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## The influence of soil texture and vegetation on soil moisture under rainout shelters in a semi-desert grassland

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### Abstract

Climate change and invasions by non-native organisms are two factors of global change likely to alter the structure and function of arid and semi-arid ecosystems. We conducted a large-scale field experiment to determine how changes in amount of summer precipitation and invasions by an African grass (*Eragrostis lehmanniana*) may interact with soil texture to affect community and ecosystem processes in temperate grasslands and savannas of southern Arizona, USA. In particular, we investigated the response of soil moisture at several soil depths within seventy-two 2.7 m<sup>2</sup> plots under six 9 m × 18 m rainout shelters to a 3-fold difference in irrigation between February and November 2002, as well as to a single large pulse of irrigation water in June 2002. In addition, we documented the effects of the rainout shelters on microclimates under the shelters. Results indicate that relatively more water is available to plants at greater depths on sand-rich soils, whereas on clay-rich soils the greatest water availability is at the surface. Typically, soil moisture under *E. lehmanniana* was lower than under plots with the native grass *Heteropogon contortus*, although soil texture and depth modified this pattern. The precipitation shelters had minimal impacts on windspeed, soil temperature, and relative humidity; small differences in microclimatic effects between the soil types were attributed to effects of surrounding vegetation on wind velocity. Differences in soil texture, grass cover and species

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identity, and amount of irrigation exert interactive controls over soil moisture in this semi-arid environment, but responses are modified by time of year and depth in the soil profile.

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## 1. Introduction

Global temperatures are predicted to increase by 1.4–5.8 °C during this century and will likely alter patterns of precipitation over much of the Earth (Houghton et al., 2001). Changes in global and regional precipitation regimes are expected to have important ramifications for the distribution, composition, and diversity of organisms on local, regional, and global scales (Easterling et al., 2000; Houghton et al., 2001; Weltzin et al., 2003b). The ecological effects of changing precipitation regimes will be particularly dramatic in arid and semi-arid environments, where the availability of water most impacts the productivity and dynamics of most ecosystems (Noy-Meir, 1973; Weltzin et al., 2003b). Of particular importance is the temporal availability of water (e.g. pulses of precipitation) and how grasses and shrubs partition the use of this finite water over relatively short time scales (e.g. Walter, 1979; Schwinning and Ehleringer, 2001; Schwinning et al., 2002).

In western North America, grassland communities themselves are becoming increasingly dominated by non-native annual and perennial grasses (Mack, 1981; McClaran and Van Devender, 1995); rates of spread and impact of these invasive grasses may be further facilitated by changing climates (D'Antonio, 2000; Smith et al., 2000; Weltzin et al., 2003a). In arid and semi-arid ecosystems of western North America, changes in summer precipitation (Giorgi, et al., 1998; NAST, 2000) will likely have the greatest impact on C<sub>4</sub> grasses, which grow predominantly during the hot summer months when soil moisture is available (Neilson and Drapek, 1998). These grasses potentially compete with woody plants for soil resources (e.g. Cable, 1971; Knoop and Walker, 1985; Van Auken and Bush, 1995, 1997). Therefore, changes in precipitation regimes are likely to have not only direct impacts on recruitment and productivity of woody species, but also indirect impacts mediated by the response of coexisting grasses. Soil texture also plays a role in recruitment and productivity by modifying the depth and availability of pulse-delivered rainfall (Noy-Meir, 1973; Sala et al., 1988); herein, we investigate how soil morphological characteristics and native and non-native grasses interact with experimental irrigation regimes to control soil moisture on contrasting soils typical of southern Arizona. Responses of soil moisture and vegetation are of particular interest because they embody the local expression of global change phenomena.

Several approaches have been used to examine the response of vegetation to climate change. Paleoecologic and historic studies reconstruct the response of vegetation, ecosystems and plants to climate fluctuations using historic, palynological, and fossil evidence (e.g. Webb, 1981; Archer, 1994; Angell and McClaran, 2001; Lyford et al., 2003). Comparative studies of plants and ecosystems across

environments that differ in soils or climate (in space or time) can represent potential outcomes of sustained climate changes on existing vegetation and species (Brown et al., 1997; Knapp and Smith, 2001; Lyford et al., 2003). Modeling studies capture climate–vegetation interactions in a quantitative way that can be used for simulating responses to different climate change scenarios (e.g. Emanuel et al., 1985; VEMAP Members, 1995; Neilson and Drapek, 1998; Rodriguez-Iturbe et al., 1999). Experimental studies measure vegetation responses to artificially manipulated changes in soil moisture (e.g. Ritchie, 1987; Svejcar et al., 1999; Fay et al., 2000; Weltzin and McPherson, 2000; Yahdjian and Sala, 2002).

Rainout shelters coupled with irrigation represent a robust technique to modify the quantity and/or seasonality of moisture input at the individual plant or stand level with minimal impact on other variables such as air and soil temperature, humidity and light (Owens, 2003). Experimental manipulations of precipitation add value to paleoecologic and modeling studies by refining our understanding of the mechanisms that govern vegetation responses to climate change. For example, rainout shelters can be used to separate the roles that demography, resource use, and species interactions play in shaping vegetation responses to altered moisture availability.

In this paper, we present results from experiments conducted under large (162 m<sup>2</sup>) rainout shelters in southern Arizona, USA, designed to investigate interactions between perennial C<sub>4</sub> bunchgrasses [the native *Heteropogon contortus* (L.) Beauv. and the non-native, invasive *Eragrostis lehmanniana* Nees.] and strongly contrasting soil types on soil moisture dynamics periodically over the course of 1 yr, and at high temporal resolution before and after a single, large irrigation event (Fig. 1). In addition, we describe the impact of the rainout shelters on microclimates under the shelters, in terms of light, windspeed, soil temperature, and relative humidity.



Fig. 1. Shelter (9 × 18 m, 4 m tall at apex) on the clay-rich site, open sides are > 1.5 m off the ground. Tall grasses visible beneath the shelter are *H. contortus*. Note the cables attached to the shelter and steel fenceposts for greater wind-stability and polypropylene rope holding down the plastic cover.

