Hydrologic response to precipitation pulses under and between shrubs in the Chihuahuan Desert, Arizona

M. S. Moran,[1] E. P. Hamerlynck,[1] R. L. Scott,[1] J. J. Stone,[1] C. D. Holifield Collins,[1] T. O. Keefer,[1] R. Bryant,[1] L. DeYoung,[2] G. S. Nearing,[3] Z. Sugg,[4] and D. C. Hymer[5]

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[1] Observations of the temporal and spatial distribution of poststorm soil moisture in open shrublands and savannas are limited, yet they are critical to understanding the interaction and feedback between moisture distribution and canopies. The objective of this analysis was to study the hydrologic impacts of precipitation pulses on the upper layer of soils under and between shrubs. The study was based on measurements of precipitation, runoff, and under- and between-shrub soil moisture over a period of 20 years (1990–2009) at a shrub-dominated site in the Walnut Gulch Experimental Watershed (WGEW) near Tombstone, Arizona. Within much of the root zone (to 30 cm depth), infiltration was not significantly different under versus between shrubs, and the under:between infiltration ratio was not related to pulse size or intensity. However, root-zone soil moisture was significantly higher between shrubs than under shrubs. The soil moisture measured at the surface (at 5 cm depth) was not consistently different under and between shrubs, but the soil moisture measured at depths of 15 and 30 cm were both significantly higher between shrubs than under shrubs. Considering mechanisms that explain the interaction between plants and soil moisture, we found no differences in infiltration, evaporative losses, and surface soil moisture in locations under and between shrubs. This led to the conclusion that lower root-zone soil moisture under shrubs was due largely to greater root density under shrubs than between shrubs. This study adds to the understanding of the impact of precipitation patterns on infiltration and soil moisture in shrub-dominated sites and the potential for vegetation change in arid and semiarid lands.

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1. Introduction

[2] In desert ecosystems, precipitation pulses are a key driver of both biological and hydrological processes [*Noy-Meir*, 1973; *Reynolds et al.*, 2004; *Huxman et al.*, 2004]. In arid systems, the soil remains relatively dry for prolonged periods, broken by infrequent precipitation pulses that can replenish root-zone soil moisture for short periods. During several days following a rain pulse, the soil moisture state is a key factor in plant productivity and reproduction. It follows that the areas best able to capture and retain soil water are also most conducive to vegetation establishment and stability. In this way, the distribution of water from discrete precipitation pulses can determine the vegetation species composition and distribution in arid and semiarid ecosystems [*Archer*, 1994].

[1]Southwest Watershed Research Center, Agricultural Research Service, U.S. Department of Agriculture, Tucson, Arizona, USA.
[2]School of Natural Resources, University of Arizona, Tucson, Arizona, USA.
[3]Department of Hydrology and Water Resources, University of Arizona, Tucson, Arizona, USA.
[4]Department of Geography and Development, University of Arizona, Tucson, Arizona, USA.
[5]NASA Goddard Space Flight Center, Greenbelt, Maryland, USA.

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[3] Previous studies have reported that pulse-related infiltration and root-zone soil moisture are higher under woody plant canopies than in areas between plants in dry lands (most recently, *D'Odorico et al*. [2007], *Bhark and Small* [2003], and *Zeng et al.*, [2004]). This result has been used to hypothesize that there is positive feedback between canopy cover and soil moisture that then explains the preferential establishment of seedlings beneath plant canopies and the stability of woody vegetation distribution patterns [*D'Odorico et al.*, 2007]. However, there remains uncertainty about the universal applicability of the hypothesis that there is greater infiltration under woody plants than between them [*Scholes and Archer*, 1997]. Results show that it may not hold for all shrub canopies at one location and it may be inverted (greater infiltration between shrubs than under them) with larger pulses [*Bhark and Small*, 2003] and in different years [*Kieft et al.*, 1998]. Further, some studies have reported consistently lower root-zone soil moisture under shrubs than between shrubs [*Nowak et al.*, 2004; *McClaran and Angell*, 2007; *Potts et al.*, 2010; *Hamerlynck et al.*, 2010], and most studies limit their conclusions to the soil type, topography, and precipitation pattern where measurements were made [*D'Odorico et al.*, 2007]. Interpretations are further complicated by the inherent differences in woody vegetation architecture (ranging from shrub to tree) and between-canopy conditions (ranging from bare soil to dense grass) in these

studies. Before a generalization can be made, results need to be tested with data from multiple plant canopies, distinct soil textures, and varying microtopography, over many years of different precipitation patterns.

[4] In addition to studying the root zone under and between woody plants, it is important to understand the vertical distribution of water in the soil. The supply and storage of water at critical layers in the soil determine plant germination, establishment, productivity, and persistence [*Mahfouf et al.*, 1996; *Feddes et al.*, 2001; *Hamerlynck et al.*, 2010]. In desert ecosystems, little is known of the impact of shrubs on the pulse-related infiltration depth and vertical soil moisture partitioning. The under- and between-shrub variations in infiltration depth and vertical soil moisture distribution are basically a function of supply and demand. For example, at the soil surface (0–5 cm), water from small precipitation pulses (0–5 mm) can be intercepted by the plant canopy (potentially decreasing the under:between soil moisture ratio) and water intercepted by the soil can be evaporated quickly with a higher radiation load between shrubs (potentially increasing the under:between soil moisture ratio). Similarly, at depths of ~30 cm, under-shrub infiltration may be increased by the stem-root system channeling water to depths greater than the surrounding soil [*Whitford et al.*, 1997], but it may be decreased by the rapid, pulse-driven transpiration response of desert shrubs [*Scott et al.*, 2006]. Desert shrubs may use water from small and large storms and are flexible in their ability to use water from different soil depths [*Snyder and Williams*, 2003]. Shrubs may use shallow water following a precipitation pulse and deeper water during dry periods (discussed by *Snyder and Tartowski* [2006]). These competing processes can be understood through analysis of soil moisture, which synthesizes the interrelated influences of climate, soil, and vegetation. Nonetheless, soil moisture is rarely measured at multiple depths over prolonged periods due to the high expense of instrument deployment and maintenance.

[5] Relations have been developed to estimate the under: between ratios of infiltration and root-zone soil moisture from easily measured surrogates. In some locations, the under: between ratio of infiltration (or soil moisture) has been related to the precipitation pulse size or intensity [e.g., *Bhark and Small*, 2003]. This relation has particular relevance to changes in vegetation distribution associated with changing climate because climate models predict higher variability in the size and frequency of storm events with increasing atmospheric temperature [*Wagner*, 1996]. This study adds to the understanding of the impact of precipitation patterns on the under:between pulse-related infiltration and soil moisture and the potential for vegetation change in arid and semiarid lands.

[6] In this study, we measured precipitation, runoff, and under- and between-shrub soil moisture over a period of 20 years (1990–2009) at the Lucky Hills shrub-dominated site in the Walnut Gulch Experimental Watershed (WGEW) near Tombstone, Arizona. The objectives of this analysis were to study the hydrologic impacts of precipitation pulses in WGEW within the root zone of soils under and between shrubs, with particular focus on (1) the pulse-related infiltration and soil moisture within the root zone, (2) the pulse-related partitioning of water into critical subsurface layers, and (3) the relation of pulse size and intensity to the under: between shrub ratio of infiltration and soil moisture. Results are presented within the context of observed vegetation patterns measured along transects at the site after periods of above- and below-normal seasonal precipitation.

