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The High Water-Holding Capacity of Petrocalcic Horizons

Michael C. Duniway*
Jeffrey E. Herrick
USDA-ARS
Jornada Experimental Range
Las Cruces, NM 88003-8003

H. Curtis Monger
Dep. of Plant and Environmental Sciences
New Mexico State Univ.
Las Cruces, NM 88003-8003

Petrocalcic soil horizons occur in most arid and semiarid ecosystems around the world, often within the plant rooting zone. Little is known, however, about the water-holding characteristic of soils indurated with $CaCO_3$. 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 zones 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 less than < -10 MPa) were measured using a chilled mirror water activity meter. Measured SWRC data were fitted to the van Genuchten equation. The SWRC methods used were found to be both reliable and repeatable. Plant-available water-holding capacity (AWHC) for desert species (with wilting point set at -4.0 MPa) ranged from 0.26 m^3 m^{-3} in plugged zones to 0.06 m^3 m^{-3} in some laminar zones in contrast to about 0.07 m^3 m^{-3} in the loamy sand parent material. Correlation analyses across morphologies of AWHC and soil properties resulted in significant statistical relationships only with bulk density and porosity. The AWHC and $CaCO_3$ content, however, were significantly negatively correlated within the laminar and positively correlated within the plugged petrocalcic horizon morphologies. Cementation by $CaCO_3$ dramatically alters the water-holding characteristics of soils and understanding these horizons is crucial to understand patterns of soil water in desert systems throughout the world.

Abbreviations: AWHC, available water-holding capacity; FC, field capacity; SWRC, soil-water release curve; WP, wilting point.

Petrocalcic horizons occur extensively in arid and semiarid ecosystems of the 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. The soil volume occupied by petrocalcic material, however, is almost always excluded when quantifying available water and water-holding capacity in the profile (Soil Survey Staff, 1996).

Calcic horizons are formed through accumulation of $CaCO_3$ (Soil Survey Staff, 1999). Although many carbonate minerals occur, calcite ($CaCO_3$) 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 ($\sim$2–10 μm) initially precipitate along roots, fungal hyphae, and 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). The formation of a laminar cap 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 (1.6–2.3 Mg m^{-3}) and carbonate contents (30–95%) (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 may absorb soil water and are potential water sources for plants. Field experiments by Hennessy et al. (1983) indicated that 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) indicated 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; Rodriguez-Marin, 2001). Most shrubs and perennial forbs excavated by Gibbens and Lenz (2001) had roots that penetrated calcic or petrocalcic horizons. Mesquite (*Prosopis glandulosa* Torr.) 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).

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*Corresponding author (mduniway@nmsu.edu).

Xylem and leaf water potentials of less than −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 soil water-holding characteristics in desert soils across a wide range of water potentials and at multiple depths, including petrocalcic horizons.

The SWRCs previously measured for a nonindurated, high-carbonate calcic horizon resembled those of soils with higher clay contents than the noncarbonate 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; Bornyasz 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 and −1.5 MPa for four size classes of petrocalcic rubble. Morphology of these horizons, however, is extremely diverse. Morphology of the "caliche rock" samples studied was not described but was probably laminar material. The SWRCs measured were highly variable among samples and the SWRC functions used fit the data poorly. Thus, the SWRC of different morphologies of petrocalcic horizons needs to be evaluated.

The main objective of this study was to evaluate the water-holding capacity of two morphologies of petrocalcic horizon material at potentials relevant to arid ecosystems and explore soil properties potentially related to petrocalcic horizon water retention. To address these objectives, existing SWRC methods were modified. Therefore, an additional objective was to develop a reliable and repeatable method to determine the SWRC of petrocalcic materials.