## 2. Materials and methods

### 2.1. Site description

The Santa Rita Experimental Range (215 km<sup>2</sup>, 56 km south of Tucson, Arizona) was established in 1903 and is managed by the University of Arizona College of Agriculture and Life Sciences. The SRER maintains a high resolution, spatial and temporal (~100 years) database that records ecological, anthropological and climatic changes (McClaran et al., 2002). Located on the western flank of the Santa Rita Mountains, the SRER is characterized by long, gently sloping alluvial fans of different ages with a few isolated buttes (McAuliffe, 1995). Precipitation varies with elevation across the SRER, from 254 mm yr<sup>-1</sup> in the low (880 m elevation) northwest corner to ~500 mm yr<sup>-1</sup> in the higher southeast corner (1300 m). A rain gauge 1 km from our research field sites has recorded a mean annual precipitation (MAP) of 387 mm yr<sup>-1</sup> (Road Station,  $n = 80$  years). Fifty-four percent of MAP falls as intense convective events during the summer monsoon (July–September). The remainder falls predominantly during the months of October through March (Fig. 2).

As recently as 1920, vegetation over most of the SRER was dominated by a shrub-free grassland (Humphrey and Mehrhoff, 1958). Currently, open stands of *Prosopis velutina* (25–50% canopy cover) are common on younger alluvial deposits with sandy soils and in lower washes. In contrast, only isolated individuals of *P. velutina* (ca. 60/ha, Dan Koepke, pers. comm.; McAuliffe, 1995) are found on the older, clay-rich soils developed on Pleistocene alluvial deposits. Other shrubs, which can comprise up to 60% of the cover at higher elevations, include *Acacia greggii* Gray, *A. angustissima* (Mill.) Kuntze, *Mimosa biuncifera* Benth., *M. dysocarpa* Benth., and *Calliandra eriophylla* Benth. *E. lehmanniana* dominates the herbaceous cover of the SRER (Anable et al., 1992). Other grasses common at our sites include *Bouteloua eriopoda* Torr., *B. curtipendula* (Michx.) Torr., *B. filiformis* (Fourn.) Griffiths,

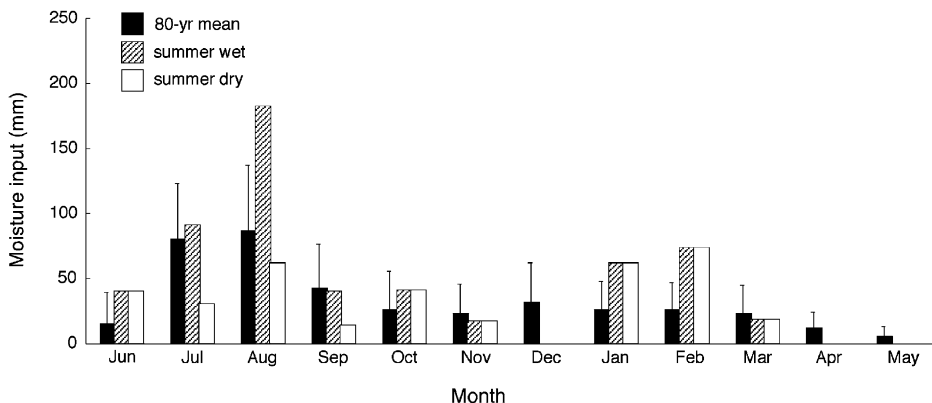


Fig. 2. Comparison of precipitation protocol for the year 2002 with monthly mean natural precipitation ( $n = 80$  years, +1 SE) at Road Station rain gauge <1 km from experimental sites.

*B. chondrosioides* (H.B.K) Benth., *B. hirsuta* Lag., *H. contortus*, *Trichachne californica* (Benth.) Chase, *Aristida hamulosa* Henr., and *A. ternipes* Cav. (McClaran et al., 2002).

Our rainout shelters are located on two sites 1 km apart (31.78°N, 110.88°W). Three shelters each were constructed on middle-Holocene (4–8 ka) and late-Pleistocene (200–300 ka) alluvial fan surfaces (McAuliffe, 1995). The active soil on the middle-Holocene surface is classified as a coarse-loamy, mixed, superactive, non-acid, thermic Ustic Torrifluvent, with 6% clay from 25 to 100 cm (Don Post, unpublished report). This loamy-coarse sand is rapidly permeable and relatively homogeneous compared to soils on the Pleistocene surface. The active soil on the late-Pleistocene surface is classified as a fine, mixed, superactive, thermic-Ustic Haplargid with 50% clay from 25 to 60 cm depth under a shallow sandy-loam surface (Don Post, unpublished report). The sand- and clay-rich soils (as we will refer to the Holocene and Pleistocene surfaces, respectively, throughout this paper) are on gentle slopes (2%) at elevations of 1070 and 1110 m, respectively.

## 2.2. Shelters and plot installation

In April 2002, we completed construction of the six shelters (using materials from CoverIt, New Haven, CT, USA) that exclude natural precipitation from the plots (Fig. 1). These inexpensive shelters were designed to withstand temperatures above 46 °C, wind gusts in excess of 36 m s<sup>-1</sup>, and >260 days of sunshine per year. The open-sided, open-ended shelters were constructed >9 m apart over each block of plots and constructed of 12-gage steel tubing bolted to hardened-steel fence posts driven into the ground. The shelters are 9.1 m wide by 18.3 m long and cover 167 m<sup>2</sup>. They are 4 m in height at the apex, open up to 1.5 m high on the sides (higher on ends) and are covered by a clear, 6-mil polyethylene film. Poultry wire (0.6 m tall, 2.5 cm mesh) was attached to the legs of each shelter and buried in the soil to ~10 cm to reduce rodent activity inside the plots. Gutters attached to each shelter divert rainwater to covered 7500 l water storage tanks on each site.

In April and May, 2001, we established twelve 1.5 m × 1.8 m plots in each of three blocks (i.e., under each shelter) on each of the sand- and clay-rich soils (72 plots total). We trenched 0.75 to 1 m deep (40 cm wide) around each plot, leaving a pedestal of soil (2.7 m<sup>2</sup>, 2–2.8 m<sup>3</sup>). We constructed, calibrated and installed 216 time-domain reflectometry (TDR, probe length = 17.5 cm) probes that measure volumetric soil water content ( $\theta_v$ ). Each probe is accurate ( $\pm 1\%$ ) as well as inexpensive, durable and easy to build (Ledieu et al., 1986; Risler et al., 1996). Probes were installed horizontally into the side of each plot at 15, 35 and 55 cm; probes were inset 5–10 cm from the vertical face of the soil surface and were backfilled with expanding foam insulation.

