Soil Moisture Enhancement Techniques Aid Shrub Transplant Success in an Arid Shrubland Restoration

Author(s): Tamera J. Minnick and Richard D. Alward

Source: Rangeland Ecology & Management, 65(3):232-240. 2012.
Published By: Society for Range Management
DOI: http://dx.doi.org/10.2111/REM-D-10-00133.1
URL: http://www.bioone.org/doi/full/10.2111/REM-D-10-00133.1

Rangeland Ecol Manage 65:232–240 | May 2012 | DOI: 10.2111/REM-D-10-00133.1

Soil Moisture Enhancement Techniques Aid Shrub Transplant Success in an Arid Shrubland Restoration

Tamera J. Minnick[1] *and Richard D. Alward*[2]

Authors are [1]*Associate Professor, Department of Physical and Environmental Sciences, Colorado Mesa University, Grand Junction, CO 81501, USA; and* [2]*Principal Ecologist, Aridlands Natural Resources Consulting, Grand Junction, CO 81503, USA.*

Abstract

In arid and semi-arid environments, where low and unpredictable rainfall is typical, establishment of perennial vegetation can be enhanced with modest increases in soil moisture. We evaluated methods for promoting shrub transplant establishment. We transplanted approximately 1 000 3-mo-old seedlings in April 2004, 2005, and 2006, using a full-factorial design with combinations of three treatments: addition of mycorrhizae spores to the root zone, addition of a hydrogel to the root zone, and placement of a wood obstruction south of the plant. We planted three shrubs: big sagebrush (*Artemisia tridentata* Nutt. ssp. *tridentate*), four wing saltbush (*Atriplex canescens* [Pursh] Nutt.), and rubber rabbitbrush (*Ericameria nauseosa* [Pall. ex Pursh] G.L. Nesom & Baird ssp. *nauseosa*) in a 1.2-ha area. The summer months of 2004 and 2006 were dry, leading to low survivorship ($<1\%$). With higher rainfall in summer 2005, transplant survivorship was ~18%. For the 2005 transplants, *A. tridentata* had the highest survivorship after one growing season (31.0%), followed by *A. canescens* (20.6%) and *E. nauseosa* (6.9%). Placing a wood obstruction near the plant was significant in the statistical model to describe short-term overall transplant survival and survival of *A. tridentata*. Placing hydrogel in the root zone also explained short-term overall transplant survival, as well as survival of *E. nauseosa*. However, by 4.5 yr after transplanting, there was no significant treatment effect on survival. Thus, for transplanting shrub seedlings on arid or semi-arid sites, we recommend some form of resource enhancement technique to increase short-term survival. In this experiment, both the obstruction and hydrogel treatments were effective. We recommend the obstruction treatment since slash is often readily available onsite, has low labor requirements and cost, and it increased transplant survival of *A. tridentata*, a species of conservation concern; however, other treatments may be appropriate for individual species.