MATERIALS AND METHODS

Study Locations and Profile Characteristics

Soil samples were obtained from two locations (~35 km apart) in the Chihuahuan Desert near Las Cruces, NM (Fig. 1). Both sites have sandy and pebbly sandy parent material that was deposited by the ancestral Rio Grande. Sediments at Site 1 (Lat. 32°17′36″, Long. 106°54′41″, elevation 1358 m) are part of the upper La Mesa formation and estimated to be 1.5 million yr old; sediments at Site 2 (Lat. 32°36′02″, Long. 106°49′49″, elevation 1323 m) are part of the Jornada La Mesa formation and estimated to be 1.6 million yr old (Gile et al., 1981; Mack et al., 1996). Depth to the petrocalcic horizon varied between sites, with the petrocalcic horizon at Site 1 slightly shallower (48 cm) than at Site 2 (89 cm), 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. 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, 2003; Gile, 2002). Additionally, based on previous sampling (Gile et al., 1981, 2003), both the laminar and plugged zones of the petrocalcic horizon at Site 2 contain more $CaCO_3$ by mass than their equivalents at Site 1. Together, the four zones sampled represent much of the range of variability found in petrocalcic horizons formed in sandy parent material in arid ecosystems.

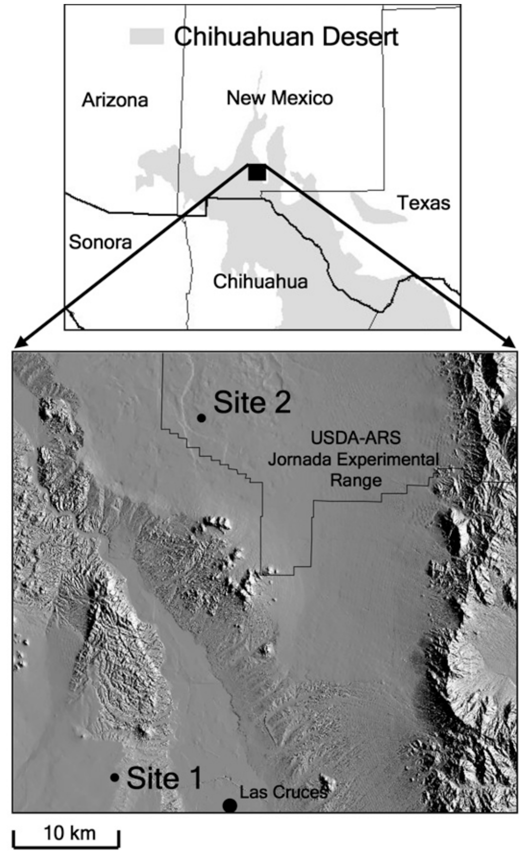

Fig. 1. Samples were collected from two locations in the Chihuahuan Desert (Schmidt, 1979) near Las Cruces, NM.

Sampling

Multiple soil samples were collected from an ~5-m horizontal section of the petrocalcic horizon at each site via preexisting soil trenches (Gile et al., 1981, 2003). We excavated back ~20 cm from the pit face before obtaining each of 12 soil samples from the plugged and laminar zones at each site (n = 48) (Fig. 2). From these larger samples, subsamples were obtained and prepared for analysis. Samples were broken and gently filed to fit into sample cups (39 mm in diam., 11 mm deep) such that each cup contained three to eight pieces of petrocalcic material that covered the sample cup bottom.

Sample Characterization

Sample porosity was measured by weighing saturated samples (saturated under vacuum, overnight, in deaired and deionized water) before measuring sample volume using Archimedes' Principle (Flint and Flint,

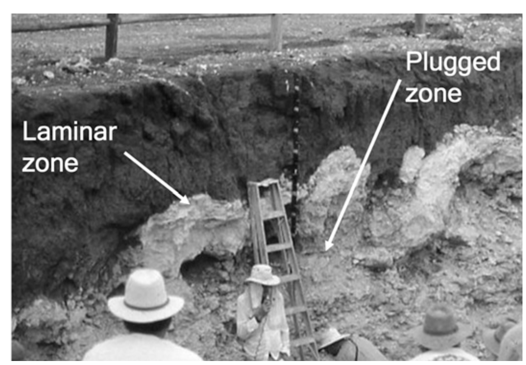

Fig. 2. Site 2 sampling trench showing laminar and plugged zones.