After installation of TDR probes, the trench faces were lined with black 6-mil PVC film attached to wooden frames set at ground level. The wooden frames bound each plot and extend 4.4–10 cm above-ground level and are sealed at the corners. They were designed to hold the plastic film up during backfilling and to prevent water from flowing onto or off of the surface of the plots during irrigation. During

plot excavation and backfilling, we minimized disturbance to the soil surface within the plot by leaving vegetation litter in place and covering the surface with plywood sheathing—the  $A_v$  horizon, a vesicular horizon at the surface common to arid soils, was carefully uncovered in each plot after construction.

### 2.3. Experimental design

Our rainout shelters were designed and built to cover numerous plots in which a wide array of variables could be manipulated in a statistically valid manner. Each of the 12 plots in each shelter (block) was randomly assigned to one of three vegetation cover treatments (*E. lehmanniana*, *H. contortus*, or bare) and one of two irrigation treatments (50% greater than average summer-moisture input, 50% less than average summer-moisture input). Each treatment combination was replicated six times on each of the two soil types and twice beneath each shelter in a randomized, complete-block design.

In June and July of 2001, we carefully removed all above-ground vegetation from plot surfaces after applying a non-specific contact herbicide (glyphosate), and transferred 56 greenhouse-grown grass seedlings into the appropriate plots (at  $\sim 20$  cm spacing and 21 plants  $m^{-2}$ ), at least 15 cm from the edge of the plot. We also added a mixture of dried leaf and culm litter from *E. lehmanniana* and *H. contortus* to each plot to simulate the natural litter component. To prevent litter from being blown off the bare plots, and to aid in future studies of plant demography, we inserted 138 colored nails 3–4 cm into the ground at regular intervals in every plot. An organophosphate insecticide was used sparingly on all plots twice a year during the growing season (March–November) to reduce insect herbivory.

Our irrigation protocols were designed to test the influence of seasonal precipitation amount on production, composition, and demography of grasses and, later, establishment of woody plants. We used a statistical software program, CLIGEN, developed by the USDA-ARS (Southwest Watershed Research Station, Jeff Stone, pers. comm.; Nicks and Lane, 1989), to generate a typical annual precipitation regime (with daily resolution) based on daily, long-term records from a given weather station (Tumacacori, AZ; NWS #02 8865, 31.6°N, 111.1°W, 996 m). Briefly, CLIGEN calculates the probability of rain falling on any given day in the year based on empirically derived probabilities that rain will precede or follow any given rainfall event (Nicks and Lane, 1989). The irrigation regime we used included 34 events each year, with event sizes ranging from 1 to 39 mm. The irrigation treatments were established based on a target 50% decrease or increase, depending on treatment, to each event occurring between July and September. These regimes correspond roughly to the HADCM2 and RegCM model predictions for the region (NAST, 2000; Giorgi et al., 1998, respectively). From October to June, the plots received equal amounts of water. Watering dates and amounts are the same from year to year (Fig. 2). Water is applied by hand using a pump, 1.9 cm diameter hose and garden-type sprayer head at a rate of  $\sim 28$   $l\ min^{-1}$  ( $0.2\ mm\ s^{-1}$ ) and measured with a digital totalizer (accuracy  $\pm 1.5\%$ , McMaster-Carr, Atlanta, GA) fitted between the hose and the sprayer. Water was applied evenly over the plot and runoff

during irrigation was prevented by the plot boundaries. Our experimental design does not allow us to account for the canopy-to-interspace infiltration ratio between vegetated and bare plots although other studies suggest the ratio is closer to unity in grasslands (Bhark and Small, 2003). When available we irrigated with precipitation collected on site, but the majority of water applied to the plots was delivered to the sites from a municipal source ( $EC_w < 0.364$  mmhos/cm). On June 10, 2002, as part of the watering protocol, we applied the equivalent of a 39 mm precipitation event to all plots on both soil types. Soil moisture was monitored intensively just before, and for 2 weeks after, this irrigation event.

#### 2.4. Data collection and monitoring

We employed several methods of manual and automatic data collection on this project. During the summer, external and internal temperatures of selected shelters were recorded continuously. Relative humidity (RH %; accuracy  $\pm 3\%$ ) was measured during 2 days using a Kestrel 3000 weather meter (Nielsen–Kellerman, Birmingham, MI). Relative humidity data were collected at 1.5 m above-ground level from the center aisle of each shelter at 1/4, 1/2 and 3/4 distance along the long axis of the shelter. Concurrent measurements of RH were collected up-wind at least 3 m from each shelter. A datalogger (CR-10X, Campbell Scientific, Logan, UT) connected to 20-gage, copper-constantan thermocouples was used to measure soil temperature every 15 min from June 10 to Aug 23, 2002. Data were collected from both sites at depths of 2 and 10 cm in several experimental plots and bare soil external to the shelters, and averaged hourly.

In December 2002 and January 2003, we measured the air temperature, relative humidity and wind velocity at 0.5 and 1.5 m height inside and outside all shelters. Both air and soil temperatures were monitored as in the summer; we measured wind velocity with anemometers (RM Young Wind Sentry Anemometer, Campbell Scientific) and RH with custom-built and calibrated HIH-3610 Humidity Sensors (Honeywell, Morristown, NJ). Air temperature and RH instruments were enclosed in 15 cm, 6-plate radiation shields. These data were collected on a CR-10X datalogger and averaged every 15 min. Interception of PFD (photosynthetic photon flux density) by the grass canopy within each plot was determined seasonally by placing a LI-191SA Line Quantum (LiCor, Lincoln, NE) at  $\sim 5$  cm above the soil surface at three locations (at equal intervals and perpendicular to the long-axis of each plot) within each plot and measuring incident light above the grass canopy immediately thereafter (measurements were only made on clear days). Light interception by the shelters was determined over 12 h of 1 day by using two circular quantum sensors (LI-190SA), placed on level surfaces 36 cm above the ground inside and outside the shelters and data were logged simultaneously. A rain gauge at each site was monitored weekly to record natural precipitation, and a rain gauge  $\sim 1$  km from each site collected continuous monthly rainfall data.