2. Methods

2.1. Study Site

[7] The study was conducted in the U.S. Department of Agriculture, Washington, D.C. (USDA), Agricultural Research Service (ARS) Walnut Gulch Experimental Watershed (WGEW) located southeast of Tucson, Arizona. The semiarid climate of WGEW is characterized by cool winters and hot summers. Approximately 60% of the annual rainfall comes during the months of July–September in the form of convective thunderstorms, and much of the rest is spread out in the cooler nonsummer months (November–March) [*Renard et al.*, 2008]. The Lucky Hills site is located around 31.744°N and 110.052°W with an elevation of ~1370 m. The 1990–2009 mean annual precipitation was about 280 mm, and the air temperature can range from a minimum of −5°C to a maximum of over 40°C [*Goodrich et al.*, 2008, *Keefer et al.*, 2008a]. During the hot summer months, more than 75% of the large storms (precipitation >8 mm) are followed by a dry interval greater than 10 days [*Moran et al.*, 2009]. The soil is Luckyhills series (coarse-loamy, mixed thermic Ustochreptic Calciorthids) with very gravelly sandy loams, noncontinuous caliche, and 3%–8% slopes [*Heilman et al.*, 2008]. Detailed measurements of the soil in LHTrench1 and LHTrench2 made in 1990 were reported as follows: surface rock cover = 46%, rock content in the top 0–5 cm = 28%, bulk density = 1.64 g cm^{-3}, and organic matter = 0.81% [*Kustas and Goodrich*, 1994]. The soil bulk density was measured again in May 2010 under and between shrubs at depths 0–7.5 and 7.5–22.5 cm near LHTrench1 and LHTrench2 using methods described by *Burt* [2004] (available online at ftp://ftp-fc.sc.egov.usda.gov/NSSC/Lab_Methods_Manual/SSIR42_2004_view.pdf). On the basis of three replicates at each trench, the soil bulk densities under and between shrubs were not significantly different at depth 0.0–7.5 cm or at depth 7.5–22.5 cm based on results of one-tailed *t* tests at $\alpha = 0.01$. Further, the average bulk density measured in 2010 to depth 0–22.5 cm (1.60 g cm^{-3}) was similar to that measured in 1990 (1.64 g cm^{-3}). Soil descriptions and physical properties for Lucky Hills and other areas of WGEW are available (D. J. Breckenfeld, unpublished manuscript, 1994; available at http://www.tucson.ars.ag.gov/dap).

2.2. Vegetation Data

[8] The Lucky Hills site is a typical Chihuahuan Desert shrub plant community dominated by creosote bush (*Larrea tridentata*), whitethorn Acacia (*Acacia constricta*), mariola (*Parthenium incanum*), and tarbush (*Flourensia cernua*) [*Skirvin et al.*, 2008; *King et al.*, 2008]. Permanent vegetation transects were established in 1994 (a detailed description was given by *Skirvin et al.* [2008]), and repeat measurements were made in 1994, 1999, 2005, and 2007. The paired transect lines are parallel, 30.5 m long, and 15.2 m apart. Vegetation data were collected by the line intercept method, in which a measuring tape was stretched between the end stakes of a transect line and vegetation crossing the line was measured to the nearest 3 mm. Individual plants were identified to species level where possible and each plant's canopy intercept value and diameter were recorded on a data sheet.

Table 1. Summary of Vegetation Measurements Made Along a 30.5 m Transect at Lucky Hills in Years 1994, 1999, 2005, and 2007

			1994			1999		
Genus Species	Common Name	Growth Habit	Number of Plants	Total Linear Cover (cm)	Shrub Diameter (cm)	Number of Plants	Total Linear Cover (cm)	Shrub Diameter (cm)
Larrea tridentata	Creosote	Shrub	15	1135	76	15	1174	78
Acacia constricta	Whitethorn Acacia	Shrub	25	1579	63	30	1827	60.9
Parthenium incanum	Mariola	Subshrub	27	726	27	24	857	35
Flourensia cernua	Tarbush	Shrub	3	258	86	7	412	59
			2005			2007		
Genus Species	Common Name	Growth Habit	Number of Plants	Total Linear Cover (cm)	Shrub Diameter (cm)	Number of Plants	Total Linear Cover (cm)	Shrub Diameter (cm)
Larrea tridentata	Creosote	Shrub	21	1993	95	21	1072	51
Acacia constricta	Whitethorn Acacia	Shrub	14	1207	86	22	955	43
Parthenium incanum	Mariola	SubShrub	19	873	46	35	1663	47
Flourensia Cernua	Tarbush	Shrub	5	424	85	11	417	38

Measurements of vegetation cover along the transects are summarized in Table 1.

[9] The transect measurements confirmed the characteristic establishment of the subshrub *P. incanum* under and along the canopy drip lines of shrubs *L. tridentata* and *A. constricta*. In 1994 after multiple years of above-normal precipitation, 27 *P. incanum* subshrubs were recorded and, without exception, were located under or within centimeters of *L. tridentata* and *A. constricta* shrubs. In 2007 after multiple years of below-normal precipitation, 35 *P. incanum* subshrubs were recorded, again under or within centimeters of shrub canopies. Over a 13 m relatively unvegetated section of one of the transects (where only three to four shrubs were recorded), there was no record of *P. incanum* in the large, open gaps between *L. tridentata* and *A. constricta* shrubs.

[10] The maximum root density for *L. tridentata* has been reported to be at depths between 10 and 30 cm below the surface, with very low root density in the bare soil between shrubs [*Kurc and Small*, 2004]. *Cox et al.* [1986] reported that 90% of the total root biomass of shrubs at Lucky Hills was located within 15 cm of the surface, and from their illustrations, the majority of root biomass was within the drip line of the shrub. This was supported by the observed lack of roots in the top 30 cm of soil during the installation of between-shrub sensors (unpublished data).

2.3. Meteorological and Soil Moisture Data

[11] The meteorological and soil moisture data for this analysis were collected with an automated weather station associated with three soil profile trenches colocated with a rain gauge and a runoff flume (for locations, see *Keefer et al.* [2008a, Figure 1]). The station records 30 min measurements of air temperature, relative humidity, wind speed, wind direction, barometric pressure, solar radiation, and photosynthetically active radiation. Runoff measurements on the Lucky Hills watershed were made with an H-flume (Figure 1), described in detail by *Stone et al.* [2008]. Precipitation measurements were made with analog-recording, mechanical-weighing rain gauges from 1954 through 1999. In 2000, new digital-recording, electronic-weighing gauges were placed adjacent to the analog gauges. The analog and digital gauges were compared in 2000–2004 with the conclusion that, for precipitation event amount and peak intensity, the analog and digital data were equivalent [*Keefer et al.*, 2008b]. Annual precipitation was above average before the first set of vegetation measurements in 1994 and below average before vegetation measurements in 2005 and 2007 (Figure 1).

