RESEARCH ARTICLE

Post Burn Restoration Response of *Encelia virginensis* within a Small Wash System in the Mojave Desert

Dale A. Devitt, Fred Landau, Scott R. Abella, Matt D. Petrie, Ann M. Mcluckie and John O. Kellam

ABSTRACT

Spatial variation in response to restoration treatments within landscapes can be a significant but poorly understood driver of successful ecological restoration. We conducted a field experiment to assess effectiveness of out-planting restoration techniques for the native shrub *Encelia virginensis* across a soil hydrological gradient. We planted seedlings at five wash locations separated by varying distances based on elevation and percent slope. At each of these plots we planted seedlings, half on the side wall slopes of the wash system and half adjacent to the central wash. Seedlings received either cages, hydrogel, cages and hydrogel, or no treatments. We assessed survival and growth over 30 months. Survival declined rapidly by summer of the first year, declining to an overall rate of 24% after 30 months. Probability of survival analysis indicated a non-significant difference in survival between cage and cage plus hydrogel treatments with both varying significantly from controls. However, two months after the last hydrogel addition a significantly higher number of plants survived in the cage plus hydrogel treatment (63%) versus. all other treatments (≤ 43%) ($F_{12,100} = 2.39$, $p = 0.009$), suggesting that if we continued hydrogel additions into the second year a significant difference in survival between the cage and cage plus hydrogel treatments might have occurred. Cost analysis based on comparing the control with the other treatments justified the expense of providing cages, as 79% of all surviving plants had cages.

Keywords: arid land restoration, hydrogel, shrub cages, shrub survival, soil moisture

Restoration Recap

- Restoration studies focused on seedling establishment in wash systems have been rare. Stabilizing slopes in wash systems with vegetation is key to reducing erosion and undercutting within washes.
- Providing plants with cages and hydrogel (in the first year) proved effective, but without hydrogel additions in the second year, survival in the cage plus hydrogel treatment began to converge on the survival in the cage treatment (statistically not different).
- The use of cage plus hydrogel increased flower and seed numbers after the second growing period, but small numbers overall suggested that additional research is needed to justify recommending the incorporation of hydrogel with cages as a management practice.
- Our results suggest that success in such systems is influenced by the position of the plants in the wash as influenced by soil conditions and water availability.

Although desert ecosystems typically produce lower fuel load for fires than other ecosystems, fires still can be extensive and damaging to mature shrublands (Fuentes-Ramirez et al. 2015). Over 0.8 million ha have burned in the Mojave Basin and Range area since 1980 (Mojave Basin and Range REA Nature Serve 2013). Over 0.4 million ha burned in the Mojave desert in 2005 alone (Brooks and Matchett 2006). Many of these fires have been fueled by stands of invasive grasses (Steers and Allen 2010) that increase fuel continuity between shrubs, allowing for the spread of fires. Brooks and Berry (2006) reported that 66 to 91% of biomass in desert tortoise habitat in the western Mojave Desert was non-native annuals.

Color version of this article is available through online subscription at: http://er.uwpress.org

Ecological Restoration Vol. 38, No. 3, 2020
ISSN 1522-4740 E-ISSN 1543-4079

Recovery from large scale perturbations (such as fires) is typically a slow process in desert ecosystems, with timelines of several centuries (Vasek et al. 1975, Web et al. 2009, Abella 2010). This slow recovery is linked to a myriad of variables but perhaps the most significant variable is annual precipitation rates of less than 25 cm that are highly variable on a spatial-temporal basis (Bainbridge 2007). As such, restoration efforts are often needed, especially when habitats for threatened and endangered species such as *Gopherus agassizii* (desert tortoise) have been severely damaged (Abella and Berry 2016). Fires alter vegetative cover and water balances. With vegetative cover reduced, wind erosion and precipitation runoff can intensify. This change alters surface conditions by displacing surface soils, leading to possible smoother surfaces (Soulard et al. 2013) and creating washes (intermittent streams) that can be cut deeper, creating a long-term legacy effect. Without foundation perennial shrubs such as *Larrea. tridentata* (Peters and Yao 2012, Abella et al. 2019) and other shrubs such as *Ambosis dumosa* and *E. virginensis,* habitat quality is severely degraded (Allen et al. 2011). These shrubs provide food and cover for wildlife and serve as "nurse plants" to facilitate the growth and development of other species by providing an altered micro environment for germination, recruitment, and survival (Ren et al. 2008). Restoration of burned areas in the Mojave Desert is key to returning ecosystem function at a critical time for offsetting population declines in such species as the desert tortoise.

Wash systems represent complex landforms that can constrain vegetative spatial patterns (Swanson et al. 1988), yet restoration studies focused on seedling establishment in wash systems have been rare (Blauth et al. 2007). Wash systems at our study site began in fairly level terrain but quickly revealed downslope under cutting (~100 m) with side walls in excess of 20%, with coarse sediments dominating the lower elevation wash locations. We hypothesized that such terrain would represent a challenging environment for seedling establishment and survival. As such, we initiated an out-planting study at a burn site located in the north eastern region of the Mojave Desert, focused on *E. virginensis*, a major perennial shrub in the area, to assess survival and flower and seed production as influenced by position in a small wash system (elevation within the wash, slope vs wash at each elevation). Additional rational for the selection of *E. virginensis* was that we observed flower production during its first year as a seedling under nursery conditions whereas no flowering occurred in *L. tridentata* seedlings during the first year. Previous research at desert burn sites in the West have demonstrated enhanced survival of out plantings, provided that plants are protected from herbivory (Grantz et al. 1998, Scoles-Sciulla et al. 2015) and given additional water during the establishment period (Aref et al. 2006, Abella et al. 2015a). We hypothesized that elevation location within the wash system would significantly influence survival and flower and seed production because of differences in infiltration and runoff (head water locations with small rills versus lower elevation wash system locations with steep slopes) and this would be enhanced further by providing herbivory protection (cages) and water (hydrogel water holding crystals).

Methods

The study site was at the Beaver Dam Wash National Conservation Area (BDWNCA) in southwest Utah (37°3′14.4″ N, −113°58′55.2″ E). The field research was conducted between November 2016 and May 2019. A post burn site was selected that incorporated a small wash system that ran in a north-south direction. The site burned in 2006 and was located within the larger 5261-ha lightning-ignited wildfire area within mixed shrubland (~ 20% of the entire BDWNCA area). The shrubland included *L. tridentata*, *E.virginensis*, *Ambrosia dumosa*, *Sphaeralcea ambigua* and *Yucca brevifolia*. Post-fire natural recruitment of native shrubs at the site was deemed poor. Given this, the Bureau of Land Management)BLM), Washington County (Utah) and the U.S. Fish and Wildlife Service funded restoration efforts to benefit habitat recovery, especially for *G. agassizii*.

