Structure and Function of Chihuahuan Desert Ecosystem
The Jornada Basin Long-Term Ecological Research Site
Edited by: Kris Havstad, Laura F. Huenneke, William H. Schlesinger
2006

Submitted to Oxford University Press for publication
ISBN 13 978-0-19-511776-9

5

Patterns and Controls of Soil Water in the Jornada Basin

Keirith A. Snyder, Katherine A. Mitchell, and Jeffrey E. Herrick

This chapter focuses on controls and patterns of soil moisture in the Jornada Basin. First we describe general properties that commonly contribute to soil water heterogeneity; second, we offer a brief overview of soil water research in the Jornada Basin; and last, we describe specific patterns of soil water content and availability observed in the Jornada Basin. Our goal is to describe general patterns of soil water that are likely to occur across the Chihuahuan Desert region.

In arid and semiarid regions, water is typically thought to be the most limiting resource to biological activity (Noy-Meir 1973), though colimitation by water and nitrogen may be a more general rule (Hooper and Johnson 1999; see also chapter 6). The availability of water affects plant productivity, microbial activity, activity of biological soil crusts, nutrient cycling, and organic matter decomposition. It also directly and indirectly affects soil erosion, chemical weathering, and carbonate formation. There are several hypotheses addressing how water availability affects plant productivity in desert environments. Beatley (1974) proposed that various functional types (shrub, perennial, annual) have different seasonal rainfall thresholds to trigger phenological responses. The annual productivity of functional types is therefore determined by the timing and amount of rainfall. Westoby (Noy-Meir 1973) proposed the pulse-reserve paradigm to explain population dynamics of desert plants. In this view, a rain event triggers a pulse of production. Some of that production is used to generate new tissue, but part of the production is diverted into reserves. The amount of reserves in part determines the next production pulse, as well as the minimum size of the next trigger event. Rainfall is highly variable both spatially and temporally in arid regions; therefore, understanding patterns of rainfall and interactions between rainfall patterns, soil characteristics, temperature, and topography are critical to predicting ecosystem responses.

The relationship between average annual precipitation and plant productivity across arid regions has substantial predictive ability (Le Houérou 1984). However, for a given site, the relationship between annual precipitation and yearly plant productivity has limited explanatory power (Lauenroth and Sala 1992). At local scales when time is substituted for space, precipitation appears to be a poor measure of water availability and productivity because of the complex effects of differences in rainfall frequency, timing and magnitude, landscape position, soil texture, soil structure, macropores, microrelief, and feedbacks between the vegetation and hydrologic processes such as stem flow, infiltration, percolation, and runoff. Soil moisture is a more direct indicator of available water for biological activity, but accurate data are rarely available at relevant spatial scales due to measurement and scaling limitations (Williams and Bonnell 1988). Recent studies on soil water availability and plant water use have emphasized that the relative availability of different sources of water (i.e., shallow soil water, deep soil water, groundwater) may play an important role in structuring communities and seasonal productivity (Ehleringer and Dawson 1992; Snyder and Williams 2000; Schwinning and Ehleringer 2001). There is also increased recognition that frequency and magnitude of dry periods (interpulse periods) relative to the frequency and magnitude of rainfall pulses affects plant and ecosystem responses in arid systems (Huxman et al. 2004; Loik et al.

2004; Reynolds et al. 2004). Soil is the regulator and interface between plants and precipitation. Therefore, understanding patterns of soil moisture is critical in establishing predictive models of ecosystem function.

The Southwestern desert regions of North America are characterized by a bimodal pattern of rainfall where precipitation is received in both the winter months and during the summer growing season. The ratio of summer to winter rainfall varies across the desert regions. Precipitation in these arid and semiarid regions is highly unpredictable, especially during the summer growing season (chapter 3). Consequently, precipitation and resultant pulses of soil moisture are very heterogeneously distributed in time and space.

As detailed in chapter 10, the Jornada Basin is an area where shrubs have invaded and dramatically changed the landscape and ecosystem processes of areas formerly dominated by grasslands. Walter (1979) proposed the two-layer model to explain the stable coexistence of woody plants and grasses in water-limited environments. According to this model, deep, rooted woody plants access water from deep in the soil profile, whereas shallow-rooted grasses rely on water in shallow soil layers. Reynolds et al. (1999b) found that co-occurring shrub species may partition water temporally with different phenological strategies. These theories highlight the importance of understanding patterns of soil water availability over multiple years, soil types, and landscape positions to explain resultant vegetation patterns.

Causes of Soil Water Heterogeneity

Climate

In the Chihuahuan Desert, region rainfall is bimodal with slightly more than half of the annual rainfall occurring in the three months from July through September and the majority of the rest falling during winter months (especially January and February). Winter precipitation is generally characterized by slow-moving frontal systems. These systems generally produce long-duration and low-intensity rainfall (chapter 3). Winter rainfall often percolates to greater depths because lower rainfall intensities allow more of it to enter the soil and because lower evapotranspirational demands increase the probability that upper soil layers will already be near field capacity when precipitation events begin. Summer rainfall is characterized by localized convective storms, which are generally of short duration and high intensity. These rainfall events generally do not percolate to deep soil layers because of high evaporation and transpiration rates and an increased likelihood of surface runoff. This pattern can sometimes be reversed in the lowest landscape positions, which benefit from run-in during more intense summer storms, generating deep water percolation during the summer months. The seasonal patterns of rainfall create differences in the vertical distribution of soil water, and the stochastic nature of rainfall, particularly during summer months, contributes to the spatial and temporal heterogeneity of soil moisture.

Landscape Position and Soil Properties

Average or seasonal precipitation is a poor predictor of soil moisture in part because the amount of water available for infiltration varies widely as a function of landscape position. Rain gauge records show that rainfall increases with elevation and that there is also a high level of variability at the same elevation in the Jornada Basin (chapter 3). The volume of water available to infiltrate at any particular point on the landscape is further modified by its relative position: lower landscape units generally have a higher probability of receiving run-in, though landscape units at the top of alluvial fans surrounding the basin can benefit from mountain runoff (chapter 7). Runoff is generally higher from steeper slopes.

Landscape position is also a good predictor of soil texture, which affects infiltration capacity, water holding capacity, and bare-soil evaporation rates. In general, infiltration capacity is highest on the sandy basin soils (refer to tables 4-1 and 4-2 figure 4-3, chapter 4), intermediate on the loamy alluvial fans and fan piedmont areas, and lowest on the fine-textured soils of the alluvial flats and lake plains. The low infiltration capacity of the fine-textured soils of the ephemeral playa lakes is balanced by the lack of runoff. Deepwater infiltration into some of these low-lying areas is facilitated by deep cracks that form in soils with 2:1 expanding clays when the soil is dry.

Deep water infiltration also varies as a function of soil profile characteristics. Whereas clay-rich soil horizons are relatively rare on the Jornada, widespread calcic horizons can have a significant effect on deep percolation of water due to their generally low hydraulic conductivity.

Volumetric water content is the proportion of the soil volume that is occupied by water. The maximum volumetric soil water content after gravity drainage is referred to as field capacity. However, water content does not reflect the actual water available to plants because available water is a function of soil water potential. Soil water potential is the summation of soil matric potential, gravitational potential, and osmotic potential, and measures how tightly water is held in the soil (Kramer and Boyer 1995). Soil matric potential is a function of soil texture and structure and reflects how tightly water is bound to adjacent soil particles due to capillary and surface binding properties. Gravitational potential is the force of gravity operating on soil water, whereas osmotic potential is a function of the chemical composition of water and increases with increasing solute concentrations. In nonsaline soils, plant available water is largely determined by soil matric potential and unsaturated soil hydraulic conductivity. Plant available water also varies with plant species characteristics such as root morphology, root length density, and microbial associations.

Plant available water-holding capacity refers to the percentage of the soil volume at soil water potentials less than field capacity that is extractable by plants. Plant available water-holding capacity is generally highest in intermediate-textured soils (loamy) and lowest in sandy soils. It is reduced by the presence of rocks but may actually be increased by the presence of calcium nodules in sandy soils (Hennessy et al. 1983a).

Evaporation rates are affected by landscape position primarily through aspect differences, with higher rates occurring on south-facing slopes. Aspect effects are readily apparent in areas north of the Jornada Basin. Evaporation is generally slower through soils with a coarse-textured surface horizon and those in which the unsaturated hydraulic conductivity is lower for the top few centimeters of soil than for the layers below. This phenomenon may be quite significant in the Jornada Basin, where deposition of eolian sand on top of relatively fine-textured basin soils has created extensive areas of these types of surfaces (chapter 4, tables 4-1 and 4-2 and figure 4-3).

