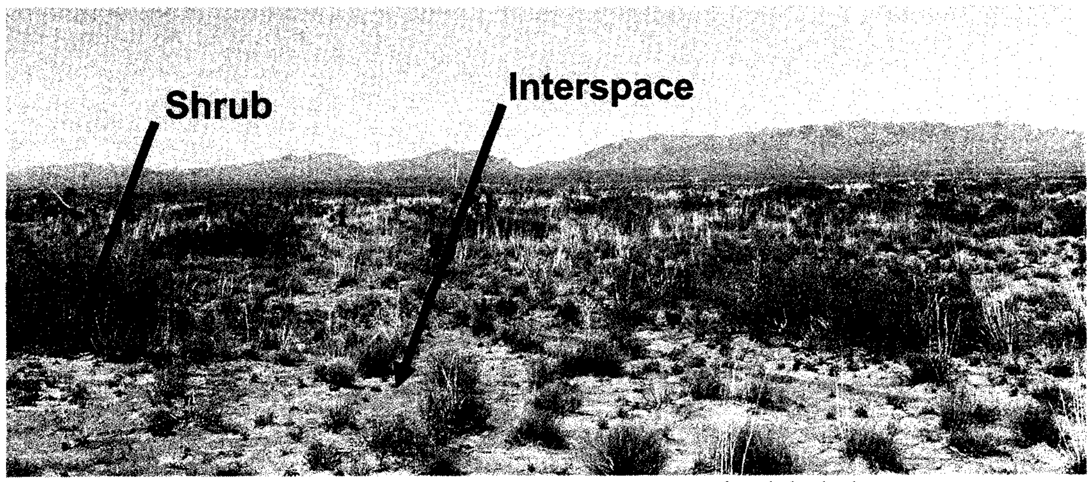

Figure 3.2. Study site location photo with strata examples labeled.

Petrocalcids). The petrocalcic horizon has a stage V morphology with a laminar layer and pisoliths evident (stages following Birkland, 1999). Additionally, there is a 1 to 10 cm thick horizon of coarse petrocalcic rubble above the laminar horizon. This is common in many shallow petrocalcic horizons. The study site has a mixed shrub-grass vegetation community dominated by mesquite (*Prosopis glandulosa*) and black grama (*Bouteloua eriopoda*). The study site represents a transitional location in the grassland to shrubland continuum, with no dune formation and no topographical difference in the elevation of interspaces and shrubs (Figure 3.2).

We obtained profile samples using the same sampling methods as in Chapter 2. Sample analysis for texture, bulk density, and calcium carbonate followed those in Chapter 2. To address hypotheses regarding soil water availability, we subtracted the soil specific permanent wilting point volumetric water content (θ_{PWP}) from measured soil water contents. We used the conventional soil water potential plant permanent wilting point of -1.5 MPa (Romano and Santini, 2002) to make the results broadly applicable. Soil-water release curves were developed and soil water content retained at -1.5 MPa calculated using the Chapter 2 methods.

Vegetation characterization

Site vegetation was characterized using the line-point method (Herrick et al., 2005) in July 2005. Twelve 1 m square grid transects centered on the soil moisture arrays were measured with 100 points per grid.

Soil water content

We instrumented the sites with time domain reflectometry (TDR) soil moisture sensors in a split plot design with two whole plot treatment levels of vegetation strata (Shrub and Interspace) and five subplot treatment levels of soil depth (Shallow, Intermediate, Upper Petrocalcic, Mid Petrocalcic, and Deep Petrocalcic) (Fig. 3.3). Six instrumented soil pits were located in unvegetated soil, approximately 60 cm from the base of black grama stands; and six pits under the canopy of mesquites, approximately one third of the canopy radius in from the shrub drip line (Fig. 3.3). We located the soil pits such that the petrocalcic horizon depth was similarly shallow (50 to 60 cm). The lateral extent of the site was limited to approximately 25 m due to allowable sensor cable lengths.

Soil moisture probes were placed based on both depth and horizon (Fig. 3.3). Two soil moisture probes were installed at depths above the petrocalcic: one at 30 cm (Shallow) and the other just above the laminar horizon or petrocalcic rubble that ccurred on top of the laminar horizon (Intermediate). The petrocalcic horizon was instrumented with three soil moisture sensors installed at 5 cm (Upper Petrocalcic),

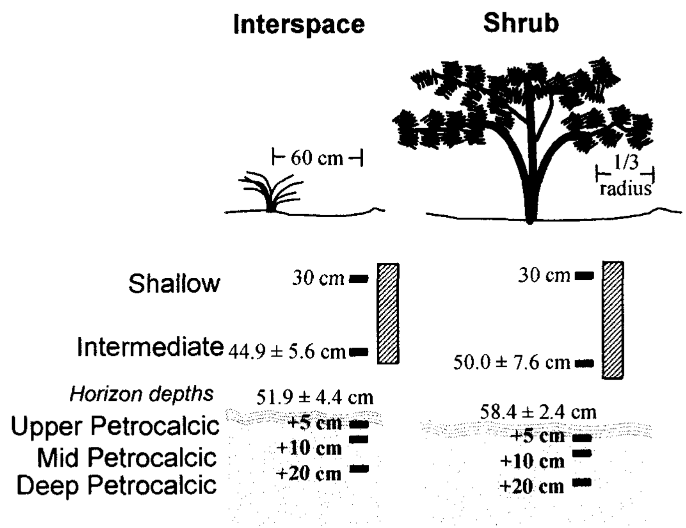

Fig. 3.3. Strata soil moisture monitoring instrumentation schematic. TDR soil moisture probes (represented by black rectangles) were placed by depth for the Shallow subplot. In the Intermediate and Petrocalcic subplots, probes were placed in reference to the upper petrocalcic horizon boundary. Intermediate subplot and petrocalcic horizon depths are strata averages and standard deviations. Cross-hatched bars represent Upper Profile depths used for analysis.