2002). Sample oven-dry weights were divided by sample volumes to obtain bulk densities. Calcium carbonate percentage was determined by dissolution of the each entire sample with 1 *M* HCl and back titration with 0.5 *M* NaOH (U.S. Salinity Laboratory Staff, 1954; Soil Survey Staff, 1996). The noncarbonate soil was saved, the titrated solution decanted, and the soil rinsed twice with 800 mL of deionized water. Each sample was then oven dried, weighed, and dispersed by soaking in approximately 200 mL of a 12.5 g L^{-1} 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 noncarbonate mass was very small (most <2 g), traditional particle size analysis methods were not appropriate. Therefore, estimates of sample clay vs. silt were obtained using a modified version of the methods described by Kettler et al. (2001) that allows direct measurement of an entire sample particle size class. Sample passing through a 53-μm sieve was saved in large mason jars. Deionized water was added to the jars so that all had volumes of ~800 mL. Each jar was then closed and shaken vigorously for 1 min. 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 and −0.10 MPa using pressure plate techniques (Dane and Hopmans, 2002; Soilmoisture Equipment Co., Santa Barbara, CA) and from −0.10 to less than −10 MPa using a dewpoint potentiameter (Scanlon et al., 2002; WP4 Dewpoint Potentiameter, Decagon Devices, Pullman, WA). Samples were initially saturated individually in deaired, deionized water for 24 h under vacuum. A 0.1-MPa pressure plate was premoistened and ~0.5 cm of fine sandy loam soil was placed within a containment ring on the pressure plate and wetted to saturation. Each saturated subsample 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 (~5 d 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 the porous pressure plate, samples were resaturated and plates prepared as described above and soil-water release under 0.10 MPa of pressure was measured (~14 d to equilibrate). It was necessary to obtain within SWRC oven-dry weights for use in calculating the water retained under 0.03 MPa pressure before resaturation 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 less than −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 min. The process of measurements, drying, and equilibration was repeated for all samples until the desired range of soil water potentials was 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. The 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 fitted for each sample separately (*n* = 48 samples, 10–20 points for each sample) using nonlinear regression techniques (PROC NLIN, SAS Institute, 2001) to the van Genuchten (1980) equation:

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

where θ is the observed volumetric water content, θ_r is the residual volumetric water content, θ_s is the volumetric water content at saturation, *a* is a scaling parameter, *n* and *m* are shape parameters with $m = 1 - 1/n$, and ψ is the measured soil-water potential. Fitting was performed with θ_s as a fitted parameter ($\theta_s \le$ porosity) and with θ_r fitted ($\theta_r \ge 0$) and assumed to be zero. The AWHC was calculated as water retained at field capacity (θ_{FC}) minus water retained at the wilting point (θ_{WP}). 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_{WP} was determined both for water retained at the traditional WP of −1.5 MPa (Romano and Santini, 2002) and at a WP 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 (α = 0.05) in average horizon sample properties, estimated SWRC parameters, θ_{FC}, θ_{WP}, and AWHC (PROC GLM, SAS Institute, 2001). Pearson's correlation coefficients were calculated between soil properties (bulk density, porosity, and $CaCO_3$, sand, silt, and clay percentages) and θ_{FC}, θ_{WP}, and AWHC (PROC CORR, SAS Institute, 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 Repeatability 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 four subsamples, SWRCs obtained from −0.10 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 subsamples and evaluating for significant differences in the fitted van Genuchten (1980) parameters (α = 0.5, *n* = 20 points for pre-oven-dry and *n* = 15 points for post-oven-dry).

RESULTS AND DISCUSSION

Sample Characterization

Petrocalcic 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 morphologies (Table 1). Laminar zones had significantly higher average bulk densities and thus lower porosities than plugged zones. Significant differences in bulk densities and porosities, however, were detected between the two laminar zones studied, with the Site 1 laminar zone being the most dense. Average sample $CaCO_3$ content was significantly different for zones within each site. The zone with the higher carbonate content, however, was reversed at the two sites. Additionally, the standard deviation of sample carbonate content was an order of magnitude larger for the two zones with lower carbonate content. The trend in noncarbonate sand content was opposite of

Table 1. Average petrocalcic horizon properties. Texture reported on a noncarbonate basis.