The relationship between soil texture and soil water properties varies with soil structure. Soil structure is formed through modification of the inorganic soil by both abiotic and biotic processes. In arid and semiarid ecosystems, soil surface structure is generated by litter decomposition under plants, microbiotic crusts in plant interspaces, and macroinvertebrates in both plant and interspace microsites (Herrick and Wander 1998). Repeated cycles of wetting and drying help form aggregates, and freeze-thaw cycles can also be important. Macroinvertebrates, especially ants and termites, are extremely important in the Chihuahuan Desert for increasing infiltration through the formation of macropores (Elkins et al. 1986; Herrick 1999). The relationship between microbiotic crusts and soil water is complex and poorly understood (Warren 2001). Development of soil structure below the soil surface is similar to more humid environments, where root decomposition and associated soil biotic activity dominate; however, ants and termites replace earthworms as the dominant macropore-forming organisms in these environments (Herrick 1999). Soil structure-forming processes are self-reinforcing as improved soil structure facilitates greater water infiltration and retention, leading to higher litter production in subsequent years and, therefore, greater substrate availability for soil biological activity. Due to the importance of these plant litter inputs, soil structure tends to be extremely patchy at nearly every spatial scale in the Chihuahuan Desert (Herrick and Whitford 1999).

Vegetation

Vegetation has a number of effects on soil moisture heterogeneity, in addition to modifying soil structure. Increased plant basal cover can increase water percolation depth by slowing runoff, and canopy cover reduces raindrop erosivity and therefore limits soil surface degradation (chapter 7). Shading by plant canopies and increased litter cover below plants reduces soil surface temperatures and resultant evaporation, which in turn can increase soil water under plant canopies relative to interspace areas. There also tends to be a greater occurrence of macropores under plant canopies that can increase infiltration and soil water. However, interception of rainfall by plant canopies and extraction of soil water by plant roots can reduce soil water beneath plant canopies (Breshears et al. 1997, 1998). Shrub canopies and stems tend to channel water to the root crown, where depending on litter cover, soil characteristics, and slope, it will either follow root channels or be an early initiator of surface runoff (Martinez-Mesa and Whitford 1996; see also chapter 7).

Hydraulic redistribution of soil water by plant roots is another important control that plants exert over soil water. The classic example is hydraulic lift, where deeply rooted plants redistribute water from wet, deep soil layers to drier, shallow soil layers (Richards and Caldwell 1987; Caldwell et al. 1998). This is a passive response by plants to changes in soil water potential. It characteristically happens at night when stomata are shut and the gradient between wet and dry soil layers becomes the driving gradient for water movement through the soil-plant-atmosphere continuum. However, the process of hydraulic redistribution may also transfer water downward through the soil in response to differences in soil water potential gradients. Specifically, it has been found that after rainfall events, roots of some species transfer water from wet shallow soil layers to drier deeper soil layers (Burgess et al. 1998, 2000; Schulze 1998; Smith et al. 1999; Ryel et al. 2002). Hydrogen and oxygen stable isotope ratios of plant xylem sap and environmental water samples have been used to determine where in the soil profile plants access water, and studies have shown that not all sources of water are used equally across functional types (Sala et al. 1989; Ehleringer and Dawson 1992; Donovan and Ehleringer 1994; Weltzin and McPherson 1997; Gebauer and Ehleringer 2000; Snyder and Williams

2000). Therefore, shifts in community composition may contribute to variation in soil moisture. These complex factors interact to accentuate the heterogeneity of soil water.

Major Historical and Ongoing Efforts to Measure Soil Water

Beginning in 1957 and continuing to 1976, gypsum blocks were installed to measure soil matric potential (or soil water availability) at 16 sites on the JER (Herbel and Gile 1973; Herbel and Gibbens 1985, 1987, 1989) at depths of 10, 25, 41, 61, 91, and 122 cm (see figure 5-1 for site locations of all studies).

The deepest block was placed at the top of any petrocalcic horizon occurring at a depth of less than 122 cm. An additional set of blocks was installed inside 3-m diameter cylinders at three sites, and two more sets were installed at a fourth site for a total of 21 moisture profiles. Data were collected one to three times during rainy periods when soil matric potential exceeded –1.5 MPa and once a month during drier periods. A threshold value of –1.5 MPa was used because this was historically classified as the permanent wilting point for many herbaceous species (Kramer and Boyer 1995). These data were used to calculate the average number of days over the 19-year period when soil matric potential exceeded –1.5 MPa. Because the data are not continuous, a high degree of interpolation between sampling dates was required. Soil matric potentials below –1.5 MPa were not measured. However, many desert soils have soil matric potentials below –1.5, and most desert species are capable of extracting water far below this theoretical wilting point. This study was the first effort at the JER to quantify spatial and temporal variability in soil moisture, and it does allow for coarse comparisons among sites.

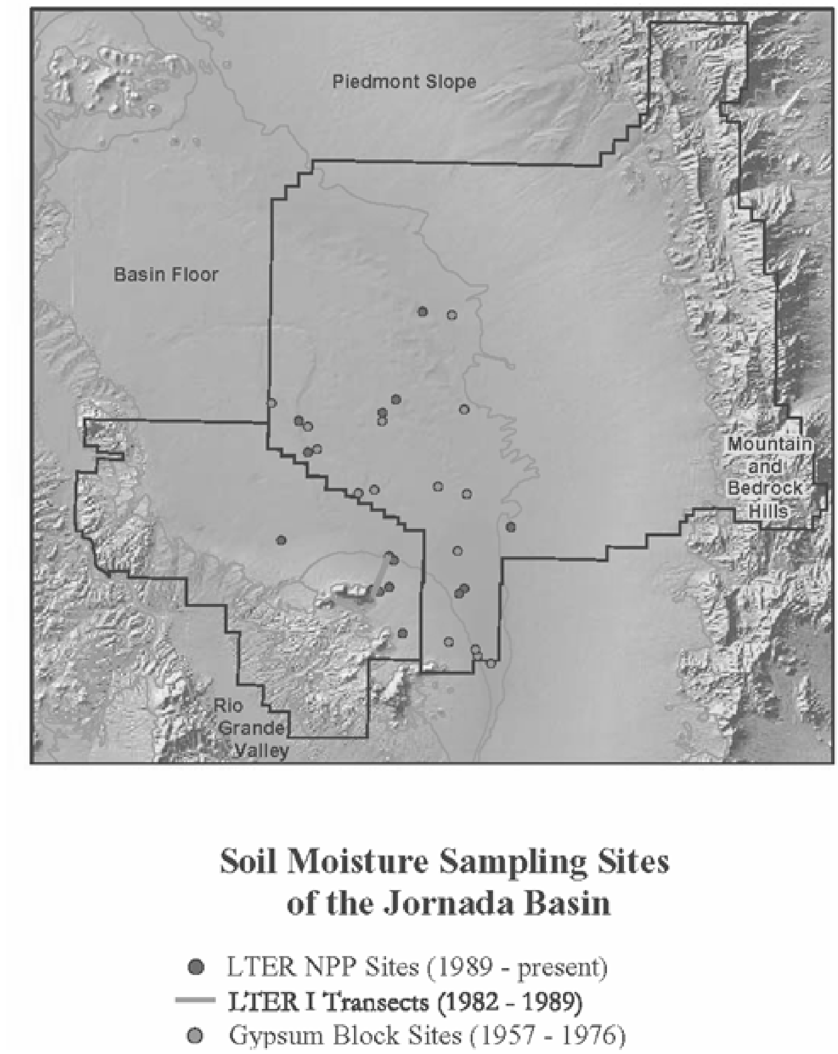


Fig. 5-1. Location map of the Long Term Ecological Research (LTER) II net primary production (NPP) sites, LTER I transect, and gypsum block soil moisture study sites.

The second major effort to measure soil water was part of Jornada Basin LTER I. Soil moisture and rainfall were measured every 30 m along a 2.7-km transect in the Jornada Basin (figure 5-1). The transect extended northeast from the base of Summerford Mountain downslope into an ephemeral playa lake. Soil water content was measured every 2 weeks with a neutron probe at depths of 30, 60, 90, 110, and 130 cm from July 1982 to February 1987 and monthly thereafter (Nash et al. 1991, 1992).