10 cm (Mid Petrocalcic), and 20 cm (Deep Petrocalcic) into the horizon, relative to the upper horizon boundary (Fig. 3.3). We concentrated petrocalcic horizon measurements in the upper sections of the firm horizons because these locations were more likely to interact with the rhizosphere. Design, fabrication, calibration, and installation of TDR probes and data collection methods and frequency were the same as those in Chapter 2. Four petrocalcic soil moisture sensors (three Interspace and one Shrub) were not usable due to equipment failure. Soil water contents were monitored from 28 July 2004 to 18 August 2006.

Statistical analysis

Analysis of variance was used to test for significant differences ($\alpha = 0.05$) in average strata vegetation cover, cover by functional group, and cover of dominant species for the two levels of vegetation strata (PROC GLM, SAS, 2001). To allow for parametric analysis, we arcsine transformed the data for significance tests and calculating variances (Snedecor and Cochran, 1980). Reported data were back calculated to percent.

Diurnal variability of TDR soil water contents was generally less than 0.01 $m^3\,m^{-3}$, so we used daily average water contents for each TDR probe. Upper Profile available water contents were calculated as the depth weighted average amount of available soil water from a depth of 25 cm to 5 cm below the Intermediate depth. The Petrocalcic available water was also calculated by weighting available soil water content measurements within the petrocalcic horizon by their representative depth to generate a horizon average. For petrocalcic replicates with a missing measurement depth, we used the average of the two remaining probes within each replicate.

Average Intermediate measurement depths were not significantly different between strata ($p = 0.213$) but within strata variability did exist, so depth was included as a covariate in Upper Profile analyses. Petrocalcic horizon depth was significantly different between strata ($p = 0.009$) (Fig. 3.3). Therefore, we did not include probe depth as a covariate in reported petrocalcic water dynamic statistical analyses. On average the Shrub Petrocalcic was 6.6 cm deeper than in the Interspace.

We tested the assumption that the 6.6 cm difference in average strata petrocalcic depth did not have any significant effect on the results by adding a depth covariate and re-running all statistical tests. Including a petrocalcic depth covariate did increase our power to detect differences in a few instances; however it had no effect on the significance of any results reported here.

To test hypotheses addressing amount of available water through time, analysis of variance (PROC GLM, SAS Institute, 2001) was done for each day of measurement. We tested for significant differences in Upper Profile and Petrocalcic available water between strata ($\alpha = 0.05$). While this approach can cause a high experimentwise type I error rate, for this exploratory study we were more concerned with minimizing the type II error rate and increasing power to detect when significant differences were most likely to exist.

To evaluate differences in petrocalcic horizon wetting and drying rates, repeated measures analysis with a heterogeneous autoregressive covariance structure and Satterthwaite degrees of freedom (PROC MIXED, SAS Institute, 2001) was done for observed wetting and drying events. Repeated measures were also used to estimate slow drying rates and detect differing strata dynamics by fitting linear models to the Petrocalcic available water contents during extended dry periods. To test for differences in strata drying rates (significant strata by time effects), a full model was fit with strata, time, and strata by time effects with time as a continuous variable. The time effect is the slope or rate across time for all strata and the strata by time effect fits a slope for each strata. To estimate rate of drying in each strata, analyses were re-run using a reduced model without the time (common slope) term. The frequency of points in time was reduced to facilitate analysis of long time periods by using five-day means of available soil-water content. For this study, the calendar year was divided into three seasons: summer (July through October), winter (November through February) and spring (March through June).

Correlation analyses were performed to test for possible relationships between relative plant cover and amount of available soil water, (PROC CORR, SAS Institute, 2001). Variables used were monthly average Shallow and Petrocalcic available water contents and select vegetation attributes.

RESULTS AND DISCUSSION

Strata characterization

Shrub and Interspace soil-water monitoring locations had significant differences in the hydrologically important attributes of total cover, litter cover and bare ground (Table 3.1). Plant functional group cover differed significantly only in percent shrub cover. The Interspace, however, had significantly higher cover of black grama with the lack of differences detected in the perennial grass functional group due to mesa dropseed (*Sporobolus flexuosus*) occurring in a few Shrub plots. *P. glandulosa* was the only shrub present at the soil moisture sensor locations. Although no significant differences were detected in annual functional group or any annual species cover, Shrub locations did have higher total average cover of the late winter, early spring active annuals panamint cryptantha (*Cryptantha angustifolia*) and pinnate tansymustard (*Descurainia pinnata*). Soil profile characteristics were very

Table 3.1. Average July 2005 canopy cover by functional group. Fisher's protected LSD ($\alpha = 0.05$) by letters, standard deviations in parentheses.

Strata	N	Total canopy		Bare ground		Litter		Perennial grasses		Shrubs		Perennial forbs/sub-shrubs		Annuals	
		----------%----------													
Interspace	6	46.9*b*	(14.6)	42.9*a*	(16.6)	26.3*b*	(11.3)	13.9*a*	(8.8)	0.0 *b*	(0.0)	7.2 *a*	(8.9)	34.5*a*	(11.4)
Shrub	6	86.2*a*	(12.6)	9.4*b*	(7.9)	58.9*a*	(22.3)	11.5*a*	(8.3)	62.4 *a*	(9.3)	5.0 *a*	(4.3)	43.7*a*	(10.7)

Table 3.2. July 2005 canopy cover of dominant species within functional groups. Fisher's protected LSD ($\alpha = 0.05$) by letters, standard deviations in parentheses.