The study focused on *E. virginensis* because the species inhabited the area before the burn and remained in low numbers after the burn and few restoration studies have been conducted on this species (Abella 2009, Abella 2010, Abella and Smith 2013). Seedlings were established from seed approximately eight months prior to planting. Seed was obtained from the BLM "Seeds of Success" seed repository in Bend Oregon where selection was based on collection from the same ecoregion (Mojave Desert). Seed was sown (March 2016) in 4 liter pots filled with a blended soil medium comprised of 10% compost and 90% wash sand. The pots were transferred to a greenhouse and maintained by watering on a near daily basis until June 2016 when they were moved outdoors under shade cloth (30% solar reduction) and watered with a sprinkler system on a per need basis to avoid visible stress. In early November 2016, 120 *E. virginensis* pots were transported to BDWNCA for planting.

The wash study site had an elevational change of 49 m over a N/S distance of 649 m (Figure 1). Five plots (P1–P5) were selected on the wash system, with plot designation based on elevation (P1.985m, P2.984m, P3.967m, P4.955m and P5.936m). Plots P1.985m and P2.984m represented the upper elevation headwater, whereas Plot P5.936m represented a deeply cut wash site with side slopes exceeding 20% (Figure 2). At each plot, 24 *E. virginensis* plants were transplanted, 12 adjacent to the main wash and 12 located on the adjacent slope. Plants were positioned on both the east and west facing slopes. No statistical difference was noted in the response of the plants located on the

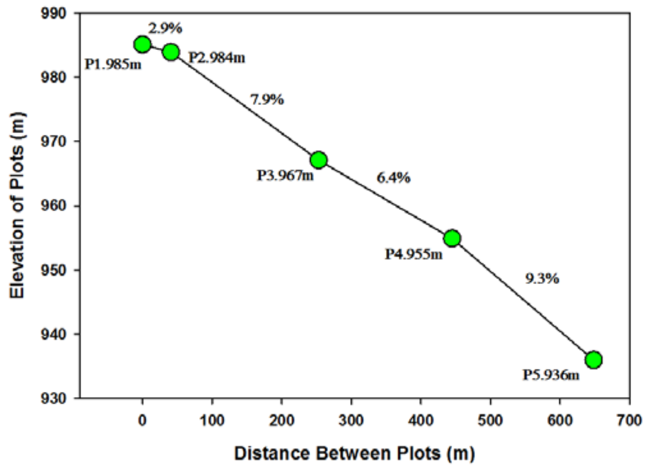

Figure 1. Plot location based on elevation and distance between plots, with percent slope between plots listed. Plots are designated by number (P1–P5) followed by elevation in m.

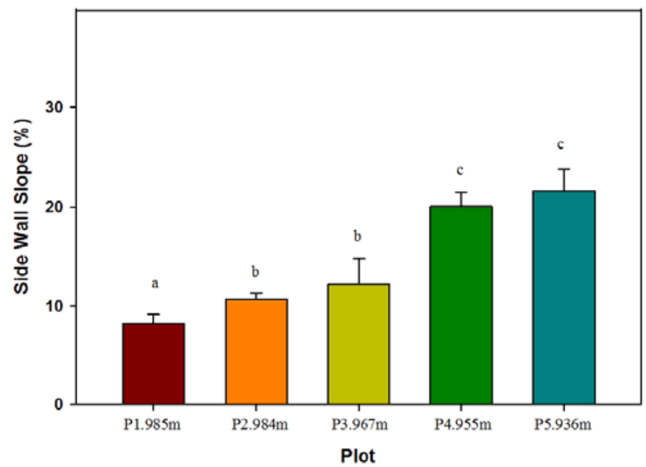

Figure 2. Side wall slopes at each plot location with error bars. Vertical bars with different lettering are statistically different at the $p < 0.05$ level.

different facing slopes so all data were combined, providing general wash versus slope locations. Four different treatments were imposed (three replicates); including control plants (no treatments), plants provided with hydrogel three times during the first year (November 2016, May 2017 and August 2017), plants provided with cages (chicken wire with 2.54 cm openings to a height of 46 cm, secured with wooden stakes and open on the top) and plants provided with both cages and hydrogel. The cages were designed to specifically keep out; *Ammospermophilus leucurus* (white-tailed antelope squirrel), *Lepus californicus* (black-tailed jackrabbit), *Sylvilagus audubonii* (desert cottontail) and *Dipodomys merriami* (Merriam's kangaroo rat) all documented to forage on vegetation in the BDWNCA (J. Kellam pers. obs.) The hydrogel was produced by mixing 20 cubic cm of a potassium polyacrylate polymer (Soil Vigor, Troy MI) into l liter of water contained in tubular plastic bags that were heat sealed at both ends. The hydrogel in plastic bags were transported to the field where one end of the tubular bag was cut. The cut end was slowly pushed into 15 cm wide plastic tubes that were inserted into the soil at 45 degrees such that the hydrogel would come in direct contact with the deepest roots at the time of planting. Once the entire bag was inside the plastic tubes, a cap was placed over the end to reduce evaporative losses. At each site intact soil cores were taken to a depth of 15 cm. These cores were returned to the lab and saturated hydraulic conductivities (K_s) were measured using a constant head technique (Klute, 1965).

Plants were monitored on day 88, 157, 214, 278, 342, 557, 658, and 889 of the experiment. All plants were assessed for survival based on the presence of leaves or the presence of green tissue when stems were lightly scratched with a fingernail. We observed no negative impact of these light scratches on the health and survival of the plants. It should be noted that at the end of the monitoring period all plants listed as surviving possessed green leaves. Plant height (in cm) and main stem diameter at a height of 2.5 cm were measured with a meter stick and calipers, respectively.

A weather station (HOBO U30-NRC WS, Onset Corporation, Cape Cod, MA) was located within 400 m of the study site. Precipitation was assessed with a tipping rain bucket (HOBO S-RGB-M002). The weather station was installed in June of 2017. Historical precipitation for the Beaver Dam AZ area was obtained from the Western Regional Climate Center (2019) and potential evapotranspiration (ET) was obtained from the Utah EvapoTranspiration Network (2020). Soil moisture was estimated every five minutes (curves based on greater than 200,000 measurements) at depths of 10, 25 and 43 cm at the site of the weather station (HOBO, 10HS soil moisture smart sensor probes S-SMD-M005). Because these soil moisture estimates were not from within the plots, we excavated a single small hole with a hand spade in each plot during each site visit (one representative side wall and wash location) such that a hand held soil moisture probe could be gently pushed into the side wall at a depth of 10 and 30 cm (ML3 theta probe, Dynamax, Houston TX). Flowers were counted and harvested in Mid-May of 2019 at the peak of phenology. Seed was separated from the flowers and counted in the laboratory.