The third comprehensive and ongoing effort to measure soil water was established as part of the Jornada LTER II program (figure 5-1). Since July 1989, soil water content measurements have been made once a month at 10 depths (where possible) at each of 10 access tubes at each of the 15 LTER II NPP (net primary production; chapter 11) sites using a neutron probe (Campbell Model 503DR Hydroprobe). Measurements are made at 30, 60, 90, 120, 150, 180, 210, 240, 270, and 300 cm or to the greatest depth possible to install the access tubing before hitting an impenetrable petrocalcic horizon. The majority of LTER I and LTER II soil water data were collected using the same neutron probe throughout the multiyear period. Another probe was used when the primary probe was being repaired. Both probes were calibrated separately at the same location. A single calibration curve for each probe was used to convert neutron probe counts to volumetric moisture content (cm^3 water/cm^3 soil) for all LTER I transect points and LTER II NPP locations and depths (Nash et al. 1992). The use of a single calibration curve is appropriate for within-soil comparisons and for comparing temporal patterns of soil moisture variability. Future analysis will incorporate soil-specific calibrations that take into account texture and coarse fragment content. Additional analyses will also take into account soil- and soil horizon–specific differences in the relationship between volumetric soil moisture content and soil matric potential, which ultimately determines how much of the water is available to plants. Preliminary analyses of the LTER I transect data were reported in Nash et al. (1991, 1992).

Patterns of Soil Moisture on the Jornada

The LTER II NPP soil water data set was selected for preliminary analysis in this chapter because it represents a much broader range of variability than the LTER I transect data. The LTER II NPP site selection was based on a replicated sampling design with three sites representing each of the five major plant communities in the Jornada Basin (see table 5-1 for abbreviations and site descriptions).

Table 5-1. The five Long Term Ecological Research II net primary production (NPP) vegetation communities, the three individual sites within each community, and the soil mapping unit name and texture class for each individual site. Soil information from the Dona Ana County Soil Survey (Bulloch and Neher 1980).

Community / Site	**Soil Name**	**Soil Texture**	
Creosote bush			
Caliche (CALI)	Nickel-Upton association	Gravelly sandy loam	(gsl)
Gravel (GRAV)	Nickel-Upton association	Gravelly sandy loam	(gsl)
Sand (SAND)	Nickel-Upton association	Gravelly sandy loam	(gsl)
Grasslands			
Basin (BASN)	Onite-Pajarito association	Loamy sand	(ls)
IBP (IBPE)	Berino-Dona Ana association	Fine sandy loam	(fsl)
Summerford (SUMM)	Onite-Pajarito association	Loamy sand	(ls)
Mesquite			
North (NORT)	Onite-Pintura complex	Loamy fine sand	(lfs)
Rabbit (RABB)	Onite-Pintura complex	Loamy fine sand	(lfs)
West Well (WELL)	Onite-Pajarito association	Loamy sand	(ls)
Playas			
College (COLL)	Stellar association	Clay loam	(cl)
Small (SMAL)	Wink-Harrisburg association	Fine sandy loam	(fsl)
Tobosa (TOBO)	Dona Ana-Reagan association	Sandy clay loam	(scl)
Tarbush			
East (EAST)	Dona Ana-Reagan association	Sandy clay loam	(scl)
Taylor Well (TAYL)	Dona Ana-Reagan association	Sandy clay loam	(scl)
West (WEST)	Stellar association	Clay loam	(cl)

Within each of the 15 sites, data from all 10 tubes were averaged to produce monthly soil water content at each sampled depth for all the years 1990–2001 (Snyder and Mitchell unpublished data). In many cases, neutron probe tubes did not extend to the full depth because a petrocalcic horizon was encountered; therefore, all depths are not represented equally across sites and communities (table 5-2). <<COMP: Insert table 5-2 about here>>

Table 5-2. Number of neutron probe measurements at each depth for each of the 15 Jornada Basin Long Term Ecological II net primary production (NPP) sampling sites.

Depth	Creosote			Grassland			Mesquite			Playa			Tarbush		
(cm)	CALI	GRAV	SAND	BASN	IBPE	SUMM	NORT	RABB	WELL	COLL	SMAL	TOBO	EAST	TAYL	WEST
30	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10
60	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10
90	10	7	10	10	10	10	10	10	9	10	10	10	10	10	9
120	10	4	10	10	10	10	10	10	8	9	10	10	10	9	7
150	8	1	9	10	6	10	10	10	6	8	10	10	10	7	5
180	5	0	8	10	4	10	10	9	5	8	10	10	10	6	4
210	4	0	7	10	3	10	10	8	4	8	10	10	8	5	2
240	2	0	6	10	2	10	9	7	2	7	10	10	5	5	2
270	2	0	5	10	2	10	9	6	2	4	8	9	1	5	1
300	1	0	3	7	0	8	7	1	0	4	8	5	0	4	0

Soil textures at the NPP sites range from clay loams to loamy sands (table 5-1). The effect of this wide variability in soil texture on plant available water limits the among-site comparisons that can be made using the data presented here.

General Patterns of Soil Water Content

To analyze general variations in soil moisture between different community types and to understand the amount of variation within a community, noncalibrated volumetric water content (hereafter referred to as water content) was averaged by depth across all sampling dates for each site, and then all sites within a community (n = 3) were averaged to calculate mean soil water content by depth (figure 5-2).

Therefore, the calculated standard deviations indicate the amount of variability between the different sites within a given community. Mean soil water content was highest in the playa community (approximately 23%), intermediate in tarbush (*Flourensia cernua*) (10%), slightly less in mesquite (*Prosopis glandulosa*) and grassland communities (6%), and lowest for creosote community (4%) (figure 5-2). The lower water content in the creosote community is likely due to a combination of higher runoff rates associated with higher slope and a relatively high proportion of the soil volume being occupied by coarse fragments (rocks) at two creosote sites (C-CALI and C-GRAV, acronyms follow table 5-1). The IBP and BASN black grama (*Bouteloua eriopoda*) sites may have lower runoff rates due to better soil structure associated with more continuous plant cover (Neave and Abrahams 2002; Schlesinger et al. 2000), generally lower slope,

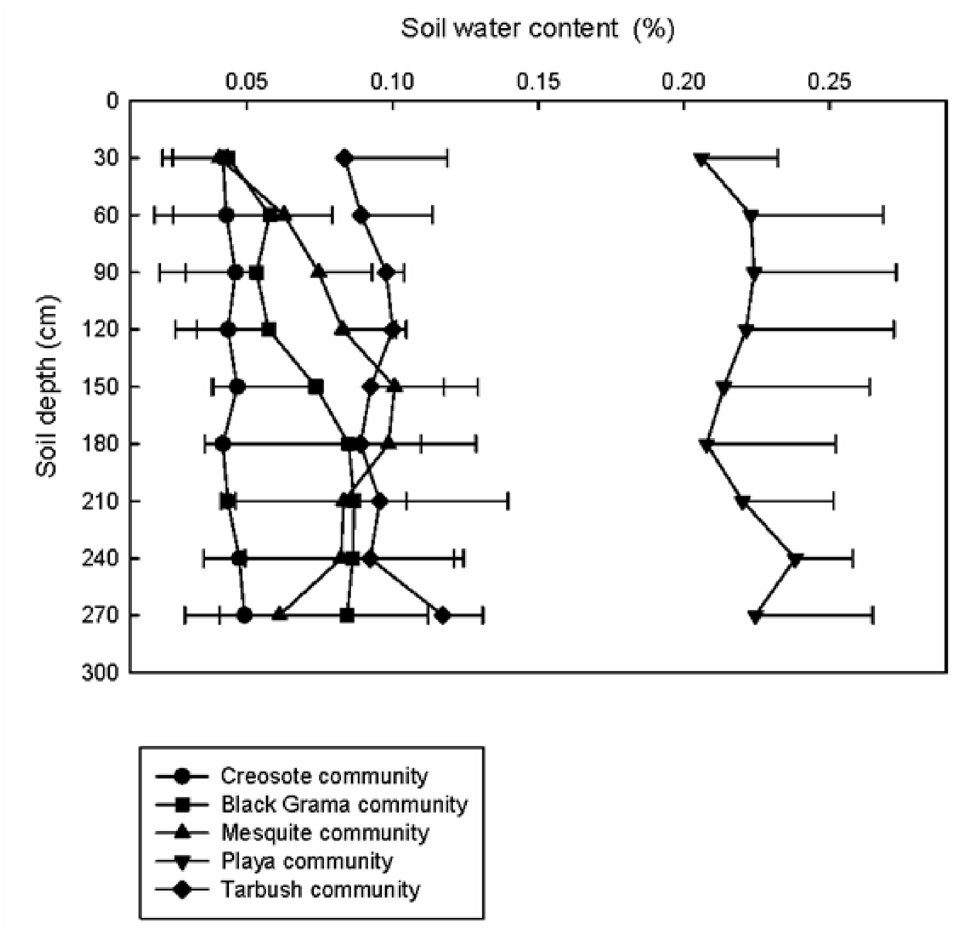


Fig. 5-2. Mean soil volumetric water content (cm^3 H_20 / cm^3 soil) by depth for each of the 5 vegetation communities. Data pooled across the 3 sites within each community and across the entire time period from 1990 to 2001. Error bars are standard deviation from the mean and represent intra-community variability (n = 3, the amount of variation among the 3 sites within each community type).

and coarser-textured soils. Because water available to plants varies with soil texture and there is limited information on texture at these sites, it is not possible to compare plant available water across sites based on water content alone without further calibration of data. In addition to texture, rock content also affects the relationship between soil water content measured with the neutron probe and plant available water. With high rock content, the water that is present is concentrated in a smaller volume.