Resumen

En zonas áridas y semiáridas, donde las bajas precipitaciones y la lluvia impredecible son típicas, el establecimiento de la vegetación perenne puede ser mejorado con pequeños incrementos en la humedad del suelo. Se evaluaron métodos para promover el establecimiento de arbustos trasplantados. Se trasplantaron aproximadamente 1 000 plántulas de 3 meses en Abril de 2004, 2005, y 2006, usando un diseño completamente factorial con combinaciones de tres tratamientos: adición de esporas de micorrizas en la zona de la raíz, adición de hidrogel en la zona de la raíz, y la colocación de una obstrucción de madera al sur de la planta. Se plantaron tres arbustos: big sagebrush (*Artemisia tridentata* Nutt. ssp. *tridentata*), four wing saltbush (*Atriplex canescens* [Pursh] Nutt.), and rubber rabbitbrush (*Ericameria nauseosa* [Pall. ex Pursh] G.L. Nesom & Baird ssp. *nauseosa*) en una área de 1.2 has. Los meses del verano de 2004 y 2006 fueron secos, dando como resultado una sobrevivencia baja ($<1\%$). Con una mayor cantidad de lluvia en el verano del 2005 la sobrevivencia de los trasplantes fue ~18%. Para los trasplantes de 2005 *A. tridentate* presentó la mayor sobrevivencia después de la época de crecimiento (31.0%) seguido por *A. canescens* (20.6%) y *E. nauseosa* (6.9%). La colocación de la obstrucción de madera cerca de la plantas fue significativa en el modelo estadístico para describir a corto plazo la supervivencia de los trasplantes en general y la sobrevivencia de *A. tridentate*. La colocación de hidrogel en la zona de la raíz también explicó a corto plazo la sobrevivencia de los trasplantes en general, así como la sobrevivencia de *E. nauseosa*. Sin embargo, cerca de 4 ½ años después de los trasplantes, no hay efecto significativo en la sobrevivencia. Así para el trasplante de plántulas de arbustos en las zonas áridas y semiáridas se recomienda algún tipo de técnica para incrementar e hidrogel fueron efectivos. Se recomienda el tratamiento de obstrucción ya que la madera se puede conseguir fácilmente en estas áreas, tiene un bajo requerimiento de labor y costo, e incrementa la sobrevivencia de los trasplantes de *A. tridentate,* una especie de interés para la conservación; sin embargo otros tratamientos pueden ser apropiados para especies individuales.

Key Words: big sagebrush, desert shrubland reclamation, drought, hydrogel, revegetation, slash

INTRODUCTION

Revegetation of disturbed areas in arid lands with less than 25 cm of mean annual precipitation is challenging (Bainbridge 2007). It is critical to establish perennial vegetation in order to increase soil organic matter accumulation, since this increases nutrient availability and water infiltration and decreases soil erosion and desertification (Tongway and Ludwig 1996). Cover by perennial vegetation can also decrease invasion or

Research was funded in part by National Park Service Cooperative Agreement H137804003.

The views and conclusions contained in this document are those of the authors and should not be interpreted as representing the opinions or policies of the US Government. Mention of trade names or commercial products does not constitute their endorsement by the US Government.

Correspondence: Tamera Minnick, Dept of Physical and Environmental Sciences, Colorado Mesa University, 1100 North Ave, Grand Junction, CO 81503, USA. Email: tminnick@coloradomesa.edu

Manuscript received 20 August 2010; manuscript accepted 28 December 2011.

re-invasion by weedy annuals (Borman et al. 1991; Sheley et al. 2001). Without active revegetation, these arid lands often remain in undesirable stable states without native, perennial vegetation for long periods (Laycock 1991; Tausch et al. 1993). However, continuous inputs into these economically marginal lands are often untenable; instead it is valuable to induce vegetation change with minimal inputs, and then rely on autogenic processes (Whisenant 1999).

Shrub establishment, in particular, is valuable in revegetating arid lands since shrubs act as facilitators by ameliorating the environment in these ecosystems, which reduces plant stress, creating a positive feedback for the establishment of more perennial vegetation (Castro et al. 2002). In arid lands, disturbed sites often have lower water interception capacity and lower nutrient availability, particularly if there has been loss of vegetative cover (Milton et al. 1994). Shrub establishment leads to increased vegetation patchiness and the formation of resource islands typical of arid and semi-arid shrublands, which in turn means ecosystem function is closer to those found predisturbance (Halvorson et al. 1994). With increased cover by shrub canopy, soil is less exposed to direct sunlight, decreasing evaporation rates. In addition, after certain disturbances such as coal mining, shrub establishment is required for enhancing ecological function and wildlife habitat. For instance, the Wyoming Department of Environmental Quality requires an average density of one shrub $\cdot$ m^{-2} be established on 20% of land disturbed by coal mining (Schuman et al. 2005). Re-establishing *Artemisia tridentata* is critical for enhancing wildlife habitat (Shaw and Monsen 1990; Connelly et al. 2011). This reclamation is often on large areas of arid or semi-arid landscapes where irrigation is not available or would be costly; therefore, determining techniques that could increase plant survivorship with fewer inputs is vital for reclaiming these disturbed landscapes. This is true in even more semi-arid and arid lands as exploration and development of oil and natural gas continues to expand and impact critical wildlife habitat (e.g., Sawyer et al. 2006; Walker et al. 2007).

