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Soil Temperature and Moisure Dynamics After Experimental Irrigation on Two Contrasting Soils on the Santa Rita Experimental Range: Implications for Mesquite Establishment

Abstract: We established a large-scale manipulative experiment in a semidesert grassland on the Santa Rita Experimental Range to determine how the recruitment and physiology of woody plants (*Prosopis velutina* Woot.) are affected by invasive grasses, seasonal precipitation regimes, and underlying soil characteristics. We established 72 2.8-m^2 plots beneath six large rainout shelters divided evenly between a clay-rich and a sandy loam soil less than 1 km apart. Monospecific stands of the the invasive African grass *Eragrostis lehmanniana* and the native grass *Heteropogon contortus* were established into four plots each, and four plots were left bare under each shelter. Our watering protocol simulated 50 percent increases and decreases in average summer precipitation. Here we compare soil water content and temperature in *Eragrostis* and bare plots during a large, isolated irrigation event that we applied to the plots in June 2002. Daily average and maximum temperatures near the soil surface declined following the irrigation compared to nonirrigated, external plots, and were cooler for several days afterwards. Soil moisture contents declined and maximum soil temperatures increased more rapidly in plots dominated by *Eragrostis* than in bare plots. Near-surface soil temperatures are apparently too high for establishment of *Prosopis* seedlings in June prior to the onset of summer rains. *Eragrostis* may further prevent successful *Prosopis* establishment by shortening the period over which moisture and soil temperatures are suitable for germination and survival of *Prosopis* seedlings following a pulse of summer rain.

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Introduction

The demography of woody plants within Southwestern savannas and grasslands is constrained by factors that affect seedling establishment and survival, and ultimately, recruitment of individuals into the population (Grubb 1977; Harper 1977; Hochberg and others 1994; McPherson 1997; Scholes and Archer 1997; Weltzin and McPherson 1999). On local scales, biotic (for example, neighboring individuals, herbivory) and edaphic factors and disturbance (for example, fire) are important determinants of vegetation patterns (Archer and others 1995; Prentice 1986). However, at larger scales abiotic constraints (for

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example, regional or global climate change) may be more important than biotic constraints on woody plant establishment. In sum, woody plant population dynamics within any given grassland, savanna, or woodland are affected by the interaction between biotic and abiotic factors operating at a variety of spatial and temporal scales.

Using large rain-out shelters (fig. 1), we are investigating many of the factors that may determine the relative abundance and distribution of woody plants within grasslands and savannas of Western North America. Specifically, we are examining the effects of geomorphic/edaphic substrates, native versus nonnative grasses, and the seasonality of precipitation on the recruitment and physiology of mesquite (*Prosopis velutina* Woot.) and ecosystem gas exchange (net photosynthesis and transpiration). We anticipate that each of these factors will influence recruitment rates; however, interactions between these factors, and their relative contributions as constraints on recruitment, are more difficult to predict.

Global temperatures are predicted to increase from 1.4 to 5.8 °C during this century and will likely alter patterns of precipitation over much of the Earth (IPCC 2001). The ecological effects of changing precipitation and temperature regimes will be particularly dramatic in arid and semiarid environments, where water availability most limits the ecosystem productivity and function (Noy-Meir 1973; Weltzin and McPherson 2003). In the Southwestern United States, two different regional climate models predict increased temperatures, but predict very different changes in the amount and timing of precipitation. The Regional Circulation Model (RegCM) of Giorgi and others (1998) predicts a decrease in the amount of winter precipitation and an increase in summer precipitation. In contrast, the Hadley Circulation Model 2 (HADCM2) developed by the Hadley Centre for Climate Prediction and Research, UK Meteorological Office (NAST 2000), predicts that by 2030 the Southwest will experience drier summers and wetter winters.

Soil temperature, and the effect of precipitation on soil temperature, can influence the germination rate and survival of woody species that grow in semiarid and arid environments (Scifres and Brock 1969). In southern Arizona, maximum daily, near-surface (0.5 cm) soil temperatures frequently exceed 50 °C and have been measured up to 61 °C (Cable 1969). After scarification, mesquite seeds require both moisture and an optimal temperature (29 °C) to emerge and survive on the soil surface (Scifres and Brock 1969). During the summer monsoon, precipitation increases soil moisture and decreases soil temperatures at the surface (Abbot 1999). The soil dries and returns to prerain temperatures very rapidly following a single rain event, leading to seedling death if the seedling has not had time to establish roots in deeper soil layers. Therefore, changes in the frequency of precipitation will likely have direct impacts on recruitment of mesquite by regulating soil temperature and moisture during the summer months. Here we present data that suggests a decrease in the frequency of summer precipitation, or the presence of *Eragrostis,* may lead to longer periods between rain events over which soil temperature is above the optimal range for *Prosopis* seedling recruitment on the Santa Rita Experimental Range.