Shallow versus Deep Soil Water

Neutron probe and gypsum block data were used to compare shallow and deep soil water. Two additional soil water content data sets were generated by averaging neutron probe measurements made at 30 and 60 cm soil depth (hereafter referred to as shallow soil water) and by averaging measurements from 90 to 300 cm soil depth (hereafter referred to as deep soil water). To examine the temporal patterns in water content, time-series plots of shallow and deep soil water for each community are shown for each monthly sampling date for the period 1990–2001 (figure 5-3).

Shallow Soil Water

Average water content in the shallow soil depth for each community type was extremely variable in response to differences in monthly rainfall (figure 5-3). The shallow depths exhibited variable soil water content in response to monthly rainfall. This variability is probably influenced by a combination of soil texture, slope, plant cover, and other factors affecting infiltration, runoff, and run-in. Finer-textured soils at playa sites were more responsive to rainfall events than sandy loams and loamy sands at the black grama and

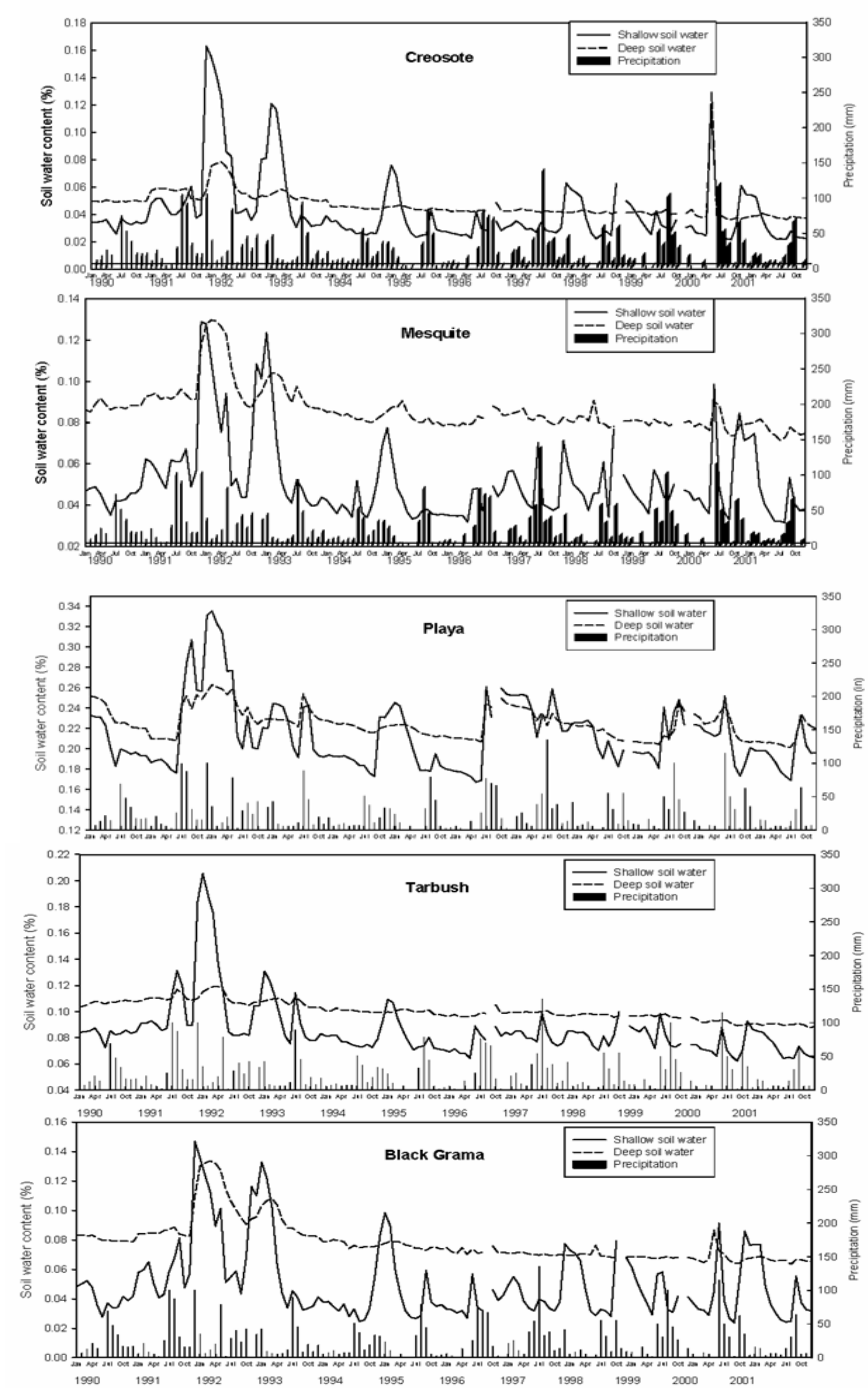


Fig. 5-3. Long-term temporal patterns in shallow vs. deep soil volumetric water content for each of the 5 vegetation communities. Soil water at 30 cm and 60 cm depth averaged for 'shallow' water content; soil water from 90 cm to 300 cm depth averaged for 'deep' water content. Vertical bars along x axis show mean monthly precipitation. (Note: y axis varies by community).

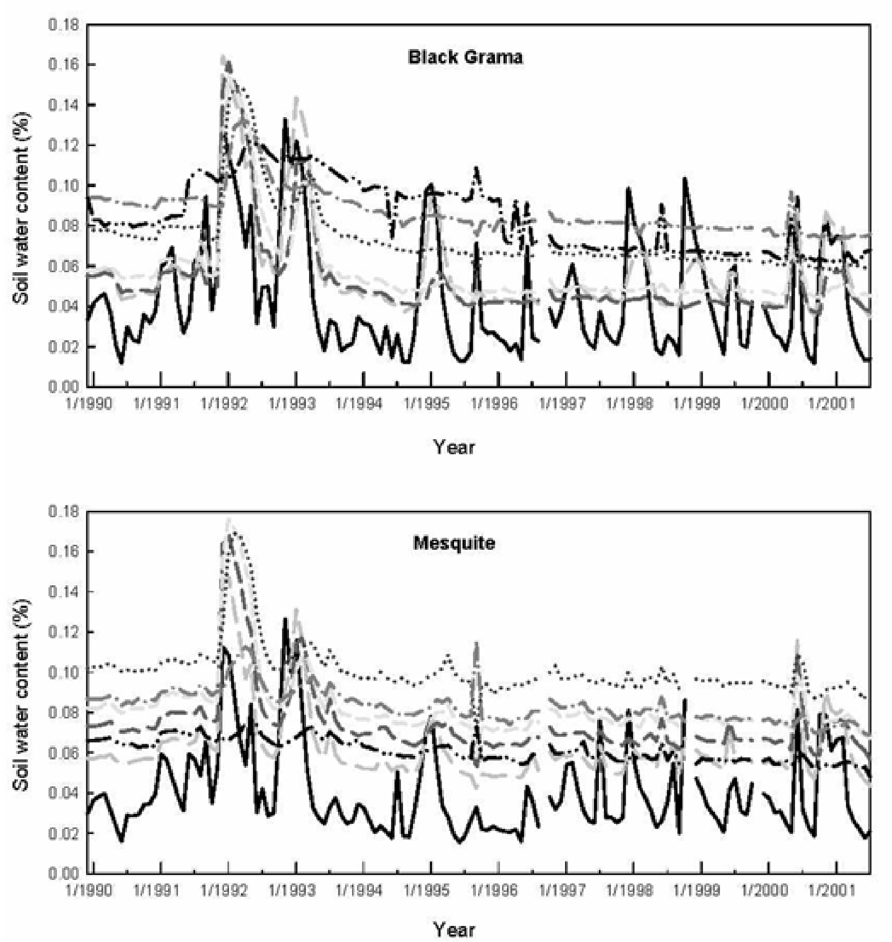
creosote sites, but extremely sandy soils of mesquite were the least variable likely due to generally rapid infiltration in these coarse soils.