		Perennial grasses				Perennial forbs/sub-shrubs						Annuals					
Strata	N	*Bouteloua eriopoda*		*Sporobolus flexuosus*		*Caesalpinia jamesii*		*Croton pottsii*		*Gutierrezia sarothrae*		*Cryptantha angustifolia*		*Descurainia pinnata*		*Dimorphocarpa wislizeni*	
		----------%----------															
Interspace	6	13.5*a*	(8.7)	0.3*a*	(0.8)	0.3*a*	(0.8)	0.0*a*	(0.0)	6.9*a*	(9.0)	7.5*a*	(4.9)	21.7*a*	(14.0)	2.0*a*	(3.1)
Shrub	6	3.8*b*	(6.1)	7.7*a*	(10.1)	0.0*a*	(0.0)	0.2*a*	(0.4)	4.8*a*	(4.5)	12.2*a*	(8.7)	36.6*a*	(13.5)	2.2*a*	(5.3)

similar in the Shrub and Interspace. Soil textures ranged from loamy sands to sandy loams in both strata profiles (Fig. 3.4). Measured bulk density, estimated θ_{PWP}, and Petrocalcic percent $CaCO_3$ were all similar between strata (Table 3.3, Fig. 3.4). Percent $CaCO_3$ within the petrocalcic horizons was 9 to 10 times larger than maximum upper profile carbonate contents for a similar Hueco series soil.

Soil water contents

Unusually high variability in precipitation during the study allowed us to evaluate interspace and under shrub canopy soil-water dynamics under a wide variety of conditions (Fig. 3.5). Well above average seasonal precipitation totals during the 2004-2005 winter and spring 2005 were followed by a dry summer 2005, very dry winter 2004-2005, and spring 2006. Summer 2006 totals were very large due to a series of heavy storms in August.

Throughout the study period, the petrocalcic horizons had consistently higher soil water contents than the Shallow and Intermediate depths in both vegetation strata

Table 3.3. Average soil properties at soil moisture sensor locations. Standard deviations in parentheses.

	θ_{PWP}				Bulk density			
Depth	Interspace		Shrub		Interspace		Shrub	
	---------------$m^3\ m^{-3}$------------------				----------------$g\ cm^{-3}$-------------			
Shallow	0.051	(0.003)	0.050	(0.005)	1.46	(0.05)	1.44	(0.05)
Intermediate	0.055	(0.005)	0.060	(0.011)	1.35	(0.07)	1.36	(0.04)
Petrocalcic								
Upper	0.135	(0.025)	0.149	(0.016)	1.76	(0.03)	1.70	(0.16)
Mid	0.135	(0.020)	0.142	(0.007)	1.78	(0.11)	1.69	(0.19)
Deep	0.136	(0.012)	0.148	(0.019)	1.68	(0.08)	1.64	(0.13)

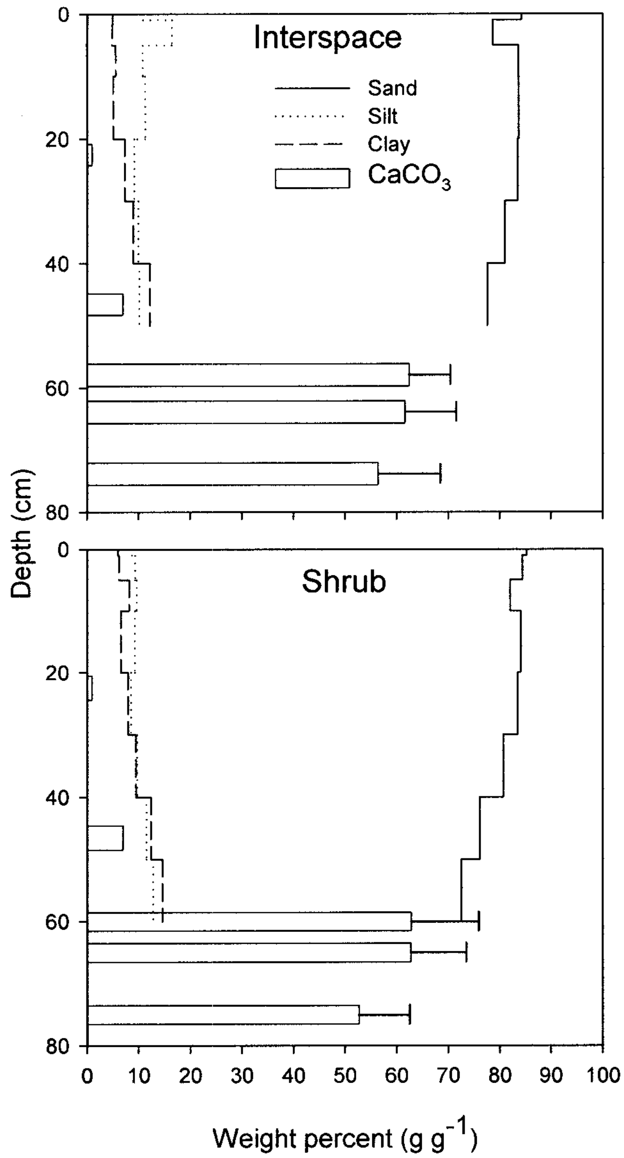

Fig. 3.4. Average strata soil profile texture and carbonate content. $CaCO_3$ values with error bars are data measured for Petrocalcic soil moisture sensor positions and depths are average for the strata. Other $CaCO_3$ values represent horizon values from a neighboring soil in the same series.