We used a time-domain reflectometer (TDR100, Campbell Scientific) connected to a portable battery and computer to measure  $\theta_v$  biweekly during the growing season and monthly at all other times. Data were collected in the morning to minimize

temperature variations that can affect TDR measurements (Alven and Stenberg, 1995; Halbertsma et al., 1995). For soil-water data collected in June 2002, we converted  $\theta_v$  to gravimetric water content ( $\theta_g$ ) using the bulk density of soil and content of rock fragments (>2 mm) for each soil depth on each surface. We then calculated soil-water potential ( $\psi$ ) using depth and site-specific soil-moisture release curves determined using a WP4 dewpoint potentiometer (Decagon Devices, Inc., Pullman, WA). Soil-moisture release curves were approximated by linear regression ( $r^2 > 0.95$ ) of log–log transformed dewpoint-potentiometer data based on five data points or more. While the  $\psi$  data presented here are robust,  $\psi$  in particular combinations of plot, soil depth and treatment exhibited a strong sensitivity to changes in  $\theta_v$ ; we discuss both  $\theta_g$  and  $\psi$  data and present results common only to both measurements.

### 2.5. Statistical analysis

We performed one-way ANOVA on daily average, maximum and minimum temperatures, RH, and wind velocity from internal shelter and external micrometeorological data (winter values only). Where significant differences were indicated ( $p < 0.1$ ), we used a protected-means separation test (Tukey–Kramer HSD,  $p < 0.05$ ) to determine which shelter measurements differed from their respective external control. Daily micrometeorological values were calculated using Microsoft Access 2000 (v. 9.0.3821, Microsoft Corporation, Redmond, WA) while statistical analyses were performed using the statistical software JMP IN 4.0.3 (SAS Institute Inc., Cary, NC). We used a mixed-model analysis of variance to determine main-fixed, interactive-fixed (vegetation cover treatment, precipitation treatment, site) and random (block) effects on  $\theta_g$  and  $\psi$  for each soil depth on selected dates. Similarly, we used repeated-measures multivariate analysis of variance (MANOVA; Pillai's Trace in SAS procedure GLM) to analyse patterns of  $\theta_g$  and  $\psi$  for each soil depth in response to the June 2002 pulse of soil moisture.

## 3. Results and discussion

### 3.1. Shelter effects on micrometeorological variables

Micrometeorological measurements made during the summer of 2002 and winter of 2002–2003 show that our shelters had a minimal impact on air temperature, RH, and wind speed (Tables 1–3). On the sand-rich site during the summer months, minimum-daily temperatures under the shelters were  $\sim 2^\circ\text{C}$  warmer than external temperatures ( $p < 0.0001$ ), but relative humidity under the shelters was within 3% of external relative humidity (Table 1). In January, the shelters on this site increased mean temperatures by  $\sim 3^\circ\text{C}$  during the early morning, but did not affect daily mean, maximum or minimum temperatures, RH or wind velocity ( $p > 0.11$ , Tables 2 and 3).

On the clay-rich site, summer—mean and maximum—daily temperatures were unaffected by the shelters ( $p > 0.78$ , Table 1). However, summer-daily minimum

Table 1  
Summer temperature and relative humidity at 1.5 m

Micromet Variables	Intersite (External) <sup>a</sup>			Sand-rich shelters <sup>b</sup>			Clay-rich shelters <sup>c</sup>			External	<i>p</i> <sup>d</sup>	External	<i>p</i> <sup>d</sup>
	Sandy	Clay-rich	<i>p</i> <sup>d</sup>	<i>A</i>	<i>B</i>	<i>C</i>	<i>A</i>	<i>B</i>	<i>C</i>				
Mean (°C)	27.3±0.4	26.5±0.4	0.13	29.9±0.4	30.1±0.4	—	29.4±0.4	0.45	—	26.7±0.6	—	26.5±0.6	0.78
Maximum	36.0±0.6	33.0±0.6	0.0004	36.5±0.5	36.7±0.4	—	37.8±0.5	0.10	—	32.6±0.8	—	32.9±0.8	0.79
Minimum	19.8±0.3	20.2±0.3	0.26	23.0±0.3	23.1±0.3	—	21.0±0.3	<0.0001	—	21.0±0.3	—	20.0±0.3	0.02
RH (%) <sup>e</sup>	—	—	—	46.3±0.3	43.7±0.7	41.7±0.3	43.8±0.6	—	24.0±1.2	28.0±1.7	25.0±0.6	23.3±3.5	—

*A*, *B* and *C* denote shelter replicate.

<sup>a</sup>Measured between July 20 and August 27.

<sup>b</sup>Measured between June 20 and July 23.

<sup>c</sup>Measured between July 19 and 26.

<sup>d</sup>Is the all-way ANOVA *F*-statistic. Italic numbers denote shelter variables that differ from their external counterparts (Tukey–Kramer HSD, *p*<0.05). Values are daily means±1 SE.

<sup>e</sup>Was collected on July 15, 2002.