Data were analyzed using SigmaStat and graphs generated using SigmaPlot (San Jose CA, USA). The experiment was set up so the data could be analyzed with two-way analysis of variance (slope and treatments on survival). Because of empty ANOVA cells, three-way ANOVAs were not possible to conduct on soil and plant parameters. Although survival did not have empty cells we felt that survival was better assessed using Kaplan and Meier survival analysis and logrank tests (Sigmastat). Linear regression analysis (R^2 and p values) were generated for relationships between monthly soil water content and monthly

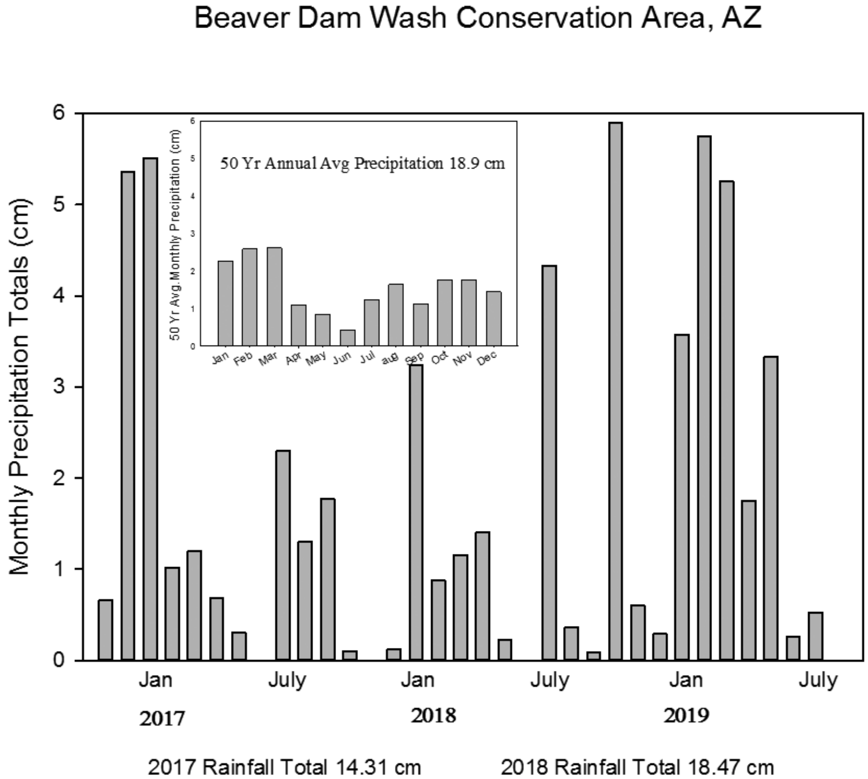

Figure 3. Monthly precipitation totals (cm) during the experimental period, along with yearly totals (cm) and historical monthly total values (50 yr. averages). All precipitation was measured as rainfall.

precipitation, plant height and stem diameters, number of flowers and stem diameters, number of seeds and number of flowers and also survival and cumulative precipitation minus potential ET. Data was also analyzed using stepwise linear multiple regression analysis on survival (square root transformation), soil moisture, stem diameters, flower and seed production at harvest but also at key times during the experimental period for survival. Independent variables considered in the multiple regression analysis included, elevation, percent slope, wash/slope location, soil moisture content, saturated hydraulic conductivity, treatment, and distance to the wash. Multiple regressions were performed in an unbiased backward stepwise manner, with deletion of terms occurring when p values for the t-test exceeded 0.05 (software controlled). To eliminate the possibility of co-correlation (over fitting the data), parameters were included only if variance inflation factors were less than 2 and the sum total was less than 10. If the accepted variance inflation factor was exceeded, parameters with the highest p value were eliminated and regressions were run a second time. In the case of the one way ANOVA on soil moisture at slope wash locations which failed normality assumptions, we used a Kruskal-Wallis analysis to detect statistical differences.

Results

Precipitation

Precipitation occurred at the site in 30 of the 33 months that we collected meteorological data (Figure 3), but only 17 months had total precipitation greater than 1.0 cm. Of the top ten precipitation months, six occurred during the winter-to-early-spring period while three occurred during the late-spring-summer period. Only the winter-early-spring period of 2019 had three sequential months with monthly precipitation totals greater than 3.0 cm. Precipitation occurring after the initial planting, during the months of December through March (2016–2017) totaled 13.1 cm, whereas in 2018 only 5.4 cm of precipitation occurred during this same time period compared to 14.9 cm in 2019. However, during May through August, precipitation varied little between the three years (3.9, 4.9, 4.1 cm, respectively). Although yearly totals in 2017 and 2018 were below the 50-year average for the area (Figure 3), 13 of the 30 months received monthly precipitation over the 50 year historical average values.

Soil Water Content

Soil volumetric water contents near the weather station (~400 m from plots) revealed strong oscillations at the 10 cm depth (Figure 4), with six well defined monthly peaks associated with the higher precipitation. Average monthly soil volumetric water content at 10 cm depth correlated with monthly precipitation totals ($R^2 = 0.59$, $p < 0.001$). Soil moisture at the 10 cm depth remained above an average

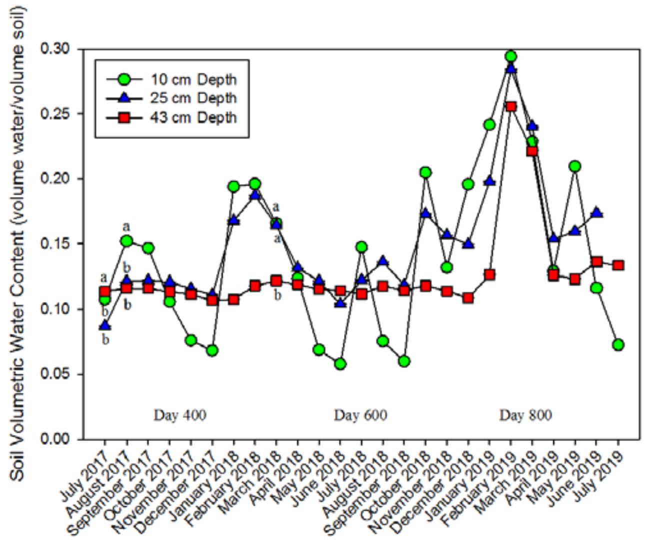

Figure 4. Average monthly soil volumetric water contents (cm3 water/cm3 soil) along with error bars at the 10 (○), 25 (Δ) and 43 (☐) cm depths during the experimental period. All depths on all dates were significantly different from each other except on those dates that are marked with different letters (*p* < 0.05).