(Fig. 3.5). Shallow and Intermediate depths recorded large increases in response to the winter 2004-2005 rains, reaching peak water contents of 0.14 to 0.17 $m^3\ m^{-3}$ by mid-February. The majority of the Shallow and Intermediate winter precipitation, however, was depleted by April 2005. Shallow and Intermediate water contents continued to decrease slightly during the spring and early summer, reaching minimums of 0.04 to 0.05 $m^3\ m^{-3}$ for the 2005 calendar year in early August. After rising slightly in response to the few precipitation events during the summer 2005, Shallow water contents declined steadily during the very dry winter 2005-2006 and spring 2006, with both strata reaching a minimum water content of 0.03 $m^3\ m^{-3}$ for the study in early July 2006. Shallow and Intermediate water contents in both strata increased abruptly during August 2006, quickly reaching levels similar to winter 2004-2005 maximums.

All Petrocalcic measurement depth water contents increased rapidly during the wet winter 2004-2005 (Fig. 3.5). In both strata, Petrocalcic water contents reached very high maximums at the end of the winter season, 0.27 to 0.29 $m^3\ m^{-3}$ in the Upper and Mid Petrocalcic depths and 0.25 to 0.26 $m^3\ m^{-3}$ in the Deep Petrocalcic depths. All Petrocalcic depths lost much of the retained winter moisture during the first two months of spring 2005. In contrast to the Shallow and Intermediate depths, however, the petrocalcic horizons continued to slowly dry during May and June, not reaching pre-winter levels until mid-July 2005. During summer 2005, the downward trend in average petrocalcic horizon water contents ceased, with a slight upward trend evident under the Shrubs. Petrocalcic horizon drying resumed during the following

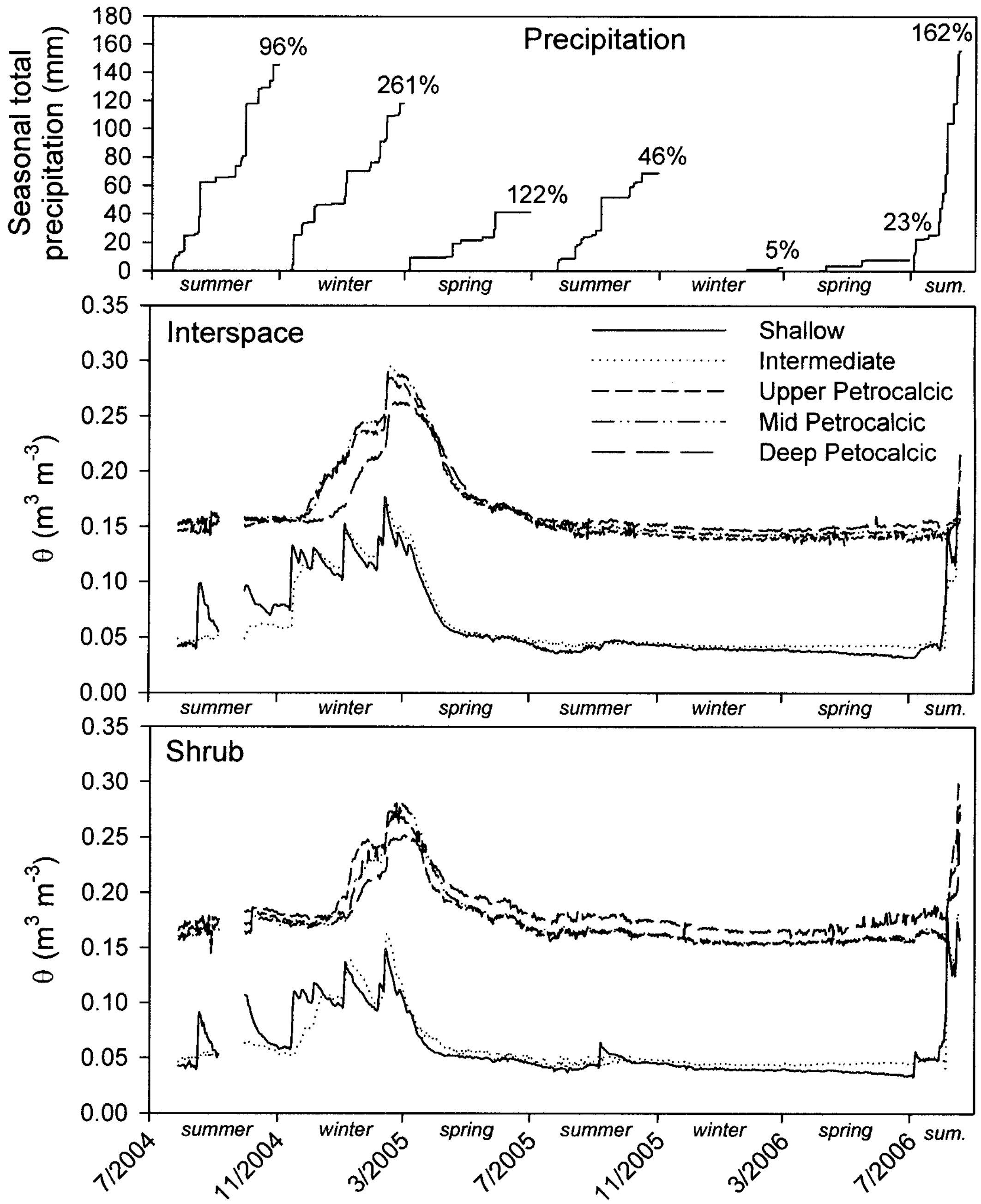

Fig. 3.5. Seasonal accumulated daily precipitation (upper panel) and depth average water contents under Interspace and Shrub strata (lower two panels). Precipitation percent of long term season average noted in upper panel. Summer 2006 rainfall total and percentage are through 18 August.

dry period reaching minimum values in the late winter of 0.14 to 0.15 $m^3\ m^{-3}$ in the Interspace and 0.15 to 0.16 $m^3\ m^{-3}$ in the Shrub. All petrocalcic horizon water contents increased sharply during the last days of the study except for the deepest Interspace position.