Table 2  
Winter temperature, relative humidity, wind speed and light interception at 0.5 m

Micromet variables	Sand-rich shelters					Clay-rich shelters				
	<i>A</i>	<i>B</i>	<i>C</i>	External	<i>p</i> <sup>a</sup>	<i>A</i>	<i>B</i>	<i>C</i>	External	<i>p</i> <sup>a</sup>
Mean temperature (°C)	11.4±1.1	11.3±1.1	10.2±1.1	9.9±1.1	0.69	13.6±0.3	13.8±0.3	14.2±0.2	13.7±0.3	0.34
Maximum	23.9±1.1	24.5±0.9	24.8±0.9	22.5±0.9	0.35	27.1±0.4	26.7±0.4	27.4±0.4	26.1±0.5	0.17
Minimum	1.2±1.1	2.6±1.1	2.6±1.1	1.3±1.2	0.68	3.3±0.4	4.0±0.4	3.9±0.4	3.5±0.4	0.55
Mean relative humidity (%)	48.0±3.6	44.4±3.7	46.1±3.6	47.6±3.8	0.88	36.1±2.1	34.3±2.1	35.1±2.1	34.2±2.2	0.91
Maximum	73.1±4.9	67.9±5.1	69.8±5.0	71.9±5.1	0.89	57.6±4.0	54.4±3.9	56.2±4.1	56.1±4.2	0.96
Minimum	19.4±0.9	17.9±0.9	19.2±0.9	19.5±0.9	0.65	18.2±1.1	17.2±1.0	17.5±1.0	16.4±1.1	0.70
Mean wind speed (ms <sup>-1</sup> )	0.54±0.09	0.58±0.05	0.72±0.05	0.58±0.09	0.13	0.54±0.05	0.54±0.05	<i>0.94±0.05</i>	0.54±0.05	<0.0001
Maximum	1.48±0.36	1.97±0.22	1.88±0.18	1.97±0.31	0.54	1.48±0.18	1.70±0.18	<i>2.46±0.18</i>	1.61±0.18	0.0027
Mean light transmitted <sup>b</sup> (%)	73	77	80			77	80	71		
Solar noon (11:30 a.m. to noon) <sup>c</sup> (%)	75	82	85			93	87	81		

Temperature, RH, and wind speed values are based on measurements from cloud free days between December 27 and January 30. *A*, *B* and *C* denote shelter replicates. Values are daily means±1 SE.

<sup>a</sup>The All-way ANOVA *F*-statistic. Italic numbers are the same as in Table 1.

<sup>b</sup>Light values are from measurements (*n* = 12) taken every hour between 6:10 a.m. and 5:07 p.m. on November 1, 2002 and represents PPFD transmitted through the shelters and includes shadows cast by structural elements.

<sup>c</sup>The maximum percent light transmitted through the shelter during any measurement period.

Table 3  
Winter temperature and relative humidity at 1.5 m

Micromet variables	Sand-rich shelters					Clay-rich shelters				
	<i>A</i>	<i>B</i>	<i>C</i>	External	<i>p</i> <sup>a</sup>	<i>A</i>	<i>B</i>	<i>C</i>	External	<i>p</i> <sup>a</sup>
Mean temperature (°C)	9.9±1.1	10.7±1.1	10.9±1.1	9.7±1.1	<i>0.82</i>	13.2±0.3	13.3±0.3	13.9±0.3	13.7±0.3	<i>0.19</i>
Maximum	23.7±1.0	23.6±0.9	23.8±0.9	20.9±1.0	<i>0.12</i>	26.0±0.4	25.3±0.4	26.5±0.4	24.6±0.4	<i>0.01</i>
Minimum	1.2±1.1	2.2±1.1	2.4±1.1	1.7±1.1	<i>0.85</i>	3.0±0.4	3.9±0.4	3.8±0.4	4.3±0.4	<i>0.17</i>
Relative humidity (%)	50.6±3.7	46.3±3.7	44.6±3.6	48.0±3.7	<i>0.65</i>	38.5±2.2	35.9±2.1	33.5±2.1	34.0±2.2	<i>0.36</i>
Maximum	75.1±4.8	69.6±5.1	67.7±5.1	70.9±4.9	<i>0.74</i>	60.4±4.1	56.0±4.0	54.1±4.0	53.8±4.0	<i>0.65</i>
Minimum	1.2±1.1	2.2±1.1	2.4±1.1	1.7±1.1	<i>0.11</i>	20.5±1.1	19.2±1.1	16.8±1.1	18.2±1.1	<i>0.13</i>

Temperature, RH, and wind speed values are based on measurements from cloud free days between December 27 and January 30. *A*, *B* and *C* denote shelter replicates. Values are daily means ± 1 SE.

<sup>a</sup>Is the all-way ANOVA *F*-statistic. Italic numbers are the same as in Table 1.

temperatures were about 1.0 °C greater under the shelters than outside the shelters ( $p < 0.02$ , Table 1). Differences in air temperatures between the shelters and external locations were greatest between 10 a.m. and 3 p.m., when mean temperatures under the shelters were 0.75–1.0 °C higher than outside the shelter. However, these differences were small compared to normal diurnal fluctuations during the summer and winter (~16 and 20 °C, respectively) and are comparable to effects observed in shelters used in other studies (Yahdjian and Sala, 2002). Relative humidity during the summer under the shelters was within 5% of external relative humidity.

On the clay-rich site in January, two of the three shelters did not appreciably alter microclimates ( $p > 0.13$ , Tables 2 and 3). However, mean- and maximum-wind velocities ( $p < 0.003$ ), and maximum-daily temperature at 1.5 m ( $p < 0.01$ ), were greater under the third shelter than locations outside the shelter; the reason for these differences among shelters could not be determined.

The effects of the precipitation shelters on microclimate were greater at the sand-rich site than the clay-rich site. The greater density of mature *P. velutina* trees on the Holocene surface likely reduces surface wind velocity at this site and thereby allows temperature and RH beneath these shelters to vary from external measurements more than under the shelters on the clay-rich soil. This is supported by our assessments of air temperature external to the shelters on each site: although mean- and minimum-daily air temperatures during July and August did not differ between the two sites ( $p > 0.13$ ), maximum daily air temperature was 2.9 °C greater at the sand-rich site than at the clay-rich site ( $p < 0.0004$ ).

Averaged over the course of a day, our shelters intercepted 24% of PPFD (Table 2). However, light interception by the shelters was greatest in the morning and afternoon, whereas at solar noon only about 16% of PPFD was intercepted. Reduction of PPFD by our shelters is comparable to that observed in other shelter studies (Fay et al., 2000; Weltzin and McPherson, 2000; Yahdjian and Sala, 2002). Soil temperatures at depth varied only slightly during the growing season. At 10 cm, the greatest daily temperature variation over the growing season is <10 °C in a typical bare plot on the sand-rich soil ( $n = 91$  days; English et al., 2003). Based on a best-fit polynomial regression of 2 and 10 cm maximum-soil temperature differences over the entire growing season in the sand-rich soil, the variations at 15, 35 and 55 cm depths were 11, 2 and 0.2 °C, respectively. Likewise, variations of maximum-soil temperature in the clay-rich soil at 15, 35 and 55 cm depths were 13, 3 and 0.5 °C, respectively. Average daily ranges in soil temperature were even smaller.