The standard deviation from the 12-year average mean water content for each community (n = 141 months, 3 missing observations) includes both within- and among-year temporal variability data from (figure 5-3). Water content of shallow soils was highly variable in playa soils (SD = 0.034). The playa sites are located on soils that are quite high in clay, and low rates of infiltration are expected (table 5-1). However, these sites are located in topographical depressions where precipitation and infiltration are enhanced by run-in processes that generally occur after larger rainfall events, creating high temporal variability in soil water content (Herbel and Gile 1973). Creosote (SD = 0.026) and black grama (SD = 0.026) communities showed similar variation in water content, while tarbush had slightly less variation (SD = 0.022). Tarbush sites are located in sandy clay loams and clay loam soils. These sites have a fairly high clay fraction that reduces infiltration, but are located on slopes of less than 1%. Intense rains generally produce significant runoff, whereas most of the rainfall from less intense events infiltrates into the soil. Shallow soil water was least temporally variable in the mesquite community (SD = 0.020). Mesquite sites are located on loamy fine sands and loamy sands that appear to have rapid infiltration and percolation, low water-holding capacity, and therefore low variability in soil water contents at monthly time scales.

Gypsum block data also illustrate that soil matric potential in shallow soil layers (30 cm and 60 cm) varied in response to rainy periods, and illustrate the importance of soil texture and landscape position (Herbel and Gibbens 1987, 1989). Soils of the narrow, level basin floor and an adjacent fan piedmont exhibited consistently different patterns of soil water availability than soils of the broad basin floor. All the coarse-textured soils (loamy sands and sandy loams) in the broad basin had a sandy surface layer that appears to have increased infiltration. The majority of these sites had a higher probability of soil matric potential less negative than –1.5 MPa in comparison to the finer-textured clay-loam soils of the narrow valley that had a lower probability of soil matric potential less negative than –1.5 MPa. For a clay-loam soil dominated by tobosa (*Pleuraphis mutica*) grass, run-in processes doubled the probability that soil moisture at 25 cm was above –1.5 MPa, in comparison to plots where run-in had been experimentally excluded by 3-m diameter cylinders inserted to a depth of 15 cm. These data further support the hypothesis that the lower variability in the NPP tarbush data are due to infiltration limitations associated with relatively fine soil texture (table 5-1) or degraded soil structure (Herbel and Gibbens 1989).

Deep Soil Water

NPP soil water data, which were averaged for all depths greater than and including 90 cm, were very stable and fairly invariant through time at the community level. Average soil water contents of deep soil were generally greater than shallow soil water contents (figure 5-3). Inspection of soil water by individual depths within the mesquite and black grama communities (figure 5-4) confirms that soil water content increases and is less variable with depth. This probably reflects actual differences in plant water availability, at least at the mesquite sites and the BASN and SUMM black grama sites, because texture is relatively consistent throughout the profile for the dominant soils at these sites and because there are relatively few coarse fragments in these soils (although the presence of calcium carbonate nodules at greater depths may increase water-holding



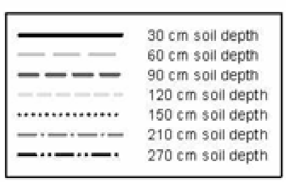


Fig. 5-4. Seasonal and interannual patterns of soil water content by soil depth for the period 1990 to 2001 in the (a) grassland community and (b) mesquite (Prosopis glandulosa) *community (the 3 individual sites for each community were averaged monthly).*

capacity at greater depths in some sites; Hennessey et al. 1983b). In general, water content variability at 90 cm decreases substantially in comparison with water content variability at 30 and 60 cm (figure 5-4). Less variability in soil water at and below 90 cm indicates that rainfall rarely infiltrates to these depths, although the aggregated monthly time scale of these measurements affects the ability to detect changes in soil water content that result from individual rain events. Playa, creosote, and tarbush communities had fairly consistent water content throughout the soil profile, but variability again decreased with depth. The amount of soil water did not consistently decrease with depth in any community type. The neutron probe data show consistent soil water at depths of greater than 1–2 m in this arid system, where groundwater is approximately 100 m below the soil surface.

Recharge of Soil Water

The presence of water at depth leads to questions about how deep soil water is recharged in these systems. Research at the nearby Walnut Gulch Experimental Watershed in Arizona found that transmission losses in ephemeral channels may be up to 80% (Renard 1970) and are the primary contributor to groundwater recharge. Less is known about the recharge of unsaturated vadose zone water for the Jornada Basin (see chapter 7). Transmission losses from smaller rills that flow fairly frequently are likely to contribute to vadose zone recharge (chapter 7), as big channel flows are rare in the Jornada Basin. Time-series techniques (cross-correlation and autocorrelation) were used to determine the relationship between soil water content down to 130 cm and rainfall for the LTER I transect (Nash et al. 1991). Rainfall samples were collected at one-week intervals, and soil water content was measured at two-week intervals for the period (July 1982 to March 1986). The soils along the 2.7-km transect were highly variable and so were divided into six relatively homogenous segments based on soil texture, morphology, vegetation, and soil water content (table 5-3) (Nash et al. 1991). Rainfall was slightly higher in the upper piedmont segment, and soil moisture increased moving downslope to the playa. Rainfall events preceded peaks in soil moisture by 4 weeks at 30 cm depth and 11 weeks at 130 cm depth. Cross-correlations of rainfall and soil water content were used to determine the

Table 5-3. Correlation of soil type, vegetation type, and soil water content along the Long Term Ecological Research I transect (taken from Wierenga et al. 1987). Zones of similar soil water content were determined using split-moving window analysis (Hotelling Lawley trace F-values for dissimilarity measure). Illustration below the table compares soil zonation, vegetation zonation, and the water content dissimilarity breaks.

Soil water zone breaks	**Soil series zonation**		**Vegetation type zonation**		
Station	**Stations**	**Soil mapping unit**	**Stations**	**Vegetation Zones**	**Vegetation**
6	1 - 6 7	Dalby (f) Headquarter variant (fl)	1 - 7	*Playa* - grassland	*Panicum obtusum* (Paob)
11	8 - 10	Headquarter (fl)	8 - 10	*Playa fringe* - shrubland	*Prosopis glandulosa* (Prgl)
19	11 - 25	Bucklebar (fl)	11 - 57	*Lower basin slope* - grassland	*Aristida longiseta* (Arlo)
42	26 - 45 46 - 55	Berino (fl) Onite (cl)			
56	56 – 70	Dona Ana (cl)	58 - 72	*Upper basin slope* - shrubland	*Larrea tridentata* (Latr)
73	71 - 89	Aladdin (cl)	73 - 81	*Lower piedmont slope* - grassland	*Erioneuron pulchellum* (Erpu)
81			82 - 89	*Upper piedmont slope* - grassland	*Bouteloua eriopoda* (Boer)
	90 - 91	Rockland (r)	90 - 91	*Rocky slope* - shrubland	*Ericamera Laricifiolia* (Erla)

[1]f = fine, fl = fine loamy, cl = coarse loamy

lag time for soil water content to respond to rainfall for the entire sampling period. The response time to rainfall was short (i.e., less than 2 weeks) at 30 and 60 cm depths for all six segments of the transect, but water content was slower to respond at deeper depths and lagged behind rainfall as much as 10 weeks at 130 cm. Furthermore, in upper and lower piedmont and playa soils rainfall reached a depth of 110 cm in two weeks. Upper and lower piedmont soils had the lowest clay fraction, whereas playa soils had an extremely high clay content. Therefore, changes in water content could not be predicted based on soil textural differences alone. Vertic clays in the soil at the College playa may facilitate deep percolation of water at the beginning of precipitation events through the formation of large, deep, vertical cracks (Nash 1985). The movement of water to 130 cm depth in nonplaya soils with an intermediate amount of clay and an increase in clay content with depth took four to six weeks. Time to reach maximum soil water content was substantially longer. Playa soil reached maximum infiltration at all depths in 8 weeks, but all other sites took between 14 and 24 weeks to reach maximum water content.

At a finer scale, variability in the structure and depth of petrocalcic horizons also affects deep soil water recharge. These horizons limit deep infiltration due to extremely low permeability caused by infilling of pores by calcium carbonate. Depth to the top of these horizons can vary by as much as 100% across distances of less than 10 m (chapters 2 and 4). Deep infiltration can occur through relatively carbonate-free “pipes,” which form where the petrocalcic horizon is penetrated by animal burrows, strong roots, or anything that allows water to preferentially move through the horizon. Increased water flow dissolves more carbonate, further increasing permeability.