Available Soil Water Content

In both petrocalcic horizons and non-carbonate soils, Interspace available water contents were higher during cool wet periods while Shrub available water contents were higher during warm wet periods (Fig. 3.6). For a period from the last week of October through the end of November 2004, Interspace Upper Profile depths absorbed significantly more available soil water than the Shrub. During the remainder of the winter, Interspace Upper Profile available soil-water contents were larger than Shrub but differences were not significant. During the drying that occurred in the Upper Profile beginning in the late winter, Shrub positions dried sooner, resulting in significantly less available water than the Interspace for the month of March 2005. After mid-spring 2005, there was no available Upper Profile soil water in either strata until the high precipitation events of August 2006. In contrast to the cool season rains during the winter of 2004-2005, however, the Shrub Upper Profile available water contents increased more rapidly resulting in significant differences for periods in August 2006.

Petrocalcic position available soil-water contents were greater than zero during the entire study period for both strata (Fig. 3.6). As in the Upper Profile, the Interspace Petrocalcic available water contents were higher on average than the Shrub

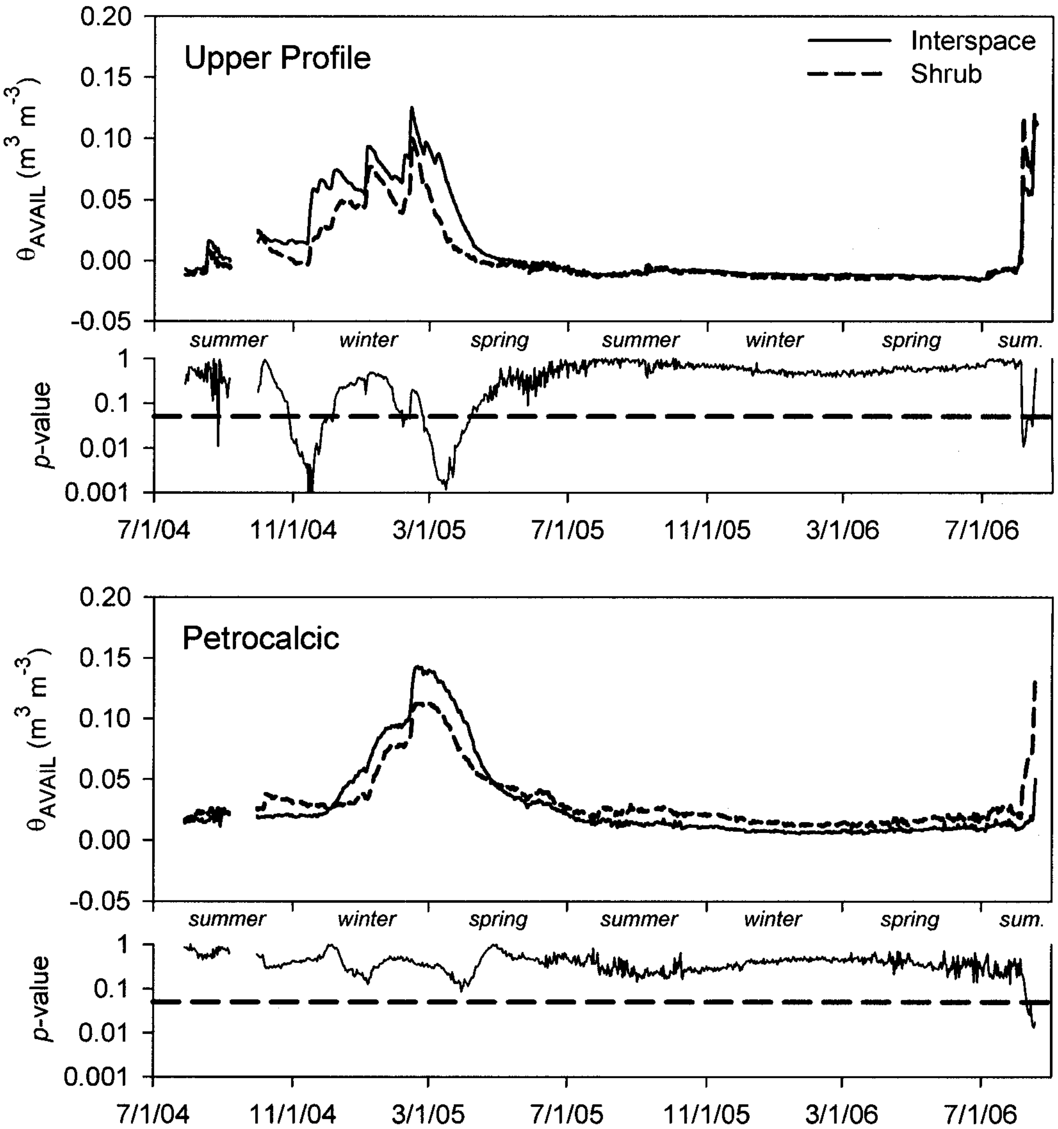

Fig. 3.6. Available soil water contents for the Upper Profile (25 to ~47.5 cm) and Petrocalcic (~55.2 to ~75.2 cm) and *p*-values testing for significant differences in strata available water through time. The 0.05 probability level is delineated with a dashed line in the *p*-value panels.

during the winter 2004-2005 and early spring 2005, though differences were not significant. In early March 2005, the Interspace and Shrub Petrocalcic reached maximum average available soil-water contents of 0.140 and 0.112 m^3 m^{-3} respectively. Petrocalcic available water contents converged during April 2005 and the Shrub Petrocalcic retained slightly more available soil water during the following dry seasons. Minimum Petrocalcic water contents occurred during early March 2006 with average water contents only slightly larger than θ_{PWP}, 0.006 and 0.011 m^3 m^{-3} of available soil water in the Interspace and Shrub, respectively. The Shrub Petrocalcic positions increased sooner than the Interspace in response to the intense summer 2006 rains, reaching significantly higher available water contents prior to the end of the study.