[12] There is a near-continuous record of soil moisture at Lucky Hills from 1990 to 2009; however, the sampling method, sampling frequency, profile depths, and exact locations have varied over the 20 year period (Table 2). In 1990, the first soil profile trench (LHTrench1) was established at Lucky Hills during the Monsoon'90 Multidisciplinary Experiment [*Kustas and Goodrich*, 1994]. Thirty-six time domain reflectometry (TDR) sensors were installed at depths of 5, 10, 15, 20, 30, and 50 cm in three profiles under bare soil and three profiles under creosote cover. The probes were calibrated using the site-specific soils to convert probe

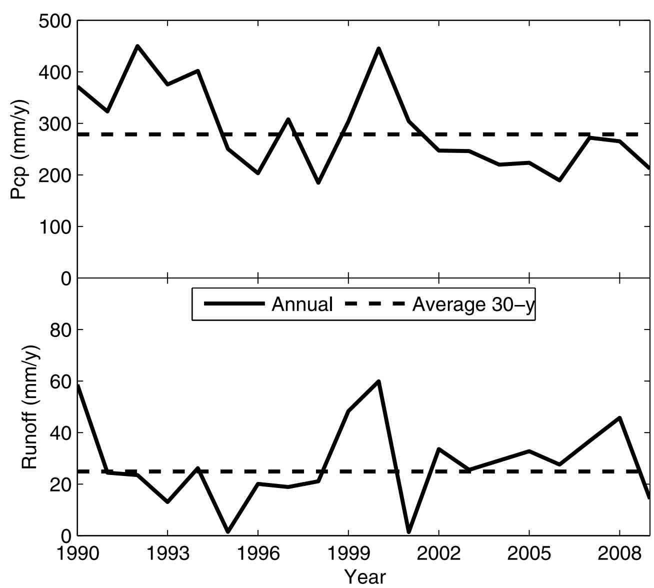

Figure 1. Annual precipitation and runoff at Lucky Hills (solid lines) and average 30 year precipitation (dashed lines).

Table 2. Description of Soil Moisture Sensors Deployed at Lucky Hills in Three Trenches, With Measurements from 1990 to 2009 Using Electrical Resistance (ER) Sensors and Time-Domain-Reflectometry (TDR) Probes

Trench	Sensor	Depth (cm)	Output Interval	Period
LHTrench2	ER and TDR	5, 15, 30	ER, continuous, every hour; TDR, intermittent, various days	Aug 1990–Jul 1991
LHTrench1	TDR	5, 10, 15, 20, 30, 50	Intermittent, various days	1990–1998
TDRL1	TDR	5, 15, 30, 50	Continuous, every 30 min	2003–2009

readings to volumetric water content. From 1990 to 1998, soil moisture was measured by manual readings of the TDR probes at all depths in LHTrench1 on an occasional (~1–2 weeks) basis. The three measurements for the under- and between-shrub profiles were averaged together. In 1996, from day of year (DOY) 232 to DOY 236, multiple gravimetric measurements (to 5 cm) were made under and between shrubs in coordination with TDR readings (at 5 cm) to monitor a soil moisture dry-down event [*Houser et al.*, 1998]. The root mean squared difference between gravimetric and TDR measurements of surface volumetric soil moisture was less than 0.02 cm^3 cm^{-3} for both under- and between-shrub locations over a range of soil moistures from 0.04 to 0.20 cm^3 cm^{-3}. This difference was reasonable, considering that the measurements were made in different under- and between-shrub locations and the gravimetric measurements represented moisture to 5 cm depth, whereas the TDR likely represented moisture to 7.5 cm.

[13] Also in 1990, 18 pairs of electrical resistance (ER) sensors and TDR probes were installed horizontally into trench LHTrench2 under three bare and three shrub-covered surfaces at depths of 5, 15, and 30 cm according to procedures outlined by *Bach* [1992]. ER sensors used in this study were identical to those described by *Amer et al.* [1994]. Three-pronged TDR probes were placed adjacent to the ER sensors at each depth in the trenches [*Bach*, 1992]. Data loggers recorded hourly values from ER sensors, and scientists collected TDR samples in the field at time intervals varying from daily to biweekly between August 1990 and July 1991. ER sensor resistance readings from 1990 to 1991 were calibrated to the colocated TDR measurements of volumetric soil moisture, with an average calibration error for all 18 sensors of 0.03 cm^3 cm^{-3} [*Hymer et al.*, 2000]. Readings from TDR probes and ER sensors were averaged, respectively, to provide under- and between-shrub soil moisture at depths of 5, 15, and 30 cm.

[14] In 2003, a third soil profile trench (TDRL1) was installed at Lucky Hills as part of the NASA Microwave Observatory of Subcanopy and Subsurface research project [*Moghaddam et al.*, 2003]. Soil moisture and temperature have been measured through the soil profile to 200 cm at TDRL1 since 2003. A Campbell Scientific, Inc., TDR100 unit processes signals at a 20 min sampling frequency. At TDRL1, there are seven TDR probes installed in a bare surface profile and another seven in a shrub cover profile, each with sensors at depths of 5, 15, 30, 50, 75, 100, and 200 cm. Averages at each depth at each location are reported for each variable.

[15] The installation process for each soil profile trench was similar and was explained in detail by *Keefer et al.* [2008a]; a short description is given here. A trench was excavated by hand or backhoe. The under-shrub sensors were installed within the drip line of the shrub, and the between-shrub sensors were installed between shrubs where no roots were observed at any depth. A small horizontal cavity, large enough to accept the soil moisture probe body, was created in the exposed trench face at the designated installation depth. Probes were inserted horizontally into this cavity, by pushing the probe tines into the soil at the recessed end of the cavity, until the probe head was within the cavity. The cavity was repacked with the soil that had been removed. Variations in sensor response and data trends at Lucky Hills induced by changes in instrument technology have been discussed by *Paige and Keefer* [2008].

[16] In the watershed, an eddy covariance (EC) station has been making measurements of ecosystem evapotranspiration on a regular basis since 2007 [*Scott*, 2010; *Cavanaugh et al.*, 2010]. In 2008 and 2009, daily soil evaporation was measured manually from microlysimeters located under and between shrubs at Lucky Hills following a precipitation pulse. Microlysimeters of 76 mm diameter and 30 cm depth were located under and between shrubs in a cross-shaped pattern centered on the EC system [*Moran et al.*, 2009].

2.4. Pulse-Related Data Processing

[17] The size and intensity of the precipitation pulse were computed from the precipitation event records at Lucky Hills. A precipitation pulse was defined as the total amount of precipitation that fell on any given day minus the runoff measured at the flume. At times, there were several distinct events over a period of 24 hours. In these cases, the multipulse precipitation was added to give a single sum for the pulse event. The maximum 30 min intensity was computed as the maximum rainfall depth that accumulated within any 30 min interval of a hyetograph divided by the duration of the interval in hours to convert it to a rate. For events with durations less than 30 min, maximum 30 min intensity is equal to the average intensity (total rainfall divided by total duration).

[18] For the continuous measurements of soil moisture (ER at LHTrench2 and TDR at TDRL1), all precipitation pulses were selected that met three criteria: (1). The selected pulse exceeded 2 mm, because infiltration from small pulses was less than the depth of the shallowest soil moisture probe at 5 cm (R. Bryant, USDA ARS, personal communication). (2) The selected pulse was not preceded by another precipitation pulse within 5 days, to avoid the influence of preceding large pulses on small pulse analysis. (3) The selected pulse was followed by more than 5 pulse-free days, to allow for the lag in soil moisture changes associated with soil depth.