Methods and Materials

Site Description

Our rainout shelters are located on two sites 1 km apart (N 31.78°, W 110.88°) on the Santa Rita Experimental Range. Three shelters each were constructed on middle-Holocene (4-8 ka) and late-Pleistocene (200-300 ka) alluvial fan surfaces (McAuliffe 1995). The middle Holocene soil is a loamy coarse sand, while the Pleistocene soil contains up to 50 percent clay beneath a shallow (0 to 25 cm) sandy loam surface. Both sites are on gentle slopes (2 percent) at about 1,100 m elevation.

Figure 1—Shelter (9 by 18 m, 4 m tall) on the Pleistocene site; open sides are 1.5 m off the ground. Tall grasses visible beneath the shelter are *Heteropogon contortus*. Note the cables attached to the shelter and steel fenceposts for greater wind stability, and polypropelene rope holding down the plastic cover.

Shelter and Plot Installations

In April and May 2001, we established twelve 1.5- by 1.8-m plots in each of three shelters on Holocene and Pleistocene surfaces (72 plots total). The 12 plots in each shelter were randomly assigned to one of three vegetation cover treatments (*Heteropogon contortus* (L.) Beauv., *Eragrostis lehmanniana* Nees., or bare) and one of two precipitation treatments (50 percent wetter than average in summer, 50 percent drier than average in summer). In June and July of 2001, we carefully removed all aboveground vegetation from plot surfaces and transferred 56 greenhouse-grown grass seedlings into the appropriate grass plot (in a regular grid with about 20 cm spacings, 21 plants per m^2). We trenched each plot to >0.75 m depth (40 cm wide), leaving a pedestal of soil (2.7 m^2, > 2 m^3). Time-domain reflectometry probes (Ledieu and others 1986; Risler and others 1996; TDR) that measure soil volumetric water content (Θ_v) of soil were installed horizontally into the side of each plot at 15, 35, and 55 cm depths. After TDR installation, the trench faces were lined with black 6-mil PVC film attached to wooden frames (10 cm tall) that sit at ground level. The plastic and frames were designed to prevent horizontal subsurface flow out of the plots and surface runon to and runoff from the plots. Twenty-gage, copper-constantan thermocouples (0.5 cm long and epoxy coated) were installed at 2 and 10 cm soil depth to measure soil temperature in two *Eragrostis* plots, two bare plots, and one unwatered and one bare plot outside the shelters (as controls) on each site. Care was taken to bury the first 10 cm behind the thermocouple junction at a depth equal to the desired measurement depth to prevent heat from direct sunlight on the wire from travelling along the cable to the thermocouple junction.

Data collection

A datalogger (CR-10X, Campbell Scientific, Logan, UT) connected to the soil thermocouples was used to measure temperature every 15 minutes and averaged hourly from June 10 to June 21, 2002. To account for variations in thermocouple temperatures and reduced radiative load on soils under the shelters caused by interception of light by the shelters (less than several degrees Celsius), we cross-calibrated experimental plot thermocouples to thermocouples at the same depth in the control plots. We cross-calibrated the thermocouples at a time when we expected soil temperature in and outside the shelters to be similar (a daily mean temperature on June 25, 2002). We used a commercially available cable tester (TDR100, Campbell Scientific) connected to a portable battery and computer to measure Θ_v from the TDR probes in the field. We determined the average bulk-density and the rock-fragment fraction from each site at the relevant depths to convert Θ_v to gravimetric water content (Θ_g).

Irrigation

Our precipitation protocols were designed to test the influence of seasonal precipitation amount and pattern on production, composition, and demography of grasses and, at a later date, establishment of woody plants. For the soil temperature and moisture data presented in this paper, we applied the rainfall equivalent of 39 mm of water to each plot on the evening of June 10, 2002. Water at 26 °C was applied manually at a rate of about 28 l min^{-1} and measured with a digital totalizer (accuracy ± 1.5 percent) connected to a gas-powered water pump.