The greater amounts of Interspace available water during parts of the winter 2004-2005 and spring 2006 contradict expected results based on greater infiltration capacities and reduced soil surface evaporation under the Shrub, indicating other hydrologic processes were more important during the cool season rains. Rainfall during this period was generally of low intensity; for days with precipitation, the average daily total was only 5.2 mm. The importance of possible difference in strata infiltration capacity would be less during low intensity rain events. The higher Shrub canopy cover (Table 3.1) may have led to greater water loss through canopy interception of rain and subsequent evaporation, thereby reducing the Shrub winter soil water inputs relative to the Interspace (Loik et al., 2004). Drier Shrub antecedent soil moisture status due to higher late summer transpirational demands than in the Interspace, however, would also delay percolation of winter moisture. Although small scale canopy cover measurements are not a good predictor of soil water extraction by the extensive root system of *P. glandulosa* (Gile et al., 1997), it is likely that the Shrub strata soils had greater rooting densities and thus greater soil water lost to transpiration than the Interspace prior to senescence of *P. glandulosa* in December.

In addition to a drier antecedent condition and canopy interception, transpiration losses from winter-active annuals appear to have contributed to consistently lower available soil-water contents in the Shrub during the winter 2004-2005 and early spring 2005. Both Shrub and Interspace had high cover and variability in cover of the late winter early spring active annuals *C. angustifolia* and *D. pinnata* (Table 3.2). The Shallow Shrub spring 2005 monthly average available water contents were strongly negatively correlated with the cover of winter annuals (as measured in July 2005, Fig. 3.7), the same months as the rapid drying of the Shallow depth (Fig. 3.5). Cover of winter annuals in July 2005 was also strongly negatively correlated with the Shrub Petrocalcic available water contents during January, February, March, and April 2005. These trends indicate that the drying of the Upper Profile water by these species was potentially of a great enough magnitude to cause greater upward loss of petrocalcic horizon water under the Shrubs. In contrast, winter annuals were not strongly negatively correlated with Interspace Shallow or Petrocalcic available water contents.

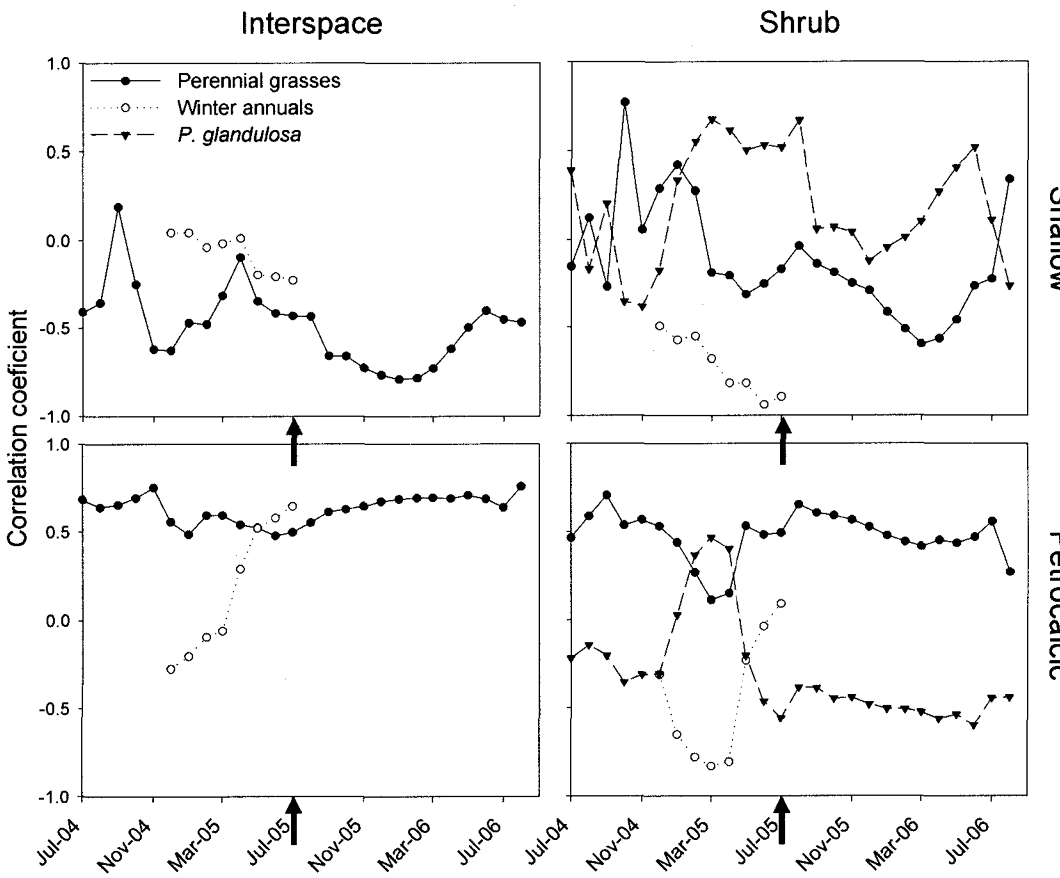

Fig. 3.7. Relationship between relative plant cover and amount of available soil water. Correlation coefficients ($n = 6$) through time of July 2005 vegetation cover (measurement date indicated by arrows) and monthly average available soil water content for two depths (Shallow and Petrocalcic) within each strata. For winter annuals, correlations were only done from estimated establishment through July 2005.