[19] Thirty-two pulses met these criteria (Table 3) for the two continuous data sets in 1990–1991 and 2003–2009 (LHTrench2 and TDRL1, respectively). The 32 selected pulses represented the general distribution of pulse size and intensity (filtered to pulse size > 2 mm) over the study period 1990–2009 (Figure 2). That is, the majority of the pulses were

Table 3. Detailed Information About the 32 Pulses Selected for This Analysis

Year	DOY	Pulse Size (mm)	Pulse Maximum 30 min Intensity (mm h^{-1})	Maximum Postpulse θ_{RZ} Between (cm^3 cm^{-3})	Maximum Postpulse θ_{RZ} Under (cm^3 cm^{-3})	θ_{RZ} Under: Between Ratio
1990	272	26.7	5.7	0.15	0.13	0.85
1990	311	10.7	9.4	0.13	0.09	0.74
1990	329	15.5	6.5	0.13	0.10	0.79
1990	350	17.0	10.4	0.14	0.12	0.83
1991	5	11.8	7.1	0.15	0.13	0.85
1991	16	12.0	3.5	0.15	0.13	0.85
1991	42	18.5	3.7	0.16	0.13	0.84
1991	49	6.1	3.4	0.15	0.12	0.83
1991	58	17.3	7.8	0.16	0.13	0.84
2003	51	18.4	6.6	0.14	0.09	0.67
2003	198	5.8	5.9	0.07	0.04	0.55
2003	239	17.3[a]	21.6	0.11	0.08	0.75
2003	267	26.8[a]	9.2	0.14	0.10	0.75
2003	316	23.3	9.8	0.13	0.09	0.72
2004	302	4.3	3.6	0.08	0.05	0.72
2004	327	4.7	2.2	0.08	0.06	0.71
2005	114	3.2	4.9	0.08	0.06	0.75
2005	251	18.4[a]	59.2	0.12	0.08	0.64
2005	347	5.0	3.9	0.08	0.05	0.62
2006	48	2.7	1.3	0.07	0.04	0.61
2006	215	11.9[a]	14.0	0.14	0.13	0.94
2006	255	9.3	22.0	0.12	0.09	0.72
2007	10	3.4	1.9	0.08	0.05	0.65
2007	81	13.1	3.1	0.13	0.06	0.49
2007	162	13.2	18.4	0.10	0.05	0.50
2008	35	2.7	2.1	0.09	0.06	0.68
2008	191	11.7	0.9	0.09	0.07	0.74
2008	201	39.5[a]	61.2	0.11	0.09	0.81
2009	166	3.2	4.5	0.07	0.05	0.69
2009	179	39.7[a]	47.9	0.16	0.10	0.66
2009	225	24.7	6.7	0.16	0.13	0.82
2009	358	5.3	5.3	0.09	0.06	0.62

[a]Pulses with measurable runoff at the subwatershed flume.

small (<20 mm) with low intensity (<10 mm/h) and large pulses (>40 mm) with high intensity (>60 mm/h) were rare.

[20] For each pulse, data were processed as follows. Root-zone volumetric soil moisture was computed as the average of volumetric soil moisture measurements at depths of 5, 15, and 30 cm (θ_5, θ_{15}, and θ_{30}, respectively) weighted by the representative depth intervals of 0–7.5, 7.5–22.5 and 22.5–35.0 cm as

$$\theta_{RZ} = (\theta_5 W_5) + (\theta_{15} W_{15}) + (\theta_{30} W_{30}), \quad (1)$$

where W_n is the representative depth interval of the soil moisture sensor at depth n divided by the nominal root-zone depth, estimated to be 35 cm [*Cox et al.*, 1986].

[21] Following the methods of *Bhark and Small* [2003], root-zone infiltration (I_{RZ}) for each pulse was calculated as

$$I_{RZ} = (\theta_{RZmax} - \theta_{RZi})D, \quad (2)$$

where θ_{RZmax} is the maximum θ_{RZ} after the pulse, θ_{RZi} is the θ_{RZ} before the pulse, and D is the representative depth of the measurements (35 cm). θ_{RZ} generally rose to a maximum within an hour after the precipitation pulse.

[22] For analysis of the partitioning of soil moisture within the root zone, estimates of average daily soil moisture were sufficient because of the observed multiday lag in pulse-related soil moisture response at subsurface depths. Therefore, infiltration at the measurement depth (I_d, where

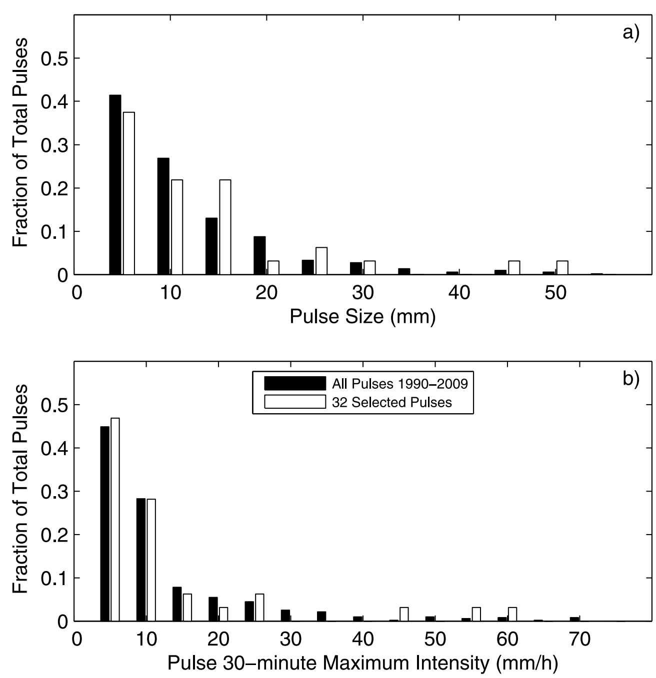

Figure 2. Frequency distributions of (a) pulse size (mm) and (b) 30 min maximum intensity (mm/h) for pulses > 2 mm over the study period 1990–2009 (n = 513) and the 32 selected pulses (Table 3).

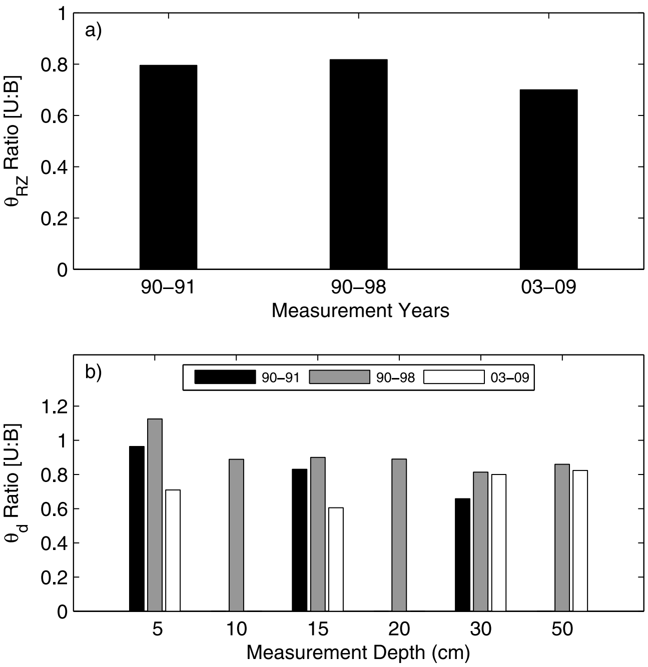

Figure 3. (a) Ratio of the average root-zone soil moisture under and between shrubs and (b) ratio of the average soil moisture under and between shrubs at multiple measurement depths for all three data sets (Table 2) over the multiyear collection periods. The statistical significance of the difference between soil moisture under and between shrubs is given in Table 4.

subscript d represents the measurement depth, e.g., 5 cm) for postpulse days was calculated as

$$I_5 = (\theta_{5\max} - \theta_{5i})d, \quad (3)$$

where, in this example, I_5 is the infiltration at 5 cm depth, $\theta_{5\max}$ is the maximum average daily θ_5 after the pulse, θ_{5i} is the average daily θ_5 before the pulse, and d is the representative depth of the measurement (5 cm). The average daily θ_5 rose to a maximum the day following the pulse, and average daily soil moisture at depths deeper than 5 cm reached a maximum within several days of the pulse.

[23] Following the methods of *Kurc and Small* [2004], we computed average soil moisture at each depth as a function of days since the last precipitation pulse over 8 mm. Data from all three trenches and all years were included in this processing to produce an under-shrub versus between-shrub comparison of soil moisture over a 4 day postpulse period for a multitude of pulses.