Another potential mechanism of deep water recharge is the poorly understood process of internal release of water from indurated caliche. Calcium carbonate ($CaCO_3$) is common in soils of the Jornada (chapters 2 and 4). Hennessy et al. (1983b) found in a laboratory study that calcium carbonate nodules derived from Jornada soils have a saturated water content of 27% by volume. Water loss from saturated nodules to the atmosphere was slow, but a majority of water was eventually released. It remains to be comprehensively tested in field settings, but buried calcium carbonate may release water to dry soils or provide a source of water that is accessible to plants. Herbel and Gibbens (1989) found some evidence for upward movement of water inside steel cylinders designed to exclude run-in on clay loam soils of the Stellar and Reagan series (chapter 4, table 4-2 and figure 4-3).

Another tentative (though untested) hypothesis is that some portion of unsaturated soil moisture in some landscape units is a result of recharge processes that occurred on millennial timescales. The increased shrub component, especially the rapid encroachment of mesquite, is a relatively new phenomenon within the past 150 years, though increased shrub dominance has been found at other times in the geologic record in response to more arid climates (Monger 2003). Thus some of the water used by shrubs at deeper depths maybe “old” water. The issue of deep diffuse recharge (i.e., in interdrainage areas) has not been resolved (Phillips 1994; Scanlon et al. 2005; Small 2005). An eight-year lysimeter studies by Scanlon et al. (2005) in the Mojave Desert found that recharge below the plant-rooting zone did not occur in the vegetated lysimeter due to vegetation feedbacks (increased biomass in response to more rainfall), even in El Niño (wet winters) years. Soil water storage was greater and at deeper depth in the nonvegetated lysimeter. Deep soil cores were used to measure soil water potential and chloride concentrations. Chloride bulges, which indicate a region of low soil moisture flux, were right above 5 m. Soil water potentials increased with depth and were remarkably consistent below 5 m. Scanlon et al. (2005) interpret these data to indicate that moisture below 5 m was derived from the Pleistocene, and currently there is gradient for water to move upward from deep soil layers. Mesquite frequently have roots at depths up to 5 m (Gibbens and Lenz 2001) and exceeding 5 m (Phillips 1963) and consequently may be using “old” water. However, focused recharge (e.g., beneath ephemeral streams, in playas and burrow pits) may be more important in some landscape units.

The Role of Seasonal Precipitation

Winter Soil Moisture

Soil water data from NPP sites indicate that recharge of deep soil moisture takes place in above-average precipitation years, especially if this precipitation falls during winter months. This is partly due to the frontal nature of winter precipitation, which is characterized by storms of low intensity and longer duration that enhance infiltration. In addition, evaporative losses are less due to lower temperatures, and transpiration losses are reduced due to the majority of plants being dormant in these cooler months. Both 1991 and 1992 were above-average precipitation years, and an example from the black grama community illustrates that extremely high rainfall during the early growing season of June and July, when convective storms dominate, had little effect on soil moisture below 60 cm (figure 5-5).

However, rainfall events in December 1992 appeared to recharge deep water down to 240 cm. The playa community had different patterns with both summer rainfall and winter rainfall recharging soil water at depth (figure 5-5). This illustrates the importance of topographic position. Playa sites are in topographic depressions that have substantial run-in in both seasons. Substantial run-in has been observed to cause prolonged flooding at College playa and the Small playa; flooding has not been observed at the Tobosa playa.

Reynolds et al. (1999b) used rainout shelters to determine the effect of summer and winter drought on creosote and mesquite. After three years of summer drought, there was little difference in soil moisture in comparison to control plots for either species (one site with a significantly larger rainout shelter and differing soils and vegetation did not follow this pattern). Conversely, imposed winter drought resulted in substantially lower soil water contents at depths down to 90 cm relative to controls plots; however,

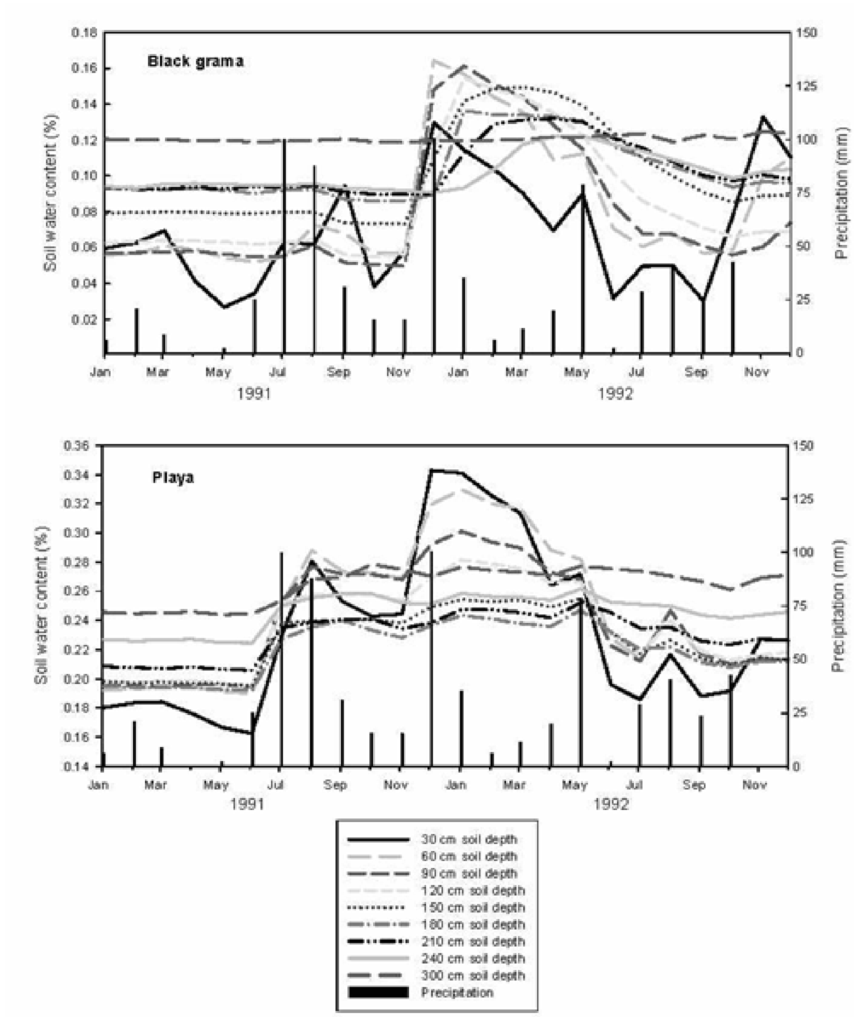


Fig. 5-5. Differences in soil moisture response to winter vs summer precipitation. Soil water by depth for (a) the grassland community and (b) the playa community for the period January 1991 through December 1992. Vertical bars along x axis show mean monthly precipitation. Winter 1991 was an unusually wet year; Fig. illustrates recharge at depth with winter rain.

extrapolation is limited by the fact that winter drought was only imposed at one site. Rainout shelter studies in these types of landscape are further limited by the difficulty of excluding blowing rain during intense summer storms and the effects of shading on reducing summer evapotranspiration.

Although rainfall is greatest during the summer monsoon months, especially July and August, shallow soil depths are generally wetter in winter months than in summer (figure 5-6). Gypsum block data illustrated that the probability of wet soil was as great or greater during winter months than during the summer growing season on both loamy sands of the basin floor and clay loams of the fan piedmont (Herbel and Gibbens 1987, 1989). Data from NPP sites show a consistent trend of available shallow soil water right after winter that then declines throughout the typically dry spring periods as air temperatures increase (figure 5-6). It appears that there is shallow water in late winter and early spring that is potentially not fully used by plants. This may represent an unused resource space that could be at risk for invasion by winter annuals, such as red brome (*Bromus rubens*) that has invaded much of the Mojave, Great Basin, and Sonoran Deserts (Hunter 1991) or early growing, warm-season perennials, such as Lehmann lovegrass (*Eragrostis lehmaniana*).