monthly value of 0.20 (cm^3 water/cm^3 soil, hereafter units omitted) for a 3-month period only in 2019 (January 5–April 5). At the 25 cm depth we only observed 3 peaks, with soil moisture above a value of 0.20 occurring for a 2.5-month period only in 2019 (January 15–April 6). Average soil volumetric water content at 25 cm also correlated with monthly precipitation ($R^2 = 0.38$, $p < 0.001$). However, at the 43 cm depth soil moisture peaked above a value of 0.20 for only a one-month period (February 2–March 20) and also only during 2019. From July 2017 to early January 2019 soil volumetric water content at the 43 cm depth remained at a baseline value of approximately 0.12 (0.12 ± 0.004, average plus standard deviation), revealing no synchronization with soil moisture peaks that occurred at the 10 and 23 cm depths. However, during the one period in which elevated soil moisture occurred at the 43 cm depth it was also associated with similar strong peaks at the other depths, suggesting a requirement of extended wet winter months at this site to move water to a depth of 43 cm. These higher soil volumetric water contents (0.30) occurred with monthly precipitation totals greater than 3 cm. However, monthly precipitation totals greater than 3 cm occurred during nine different months at the site but elevated soil moisture at the 43 cm depth only occurred when a series of three sequential months each had greater than 3.0 cm of precipitation. Because soil water content at the 43 cm depth was unresponsive to all precipitation events except during a wet period in early 2019, the correlation between average monthly soil water content and monthly precipitation failed both the normality and constant variance tests,

Table 1. Saturated Hydraulic conductivity (cm/hr) with USDA ratings (2019).

Plot	K_s (Slope)	K_s (Wash)	Rating
P1.985m	0.36	1.07	Very Slow/ Slow
P2.984m	1.92	0.18	Moderately Slow/Very Slow
P3.967m	0.68	0.61	Slow/Slow
P4.955m	0.47	25.10	Slow/ Moderately Rapid
P5.936m	1.47	412.39	Moderately Slow/Very Rapid

as 5.9 cm of precipitation occurred in October 2018 with a corresponding soil water content of 0.12 which contrasted with 5.7 cm of precipitation in February 2019 with a soil water content of 0.26.

Soil volumetric water contents within the plots assessed during each site visit produced limited data. Extremely low soil water contents at the 10 and 30 cm depths occurred at all of the sites on the eight visits (typically below a value of 0.05) except on one site visit that occurred during the winter period of 2017 within a few days of a rainfall event. At each of these plot locations we also took intact cores to assess saturated hydraulic conductivity (K_s) in the near surface soil (0–15 cm depth). K_s values in the 0.1 to 2.0 cm per hour range occurred at all slope locations, and at wash locations for plots P1.985m, P2.984m and P3.967m (Table 1). However at P4. 955m wash site the K_s was ~ 24 cm hr^{-1} and at P5. 936m wash site ~ 412 cm hr^{-1} (rated moderately rapid to very rapid). We ran a backward stepwise regression on this one data set of soil volumetric water contents (n = 20) including K_s, elevation and percent slope as independent factors, rejecting K_s at the $p < 0.05$ level. The correlation (elevation and percent slope, $p < 0.001$) accounted for 42% of the variability in soil moisture content at the 30 cm depth and 38% ($p < 0.001$) at the 10 cm depth. Analysis based on soil water contents (measured during site visits) grouped by slope versus wash at upper elevation headwater versus lower elevation wash locations revealed that there was a significant difference ($H = 9.88_3$, $p = 0.02$) between slope (0.12 volumetric water) and wash (0.04 volumetric water) locations in the lower three elevation plots (P3.967m, P4.955m and P5.936m).

Growth

Plants surviving at the end of the monitoring period revealed a linear correlation (r = 0.59, $p = 0.001$) between plant height and stem diameters (Height = 6.194 + 1.556 [Stem Diameter]), with taller plants having larger main stem diameters. However this correlation was impacted by herbivory as only 41% of surviving plants revealed positive change in height by the end of the 30 month period. Only 6% of the initial 120 plants were totally missing (all without cages) as herbivory was typically confined to upper stems and leaves. The change in growth from day 88 to day 157 (n = 120, first spring period) was statistically greater at slope than wash locations ($F_{1,112} = 5.54$, $p = 0.02$). Although treatments with cages had lower herbivory as inferred from change in height measurements between day 88 and 157, the differences were not significant ($p = 0.22$). Herbivory occurred in all treatments and at all locations (percent of plants in each plot where loss in height occurred; 63%, 67%, 88%, 67%, and 71%, plots 1–5 respectively). We assessed whether growth in stem diameter was influenced by treatments, calculating changes in stem diameter between all possible dates. We found no statistical separation in stem growth based on treatments when comparing surviving plants to their initial stem diameters, however there was a difference between stem growth during two dates (Day 214 and Day 658) which captured a post hydrogel application period, with a p value of 0.07 ($F_{3,22} = 2.69$). Although this p value was above the standard 0.05 level we believe the results reflect an important biological effect worthy of reporting (Furuya et al. 2014). The cage plus hydrogel treatment (2.03 mm, SE 0.36) was found to have higher stem growth than all other treatments (hydrogel 0.54 mm SE 0.39, cage 1.12 mm SE 0.29 and control 0.70 mm SE 0.48).

Flower and Seed Production

Only six of the surviving 29 plants flowered during spring of 2019, producing 28 flowers. A larger number of flowers were produced on plants with larger main stem diameters (number of flowers = −3.772 + 0.704 [Stem Diameter], r = 0.57, $p = 0.001$). There was also a positive linear correlation between seed and flower numbers produced (r = 0.64, $p < 0.001$). However, the dataset was small and no statistical approaches could be found to link treatment effects and percent slope to flower and seed production. We believe it is still valuable to report these results because it provides greater insight into seed contribution to the local seed bank. Ninety-six percent of flowers and 100% of all seeds occurred in the upper elevation headwater locations (plots P1.985m and P2.984m). Sixty-one percent of the flowers occurred in the cage plus hydrogel treatment with 29% in the cage treatment. With regards to seed, 72% of all seeds were produced from plants in the cage plus hydrogel treatment and 28% were produced from the cage treatment.

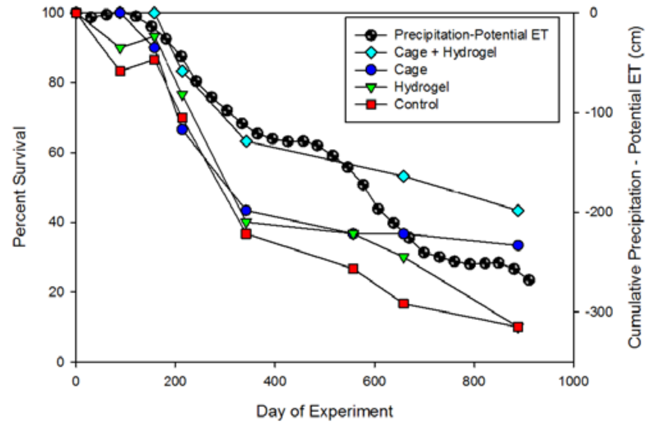

Figure 5. Percent survival of *E. virginensis* over time based on treatments, along with cumulative monthly precipitation minus monthly potential evapotranspiration (cm).