For revegetation in arid and semi-arid environments, where low and unpredictable rainfall is typical, seed germination and seedling establishment is improved with techniques that modestly increase soil moisture availability (Ludwig and Tongway 1996). Mycorrhizae have been shown to increase survival by improving plant water status (e.g., Frost et al. 1998; Richter and Stutz 2002). Obstructions such as slash placed on the site can act as abiotic resource islands, which enhance microclimate and nutrient capture (Ludwig and Tongway 1996; Tongway and Ludwig 1996; Stoddard et al. 2008). A hydrogel application can increase water-holding capacity of soils and decrease evaporative loss (Huttermann et al. 1999; Fenchel et al. 2002; Abedi-Koupai et al. 2008).

One beneficial technique to increase shrub establishment and cover in revegetation attempts is to bypass the most difficult life history stage—germination—by transplanting seedlings instead of using seeds, especially in semi-arid and arid environments (Van Epps and McKell 1980; Grantz et al. 1998). In arid environments, evaporation from upper soil layers drives soil water potential lower than that required for germination (Harper and Benton 1966; Minnick and Coffin 1999). Seeds on or near the soil surface lack roots to access water lower in the soil profile. Under these conditions, successful germination is limited to infrequent wet years with multiple days of precipitation in a row (Austin and Williams 1988; Minnick and Coffin 1999).

Our objectives in this study were 1) to initiate restoration to native perennial vegetation, replacing the current weedy, annual-dominated system, by establishing shrub transplants, 2) to provide local land managers more information on promising techniques for restoration in this arid environment, and 3) to relate transplant success to soil water availability in bare interspaces vs. areas that are covered with living or nonliving material. Our specific hypothesis was that using a technique or a combination of techniques to enhance water relations would increase transplant success when compared to the control in which no enhanced transplant techniques were used, but that these techniques would be less important in survivorship once the transplants were established. We hypothesized that the wood obstruction treatment would prove particularly favorable because of its ability to decrease evaporation rates from bare soil without increasing transpiration rates.

METHODS

Site Description

This project was conducted at the west entrance to the Colorado National Monument, near Fruita, Colorado, at an elevation of 1 420 m. Long-term (1948–2005) precipitation (222 mm $\cdot$ yr^{-1}) and mean temperature maximum (19.3°C) and minimum (1.3°C) records were obtained from the nearby Fruita weather station. Soil is a Moffat sandy loam, with 2–6% slopes, which is a sandy loam texture of alluvium derived from sandstone (USDA-NRCS 2009b). The soil is well drained with pH in the range of 8 and normal salinity. This area previously featured a camp constructed to house men and equipment for the building of roads through the Colorado National Monument. It was cleared of vegetation in 1934 and occupied by Civilian Conservation Corps until 1944. Revegetation attempts have reportedly failed twice at the site, in the 1960s and 1980s (D. Price, personal communication, January 2003). The ecological site description is Sandy Salt Desert (USDA-NRCS 2009b). Nearby undisturbed vegetation is dominated by *A. tridentata* Nutt. ssp. *tridentata* with some *Sarcobatus vermiculatus* (Hook.) Torr., *Atriplex canescens* (Pursh) Nutt., *Ericameria nauseosa* (Pall. ex Pursh) G.L. Nesom & Baird ssp. *nauseosa*, and *Achnatherum hymenoides* (Roem. & Schult.) Barkworth. The study site itself is dominated by the annuals *Erodium cicutarium* L. L'Hér. ex Aiton, *Salsola tragus* L., *Bromus tectorum* L., and *Sisymbrium altissimum* L. (nomenclature follows USDA-NRCS 2009a).