3. Results

[24] Three data sets of soil moisture under and between shrubs at Lucky Hills (Table 2) were brought to bear on this study. This analysis of multisensor, multisite measurements allowed flexibility in analysis and confidence in results.

3.1. Pulse-Related Soil Moisture and Evaporation

[25] For all three data sets at all depths under and between shrubs, the root-zone volumetric soil moisture (θ_{RZ}) was averaged over the collection period and the ratio of under-shrub average soil moisture to between-shrub average soil moisture was computed (Figure 3a). In all cases, the under:between soil moisture ratio was less than 1, with an average value of 0.82 and standard deviation 0.05 (Table 4). A ratio of less than 1 indicates that the under-shrub θ_{RZ} was less than the between-shrub θ_{RZ}. For all profiles, the under:between ratios of volumetric soil moisture at depth (θ_d) were computed (Figure 3b). At the surface, there was no consistent trend in the under:between ratio of θ_5. At depths from 10 to 50 cm, the under:between soil moisture ratio was consistently less than 1 for all three data sets (Table 4).

[26] The behavior of root-zone soil moisture throughout the measurement periods in all three trenches is exemplified by the response to summer storm pulses in 1990 (Figure 4). The θ_5 was similar immediately following large pulses until 3–5 days following the pulse when under-shrub θ_5 dropped below between-shrub θ_5 (Figure 4a). At depths of 15 and 30 cm, the under-shrub soil moisture was consistently below between-shrub soil moisture, with differences increasing with time since the last pulse (Figures 4b and 4c). The under-shrub θ_{RZ} remained below the between-shrub θ_{RZ} throughout summer events with a under:between θ_{RZ} ratio for the period of 0.83 (Figure 4d).

[27] Values of θ_5, θ_{15}, and θ_{30} on days since the last precipitation pulse (>8 mm) were computed for the under- and between-shrub measurements over all dates in the 1990–1991 and 1990–1998 data sets (Figure 5). The time series were limited to only the few days following the pulse because longer dry intervals were uncommon and ET decreased to relatively low values in less than 3 days [*Kurc and Small*, 2004; *Scott et al.*, 2006]. For the critical days following a

Table 4. Average Soil Moisture Values Under and Between Shrubs at Multiple Measurement Depths and the Root Zone (~30 cm) for All Three Data Sets (Table 2) Presented as Ratios in Figure 3[a]

		5 cm	10 cm	15 cm	20 cm	30 cm	50 cm	RZ
1990/1991	θ_d Under	0.08		0.09		0.09		0.09
	θ_d Between	0.08		0.11		0.13		0.11
	P value	0.42		$<10^{-5a}$		$<10^{-5a}$		$<10^{-5a}$
1990/1998	θ_d Under	0.08	0.07	0.08	0.08	0.08	0.11	0.08
	θ_d Between	0.07	0.08	0.09	0.09	0.10	0.13	0.09
	P value	0.33	1.3×10^{-3a}	3.3×10^{-3a}	5.7×10^{-3a}	$<10^{-5a}$	$<10^{-5a}$	1.3×10^{-3a}
2003/2009	θ_d Under	0.06		0.05		0.06	0.06	0.06
	θ_d Between	0.08		0.09		0.07	0.07	0.08
	P value	$<10^{-5a}$		$<10^{-5a}$		$<10^{-5a}$	$<10^{-5a}$	$<10^{-5a}$

[a] P values show results of one-tailed t tests, where the superscript "a" signifies a significant difference between soil moisture under and between shrubs at $\alpha = 0.01$.

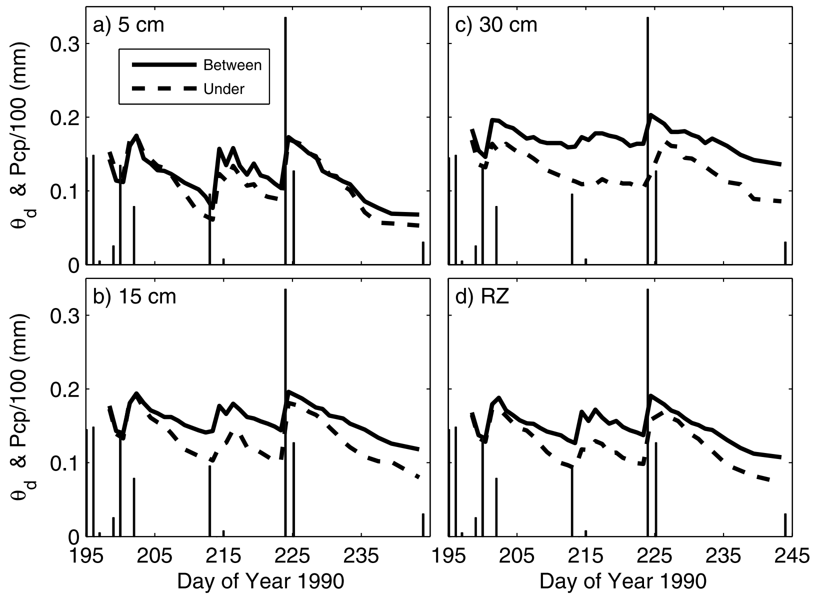

Figure 4. Trends in root-zone soil moisture under and between shrubs after a summer precipitation pulses in 1990 at depths of (a) 5 cm, (b) 15 cm, (c) 30 cm, and (d) through the root zone (to 30 cm).

precipitation pulse, the ratio of under:between soil moisture remained near 1.0 at the surface, but was less than 1 at depths of 10, 15, 20, and 30 cm. This implies that the (1) near-surface soil under and between shrubs received and retained similar soil moisture and (2) subsurface soils (even as shallow as 10 cm) were wetter between shrubs than under shrubs.

[28] The evaporation rates were measured in 2009 with microlysimeters located under and between shrubs following a pulse of 35 mm at Lucky Hills (Figure 6). From this limited data set, it appears that the evaporation under and between shrubs was similar during the days following the pulse when evaporation rates were the highest. By day 6 after the pulse, the difference between under and between shrub cumulative evaporation was 0.1 mm.

3.2. Pulse-Related Infiltration

[29] Root-zone infiltration (I_{RZ}) under and between shrubs was computed (equation (2)) for the 32 selected precipitation pulses in 1990–1991 and 2003–2009 (Figure 7). The I_{RZ} varied by pulse, but it was greater between shrubs than under