No seeds were produced from plants growing in control or hydrogel treatments.

Seedling Survival

A percent survival curve for *E. virginensis* seedlings over the 30-month monitoring period revealed considerable variation based on treatments (Figure 5). Survival remained high for the first 157 days of monitoring, with only the cage plus hydrogel plants remaining at 100% survival by day 214 (May 31, 2017) coinciding with high values of cumulative precipitation minus potential ET. However, survival began to decline quickly over the next 128 days, declining below 43% for all treatments except the cage plus hydrogel which maintained survival at 63% on day 342. Day 342 occurred after the third and final hydrogel application. A two way analysis of variance (elevation and treatment) revealed a significant elevation by treatment interaction effect on this date ($F_{12,100} = 2.39$, $p = 0.009$) with higher survival in the upper elevation headwater locations in the cage and cage plus hyrogel treatments.

The precipitation minus potential ET values leveled off around day 380 and day 675 when higher precipitation occurred. This wetter period was not enough to maintain a legacy effect of the hydrogel applications as the survival of the cage plus hydrogel plants began converging with the survival of the cage treatment. Survival continued to decline over the last 546 days as the cumulative precipitation minus potential ET declined, with final separation

Table 2. Probability of survival p values based on Logrank tests for comparison of plots.

Site	P1.985m	P2.984m	P3.967m	P4.955m	P5.936m
P1.985m	—	0.970	0.026	0.047	0.210
P2.984m	—	—	0.034	0.068	0.250
P3.967m	—	—	—	—	0.320
P4.955m	—	—	—	—	0.390
P5.936m	—	—	—	—	—

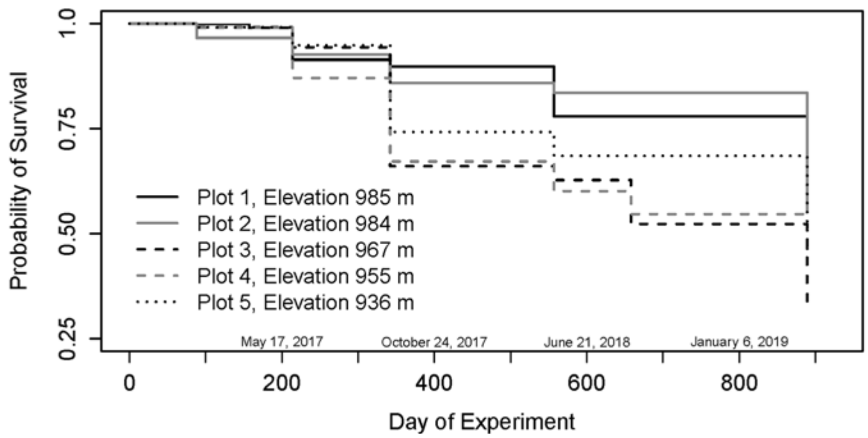

Figure 6. Probability of survival of *E. virginensis* over time based on elevation.

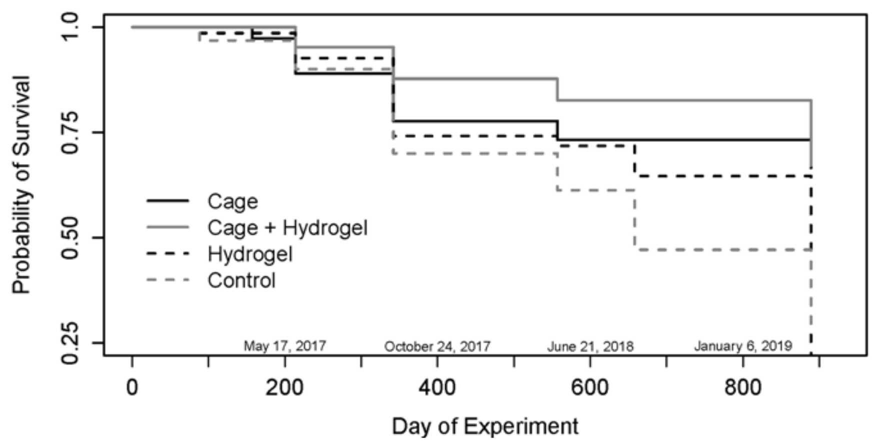

Figure 7. Probability of survival of *E. virginensis* over time based on imposed treatments.

between those plants with cages versus those plants without cages (two-way ANOVA, elevation by treatment, treatment effect, $F_{3, 84} = 3.03$, $p = 0.034$). A high correlation existed between survival over time (for all treatments) with the cumulative precipitation minus potential ET (r values of 0.93 to 0.94, $p < 0.001$, except for the cage plus hydrogel which was 0.83, $p < 0.001$). We note that the hydrogel treatment did not respond in a similar fashion as the cage plus hydrogel treatment suggesting a greater impact of herbivory, as the hydrogel final survival was identical to the control survival at 10%.

The probability of survival based on plot location (elevation), treatment, and based on slope versus wash is shown in Figures, 6, 7 and 8. We also generated a probability of survival matrix of p values in Tables 2–4. The probability of survival based on plot location separated by day 342, with the two upper elevation head-water locations maintaining higher survival. However, the logrank tests indicated that these two upper elevation headwater locations could only be separated from plot P3.967m and P4.955m. The logrank tests indicated that there was no statistical difference between cage and cage plus hydrogel ($p = 0.14$), with cage and cage plus hydrogel higher and significantly different from the control but only the cage plus hydrogel was found to be significantly different (higher) from the hydrogel alone. The probability of survival based on slope versus wash revealed a clear separation between upper elevation headwater locations and the lower elevation wash locations. There was no distinction based on slope versus wash in the upper elevation headwater locations but there was a clear separation based on slope versus wash in the lower elevation wash locations. The logrank tests revealed that the highest level of significance ($p = 0.001$) was found when comparing survival probability on slopes versus washes and specifically when contrasting the slopes and washes in the lower elevation wash locations (P3.967m, P4.955m, P5.936m). Survival of plants growing on slopes in the lower elevation three wash locations was 28% versus only 8% when in close association with the wash.