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

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

that measured in sample carbonate content, with the highest sand contents occurring in the two lower carbonate zones. 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 pressure dissolution of the parent material grains by the expansion of carbonate crystals during precipitation (Maliva and Siever, 1988; Reheis, 1988; Monger et al., 1991a). Additionally, relatively high clay contents in the Site 1 laminar zone could be attributed to the shallow petrocalcic 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 with each other and there was no effect of oven drying. Comparison of curves obtained before and after oven drying indicated no significant changes in either curve shape or scale (Fig. 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. 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, however, the few wet measurement points carried large leverage on the curve fit. Additionally, the stated accuracy of the potentiameter is ±0.1 MPa, which can generate relatively large errors for readings greater than −0.5 MPa. Therefore, in final analysis, the potentiameter readings greater than −0.5 MPa were not used if they appeared to 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 with 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_{WP}, thereby meeting the goals of this study.

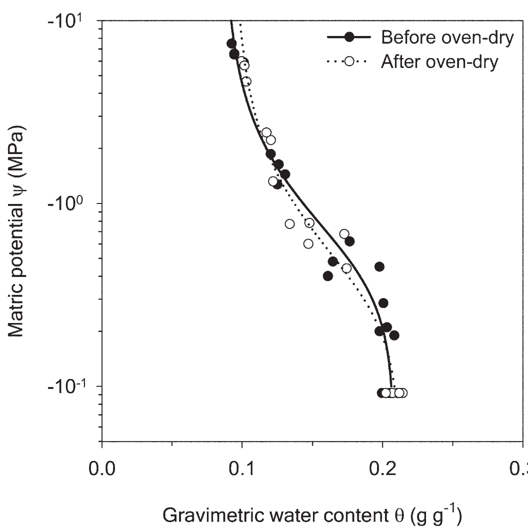

Fig. 3. Measured points and fitted van Genuchten (1980) equation lines of soil-water potential as a function of gravimetric water content in testing soil-water release curve method repeatability before oven drying (closed circles, solid line) and after oven drying (open circles, dotted line).

Soil Water Release Curves

Fitting of the measured SWRC points to the van Genuchten (1980) equation was successful for all samples, with average RMSE from each zone <0.015 $m^3\ m^{-3}$ (Table 2, Fig. 4). Average RMSE values, however, were higher in both plugged zones than the laminar zones, indicating either lower precision in SWRC measurements, or the model or model assumptions used were less appropriate for the plugged zone 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 compared favorably at drier water contents (less than −0.8 MPa) to the calcic horizon curve from Baumhardt and Lascano (1993) (Fig. 5). The curves diverge at wetter water contents, however, probably due to the 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. 5). The petrocalcic horizon material curve estimated from Hennessy et al. (1983)

Table 2. Average horizon van Genuchten (1980) equation parameters of saturated volumetric water content θ_s, scaling parameter *a*, and shape parameter *n* (residual volumetric water content θ_r set to zero) and curve-fitting root mean square error (RMSE) from each site.

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

† Parameter log-transformed for analysis.

‡ Averaged across equations for all samples from each zone at each site.