### 3.2. Plant responses to experimental irrigation

At the end of the first growing season, grass density and interception of PPFD by the grass canopy were dependent on soil texture, vegetation cover, and irrigation treatments (Table 4). After one summer of irrigation treatment: (1) grasses intercepted more light on the summer-wet than on summer-dry plots, with the exception of *H. contortus* on the clay-rich soil; (2) the *H. contortus* canopy intercepted more light than the *E. lehmanniana* canopy on both soil types, although (3) the density of *E. lehmanniana* was about equal to (on the sand-rich soil) or greater

Table 4  
Grass population, light interception and soil moisture

	Grass population (plants/m <sup>2</sup> ) <sup>a</sup>		Light interception (% PPFD) <sup>b</sup>	
	Dry summer	Wet summer	Dry summer	Wet summer
Sand-rich soil				
<i>E. lehmanniana</i>	17.7±1.1	17.2±0.9	18±2	28±3
<i>H. contortus</i>	16.6±0.4	16.0±0.4	42±4	57±2
Clay-rich soil				
<i>E. lehmanniana</i>	19.4±0.3	18.7±0.7	37±4	49±5
<i>H. contortus</i>	14.0±1.1	13.6±1.3	58±6	57±6

Values are means ± 1 SE ( $n = 3$ ).

<sup>a</sup>Plant data collected January 8, 2003.

<sup>b</sup>Grass canopy light interception data was collected on August 7, 2002.

than (on the clay-rich soil) the density of *H. contortus*. These results indicate that individual plants increased in size in response to the watering treatments, and that differences in light interception were not caused by differences in plant density. Observable changes in grass density caused by recruitment within plots would not be expected after only one season of irrigation or during the time period between August and January, but future patterns of recruitment may affect plant density, canopy structure, and resultant microclimatic conditions or soil-water balance. Differences in density between the two species on the clay-rich soil were attributed to mortality of *H. contortus*.

### 3.3. Soil-water response to seasonal irrigation treatments

Gravimetric water content of the soil was affected by soil texture, vegetation cover, and irrigation treatment (Table 5). In February and June, prior to the initiation of summer wet and dry irrigation treatments, there were no differences in soil moisture between irrigation treatments ( $p > 0.1$ ). However, there were differences between grass-cover treatments. In February,  $\theta_g$  of *H. contortus* and bare plots were roughly equal but greater than *E. lehmanniana* on both sites and  $\theta_g$  on the clay-rich soil was three times greater than the sand-rich soil. Soil  $\theta_g$  on all plots on both soils decreased between February and June (Table 5). By June,  $\theta_g$  of *H. contortus* was less than the bare plots but still higher than *E. lehmanniana* and  $\theta_g$  of the clay-rich soil was ten times greater than loamy sand soils. On the clay-rich site in August, after initiation of summer watering treatments, there were differences in  $\theta_g$  between grass-cover treatments at the 15 and 55 cm depths ( $p < 0.10$ ), irrigation treatments at all depths ( $p < 0.002$ ), and interactive effects between grass-cover and watering treatments at 15 cm ( $p < 0.08$ ). On the sand-rich soil in August, there were no differences in  $\theta_g$  between grass-cover treatments ( $p > 0.26$ ) at any depth, but there were strong differences between dry and wet plots at all depths ( $p < 0.002$ , Table 5). Sand-rich soils had lower  $\theta_g$  than clay-rich soils throughout the year ( $p < 0.0001$ ). In

Table 5  
Soil gravimetric water content ( $\theta_g$ )

Soil type	Treatment, depth	February 24, 2002		June 9, 2002		August 18, 2002		November 23, 2002			
		Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet		
Sand-rich	Bare, 15 cm	4.0±0.4	4.1±0.3	1.3±0.4	0.7±0.3	5.4±1.1	8.0±0.3 <sup>†</sup>	2.7±0.8	2.2±0.4		
		35 cm	3.6±0.5	3.2±0.3	1.7±0.5	1.8±0.2	3.6±1.0	6.0±0.8	2.5±0.6	1.7±0.3	
		55 cm	3.7±1.3	3.2±0.7	2.7±0.8	3.2±0.7	4.1±1.9	7.1±0.7	3.4±1.2	2.9±0.9	
	<i>E. lehmanniana</i> , 15 cm	3.2±0.3	2.8±0.2	0.5±0.2	0.5±0.2	3.7±1.1	7.7±0.5 <sup>†</sup>	1.6±0.3	1.8±0.4		
		35 cm	2.3±0.4	2.6±0.7	1.0±0.2	1.6±0.6	1.6±0.4	7.2±0.5*	2.2±0.5	2.2±0.6	
		55 cm	2.6±0.5	2.7±0.8	2.0±0.4	2.1±0.6	2.6±0.4	7.8±1.8 <sup>†</sup>	3.1±0.7	3.0±0.7	
	<i>H. contortus</i> , 15 cm	3.6±0.1	3.9±0.3	0.9±0.3	0.9±0.3	3.5±0.9	7.6±0.4 <sup>†</sup>	1.5±0.3	1.4±0.2		
		35 cm	2.6±0.4	3.3±0.3	0.9±0.1	0.9±0.3	1.4±0.2	5.4±1.0*	1.3±0.2	1.2±0.3	
		55 cm	2.0±0.4	2.4±0.7	1.5±0.5	1.7±0.4	1.8±0.4	6.4±1.4*	1.5±0.4	1.4±0.5	
	Clay-rich	Bare, 15 cm	12.9±0.9	11.3±0.6	10.6±1.3	8.5±0.5	13.5±0.6	13.5±0.6	12.0±0.8	9.7±0.6 <sup>†</sup>	
			35 cm	15.9±0.6	15.7±1.6	16.8±1.7	14.5±1.2	17.1±1.2	18.7±1.7	15.5±0.9	14.0±0.7
			55 cm	14.2±0.6	14.1±0.9	14.3±0.6	14.3±1.6	15.7±0.9	17.8±1.5	13.5±0.7	12.9±1.0
<i>E. lehmanniana</i> , 15 cm		7.9±1.4	8.7±0.7	5.0±1.3	5.5±0.8	7.8±2.1	12.7±1.0 <sup>†</sup>	6.3±1.5	6.8±1.1		
		35 cm	14.3±1.2	12.1±0.7	11.0±0.9	10.2±1.1	13.8±1.9	15.6±0.8	12.1±0.7	10.1±1.0	
		55 cm	11.2±0.9	12.0±1.0	9.9±1.0	10.2±0.6	11.4±1.0	15.8±2.1	9.9±0.8	9.5±0.4	
<i>H. contortus</i> , 15 cm		11.2±0.9	10.3±1.0	7.5±0.9	6.1±0.9	8.6±1.2	14.5±1.1*	8.1±0.8	6.8±0.9		
		35 cm	15.2±1.4	16.5±0.8	13.6±1.6	12.8±0.3	13.4±1.4	21.1±1.8*	12.0±1.0	11.9±0.2	
		55 cm	11.8±0.9	12.0±0.6	11.0±1.0	11.0±0.4	11.5±0.8	15.9±0.9*	9.8±0.7	9.5±0.2	