Discussion

Numerous variables determine the overall success of any restoration project, but in desert areas, the amount, duration, and intensity and time intervals between rainfall events play a significant role in the success. Unfortunately, rainfall lacks stationarity making it difficult to predict the future from the past, meaning any planting faces a degree of uncertainty with regards to water availability. In our study we selected a November planting knowing that environmental demand would be lower and that the winter months would be relatively wet months (based on historical precipitation). Fortunately, the planting was followed by a 4-month wet period. However, if the planting had occurred

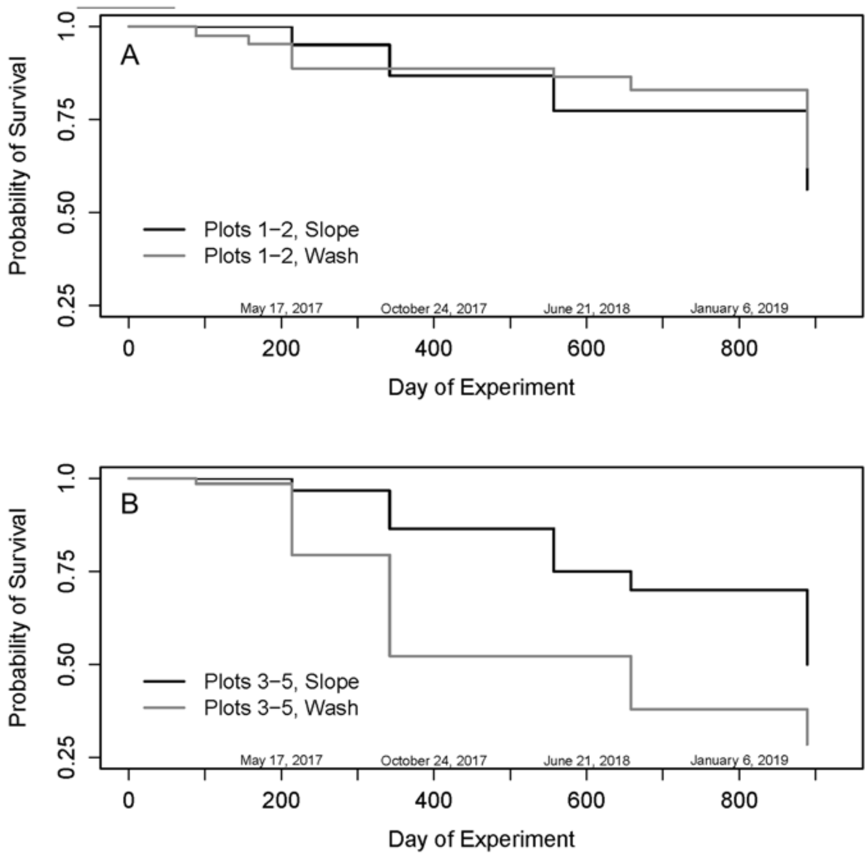

Figure 8. Probability of survival of *E. virginensis* over time based on slope wash locations. Probablity of survival in upper elevation head water locations (A) vs. lower elevation wash locations (B).

a year later the seedlings would have received ~8 cm less precipitation during this same 4-month period, facing a likely different outcome in terms of seedling survival. Other investigators have also stressed the importance of the timing of precipitation events relative to the timing of planting (Helenurm 1998, Abella and Newton 2009, Minnick and Alward 2012). It is difficult to compare studies in terms of assessing seedling survival to different treatments without clear knowledge of water availability, especially precipitation and soil moisture content. Helenurm (1998) suggested that success of out-planting efforts should be linked to sites chosen in conjunction with rainfall and soil moisture data. Deep movement of water in arid and semiarid environments does not occur on a regular basis as it is estimated that 90% of precipitation is lost through the process of ET (Huxman et al. 2005, Scott 2010). However it is these large precipitation events that contribute directly to deep movement of water, often triggering higher growth (Nagler et al. 2007) and transpiration rates (Cavanaugh et al. 2011) favoring deep rooted perennial shrubs like *Larrea tridentata* (Cavanaugh et al. 2011).

At what point is a young establishing perennial shrub out of danger with regards to extended dry periods and at what point is the restoration work considered a success? Deep penetration of rainwater in the soil generally enhances a deeper root system (Ogle and Reynolds 2004), enabling the plant access to a larger soil water storage component to help offset stress. In our study rainfall penetration to 43 cm only occurred during one month of the 33-month monitoring period (soil moisture data). Young seedlings had a 15 cm rooting depth at planting and although we did not measure rooting depth during the study, the fact that no response in soil water content at the 43 cm depth persisted until late in the monitoring period suggests that root development and activity was probably greater nearer the surface. Strong oscillations in soil water content at shallower depths reflected a more stressful soil moisture condition at our site. The soil water status at our site (weather station) was a precipitation driven response with cumulative precipitation minus potential ET being highly negative except during winter months. Based on the alternating wet dry periods we observed in this study, the success we had at 30 months may still not be reflective of the long-term survival. This is especially true in light of possible climate warming as pointed out by Palma et al. (2015), where global climate change models predict less precipitation for the southwestern portion of the US (National Climate Assessment 2014). We believe success must not be based on survival alone but instead on survival and seed production. Long term studies (> 5 years) are needed that quantify the dynamic relationship between survival, growth and flower, and seed production. Abella et al (2015b) also mentioned the importance of assessing seed production and whether those seeds facilitate recruitment of their own populations. Minnick and Alward (2012) reported that 4.5 years after transplanting, there was no significant treatment effect that

Table 3. Probability of survival *p* values based on Logrank tests for comparison of treatments.

Treatment	Cage	Cage + Hydrogel	Hydrogel	Control
Cage	—	0.140	0.220	0.046
Cage + Hydrogel	—	—	0.003	0.001
Hydrogel	—	—	—	0.280
Control	—	—	—	—

Table 4. Probability of survival *p* values based on Logrank tests for comparison of slope versus wash sites.

Slope vs. Wash	All Wash	Wash (Plots P1, P2)	Wash (Plots P3, P4, P5)
All Slopes	0.001	—	—
Slopes (P1, P2)	—	0.90	—
Slopes (P3, P4, P5)	—	—	0.001

could still be observed, also indicating the need for longer term monitoring.

Many studies have demonstrated the significance of adding water during the establishing period to enhance survival (Minnick and Alward 2012, Abella et al. 2015a). It was interesting in our study that hydrogel by itself provided little to enhance survival over control plants, most likely due to herbivory (Figures 5 and 7) Although the combination of cage plus hyrodgel had the highest survival rate (43%) after 30 months, survival analysis indicated a non- significant difference with the cage treatment (33%). We only applied hydrogel during the first year (3 times), with survival on Day 342 20% higher than in any of the other treatments. However, with time after the last hydrogel application, survival declined but still remained higher in the cage plus hydrogel treatment, suggesting that this treatment enabled those plants to better establish, possibly by developing deeper roots. This was further substantiated by the significantly higher stem growth in the cage plus hydrogel treatment (after the third and final hydrogel application) during part of 2018 compared to all other treatments, although the growth assessed over the full 889 days did not reveal a treatment effect on stem growth. It should also be noted that the control plants in the upper elevation head water plots (P1.985m and P2.984m) represented only 12.5% of the surviving plants, whereas cage plus hydrogel represented 50% of the surviving plants and cage alone represented 25% of the surviving plants. Although upper elevation head water plots had the highest survival rates, enhanced survival occurred associated with treatments (67% survival of cage plus hyrogel in the two upper elevation wash locations) indicating that location alone (plants in the upper elevation head water area) would not represent an acceptable low cost alternative. Similar results occurred in the lower elevation wash sites (plots P3.967m, P4.955m and P5.936m) where treatments had higher survival rates (cage 33%, cage plus hydrogel 28%) with only 8% of the control plants surviving.