The more rapid Shrub Upper Profile and Petrocalcic wetting and greater water availability during August 2006 is attributed to greater water capture capability of the Shrub during intense summer rains (Abrahams et al., 2003). In contrast to the gentle winter rains, storms during August 2006 had nearly three times the average winter rainy day totals (14.9 mm). During this period, the Shrub Petrocalcic increased by 0.12 m^3 m^{-3} compared to only a 0.04 m^3 m^{-3} increase in the Interspace Petrocalcic

(Fig. 3.6). The wetting of the Shrub Petrocalcic lagged behind Upper Profile wetting by less than 8 h, indicating rapid deep penetration of the summer rains, potentially due to macropores and preferential flow along woody roots (Devitt and Smith, 2002).

Petrocalcic wetting and drying dynamics

The Upper Profile water dynamics and Petrocalcic hydrologic properties contributed to the statistically significant time and strata by time interactions observed in the petrocalcic horizon (Table 3.4). The significant strata by time interaction effect during the initial wetting in December 2005 (period A, Fig. 3.8, Table 3.4) and the tail-end of the spring 2005 drying event (period E) were both to some extent a reflection of Upper Profile water dynamics. The significant Petrocalcic strata by time interaction during period A was probably a result of the drier Shrub Upper Profile in November 2004 delaying penetration of the winter moisture. The significant time effect but lack of interaction in the central periods of maximum soil water contents (periods B, C, and D) indicate that after the initial wetting, petrocalcic horizons in the two strata were wetting and drying in a fairly parallel pattern. Convergence of the Petrocalcic available soil-water contents during period E, causing the significant strata by time interaction, occurred after the Shrub Petrocalcic had partially dried in response to earlier spring Shrub Upper Profile drying. This slowing of Petrocalcic water dynamics at fairly high water contents (~0.18 m^3 m^{-3}) (Fig. 3.5) indicates that the petrocalcic horizon has low unsaturated hydraulic conductivity. The rapid wetting of the petrocalcic horizon, however, during August 2006, a period with

Table 3.4. Petrocalcic horizon repeated measures analysis results for winter 2004-2005 wetting, spring 2005 drying, and summer 2006 wetting events. Period lettering corresponds to Fig. 3.8.

	Period A 26 Nov. 2004 to 6 Jan. 2005				Period B 7 Jan. to 29 Jan. 2005				Period C 30 Jan. to 23 Feb. 2005				Period D 06 Mar. to 25 Mar. 2005				Period E 25 Mar. to 29 April 2005				Period J 8 Aug. to 18 Aug. 2006			
Source of variation	Num df	Den df	F-value	*p*-value	Num df	Den df	F-value	*p*-value	Num df	Den df	F-value	*p*-value	Num df	Den df	F-value	*p*-value	Num df	Den df	F-value	*p*-value	Num df	Den df	F-value	*p*-value
Main effects																								
Strata (S)	1	10.2	0.63	0.445	1	10.0	0.97	0.348	1	10.0	0.65	0.440	1	10.0	1.52	0.246	1	10.1	1.30	0.280	1	12.0	7.73	0.017
Time (T)	41	156.0	3.69	<0.001	22	98.2	10.02	<0.001	24	96.4	8.32	<0.001	19	86.3	6.92	<0.001	34	153.0	11.74	<0.001	13	55.4	5.78	<0.001
Interaction effects																								
S x T	41	156.0	1.81	0.005	22	98.2	1.41	0.129	24	96.4	0.85	0.671	19	86.3	1.20	0.277	34	153.0	2.02	0.002	13	55.4	2.18	0.023