Species Descriptions

We transplanted 3-mo-old seedlings of three shrub species into the site: *A. canescens*, *A. tridentata* var. *tridentata*, and *E. nauseosa* var. *nauseosa*. Seed was obtained from Granite Seed Company (Lehi, UT). *E. nauseosa* and *A. tridentata* were collected in Utah; *A. canescens* was collected in New Mexico at an elevation of approximately 1 200 m, making it ecologically similar to our site. In January of the transplant year, seed was planted into Ray Leach Cone-tainers of diameter 3.8 cm and depth 21 cm (Stuewe and Sons, Tangent, OR). Seedlings were thinned to one per container and remained in a greenhouse until approximately 2 wk before planting, when seedlings were moved to a covered area to begin acclimatizing. All three species are native and widespread throughout the western United States (Tirmenstein 1999a, 1999b; Howard 2003).

Experimental Design

The approximately 1.2-ha site was divided into 64 plots each measuring 20×20 m. In April of 2004, 2005, and 2006, two of three species of 3-mo-old seedlings (*A. tridentata*, *A. canescens*, and *E. nauseosa*) were transplanted into randomized locations in each plot. A full-factorial combination of four treatments was used in 2004: 1) AquaSorb, a cross-linked sodium polyacrylate gel (G) added to the root zone (Ark Enterprises, Warsaw, MO), 2) mycorrhizal spores (M) in water added to the root zone (Root Dip Gel, a combination of nine endomycorrhizal and seven ectomycorrhizal fungi, Mycorrhizal Applications, Grants Pass, OR), 3) small wood obstructions (W) placed on the ground surface, approximately 5 cm to the south of the seedling (quarter split pine 30–40 cm in length and 10–15 cm height), and 4) short, shallow pits (P) excavated on two sides of the plant. In subsequent years, the pit treatment was not used since the sandy soil texture eliminated water infiltration as a deterrent to seedling survival. By spring 2005, transplant mortality from 2004 was so high that the area was disked and an herbicide applied before planting. Therefore, in 2005, 16 new seedlings were transplanted per plot into the same locations used in 2004. These 16 seedlings were comprised of eight individuals each of two species, with one of each treatment combination (GMW, GW, MW, GM, G, M, W, or control) applied to the transplant. In 2006, transplants that had experienced mortality in 2005 were replaced to bring the total transplants back to 16 per plot. In each year, plastic mesh cages were added around each transplant to decrease herbivory. Seedling survivorship was assessed 4 mo after planting, and for the 2005 transplanting again in spring 2006, fall 2006, and summer 2009.

Soil Water Content Measurements

In a separate experiment at the same site, we estimated volumetric soil water content under shrub canopies, in the bare interspaces between shrub canopies, and under a nonliving obstruction (a rock or a log) on eight dates in April 2004. We established 10 plots; each plot was divided into three sections with each of the above treatments established in a section of each plot. We placed a pair of 17 cm $\times$ 0.5 mm steel welding rods to a depth of 15 cm and used a MiniTrase TDR unit (SoilMoisture Equipment Corporation, Santa Barbara, CA) to estimate volumetric soil moisture content in the same place for each measurement that occurred on the eight dates in April.

Data Analysis

Data analyses were performed using JMP 9.0 (SAS Institute Inc 2009). We used logistic regression to determine the best model of treatment effects of G, M, and W and the interactions of these treatments on overall survivorship. Nominal logistic regression is used with binary data—those which have two categorical outcomes (e.g., survival or no survival) since each treatment has only one value associated with it. The probability of survival in the full factorial model is estimated:

$$P(Survival) = \frac{1}{1+e^{-(\beta_0+\beta_1 G+\beta_2 M+\beta_3 W+\beta_4 GM+\beta_5 GW+\beta_6 MW+\beta_7 GMW+\varepsilon)}} \quad [1]$$

where the value of each treatment is either 0 (treatment absent) or 1 (treatment present). We determined the best model by using backwards model selection. We began with the full-factorial model and removed main effects and their interactions according to which had the least significant effect on survival until the model was significantly better than an intercept alone. We performed these analyses on the data collected 4 mo, 1 yr, 16 mo, and 4.5 yr after transplanting. We performed these analyses on all three species together as well as each species individually.