Restoration of desert ecosystems comes with a price. As such, costs need to be evaluated relative to the benefits (Scoles-Sciulla et al. 2015). McLuckie et al. (2019) reported on the estimated costs of planting 5,000 seedlings at the Red Cliffs Desert Reserve, UT (part of a larger project that included this study at BDWCA, 52 km apart) at $58,500. This dollar value was modified by adding an additional $7,550 for the cost of pvc pipe, stakes, hydrogel, and personnel costs for all 5000 plants, resulting in a final estimate of $66,050. If the overall seedling survival after 30 months in our study (24%) was projected for the larger study (realizing some limitations in this projection, especially since planting of the larger study included four species) it would drive the cost up from approximately $13 ($66,050/5000 plants) to approximately $55 per plant. If the entire planting was based on the cage plus hydrogel treatment with 43% survival, the cost would have been greater (additional $7550) but the cost per surviving plant would have been approximately $34. (This again projects *E. virginensis* results on the larger planting and realizes that limitations exist in this projection). These dollar estimates are similar to the $54 cost per plant estimate made by Abella et al. (2015b).

Topography was a key element in the survival response of *E. virginensis* at the BDWCA. Wirth and Pyke (2003) also reported on the important role of topography (micro) in the establishment of plants. At the headwaters of the small wash system, plots P1.985m and P2.984m had shallow slopes, where only small rills collected surface water which was then moved slowly down gradient. However, in the case of plots P4.955m and P5.936m they had greater slopes between plots and they had greater side wall slopes in the wash, increasing to over 20%. Wash systems represent a unique challenge to restoration efforts in desert ecosystems because of high variability in spatio-temporal growing conditions that directly influence survival, flowering, and seed production. Although water is collected and transmitted from a larger area concentrating significant quantities of water, this water moves rapidly away, often scouring top soil and sediments in the process, contributing to patchwork ecosystems (Swanson et al. 1988). Based on our results, poorer seedling survival was observed at the lower elevation wash sites closer to the central wash system (saturated hydraulic conductivities two orders of magnitude greater at some of the wash sites compared to slope sites). Although we observed a few, healthy *E. virginensis* plants flowering in the lower wash system, the general area had few mature shrubs. No surviving seedlings in this area produced seed during the 30-month monitoring period. We conclude that much more detailed work is needed on restoration of wash systems in desert environments, especially detailed water balances at different elevation and slope locations. Precipitation in desert environments is low and highly variable. Our understanding of how water is partitioned into evaporation and transpiration (Cavanaugh et al. 2011), and what percentage of precipitation infiltrates the soil or contributes to runoff in wash systems is still poorly understood. We were unable to develop a generalized model linking K_s, soil volumetric water content and precipitation to survival as a more detailed approach is needed. Our results would suggest that providing cages enhances survival of seedlings as 79% of plants surviving on day 889 had cages (with or without hydrogel). Although survival analysis did not support the added expense of incorporating hydrogel with cages ($p = 0.14$) it did support it after the third hydrogel application during the first year (20% higher survival). This suggests that if a second year of hydrogel had been applied, survival might have even been higher. The small data set on flowering and seed production suggests that hydrogel in combination with cages deserves further attention as a management option. Survival is important but if plants do not flower and contribute seed to the seed bank, it does little to accelerate the recovery of the plant community after a disturbance event.

Acknowledgements

We wish to thank Washington County Utah, State of Utah Fish and Wildlife Service and Bureau of Land Management for funding this research. We also wish to thank Mr. Logan Love, Mr. Joel Herd, Mr. Terry Zajic and Ms. Daisy Torres Dizon for assistance with the lab and field work.

References

Abella S.R. 2009. Post fire plant recovery in the Mojave and Sonoran Deserts of western North America. *Journal Arid* Environments 73:699–707.

Abella S.R. and A.C. Newton. 2009. A systematic review of species performance and treatment effectiveness for revegetation in the Mojave Desert, USA. Pages 45–74 in A. Fernandez-Bernal and M.A De La Rosa (eds), *Arid Environments and Wind Erosion*. Hauppauge, New York, NY: Nova Science Publishers.

Abella S.R. 2010. Disturbance and plant succession in the Mojave and Sonoran Deserts of the American Southwest. *International Journal of Environmental Research and Public Health* 7:1248–1284.

Abella S.R. and S.D. Smith. 2013. Annual-perennial plant relationships and species selection for desert restoration. *Journal Arid Land* 5:298–309.

Abella S.R., L.P. Chiquoine, A.C. Newton and C.H. Vanier. 2015a. Restoring a desert ecosystem using soil salvage, revegetation and irrigation. *Journal Arid Environments* 115:44–52.

Abella S.R., K.L. O'Brien and M.W. Weesner.2015b. Revegetating disturbance in National Parks: Reestablishing native plants in Saguaro National Park, Sonoran Desert. *Natural Areas Journal* 35:18–25.

Abella S.R. and K.H. Berry. 2016. Enhancing and restoring habitat for the desert tortoise. *Journal of Fish and Wildlife Management* 7:255–278.

Abella S.A., L.P. Chiquoine and J.F. Weigand. 2019. Developing methods of assisted natural regeneration for restoring foundational desert plants. *Arid Land Research and Management* 34:231–237.

Allen E.B., R.J. Steers and S.J. Dickens. 2011. Impacts of fire and invasive species on desert soil ecology. *Rangeland Ecology and Management* 64:450–462.

Aref I.M., L.I. El-Juhany and M.N. Shalby. 2006. Establishment of acacia plantation in the central part of Saudi Arabia with the aid of Driwater. *2nd International Conference on Water Resources and Arid Environment*. Saudi Arabia: Prince Sultan Research Centre for Environment, Water and Desert, King Saud University.

Bainbridge D.A. 2007. *A Guide for Desert and Dryland Restoration*. Washington, DC: Island Press.

Blauth J.R., D. Schrum, T. Harp, H. Woolverton, S. Guthrie, J. Garcia, I. Sandri. 2007. Towards Revegetation of a Disturbed Desert Wash Using Native Woody Legumes, Rhizobia, and Arbuscular Mycorrhizae. Botany and Plant Biology Joint Congress.