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

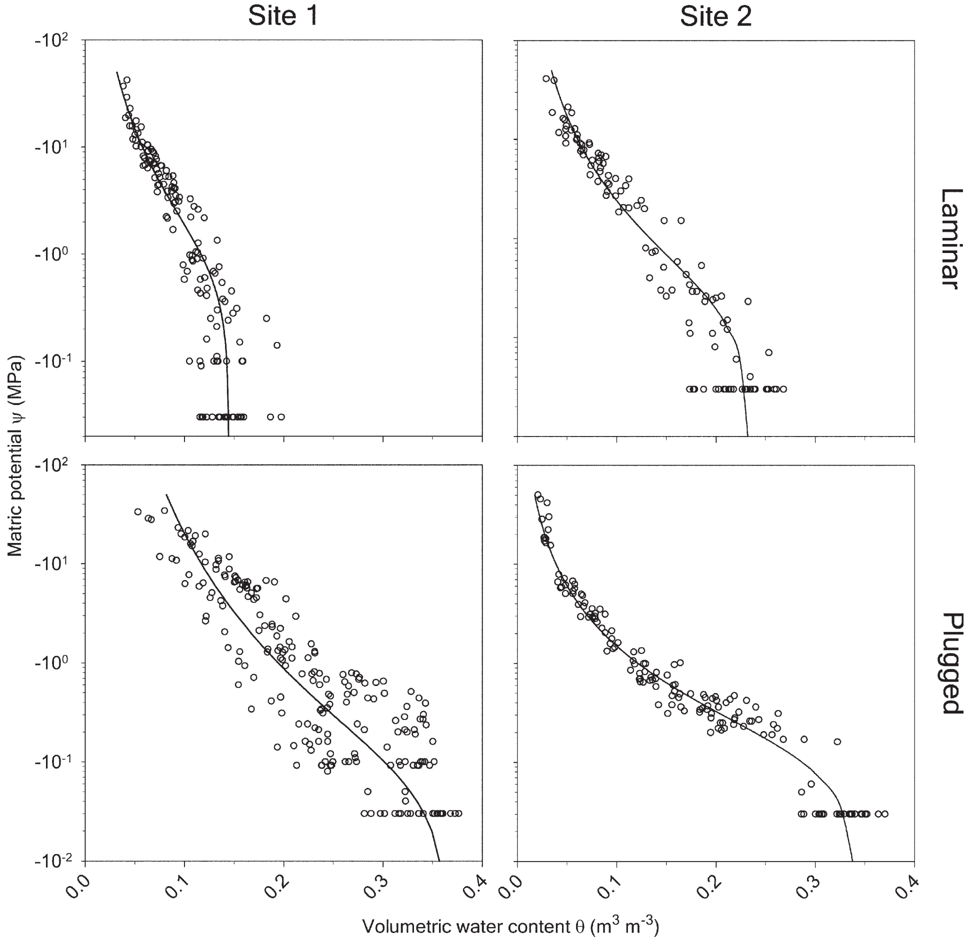

Fig. 4. Measured and average fitted values of all samples for Sites 1 (left) and 2 (right) and laminar (top) and plugged (bottom) zones.

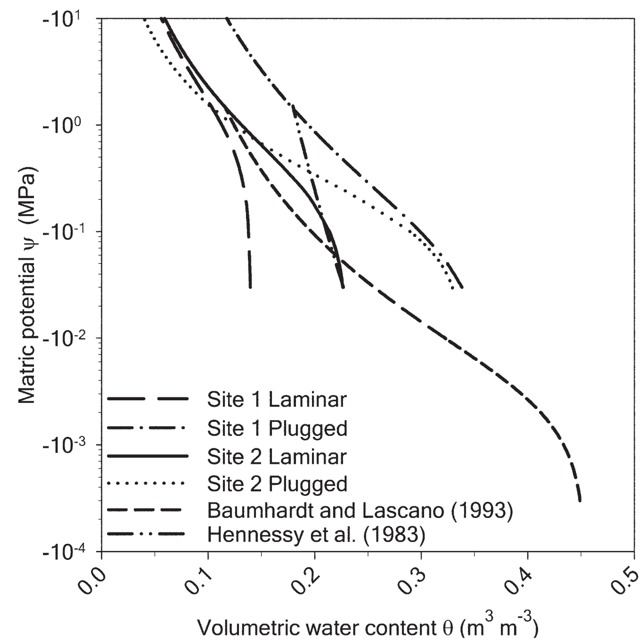

Fig. 5. Average fitted curves from Sites 1 and 2, laminar and plugged zones plotted against a calcic horizon curve (Baumhardt and Lascano, 1993) and pectrocalcic material curve (Hennessy et al. (1983). Ranges plotted represent the range of soil water potential measured in each study.