We used odds ratios to determine the odds of survival at 4 mo, 1 yr, 16 mo, and 4.5 yr after transplanting, contrasting survival with any treatment compared to the control. Odds ratios are a subset of logistic regression and can be used similarly to treatment means in analysis of variance (ANOVA; Field 2009). The odds of survival for each population being compared are first estimated:

$$\hat{\omega} = \hat{\pi}/(1-\hat{\pi}) \quad [2]$$

where $\hat{\omega}$ is the odds, $\hat{\pi}$ is the number of survivors, and $(1-\hat{\pi})$ is the number of individuals that did not survive. Then, the odds ratio of the two populations is estimated

$$\widehat{\phi} = \widehat{\omega_1}/\widehat{\omega_2} \quad [3]$$

where $\hat{\phi}$ is the odds ratio of the two populations (Ramsey and Schafer 2002). Therefore, the odds ratio is odds of survival in one treatment divided by the odds of survival in the other treatment. If the odds ratio is 1.5, for instance, the odds of survival with any treatment were 1.5 times higher than the odds of survival of the control. The results of the odds ratio are then compared to a Z distribution.

We performed a repeated measures analysis on log transformed soil water content data with position under the canopy as the between-subjects factor and date and the interaction of position x date as within-subjects factors. We then analyzed each date separately using a split-plot ANOVA to determine differences in soil water content under a shrub canopy, next to an obstruction or in the interspace. Plot was a random-effect, whole-plot factor while position under the canopy was a fixed-effect subplot factor, nested within plot.

RESULTS

The growing seasons, April to September, of 2004, 2006, and 2008 were dry, impacting both transplant survival and longer-term survival (Fig. 1A). Initial survival of shrub transplants was extremely low ($<1\%$) in 2004 and 2006 due to extreme drought in the 2 mo following transplanting; only 6.9 mm and 10.7 mm of precipitation were recorded in May through June in 2004 and 2006, respectively (Fig. 1B). Survival of shrub transplants through the initial growing season in 2005 was 18.4%, coinciding with 43.2 mm of precipitation in May through June 2005. In 2005, *A. tridentata* had highest survival (31.0%), followed by *A. canescens* (20.6%), and *E. nauseosa* (6.9%).

Survival through the 2005 growing season for the transplants of that year revealed that treatments that included a wood obstruction near the seedling (W) or the gel added to the root zone (G) significantly increased the odds of survival of the plants overall (Fig. 2; Table 1). Additionally, the odds of