Brooks, M.L. and J.R. Matchett. 2006. Spatial and temporal patterns of wildfires in the Mojave Desert, 1980–2004. *Journal of Arid Environments* 67:148–164.

Brooks M.L. and K.H. Berry. 2006. Dominance and environmental correlates of alien annual plants in the Mojave Desert, USA. *Journal of Arid Environments* 67:100–124.

Cavanaugh M.L., S.A. Kurc and R.L. Scott. 2011. Evapotranspiration partitioning in semiarid shrubland ecosystems: a two site evaluation of soil moisture control on transpiration. *Ecohydrology* 4:671–681.

Fuentes-Ramirez A., J.L. Schafer, E.L. Mudrak, M. Schat, H.A. Parag, C. Holzapfel and K.A. Moloney. 2015. Spatio temporal impacts of fire on soil nutrient availability in Larrea tridentata shrublands of the Mojave Desert USA. *Geoderma* 259:126–133.

Furuya Y., D.K. Wijesundara, T. Neeman and D.W. Metzger. 2014. Use and misuse of statitical signifcance in survival analyses. *mBio.* doi:10.1128/mBio.00904–14.

Grantz D.A., L. Vaughn, R.J. Farber, B. Kim, L. Ashbaugh, T. VanCurren, et al. 1998. Transplanting native plants to revegetate abandoned farmland in the western Mojave Desert. *Journal of Environmental Quality* 27:960–967.

Helenurm, K. 1998. Outplanting and differential source population success in *Lupinus guadalupensis. Conservation Biology* 12:118–127.

Huxman T.E., B. P. Wilcox, D.D. Breshears, R.L. Scott K.A. Snyder, E.E. Small, et al. 2005. Ecohydrological implications of woody plant encroachment. *Ecology* 86:308–319.

Klute A. 1965. Laboratory measurement of hydraulic conductivity of saturated soil. Pages 210–220 in *Methods of Soil Analysis. Agronomy 9*. Madison, WI: American Society of Agronomy.

McLuckie, A.M., S.N. Siefken and I.E.L. Tween, 2020. Desert tortoise habitat restoration in burned areas within Red Cliffs National Conservation Area, August 2019. Pages 129–134 in R.A. Fridell (ed.), *Southern Region Native Aquatics 2019 Field Summary*

Program Report for Amphibians, Reptiles, Native Fishes and Mollusks. Salt Lake City, UT: Utah Division of Wildlife Resources.

Minnick T.J. and R.D. Alward. 2012. Soil moisture enhancement techniques aid shrub transplant success in an arid shrubland restoration. *Rangeland Ecology and Management*. 65:232–240.

Mojave Basin and Range REA (Nature Serve). 2013 *Bulletin No. NV* 2013–034.

Nagler P.L., E.P. Glenn, H. Kim, W. Emmerich, R.L. Scott, T.E. Huxman et al. 2007. Relationship between evapotranspiration and precipitation pulses in a semiarid rangeland estimated by moisture flux towers and MODIS vegetation indices. *Journal of Arid Environments* 70:443–462.

National Climate Assessment 2014. Precipitation Change. nca2014.globalchange. Gov/report/out-changing-climate/precipitation-change.

Ogle K. and J.F. Reynolds. 2004. Plant responses to precipitation in desert ecosystems: integrating functional types, pulses, threshold and delays. *Oecologia* 1:282–294.

Palma A.C. and S.G.W. Laurance. 2015. A review of the use of direct seedling and seedling plantings in restoration: What do we know and where should we go. *Applied Vegetation Science* 18:561–568.

Peters, D.P.C. and J. Yao. 2012. Long-term experimental loss of foundation species: Consequences for dynamics at ecotones across heterogeneous landscapes. *Ecosphere* 3:1–23. doi:10.1890/ES11-00273.1.

Ren H., Y. Long and L. Nan. 2008. Nurse plant theory and its application in ecological restoration in lower subtropics of China. *Progress in Natural Science* 18:137–142.

Scoles-Sciulla S.J., L.A. DeFalco and T.C. Esque. 2015. Contrasting long-term survival of two outplanted Mojave Desert perennials for post-fire revegetation. *Arid Land Research and Management* 29:110–124.

Scott R.L. 2010. Using watershed water balance to evaluate the accuracy of eddy covariance evaporation measurements for three semiarid ecosystems. *Agriculture and Forest Meteorology* 150:219–225.

Soulard C.E., T.C. Esque, D.R. Bedford and S. Bond. 2013. The role of fire on soil mounds and surface roughness in the Mojave Desert. *Earth surface Processes and Landforms* 38:111–121.

Steers R.J. and E.B. Allen. 2010. Post fire control of invasive plants promotes native recovery in a burned desert shrubland. *Restoration Ecology* 18:334–343.

Swanson F.J., T.K. Kratz, N. Caine and R.G. Woodmansee. 1988. Landofrm effects on ecosystem patterns and processes. *BioScience* 38:92–98.

USDA (2019). Saturated hydraulic conductivity. www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/survey/office/ssr10/tr/?cid.

Utah EvapoTranspiration Network Potential evapotranspiration (accessed June 2019) www.conservewater.utah.gov/ET/ETSi.

Vasek, F.C., H.B. Johnson and C.D. Brum. 1975, Effects of power transmission lines on vegetation of the Mojave Desert: *Madroño* 23:114–130.

Web R.H., J. Belnap and K.A. Thomas. 2009. Natural recovery from severe disturbance in the Mojave Desert. Pages 343–377 in R.H. Webb, L.F. Fenstermaker, J.S. Heaton, D.L. Hughson, E.V. McDonald and D.M. Miller (eds). *The Mojave Desert: Ecosystem Processes and Sustainability*. Reno, NV: University of Nevada Press.

Western Regional Climate Center.2019. Precipitation Beaver Dam, AZ (accessed June 2019). wrcc.dri.edu.

Wirth T.A. and D.A. Pyke. 2003. Restoring forbs for sage grouse habitat: fire, microsites and establishment methods. *Restoration Ecology* 11:370–377.

Dale Devitt (corresponding author), School of Life Sciences, University of Nevada Las Vegas, Las Vegas, NV 89154. dale.devitt@unlv.edu.

Fred Landau, School of Life Sciences, University of Nevada Las Vegas, Las Vegas, NV.

Scott Abella, School of Life Sciences, University of Nevada Las Vegas, Las Vegas, NV.

Matt Petrie, School of Life Sciences, University of Nevada Las Vegas, Las Vegas, NV.

Ann Mcluckie, Utah Division of Wildlife Resources, Hurricane, UT.

John Kella, Red Cliffs National Conservation Area, Bureau of Land Management, St. George UT.