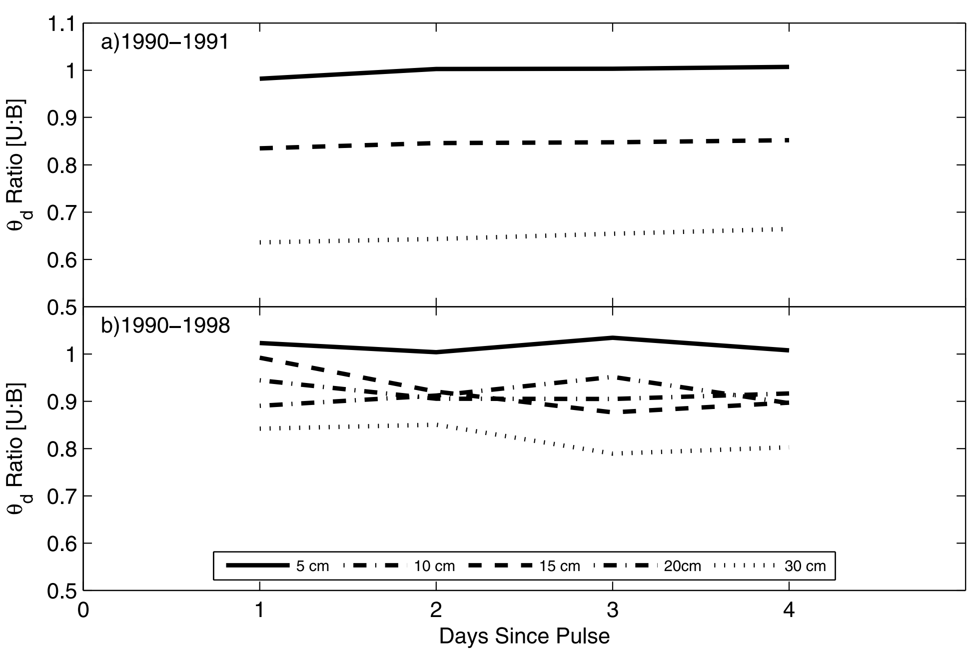

Figure 5. Ratio of the average soil moisture under and between shrubs at multiple measurements depths for measurements in (a) 1990–1991 and (b) 1990–1998 (Table 2). Curves show average values as a function of days since last rainfall over 8 mm.

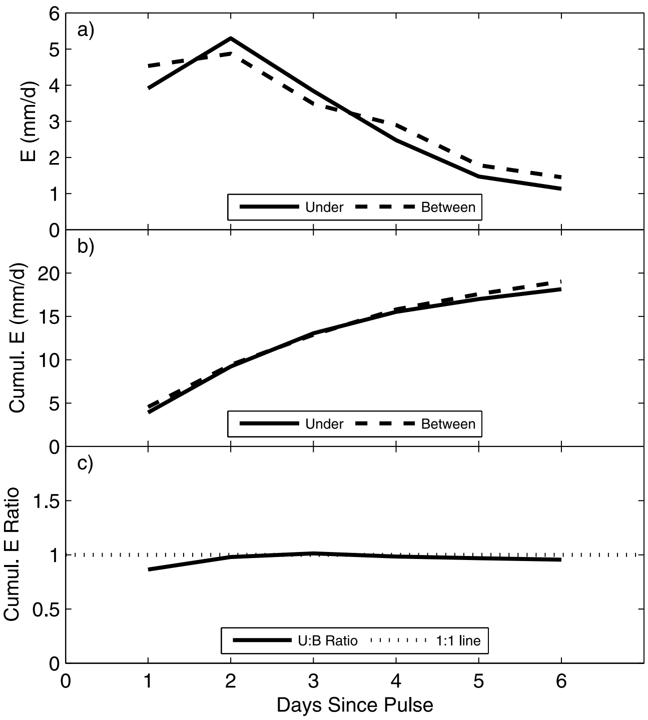

Figure 6. Pulse-related (a) evaporation rates, (b) cumulative evaporation, and (c) under:between ratio of cumulative evaporation measured by microlysimeters located under and between shrubs at Lucky Hills on days since pulse in 2009.

shrubs for 25 of 32 pulses (78%). The average under-shrub I_{RZ} was 0.97 cm, and the average between-shrub I_{RZ} was 1.33 cm, resulting in an under:between I_{RZ} ratio of 0.81 with standard deviation 0.29 (Table 5). For these storms, the average θ_{RZ} was lower under shrubs (0.09 cm^3 cm^{-3}) than between shrubs (0.12 cm^3 cm^{-3}) with an under:between θ_{RZ} ratio of 0.73 and standard deviation 0.11.

[30] The under:between I_{RZ} ratio was not significantly related to either pulse intensity or pulse size. The results are presented in a lognormal relation (Figure 8) to compare with the behavior measured for the Chihuahuan Desert creosote site in the Sevilleta National Wildlife Refuge (SNWR) reported by *Bhark and Small* [2003, Figure 5a]. The relation I_{RZ} ratio = a ln(precipitation) + b was significant (r^2 = 0.71) for measurements in the SNWR, but it does not hold for these measurements in the WGEW (r^2 = 0.00). The SNWR and WGEW have much in common: the annual precipitation is 250 (SNWR) to 280 (WGEW) mm; more than half the precipitation falls in July through September; both sites are dominated by *L. tridentata*; the soils are sandy loam. A notable difference between the locations is the flat topography of SNWR (slopes of 0%–2%) and the steeper slopes at Lucky Hills (3%–8%), although runoff is only associated with the largest pulses at both locations. The locations may also differ in the microtopography associated with vegetation canopies, which was not measured as part of this study but would certainly affect infiltration capacity [*Kieft et al.*, 1998].

[31] For the 32 selected pulses in 1990–1991 and 2003–2009, infiltration was partitioned with depth (equation (3)). I_d was related to pulse size (but not pulse intensity) at depths of 15 and 30 cm (Figure 9). However, the under:between I_d ratio was not related to pulse size or intensity at any depth. This offered a better understanding of and stronger support for the results for I_{RZ} presented in Figure 8. That is, the average infiltration ratios (under:between shrub) at each depth of 5, 15, and 30 cm were similar (0.94, 1.10, and 0.91, respectively) and were not significantly different from 1.0.

4. Discussion and Conclusions

[32] In summary, the pulse-related infiltration within the root zone was not significantly different under shrubs versus between shrubs, and the under:between root-zone infiltration ratio was not related to pulse size or maximum 30 min intensity. However, root-zone soil moisture was about 20% lower under shrubs than between shrubs across all pulses. The soil moisture measured at the surface (at 5 cm depth) was not consistently different under and between shrubs, leading to the conclusion that near-surface soil under and between shrubs received and retained similar soil moisture. The soil moisture measured at depths of 15 and 30 cm were both higher between shrubs than under shrubs.

[33] Several mechanisms have been identified to explain the interaction between plants and soil moisture [e.g., *D'Odorico et al.*, 2007; *Wainwright et al.*, 2000; *Abrahams et al.*, 2003; *Bhark and Small*, 2003; *Lyford and Qashu*, 1969; *Devitt and Smith*, 2002], including the following: (1) Vegetation may enhance under-shrub soil infiltration. (2) Lateral redistribution of water via runoff may increase under-shrub soil moisture. (3) Canopy interception may impact under-shrub evaporative losses. (4) Evaporative losses may be lower in under-shrub soils. (5) Stemflow may contribute to higher soil moisture at the base of shrubs. (6) Greater root density under shrubs may decrease under-shrub soil moisture. These mechanisms will be discussed here in the context of the results of this analysis.

[34] In our study, vegetation did not enhance under-shrub soil infiltration (mechanism 1). Instead, I_{RZ} between shrubs was generally greater than that under shrubs for a given pulse, and the I_d ratio (under:between) was close to 1.0 at depths of 5, 15, and 30 cm (Figures 7–9). Previously reported increases in infiltration under *L. tridentata* through reduction in rain splash compaction were conducted with rainfall simulations at high rainfall intensities (on the order of 150 mm/h average [*Wainwright et al.*, 2000]) which are higher than natural rainfall [*Martinez Mesa and Whitford*, 1996]. For the 32 pulses analyzed in this study, the mean maximum 30 min pulse intensity was 11.7 mm/h and the highest maximum 30 min pulse intensity was 61.2 mm/h (Table 3). Other studies have reported that higher under-shrub infiltration is associated with higher microtopography and saturated conductivity found under vegetation canopies that decay with distance from the plant center [*Bedford and Small*, 2008]. Though a study of these under- and between-shrub soil properties has not been conducted at Lucky Hills, the increase in soil infiltration associated with these soil properties was not observed with this range of natural rainfall intensities.