Summer Precipitation

During the summer growing season, soil matric potentials of sandy loams at 10 cm were not greater than –1.5 MPa if daily precipitation was less than 13 mm (Herbel and Gibbens 1987). Likewise, it took greater than 20 mm of daily precipitation to raise the water potential of clay loams at 10 cm depth to greater than –1.5 MPa (Herbel and Gibbens

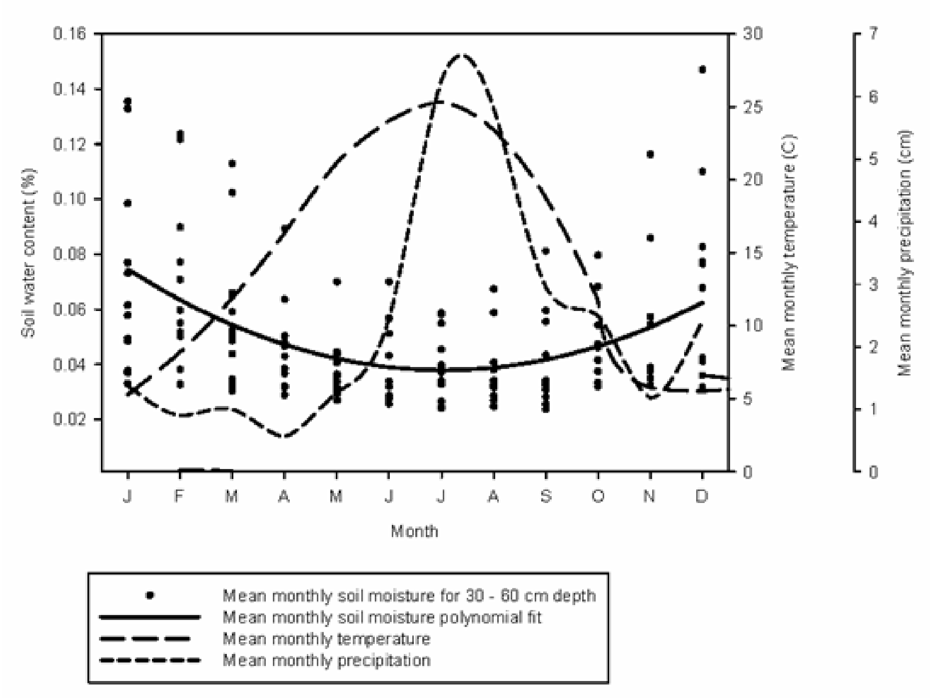


Fig. 5-6. The relationship between mean monthly soil moisture, temperature and precipitation. Grassland community mean monthly shallow soil water (30 – 60 cm) data points for each year, 1990 to 2001, and the polynomial function fitting soil water content to month. Also shown are mean monthly temperature and precipitation for the 1990 to 2001 period. Climate data from Jornada Long Term Ecological Research meteorological station.

1989). Although these data indicate that fairly large rain events are needed during the summer months to change soil moisture at depths greater than 10 cm, the importance of smaller rainfall events on near-surface soil layers, sandy soils (Reynolds et al. 1999b), and vegetation is potentially not trivial. Again, only soil matric potentials above –1.5 MPa were measured, so changes in soil matric potential at more negative water potentials were undetected. Small storm events account for a large proportion of precipitation events in semiarid regions (Sala et al. 1992; Hochstrasser et al. 2002). Blue grama (*Bouteloua gracilis)* was found to have a significant increase in leaf water potential and conductance in response to simulated 5 mm rainfall events on the short-grass steppe in

Colorado (Sala and Lauenroth 1982). The importance of moisture in near-surface soil layers is likely to be extremely important to shallow-rooted species.

Vegetation and Soil Moisture

Consistent patterns of soil chemistry and vegetation type have been found to exist for four vegetation groups on the Jornada Basin (Stein and Ludwig 1979). However, the relationship between soil water content, soil texture, and vegetation type is less clear.

Transect data from LTER I were used to determine the correlations between soil moisture, soil texture, and type of vegetation (Wierenga et al. 1987). A multivariate, moving, split-window technique was used to delineate different zones along the transect. On the basis of soil texture, nine distinct zones were found that correlated well with the soil survey. Seven distinct vegetation types were identified that were generally correlated with a soil-mapping unit (i.e., soil series plus surface textural characteristics) (table 5-3). Seven distinct zones of soil water were found that were in general well correlated with vegetation and soil texture. The exception to the general pattern of distinct zones was in vegetation zone 3, which spanned a majority of sampling stations (stations 15–60) and was historically dominated by black grama, but at the time of the study, black grama cover was greatly reduced. The area was dominated by threeawn (*Aristida longiseta*), a perennial grass; soaptree yucca (*Yucca elata*); and globe mallow (*Sphaeralcea subhastata*). This same vegetation zone encompassed three soil-mapping units (two fine loams and one coarse loam) and three distinct changes in soil moisture that corresponded roughly to changes in soil series. These data indicate that soil texture and soil moisture are related at a landscape scale to vegetation patterns; however, within vegetation types there may still be substantial difference in soil moisture and changes in soil-mapping units. Analysis of plant cover and soil water from LTER I using two geostatistical analysis methods reached the conclusion that volumetric soil water content could not fully explain vegetation patterns along the transect (Nash et al. 1992).

Gypsum block data showed substantial changes in soil moisture under different vegetation on the same soil type. For example, on a Stellar soil series comparison of soil water under tobosa grass showed much higher soil matric potential than the same soil under burrograss. This pattern was attributed to difference in near-surface soil structure; a silty platy structure may have decreased infiltration of soil water under burrograss (Herbel and Gibbens 1989). Runoff from burrograss plots was three times higher than tobosa grass under simulated rainfall events (Devine et al. 1998). It is also plausible that feedbacks between vegetation type and soil type have positively reinforced this decline in soil matric potential. For example, feedbacks between carbon exudates of roots and soil aggregate formation affect both infiltration capacity and the water-holding capacity of soils. However, on sandy loams and loamy sands, Herbel and Gibbens (1987) came to the conclusion that the type of vegetation, shrub or grass, did not appear to influence soil matric potentials.

Soil water content averaged across all months (n = 141 months) at up to 10 measured depths (see figure 5-2) was used to obtain the total water content of the soil profile (figure 5-7). Measured content at each available depth was assumed to represent water content ± 15 cm around the measured point (see table 5-2), and values were summed to obtain content of the profile. There is a general relationship between total profile soil water content and soil surface texture; finer surface soil textures were associated with higher total water content. This is expected based on their higher water

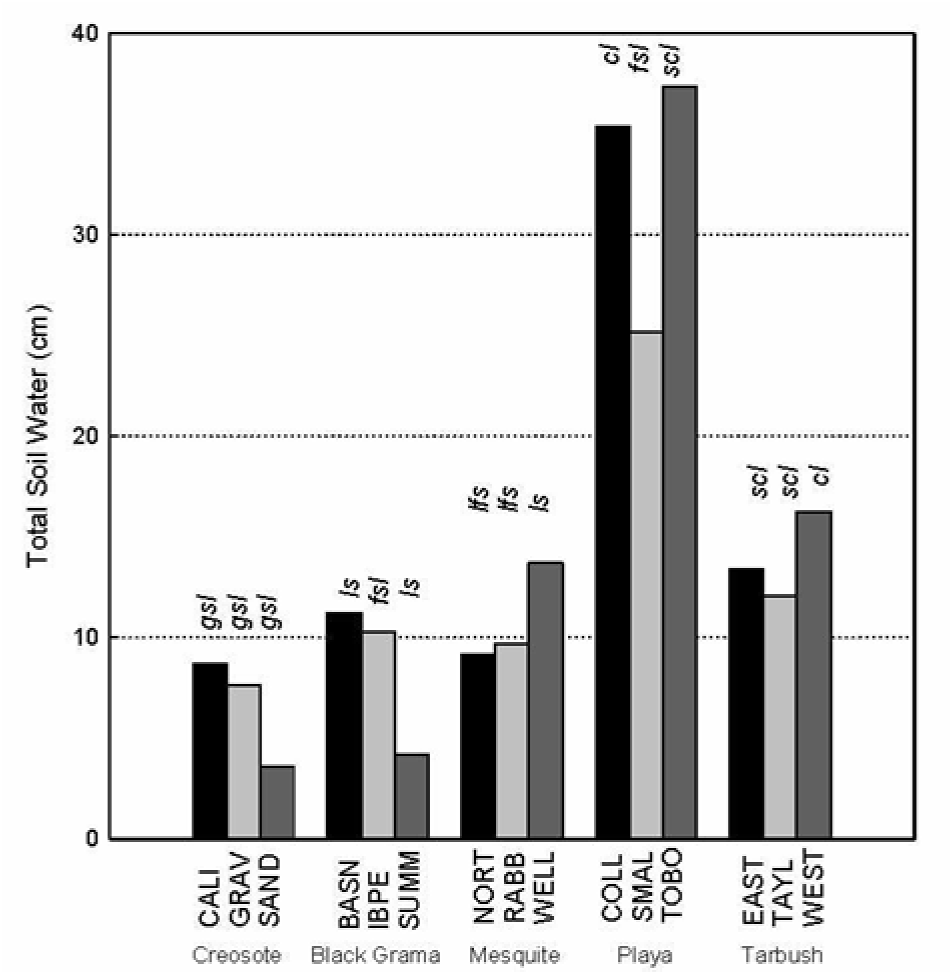


*Fig. 5-7. Total soil water in the soil profile from 15 cm to 285 cm depth for each of the 15 individual net primary production (NPP) sites. (Soil water content at each depth * 30 cm, summed, up to and including soil water at 270 cm. Four-letter notation on the x-axis is for each of the three sites within each of the five vegetation types (creosote, black grama* (Bouteloua eriopoda), *mesquite* (Prosopis glandulosa), *playa, and tarbush* (Flourensia cernua*) follows Chapter 11, Fig. 11-1. Creosote at the gravel site only has data to 150 cm - therefore soil water was estimated for depths from 180 cm to 270 cm). Average of all sampling dates (n = 141). Above each site there is notation of the soil texture class from Table 5-1.*

content at soil water tensions that may be inaccessible to plants. However, when the playa sites are excluded, the variation in cm of total water showed as much variation within a community as across communities.