is similar at higher water contents (greater than −0.10 MPa) to the average Site 2 laminar zone curve but quickly diverge at drier soil water potentials (Fig. 5). This is probably due to a poor fit and few measurement points by Hennessy et al. (1983). The laminar zone SWRCs generated, however, 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. 4) and the fitted van Genuchten (1980) equation parameters (Table 2). The two plugged zone average curves were similar but both quite different from those of the laminar zones, as indicated by significant differences in fitted parameters. The log-transformed scaling parameter *a* was shown to be significantly higher for the plugged zones than the laminar zones ($P < 0.001$). No difference was detected, however, 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 zones 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 zone (Fig. 4) is reflected in the high variability in the *a* parameter (Table 2). Average values for the shape parameter *n* were very similar for both laminar zones but significantly different from either plugged zone. Plugged zone shape parameter estimates were both significantly smaller and larger than those of the laminar zones at Sites 1 and 2, respectively. The average value ($n = 1.22$) for the Site 1 plugged zone (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 AWHCs were higher than the 0.06 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 WP from −1.5 to −4.0 MPa ranged from 0.025 to 0.039 m^3 m^{-3}. This change is a substantial increase in estimated AWHC, especially for the lower porosity laminar zones.

Sample morphology and site effects were also reflected in θ_{FC} and θ_{WP} (Fig. 6a). Much of the sample pore space remained filled with water at –0.03 MPa (Table 1, Fig. 6a). Field capacities were, on average, 85% of measured porosities and 96% of estimated θ_s. The plugged zones had significantly larger average field capacities than either of the laminar zones, with the laminar zone