[35] Lateral redistribution of water via runoff, combined with either microtopography or differences in under:between shrub infiltration capacity, may increase soil moisture under shrubs. At Lucky Hills, runoff was not a common feature of the majority of pulses. On the basis of measurements made by *Parsons et al.* [2006], pulses at Lucky Hills at the scale of this study (4 and 15 m lengths) at slopes of 5–8° did not

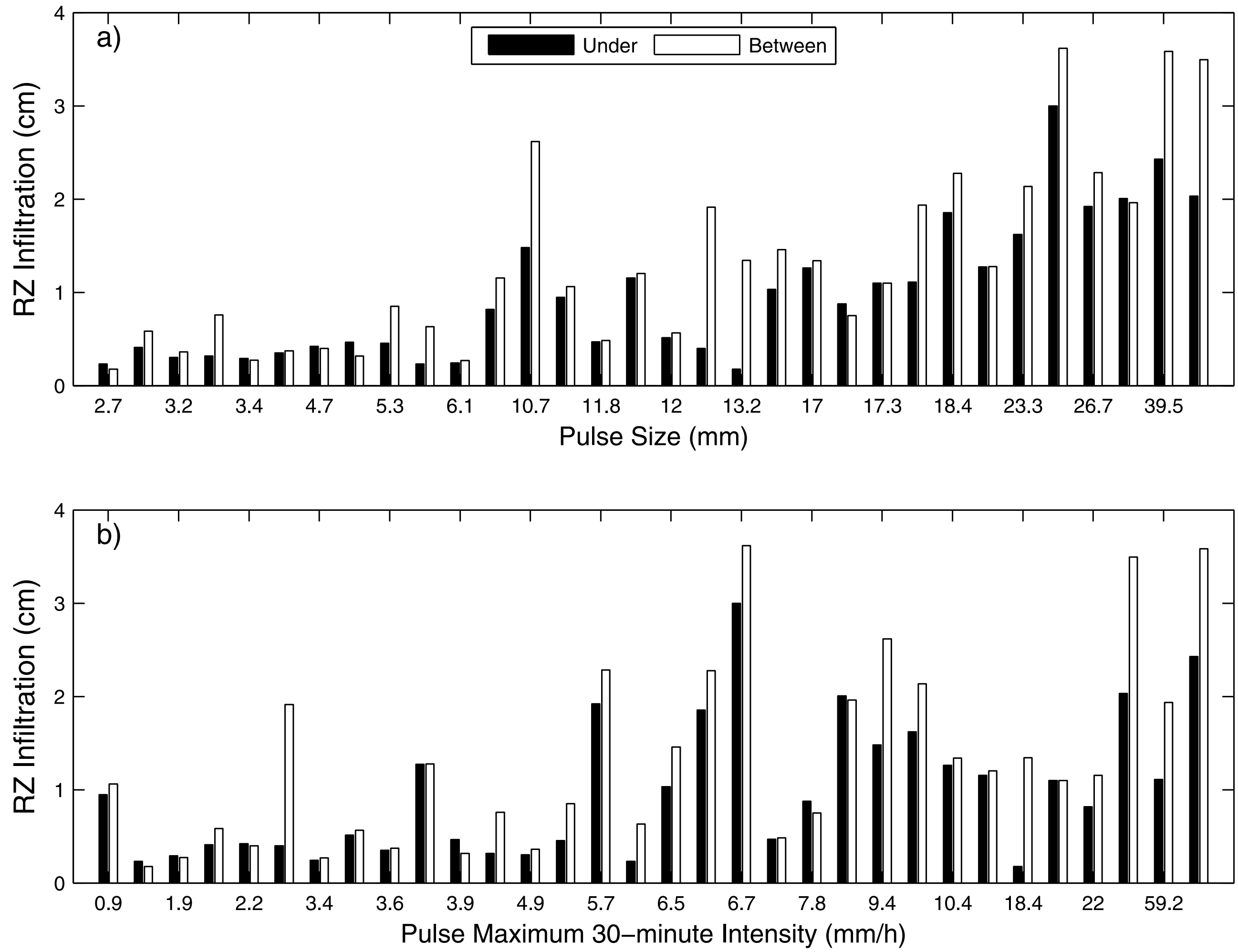

Figure 7. Root-zone infiltration under and between shrubs for 32 selected precipitation pulses in 1990–1991 and 2003–2009, sorted by (a) pulse size and (b) maximum 30 min pulse intensity. The average infiltration values for all pulses are summarized in Table 5.

produce runoff at maximum 30 min pulse intensities less than 5 mm/h and runoff was minimal (<1.5 mm at 4 m length and <0.5 mm at 15 m length) for intensities less than 10 mm/h. Twenty-four of the 32 pulses in this study had maximum 30 min pulse intensities less than 10 mm/h. The 13 pulses with intensities less than 5 mm/h did not respond differently from the 19 pulses with intensities greater than 5 mm/h (Figure 7). The six pulses (indicated by footnote a in Table 3) in our study with measurable runoff at the watershed flume did not respond differently from the other 26 pulses in this study; that is, with lateral redistribution of water via runoff, the I_{RZ} between shrubs was not significantly different than that under shrubs for that pulse. If mechanism 2 were a dominant process, the I_{RZ} would likely be different for pulses with and without measurable runoff at the plot or hillslope scales. Further, nearly half the pulses at Lucky Hills over the past 20 years were less than 5 mm/h 30 min maximum intensity (Figure 2) and likely had no measurable runoff at the 4 m length.

[36] Apparently, canopy interception was not a significant factor in under-shrub soil moisture for pulses > 2 mm (mechanism 3). The θ_5 value was found to be similar under and between shrubs at the 5 cm depth for days immediately following precipitation pulses and for the entire multiyear collection period (Figures 3– 5). This result, combined with the observed lack of lateral redistribution of water via runoff, implies that there was minimal interception of water by the shrub canopy at Lucky Hills.

[37] Our results do not support the premise of mechanism 4 because daily evaporation rates measured by microlysimeters under and between shrubs were not significantly different (Figure 6). This result differs from reports of lower evaporative losses under pinyon-juniper trees [*Breshears et al.*, 1998], and the difference may be due to the relatively low above-ground biomass of *L. tridentata* at Lucky Hills (esti-

Table 5. Average Root-Zone Infiltration and Soil Moisture Values for All Pulses Illustrated in Figure 7[a]

	Under		Between		U:B Ratio	
	Mean	SD	Mean	SD	Mean	SD
Infiltration	0.97[a]	0.74	1.33[a]	1.00	0.81	0.29
Soil Moisture	0.09[a]	0.03	0.12[b]	0.03	0.73	0.11

[a]Within the same row, values with different superscript letters were significantly different under and between shrubs at $\alpha = 0.01$ for one-tailed *t* test. Infiltration is in millimeters.