Results and Discussion

While scarification, ample moisture, and a thin layer of soil are prerequisites for *Prosopis* seedling establishment, soil temperature also exerts a strong influence (Scifres and Brock 1969, 1972). Scifres and Brock (1969) found that the optimum temperatures for establishment of honey mesquite (*Prosopis glandulosa* Torr. *var glandulosa*) seedlings were 29 °C, and that temperatures below 21 °C and above 38 °C led to reduced emergence rates and greater sensitivity to soil moisture stress. Although mesquite may germinate at temperatures greater than 38 °C, they will not survive in these temperatures for more than 10 days at soil water potentials less than –0.2 MPa (Scifres and Brock 1969). Typically, our research plots on the Holocene and Pleistocene soils reach this moisture threshold at Θ_g values of 5 percent and 9 percent, respectively (Schwinning, unpublished data).

Prior to watering in early June, mean daily soil temperatures on both sites at 2 cm were about 37 °C, and maximum daily temperatures at 2 cm exceeded 42 °C and ranged up to 53 °C (fig. 2). These temperatures are consistent with temperatures measured on a Holocene site by Cable (1969) and are well above the optimum seedling establishment temperature for *Prosopis*. Gravimetric soil moisture content (Θ_g) at 15 cm was less than 1 percent on the Holocene plots, and was 9 percent and 6 percent on bare and *Eragrostis* plots, respectively, on the Pliestocene plots prior to irrigation. For all plots, Θ_g measured at 15 cm was likely higher than at 2 cm depth.

The watering event reduced soil temperatures and increased Θ_g on all plots, but soil temperatures and Θ_g recovered to prewatering values more quickly on *Eragrostis* plots (fig. 2) than on bare plots. Mean daily soil temepratures on both sites remained near the optimum seedling recruitment temperature (29 °C) for less than 2 days. Watering reduced both maximum and mean daily soil temperatures on the Holocene and Pleistocene soils at 2 cm by up to 20 and 11 °C, respectively, compared to the control plots. Recovery of mean temperatures to >30 °C occurred within 2 days after the precipitation event on vegetated and bare plots regardless of site or the presence or absence of *Eragrostis*. Recovery of daily maximum temperatures to within 20 percent of that in the control plot occurred 3 days after the pulse on both sites. *Eragrostis* plots returned to higher maximum daily temperatures more quickly than did bare plots. Reductions of maximum daily soil temperature in bare plots was observed beyond the 12-day duration of the experiment. Patterns of rewarming at 10 cm depth are similar, but generally occur 1 to 2 days later than at 2 cm.

Gravimetric water content (Θ_g) varied by vegetative treatment and site. Θ_g exceeded 5 percent after watering in both treatments on the Holocene and 9 percent in Pleistocene bare plots for 2 days (fig. 2). Θ_g exceeded 9 percent for the duration of the experiment on Pleistocene bare plots. Although Θ_g in the Pleistocene bare plots was higher (9 percent) than in vegetated plots (6 percent) before the watering