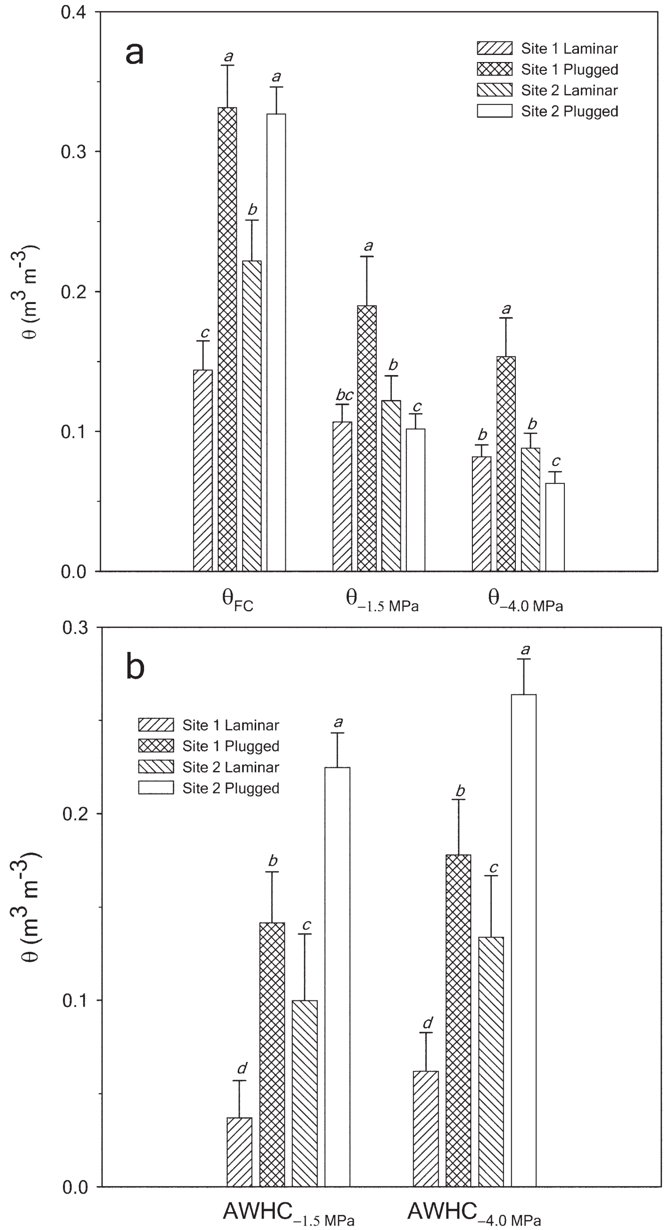

Fig. 6. (a) Volumetric water retained by two morphologies of petrocalcic horizon at field capacity (θ_{FC}) and two wilting points ($\theta_{-1.5\ MPa}$ and $\theta_{-4.0\ MPa}$) and (b) available water holding capacity (AWHC) based on $\theta_{-1.5\ MPa}$ and $\theta_{-4.0\ MPa}$. Fisher's protected LSD (α = 0.05) within measurement by letters, error bars represent sample standard deviations.

from Site 1 retaining the least amount of water. The average Site 2 laminar zone 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. 5). The average field capacities of the plugged zones (both were 0.33 $m^3\ m^{-3}$) were slightly less than the field capacity estimated by Hennessy et al. (1983) in a field study of water retention by a petrocalcic horizon (0.36 $m^3\ m^{-3}$). The Site 1 plugged zone retained significantly more water on average at both −1.5 and –4.0 MPa than any other horizon. Water release was similar in the laminar zones, with both retaining significantly more water at –4.0 MPa than the Site 2 plugged zone.

Table 3. Correlations of sample properties and volumetric water content at field capacity (θ_{FC}) and wilting point (θ_{WP}, based on −4.0 MPa) and available water-holding capacity (AWHC).

Property	Zone	Correlation	θ_{FC}	θ_{WP}	AWHC
Bulk density	all	Pearson's *r*	−0.979	−0.312	−0.884
		P (*n* = 48)	<0.001*	0.031*	<0.001*
	laminar	Pearson's *r*	−0.960	−0.151	−0.957
		P (*n* = 24)	<0.001*	0.482	<0.001*
	plugged	Pearson's *r*	−0.759	−0.302	−0.074
		P (*n* = 24)	<0.001*	0.152	0.731
Porosity	all	Pearson's *r*	0.978	0.275	0.902
		P (*n* = 48)	<0.001*	0.058	<0.001*
	laminar	Pearson's *r*	0.957	0.147	0.955
		P (*n* = 24)	<0.001*	0.494	<0.001*
	plugged	Pearson's *r*	0.684	−0.110	0.450
		P (*n* = 24)	<0.001*	0.608	0.028*
$CaCO_3$	all	Pearson's *r*	−0.339	−0.777	0.017
		P (*n* = 48)	0.019*	<0.001*	0.907
	laminar	Pearson's *r*	−0.732	−0.014	−0.752
		P (*n* = 24)	<0.001*	0.948	<0.001*
	plugged	Pearson's *r*	−0.127	−0.885	0.823
		P (*n* = 24)	0.554	<0.001*	<0.001*
Sand	all	Pearson's *r*	0.354	0.712	0.031
		P (*n* = 48)	0.014*	<0.001*	0.834
	laminar	Pearson's *r*	0.776	−0.015	0.803
		P (*n* = 24)	<0.001*	0.943	<0.001*
	plugged	Pearson's *r*	0.096	0.883	−0.837
		P (*n* = 24)	0.655	<0.001*	<0.001*
Silt	all	Pearson's *r*	0.261	0.852	−0.135
		P (*n* = 48)	0.073	<0.001*	0.360
	laminar	Pearson's *r*	−0.649	0.129	−0.697
		P (*n* = 24)	<0.001*	0.547	<0.001*
	plugged	Pearson's *r*	0.227	0.904	−0.793
		P (*n* = 24)	0.286	<0.001*	<0.001*
Clay	all	Pearson's *r*	−0.244	0.019	−0.267
		P (*n* = 48)	0.095	0.897	0.066
	laminar	Pearson's *r*	0.019	0.122	−0.007
		P (*n* = 24)	0.931	0.570	0.973
	plugged	Pearson's *r*	0.119	0.153	−0.094
		P (*n* = 24)	0.579	0.476	0.662

* Significant at α = 0.05.