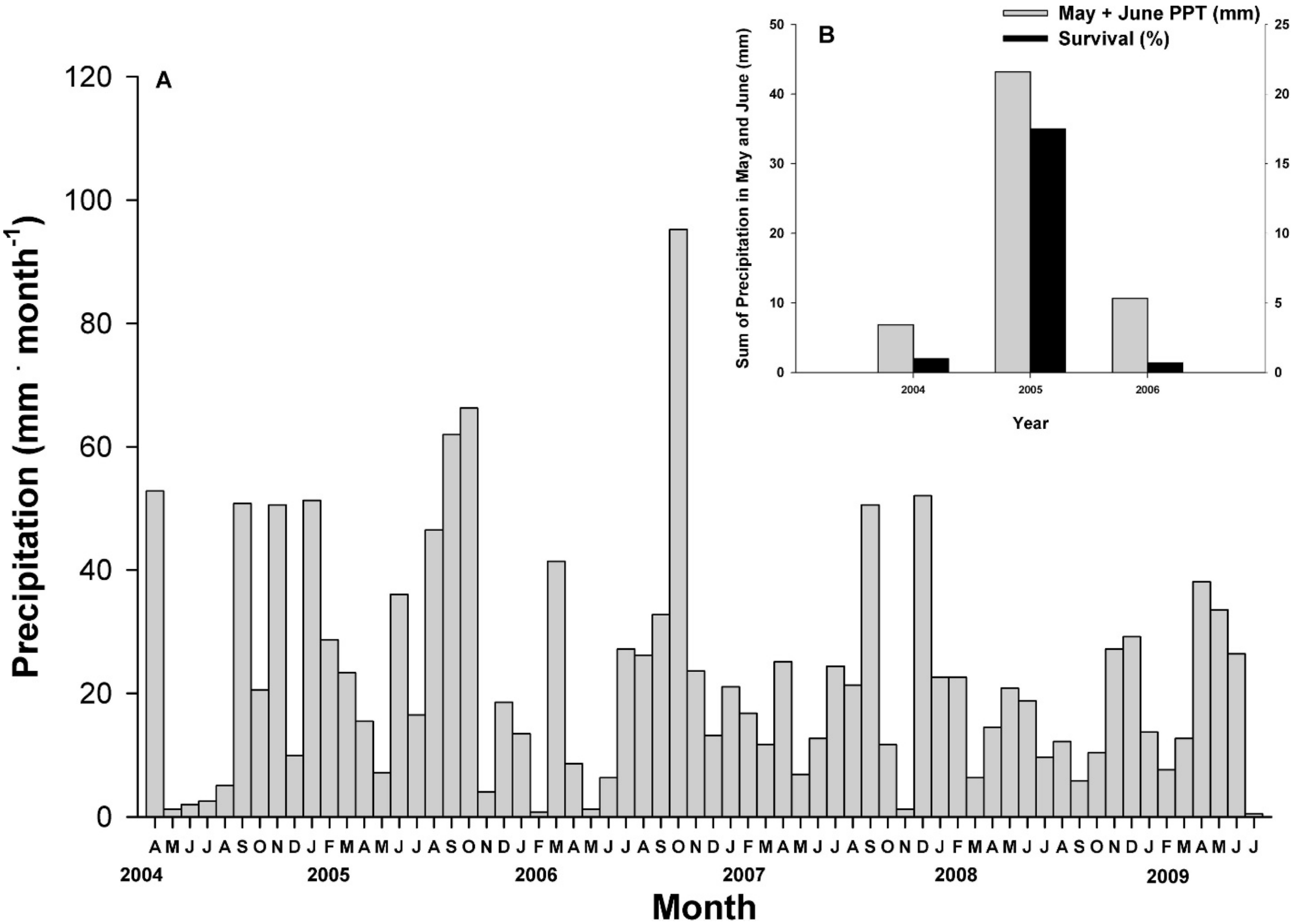

Figure 1. **A**, Precipitation (PPT) by month at the nearby Fruita, Colorado, weather station is shown for the duration of the experiment. **B** (inset), Overall survival of the shrub transplants through the first growing season was very low in 2004 (1.0%) and 2006 (0.7%) when there was little precipitation (PPT) in May and June. In 2005, with higher precipitation, survival rose considerably (18.4%).

survival were increased by 1.70 times for *A. tridentata* transplants with a wood treatment, whereas survivorship was increased 2.58 times for *E. nauseosa* with the gel treatment (Fig. 2; Table 1). Mycorrhizae additions and the interactions of the main effects were never significant in the logistic regression models, although the wood by gel interaction was present in the models for all species and *A. tridentata* (Fig. 2; Table 1).

The overall success of the treatments following one growing season did not necessarily persist through time (Fig. 3; Table 1). Similar results were seen after 4 mo and 1 yr, but 4.5 yr after transplanting the seedlings, there was no significant difference when contrasting any treatment combination to the control for all species, *A. canescens* and *E. nauseosa*; there was a significant difference in the odds ratio for *A. tridentata* (Fig. 3; Table 2).

The within-subject results from the repeated measures analysis indicated that there was a significant interaction of time and canopy position on volumetric soil water content, $F_{8.03,108.45} = 5.36$, $P < 0.0001$ (Fig. 4). Mauchly's test demonstrated that the assumption of sphericity had been violated $\chi^2_{27} = 59.38$, $P < 0.0004$; therefore, degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity (von Ende 1993; Field 2009). According to the univariate analyses, there were significant differences on 1 April, 25 April, and 29 April among treatments; on these dates, the bare interspaces had significantly lower soil water content than either the position with a nonliving obstruction, a shrub canopy, or both (Fig. 4).