\*Indicates difference from summer dry water treatment  $p < 0.05$  on the same day. <sup>†</sup>Indicates difference at  $p < 0.1$ .

November, *E. lehmanniana* and *H. contortus* have similar  $\theta_g$  but are still four times less than the  $\theta_g$  of bare plots. These seasonal magnitude changes of soil moisture differences between vegetative treatments suggest the differential activity of grasses depending on season.

### 3.4. Soil-water response to a precipitation pulse event

#### 3.4.1. Pre-pulse $\theta_g$ and $\psi$

On June 9, the day prior to the addition of the water pulse, we found differences in soil moisture between soil textures, vegetated and bare plots, and between *E. lehmanniana* and *H. contortus* plots (Fig. 3, Table 6). Sand-rich soils had much lower  $\theta_g$  and  $\psi$  than clay-rich soils at all depths. At both sites, mean  $\theta_g$  increased with depth. On the sand-rich soil, where soil texture was relatively homogeneous throughout the soil profile, this increase in  $\theta_g$  also increased  $\psi$ , which is a measure of water available to plants. However, on the clay-rich soil, increased clay content with depth in the soil actually reduced  $\psi$  while  $\theta_g$  increased (Fig. 3). On both soils, bare plots had greater  $\theta_g$  and  $\psi$  at all depths than did plots with either *E. lehmanniana* or *H. contortus*. Generally,  $\theta_g$  and  $\psi$  of soils—at all depths on the clay-rich soil and at 15 cm on the sand-rich soil—in plots with *E. lehmanniana* were either equal to or lower than soils in plots with *H. contortus*. At 35 and 55 cm on the sand-rich soil,  $\theta_g$  and  $\psi$  in plots with *E. lehmanniana* were greater than plots with *H. contortus*. This suggests that on the clay-rich soil, *E. lehmanniana* may be more effective than *H. contortus* at either removing soil moisture from all depths or preventing infiltration of soil moisture down through the soil profile. Alternatively, evaporative losses of water from plots of *E. lehmanniana* may have been greater than *H. contortus* (Huxman et al., 2004). On the sandier soils, *H. contortus* may have been more effective than *E. lehmanniana* at removing moisture, particularly from deeper depths in the soil.

#### 3.4.2. Post-pulse $\theta_g$ and $\psi$

The dynamics of the irrigation pulse at all soil depths were affected by both soil textures and the grass-cover treatments (Fig. 3, Table 6). On both sites, increases in  $\theta_g$  and  $\psi$  after the irrigation event were most obvious in shallow soil layers and were dampened with depth. Regardless of grass type, vegetated plots at 15 cm on both sites show rapid declines in  $\theta_g$  2 days after the pulse ( $-0.5\%/day$ ) compared to bare plots ( $-0.2\%/day$ ). Furthermore, in the clay-rich soil at 15 and 35 cm depth,  $\theta_g$  in *E. lehmanniana* plots declined more rapidly ( $-0.8\%/day$ ) than in *H. contortus* plots ( $-0.5\%/day$ ). At 55 cm depth on the well-drained loamy coarse sand, vegetated plots were nearly as dry as bare plots. However, on the clay-rich soils at the same depth, *E. lehmanniana* and *H. contortus* plots were drier ( $\psi$ ) than bare plots ( $\alpha < 0.05$ ). We attribute this difference to the lower hydraulic conductivity of clay-rich soils, whereas on the sand-rich soils, a greater proportion of the water pulse percolated below the root level before the grasses could use this moisture.

Differences in  $\psi$  due to grass cover ( $p < 0.08$ ) were also seen at 35 cm depth over the course of the 12-day measurement period (Table 6). At this depth on the