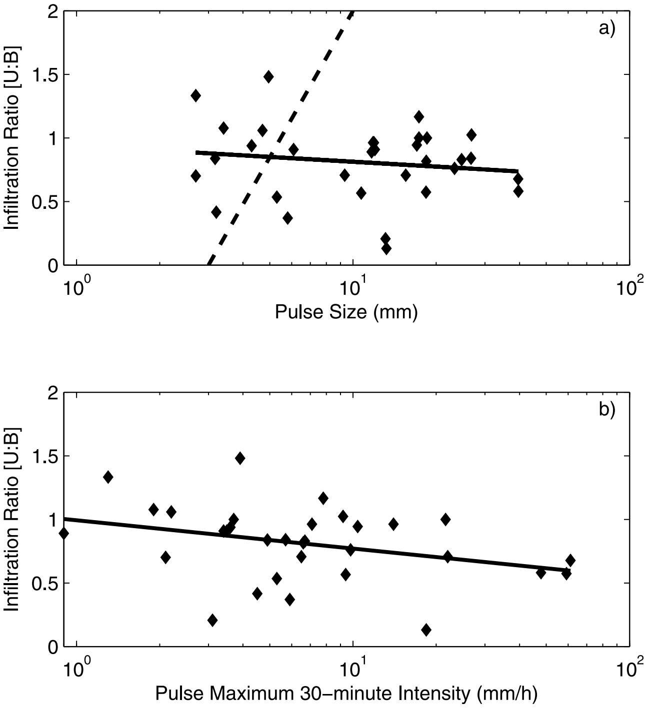

Figure 8. Ratio of infiltration under and between shrubs related to (a) pulse size and (b) maximum 30 min pulse intensity. The solid lines represent the best fit regressions for the Lucky Hills measurements ($r^2 < 0.01$) ; the dashed line represents the relation determined by *Bhark and Small* [2003] for similar measurements at the Sevilleta National Wildlife Refuge.

mated to be 8 g/m^2 by *Cox et al.* [1986]). On the other hand, these results support similar findings that under-shrub evaporation rates were not significantly different for *L. tridentata* at SNWR [*Bhark and Small*, 2003] and for different shrubs at the Santa Rita Experimental Range in southern Arizona [*Hamerlynck et al.*, 2010].

[38] As discussed by *Bhark and Small* [2003], shrub stemflow likely had little impact on under-shrub infiltration. In our study, the I_d was related to pulse size, not to under- or between-shrub location, and the I_d ratio (under:between) was close to 1.0 at depths of 5, 15, and 30 cm (Figure 8). It has been reported that that the infiltration at the stem of the *L. tridentata* is 3 times greater than infiltration between shrubs [*Lyford and Qashu*, 1969]. For a typical shrub at Lucky Hills, the shrub diameter is 67 cm and the stem diameter is on the order of 2 cm; the shrub basal area is substantially less than 1% of the total study area. Moreover, larger pulses did not result in higher under-shrub I_d, a feature that has previously been associated with enhanced soil moisture stemming from root macropore formation in *L. tridentata* [*Devitt and Smith*, 2002].

[39] Since none of the first five mechanisms of interaction between plants and soil moisture were supported by our measurements, it follows that our results are consistent with the premise of mechanism 6 that greater root density under shrubs may decrease under-shrub soil moisture. That is, we found no significant differences in infiltration, evaporative losses, and θ_5 in locations under and between shrubs. However, the soil moistures measured at depths of 15 and 30 cm (θ_{15} and θ_{30}) were significantly lower under shrubs than between shrubs throughout all pulse events selected during the study period. Since the measured soil bulk densities under and between shrubs were statistically similar, this implies that differences in soil water potential exist under shrubs versus beneath shrubs as well. This result could be important in understanding vegetation patterns because many plant processes are regulated by soil water potential rather than by volumetric water content.

[40] Given that the vast majority of root biomass of Lucky Hills shrubs is located within the drip line of the canopy [*Cox et al.*, 1986], it follows that the under-canopy water use by the shrub may lower the root-zone soil moisture compared to soil moisture content between shrubs. Both woody and fibrous roots of shrubs at Lucky Hills are mainly restricted to the top 30 cm, but woody roots can extend to 50 cm and fibrous roots are reported at depths exceeding 1 m [*Cox et al.*, 1986; *Ogle et al.*, 2004]. Roots at these depths permit transpiration even when the surface is dry, resulting in dryer root-zone soils under shrubs than between shrubs. Indeed, recent analysis at WGEW Lucky Hills showed that daily transpiration was correlated with $\theta_{37.5}$ (r^2 = 0.65) whereas daily evaporation was correlated with surface soil moisture (r^2 = 0.57 at θ_5) [*Cavanaugh et al.*, 2010].

[41] Our results offer some insight into the apparent preferential establishment of *P. incanum* beneath *L. tridentata* and *A. constricta* canopies. Since soil moisture was not found to be greater under shrubs, *P. incanum* may establish within the drip lines of shrubs at Lucky Hills due to a nutrient advantage [*Schlesinger and Pilmanis*, 1998] or amelioration

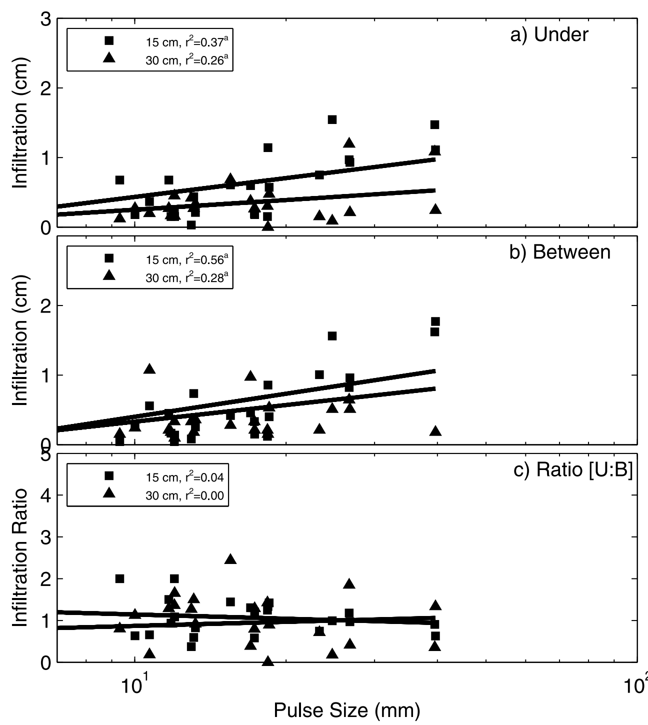

Figure 9. Relation between pulse size and infiltration at depths of 15 and 30 cm (a) under shrubs, (b) between shrubs, and (c) presented as a ratio of under:between shrubs for 32 selected precipitation pulses in 1990–1991 and 2003–2009. Solid lines represent the best fit relation with correlation coefficients given in the legend box. The superscript "a" signifies statistical significance at $\alpha < 0.01$.

of high temperature and light conditions [*Turner et al.*, 1966; *Franco and Nobel*, 1989], rather than increased water availability. Some researchers have suggested that the subshrub microenvironment is water limited and provides a suitable habitat for establishment and persistence of highly drought-tolerant species [*McClaran and Angell*, 2007; *Hamerlynck et al.*, 2010]. Thus, it may be that *P. incanum* is a drought-tolerant plant. Indeed, the marked increase in *P. incanum* came after a prolonged and highly severe drought, suggesting that this species was capable of maintaining reproductively viable adults throughout these challenging conditions.

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R. Bryant, E. P. Hamerlynck, C. D. Holifield Collins, T. O. Keefer, M. S. Moran, R. L. Scott, and J. J. Stone, USDA ARS, Southwest Watershed Research Center, 2000 E. Allen Rd., Tucson, AZ 85719, USA. (susan.moran@ars.usda.gov)

L. DeYoung, School of Natural Resources, University of Arizona, Tucson, AZ 85721, USA.

D. C. Hymer, NASA Goddard Space Flight Center, 8463 Greenbelt Road, Greenbelt, MD 20770, USA.

G. S. Nearing, Department of Hydrology and Water Resources, University of Arizona, 4210 North Campbell Avenue, Tucson, AZ 85719, USA.

Z. Sugg, Department of Geography and Development, University of Arizona, Tucson, AZ 85721, USA.