DISCUSSION

Precipitation in arid environments is highly variable from year to year (Ludwig 1986). Extremely low transplant success in the two dry years of this experiment (2004 and 2006; Fig. 1B) suggests that successful transplanting of perennial vegetation in arid environments may require repeated attempts over multiple growing seasons, especially if no supplemental water is used. However, the ability to apply supplemental water in many arid and semi-arid reclamation projects of large size outside of riparian areas is limited. In addition to 2005 having a wetter period following the transplanting, the area was disked and an herbicide was applied to decrease annual weed cover, possibly increasing soil moisture availability and transplant survival due to lower transpiration by weedy vegetation (Van Epps and McKell 1983; Harrington 1991).

The wood obstruction treatment shows promise as a low cost, effective technique for increasing transplant success, especially for *A. tridentata*, a species of particular conservation concern (Lysne 2005). Potential mechanisms for the beneficial results of

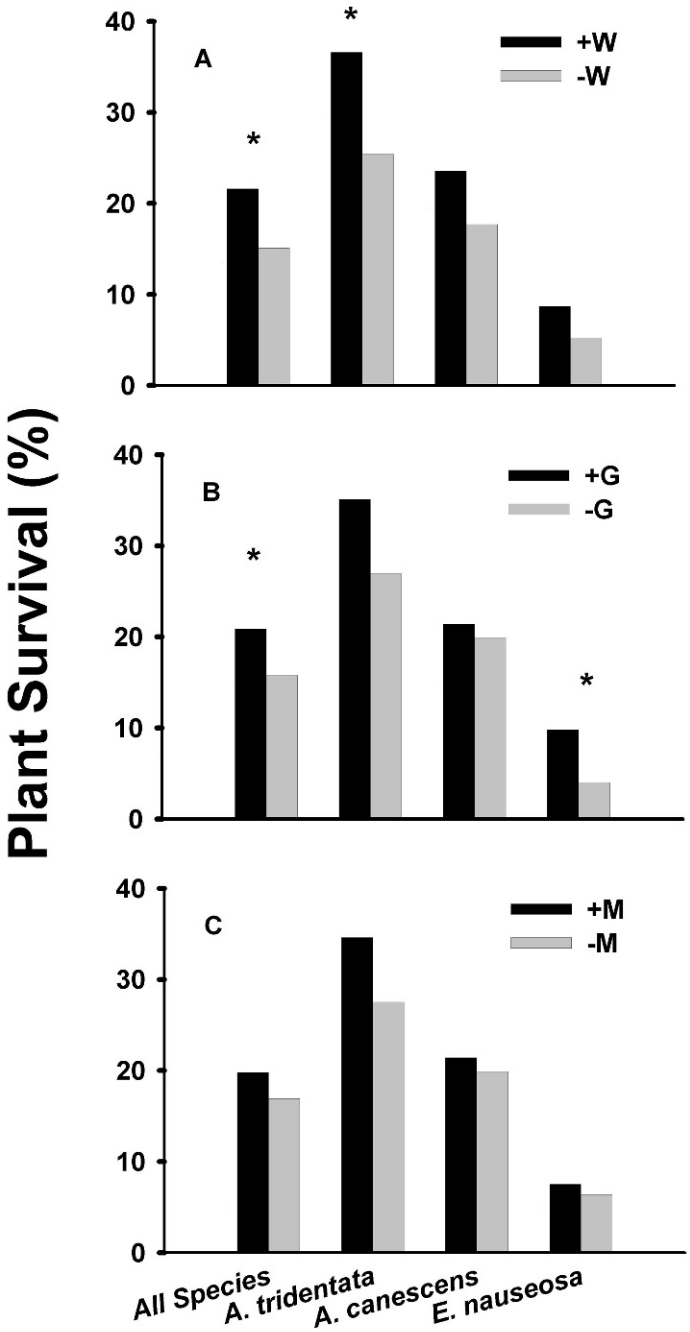

Figure 2. The main effects of **A**, wood (W), **B**, gel (G), and **C**, mycorrhizae (M) on transplant survival (after 4 mo) are shown. The black bars represent the percentage of survival averaged across all treatment combinations that include the specific treatment, while the gray bars are the percentage survival averaged across all treatment combinations without the specific treatment. An asterisk indicates a significant effect in the nominal logistic model at $P < 0.05$.