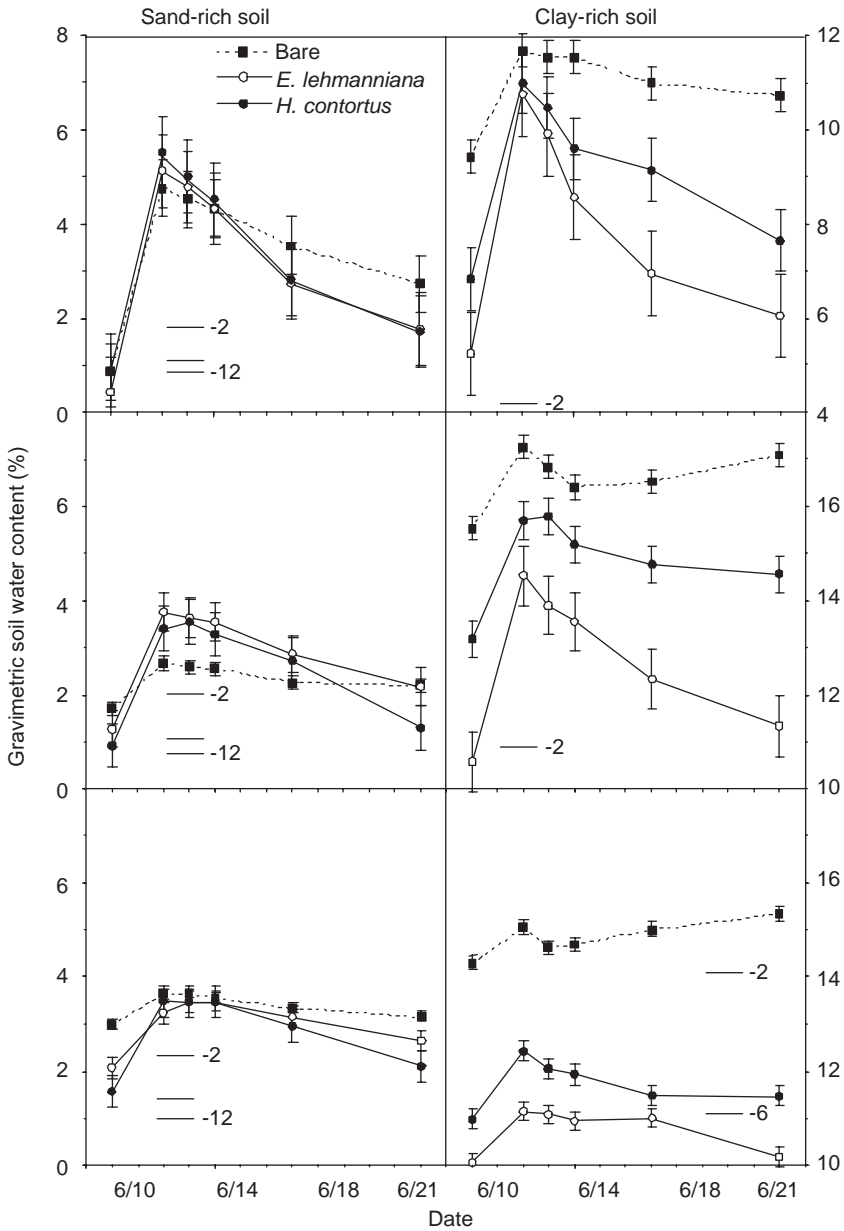


Fig. 3. Mean percent gravimetric water content ( $\theta_g$ ) of sand-rich and clay-rich soils at 15 cm (top panels), 35 cm (middle panels) and 55 cm (bottom panels) depth for three grass-cover treatments. The 39 mm water pulse was applied on June 10, 2002. Error bars are 1 standard error ( $n = 3$ ). Horizontal bars within panels represent soil water potential ( $\psi$ ) thresholds at  $-2$ ,  $-6$  and  $-12$  MPa for an equivalent  $\theta_g$ . Note that vertical scale differs between panels.

Table 6  
Differences in soil water potential ( $\psi$ ) for June 9–June 21, 2002

Treatment	15 cm	35 cm	55 cm
Site	<i>0.0005</i>	<i>0.0003</i>	<i>0.0002</i>
Plant	0.3	0.02	0.19
Site by plant	0.37	0.76	0.02
Date	<i>&lt;0.0001</i>	<i>0.0005</i>	<i>0.03</i>
Date by site	<i>&lt;0.0001</i>	0.07	0.68
Date by plant	<i>0.005</i>	<i>0.005</i>	0.57
Date by site by plant	<i>0.08</i>	<i>0.003</i>	0.71

Significant  $p$ -values ( $\alpha < 0.1$ ) are italicized.  $P$ -values are from a CRD/MANOVAR analysis of site by plant by date interactions run by depth. Any values lower than  $-40$  MPa were removed prior to the analysis.

sand-rich soil, large positive changes in  $\psi$  occurred rapidly on *E. lehmanniana* and *H. contortus* plots when compared to bare plots. Twelve days after the pulse, the grass-covered plots (at 35 cm) had apparently dried more quickly than the bare plots (although only *H. contortus* plots differed from bare plots,  $p < 0.05$ ). On the clay-rich soil, averaged across the pulse,  $\psi$  at 15 cm within *E. lehmanniana* plots was lower than in bare plots ( $p < 0.05$ ); at 35 cm,  $\psi$  was lower than either *H. contortus* or bare plots ( $p < 0.05$ ).

#### 4. Conclusion

Our rainout shelters had minimal effects on air and soil temperature, RH, and wind velocity; this was likely facilitated by the open sides and ends of each shelter. Observed reductions in PPFd varied diurnally, and though at times substantial, affected experimental units equally, and are commensurate with rainout shelters used in similar studies (Fay et al., 2000; Weltzin and McPherson, 2000; Yahdjian and Sala, 2002).

Our data show significant differences in the use and movement of soil water after a moisture pulse. We found that a 39 mm rainfall event applied in early June affects  $\theta_g$  and  $\psi$  as deep as 55 cm, depending on soil texture and presence and identity of grasses. Moreover, two ecologically important patterns emerge from our data. First, for a given  $\theta_g$ , relatively more water is available to plants at greater depths on the sand-rich soil, whereas on the clay-rich soil water availability is greatest at the surface. That said, the clay-rich soil has consistently higher  $\psi$  than the sand-rich soil. We infer that slower infiltration of water in clay-rich soils on the Pleistocene surface allows grasses to use a greater proportion of pulse water than is lost to drainage compared to sandier soils on the Holocene surface. These data support earlier studies (Noy-Meir, 1973; Sala et al., 1988) that found similar patterns of soil moisture and vegetation on fine and coarse soils. Second, on both soils, vegetated plots lose water more quickly than bare soil, presumably because of transpiration by the grasses (Huxman et al., 2004). Water was lost at equal rates from *E. lehmanniana*

and *H. contortus* plots on the sand-rich soil. However, water was lost at a greater rate on *E. lehmanniana* plots compared to *H. contortus* plots on the clay-rich soil. These patterns have important implications for *P. velutina* seedling establishment and invasion onto sand-rich and clay-rich soils in the desert southwest where there are high densities of grass cover. It may also partly explain the relatively low density of mesquite found on the clay-rich soils of the Santa Rita Experimental Range and why clay-rich soils in Arizona may be less susceptible to future woody plant invasions in a changing climate.

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