There is also tremendous variation in soil water content by depth between sites within a given community type and with depth (figure 5-8).

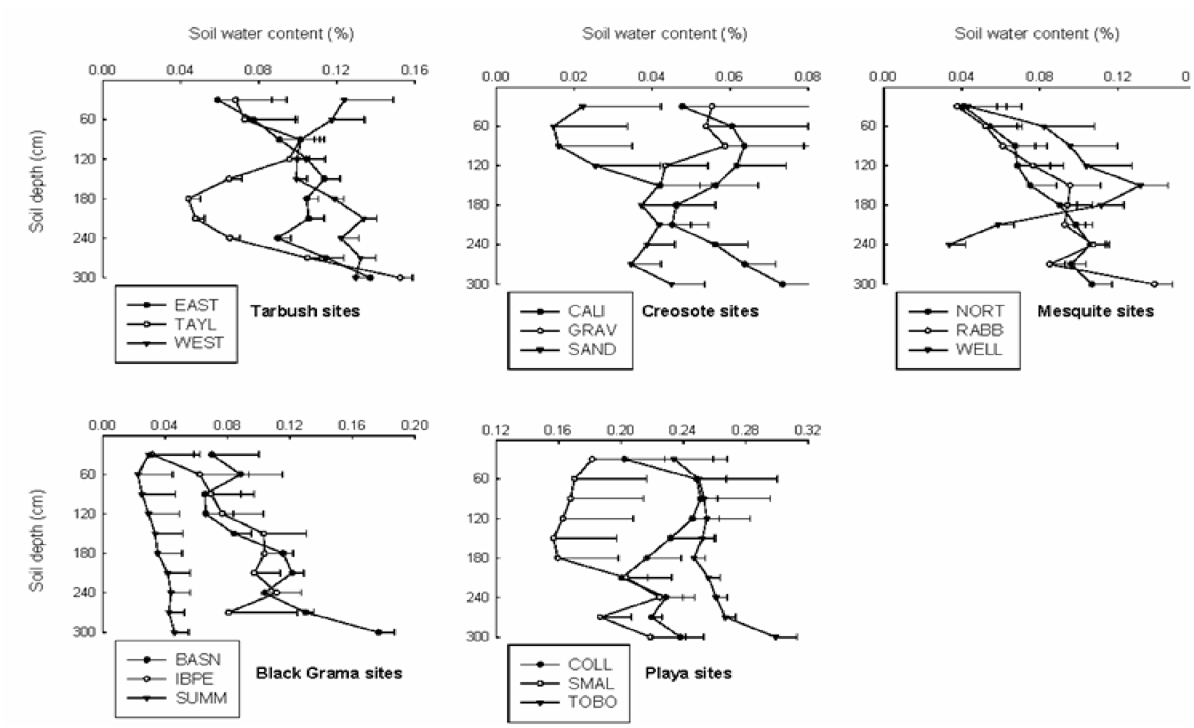


Fig. 5-8. Mean soil water content (± 1 sd, n = 141) by depth for each site within each of the 5 vegetation communities for the period 1990-2001. Individual site names correspond to Table 5-1.

Variability in water content is highest near the surface and decreases with depth. If the playa sites are excluded, there appears to be nearly as much variation with depth and within a community as across all communities (figures 5-2 and 5-8). Even though the three sites within a community type were selected to include minimum and maximum biomass of each community type (see Huenneke et al. 2002; chapter 11), we still expected soil water contents to be more similar within a community type than across community types. Similarly, extreme variability in soil texture and depth were found over a small spatial scale dominated by a single vegetation type, mesquite (Gile et al. 1997). Our analyses strongly suggest that community composition and surface soil texture are not the only controlling factors for soil water and that landscape linkages must also be considered.

Interspaces versus Beneath-Plant Canopies

There may also be variation in soil water within a site due to feedbacks between hydrology and vegetation. Much research in the Jornada Basin has contributed significantly to our understanding of the processes behind “resource island formation,” whereby spatially homogenous grasslands are converted to patchy shrubland communities (Schlesinger et al. 1990). Shrub communities are characterized by a heterogeneous spatial distribution of resources which become increasingly concentrated below and around shrubs while the bare interspaces between shrubs have reduced amounts of litter, nutrients, and inputs from animal activity (Schlesinger et al. 1990; Cross and Schlesinger 1999). It has been proposed that increased interception of precipitation by shrub canopies leads to increased stem flow and, subsequently, increased depth of infiltration below shrubs (Martinez-Meza and Whitford 1996). In keeping with this view, Reynolds et al. (1999b) hypothesized that large shrubs should have greater soil moisture relative to small shrubs. Contrary to their hypothesis, small mesquite shrub islands were found to have greater soil moisture in summer (measured biweekly at depths > 30 cm) than large shrub islands. Furthermore, there was no indication that large shrub islands of either creosote or mesquite had greater soil moisture storage than young islands. Hennessy et al. (1985) compared soil properties under mesquite dunes with bare interdunal spaces. Dune soils with established mesquite had greater infiltration, greater hydraulic conductivity, and less evaporation than interdunal soils. However, gravimetric water content at 15 cm did not differ between dunes and interdunes and was closely related to rainfall. At 30 cm in depth water content, measured with a neutron probe every two weeks, was significantly less in vegetated dunes than in interdune areas. Similarly, preliminary analysis of NPP soil water data indicates that water content measured in neutron probe tubes in interspaces of the mesquite sites is consistently greater than water contents measured in neutron probe tubes under mesquite canopies (Snyder and Mitchell unpublished data). Because neutron probes measure water stored in nearby plant roots, as well as nearby soil, actual soil water content may potentially be even lower under shrubs (Hennessy et al. 1985). Although water may infiltrate faster and deeper below shrubs, limited evidence suggests there is not more water stored in shrub islands. This is likely due in part to plants having greater root volume in canopy areas and, consequently, using more water from the canopy area. Shrub islands may be areas of greater infiltration and percolation, but plants may quickly take up this water; to detect these differences, continuous measurements of soil water may be necessary.

Conclusions

Patterns of soil water appear to vary greatly within a community type as well as across the landscape, and the relationship to community type and production appears to be complex. However, some patterns did emerge from previous Jornada research and our current data analyses presented herein. Shallow soil water is highly variable and cannot be completely explained by temporal differences in precipitation and spatial differences in soil texture. There is water at depth in these systems, and this water is less temporally variable. Recharge of unsaturated soil moisture at depth is a poorly understood process but appears to occur mostly in wetter-than-average winter months. There is little evidence to support predictions that shrub islands have more stored soil water than barren interspaces, but these islands do appear to be areas of greater infiltration.

Recommendations

More detailed calibration of existing soil water content data and developing relationships between soil water content and soil water potential would allow for better comparisons across different soil types and would resolve whether water stored at depth is available to plants. More detailed measurements at shallower depths (< 30 cm) are needed to determine the importance of small, frequent rainfall events on plant productivity and potential competitive interactions between grasses and shrubs. Because of the need for detailed, continuous measurements on soil water availability and plant composition and production, it is impractical to attempt this for every soil series in the Jornada Basin. Instead, care should be taken to select soil series that appear to be most susceptible to vegetation change and erosion. Sandy loams appear to be a particularly susceptible soil type—where temporal interactions are greater, vegetation change is dynamic and enhanced information on the feedbacks between soil water and vegetation is particularly warranted.