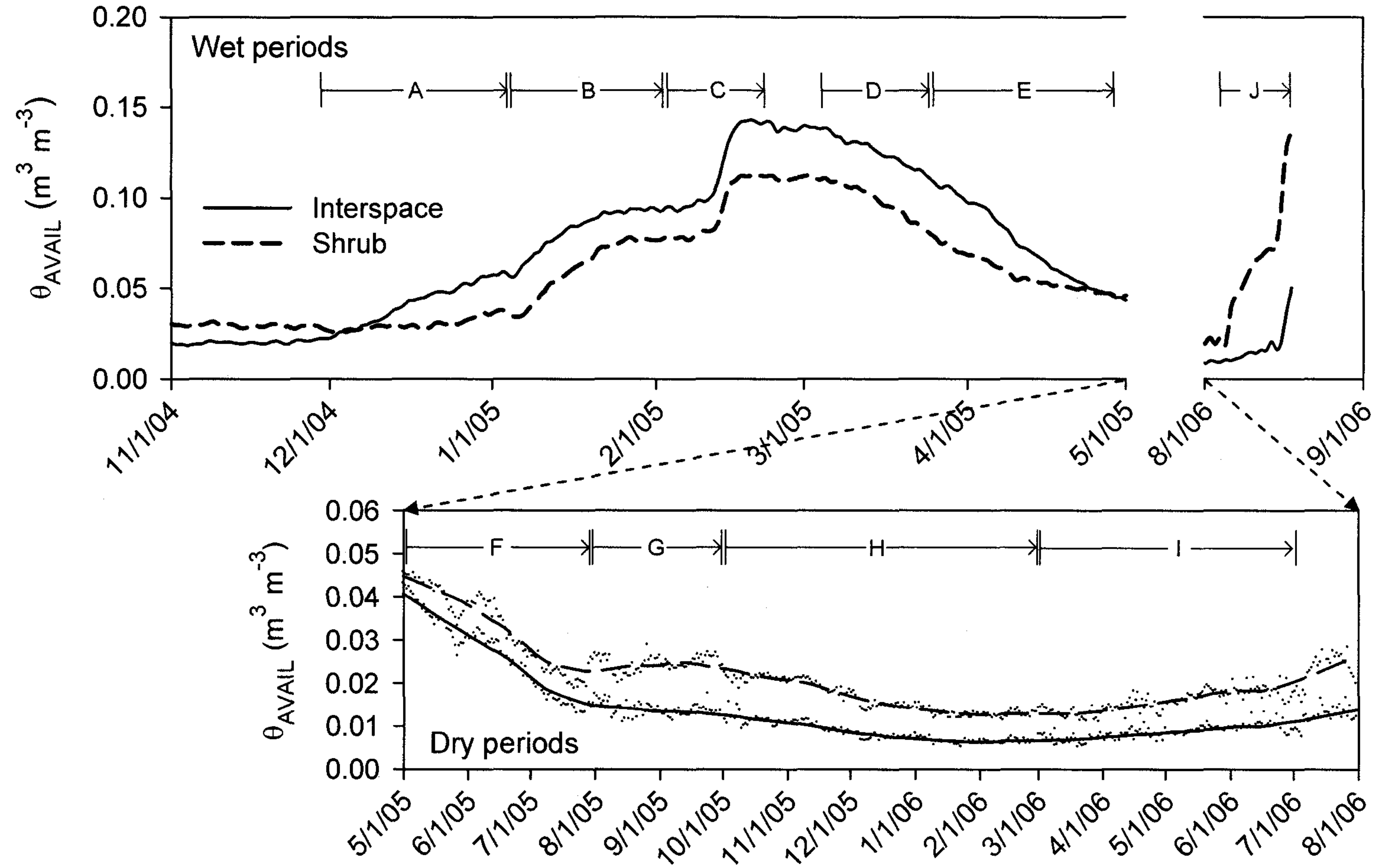

Fig. 3.8. Time intervals where petrocalcic horizon available soil water content was analyzed with repeated measures. Periods analyzed noted by letters. Data were smoothed for plotting lines in dry period (lower panel), small dots are observed data.

Table 3.5. Petrocalcic repeated measures linear modeling of dry periods. Period lettering corresponds with those on Fig. 3.8.

	Rate of change in available soil water content			
	Period F	Period G	Period H	Period I
	1 May to	1 Aug. to	1 Oct. 2005 to	1 Mar. to
Strata	1 Aug. 2005	1 Oct. 2005	1 Mar. 2006	1 July 06
	---------------------------$m^3\ m^{-3}\ d^{-1}$ x 10^{-3}†	---------------------		
Interspace	-0.250****a*‡	0.023*a*	-0.130****a*	0.023*a*
Shrub	-0.190****a*	0.045*a*	-0.190****b*	0.032*a*

*** Rate of change significantly different than zero at the 0.001 probability level.

† Reported values are the actual values multiplied by 1000.

‡ Values within columns with the same letter do not differ as determined by the time x strata interaction test ($p > 0.05$).

significant time by strata interaction effects (period J, Table 3.4, Fig. 3.8), indicates that petrocalcic horizons can have relatively high hydraulic conductivity when nearly saturated.

Significant decreasing trends in available soil-water content during periods with minimal precipitation input indicate the Petrocalcic was slowly releasing stored water, potentially in response to vegetation demands (periods F and H, Table 3.5). Furthermore, during the long dry period from October 2005 through March 2006 (period H, Fig. 3.5), there was a significant strata by time interaction effect indicating the higher Shrub drying rate was significant. There was no detectable drying, however, of either strata Petrocalcic during the summer of 2005 (period G) even though seasonal precipitation was less than half of long term average (Fig. 3.5). The slight increase evident in period I (Fig. 3.7) was not statistically significant (Table 3.5). TDR sensors used in medium to coarse textured soils have been shown to be very insensitive to temperature effects, even in high carbonate soils (Evett et al., 2005), indicating that the gradual drying observed was not an equipment effect. These very slow dynamics provide further evidence of the very slow unsaturated petrocalcic hydraulic conductivity. Furthermore, *B. eriopoda* and *P. glandulosa* have been shown to be photosynthetically active at xylem and leaf potentials well below -1.5 MPa (Senock et al., 1994; Pockman and Sperry, 2000). The lack of drying of either strata petrocalcic horizon below G_{pwp} (-1-5 MPa) during the very dry late spring, early summer 2006 growing season (period I) indicates these plants are not fully exploiting soil water stored in the petrocalcic horizon.

CONCLUSIONS

Shrub and Interspace soil water dynamics differed both in the upper soil profile and petrocalcic horizons. Dynamics were affected by vegetation-soil-water feedbacks including perennial and annual transpirational demands. These confounding factors likely caused the strata with greater plant-available water during wet periods to change with the season of precipitation. Significantly different available water contents were observed, however, during only four of the more than 24 months monitored, highlighting the importance of continuous soil water monitoring even at these deeper depths.

Retention of winter moisture by the Petrocalcic and apparent slow release of the stored soil-water within the rooting zone of grasses and forbs indicate that *P. glandulosa* rooted in soils shallow to a petrocalcic horizon do not benefit from winter rains more than shallow rooted species. Drying dynamics and consistently high water contents, however, do not provide evidence for substantial petrocalcic horizon water extraction by plants during dry periods. Furthermore, evaporation and under-shrub winter annuals appear to have removed much of the winter precipitation prior to spring shrub bud break. Improved water capture capabilities under the *P. glandulosa* canopy were important for intense summer rains, but the longer term impacts of the summer recharge are still to be determined. Moreover, the near surface storage of winter rains by shallow petrocalcics might be beneficial to establishment and persistence *B. eriopoda.* Further work is needed to quantify the importance of petrocalcic horizons for resistance of grasslands to woody-shrub invasions on the landscape scale.

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