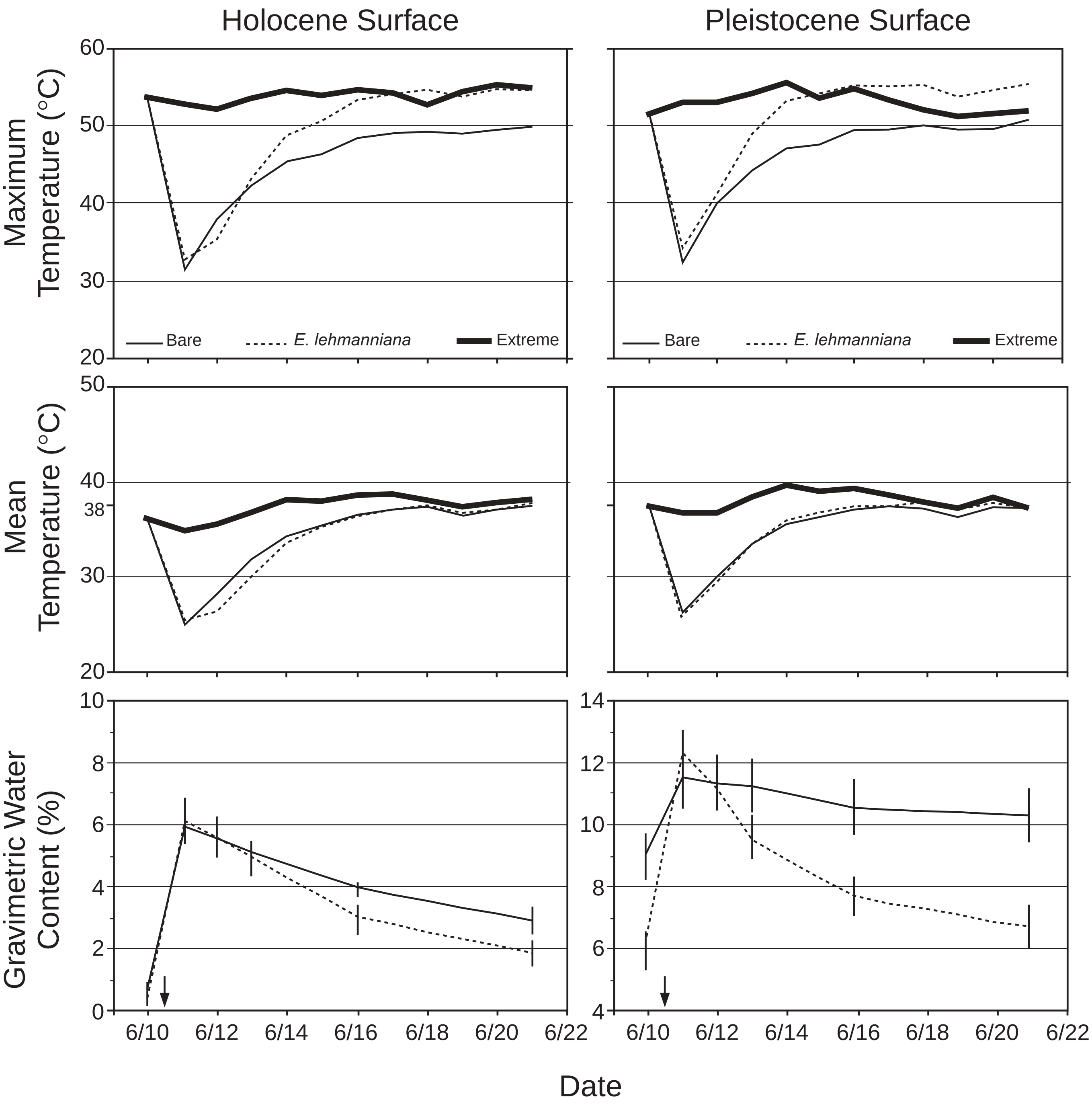

Figure 2—Maximum and mean daily soil temperature at 2 cm depth for Holocene and Pleistocene plots (bare, n = 2; *Eragrostis lehmanniana*, n = 2; external n = 1) and gravimetric water content (Θ_g) at 15 cm depth. Arrow indicates the application of a 39 mm rainfall equivalent water pulse added to the plots between 4 p.m. and 10 p.m. on June 10, 2002. Vertical lines on Gravimetric Water Content graphs represent ± 1 standard error (n > 9).

pulse was applied, both plots had comparable Θ_g (12 percent) immediately following the water addition. Two days after watering, Θ_g in *Eragrostis* plots on both sites was lower than in bare plots at the same site. Six days after watering, Θ_g in *Eragrostis* plots was 1 percent and 3 percent lower than in bare plots on the Holocene and Pleistocene, respectively.

Soil temperatures in excess of 29 °C and very dry soils in late spring and early summer on the SRER make *Prosopis* seedling establishment during this time very difficult. Our data suggest that (1) infrequent storm events in late spring and early summer, while triggering seed germination, will neither wet nor cool the soil at 2 cm or shallower for a long enough period of time to allow for successful seedling establishment; and (2) *Eragrostis* appears to rapidly take up soil moisture and drive maximum daily temperatures up, and reduce the period of time soils remain at optimal temperatures for seedling establishment. Our continuing studies will test the hypothesis that while mean soil temperatures above 21 °C in the upper 2 cm occur between April and October on the SRER, mean soil temperatures over 35 °C coupled with low soil moisture prevent seedling establishment until the onset of the monsoon, when frequent rains consistently wet soils and reduce soil temperatures to the optimum temperature for seedling establishment.

Conclusions

We instrumented several bare and grass-covered plots, and a bare external control plot, on two different soil types with TDR probes and thermocouples at various depths to measure the effect that a pulse of precipitation would have on maximum and mean daily soil temperatures. After an artificially applied precipitation pulse, maximum daily soil temperatures at 2 cm on both sites were depressed by up to 20 °C, and mean temperatures remained near the optimal temperature range (29 °C) for seedling recruitment several days after the pulse. Within 3 to 4 days, mean daily temperatures of soils on both sites had returned to within 20 percent of that in the control plots and well beyond the optimal temperature range for seedling recruitment. Average temperatures in late spring and the premonsoon months are too high for successful *Prosopis* establishment, despite infrequent rains. *Eragrostis* reduces soil moisture and drives up maximum daily temperatures compared to that in bare plots.

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