Calculated AWHCs were highly variable both within and between sites (Fig. 6b). The AWHC based on a WP of −1.5 MPa ranged from 0.04 to 0.22 $m^3\ m^{-3}$ and was similar to the range reported for calcareous rock fragments (0.025–0.14 $m^3\ m^{-3}$; Cousin et al., 2003). The AWHC based on a WP of –4.0 MPa ranged from 0.06 to 0.26 $m^3\ m^{-3}$. Plugged zone AWHCs (based on both −1.5 and –4.0 MPa) were significantly higher than those of the laminar zones. 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_{WP}, with many significant correlations detected. The strength and significance of the correlations with soil properties changed, however, when samples were grouped by petrocalcic morphology (Table 3). Bulk density and porosity were strongly and significantly correlated with θ_{FC} compared both across all samples and within morphologies. Sample $CaCO_3$, sand, and silt content, however, were significantly correlated with field capacity within the laminar but not the plugged zone. Morphological differences in water retention–soil property correlations are partially explained by the low or high variability of some of the water retention measurements and soil properties, but are also probably a reflection of differences in horizon genesis. For example, the standard deviations of $CaCO_3$ percentage are fairly similar if pooled by morphology (SD = 13.46 in the laminar and 25.18 in the plugged). Because the matrix of laminar material is formed by the accumulation of precipitated $CaCO_3$ (Gile et al., 1966) and the grains of noncarbonate parent material are unevenly distributed (Monger et al., 1991a), it would be expected that the amount of $CaCO_3$ is important for the laminar zone θ_{FC}. Plugged morphologies are formed by the precipitation of $CaCO_3$ within the pore space of an existing soil matrix (Gile et al., 1966; Monger et al., 1991a), implying that the $CaCO_3$ content might be less important for θ_{FC} than in the laminar.

Sample $\theta_{-4.0\ MPa}$ was significantly correlated with sample bulk density, $CaCO_3$ content, and texture when comparisons were done across all samples. Because there is little variability in water release at the dry end in the laminar zone, however, no significant correlations between $\theta_{-4.0\ MPa}$ and the soil properties were detected within the laminar zones. Within the plugged zones, sample $CaCO_3$, sand, and silt contents were all significantly correlated with $\theta_{-4.0\ MPa}$. Sand and silt contents were positively correlated with $\theta_{-4.0\ MPa}$, indicating that samples with more sand and silt on a whole-soil-weight basis retained more water that was unavailable to plants. In contrast, sample $CaCO_3$ content 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 $CaCO_3$ 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 $\theta_{-4.0\ MPa}$ values 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 zones, all soil properties except clay content were significantly correlated. Similarly, all properties except sample bulk density and clay content were significantly correlated in the plugged zones. 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, $CaCO_3$ percentage is strongly negatively correlated with $AWHC_{-4.0\ MPa}$ in laminar zones but strongly positively correlated in the plugged zone. Again, differences in the hydrologic function of differing morphologies are probably due to horizon genesis. Larger carbonate percentage by mass in the laminar zone appears to result in a much lower field capacity and thereby reduced AWHC. In plugged zones, the filling of the soil pores by $CaCO_3$ appears to actually reduce the amount of water retained at WP and thereby increasing the AWHC.

CONCLUSIONS

Petrocalcic horizons are common in arid and semiarid 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 that 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 zones were up to four times that of the coarse-textured parent material. Laminar zone AWHC was one-half to one-third that of the plugged zone. The wide range of AWHCs observed indicates that petrocalcic horizons can behave like both calcareous soils (Baumhardt and Lascano, 1993) and calcareous rock fragments (Cousin et al., 2003). Reducing the WP used in calculating AWHC from −1.5 to −4.0 MPa increased the estimated AWHC by 20 to 50%.

The significance and strength of statistical correlations between sample characteristics and θ_{FC} and θ_{WP} changed when samples were separated by petrocalcic morphology. These differences resulted in few significant correlations of soil properties and AWHC when done across morphologies but many when done within morphologies. 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 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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