the obstruction include decreasing evaporation under and near the obstruction or increasing infiltration rates around the obstruction. In this case, the former mechanism is more likely since soil at the site is coarse textured with high infiltration rates. In the concurrent soil water content study, we found soil water content beneath living adult shrubs, and beneath rock and wood obstructions, to be higher than that found in bare ground on some dates, lending further credence to this as a mechanism. Similarly, adding slash as an aboveground obstruction has been shown to increase soil water content and organic matter content, decrease erosion, and increase seedling establishment (Ludwig and Tongway 1996; Tongway and Ludwig 1996; Stoddard et al. 2008). If slash is readily available near a disturbed site, this treatment may be both ecologically and economically effective at increasing transplant success for some species.

The addition of a hydrogel to the root zone also provided an increase in overall transplant success. The benefits of the hydrogel-combination treatments were significant for *E. nauseosa*, specifically (Fig. 2B). Hydrogels increase the water holding capacity of soils (Huttermann et al. 1999). Abedi-Koupai et al. (2008) found that hydrogel addition increases both residual water content and saturated water content, leading to a 3.2-fold increase in available water in a sandy loam soil. This increased water availability can lead to higher xylem pressure potential in transplants (Huttermann et al. 1999; Savé et al. 1995) and increases in seedling and transplant survival (Callaghan et al. 1989; Huttermann et al. 1999; Mangold and Sheley 2007). However, the hydrogel impact may not be long lasting: the hydrogel appears to degrade in the environment after as little as 18 months (Holliman et al. 2005), and roots quickly outgrow the area where it is added to the soil (Callaghan et al. 1989). Because there would also be additional logistic, economic, and labor costs of this treatment compared to the obstruction treatment, we would argue for its use when it would confer significant advantages for particular species or if slash is not readily available.

The addition of mycorrhizae spores alone, or as part of a combination of treatments, did not significantly increase the survival of these shrub transplants (Fig. 2C) even though the literature suggests that mycorrhizae are important for germination of *A. canescens* and seedling establishment of *A. tridentata*. For instance, the mycorrhizae *Glomus* spp. are important for the successful establishment of sagebrush seedlings (Bethlenfalvay and DaKessian 1984). In addition, Barrow et al. (1997) found that mycorrhizal infection was critical for germination of *A. canescens*. We did not test for mycorrhizae presence prior to the treatment application. If mycorrhizae were already present in either the transplant or site soils, this may have contributed to the lack of effect observed in this experiment. Furthermore, in this experiment we were establishing transplants, not germinating seed, and mycorrhizal infection may be less important at this later stage.

A. tridentata and *E. nauseosa*, in particular, benefited from some form of resource enhancement for transplant establishment, even in a wetter year. The differences among the species in their responses to resource enhancement are not surprising since they have different resource requirements and growth rates (Anderson et al. 1979; Monsen and Stevens 1987). *A. tridentata* has been seen to have more favorable establishment within the canopy of an adult plant, of either its own species (Owens and Norton 1992) or *A. canescens* (Booth 1985), and thus the obstruction treatment may function similarly to decrease evaporation from the soil. *A. canescens* is salt, cold, and drought tolerant, able to drive its water potential below −3 MPa (Wilkins and Klopatek 1987; Aldon et al. 1995), and thus may not have benefitted from any of the treatments to enhance water availability; however, Stevens (2004) reports it as being difficult to establish bareroot or container-grown stock, which could explain its lower transplant success.

Table 1. The parameters are shown for the logistic regression models if significantly better than the intercept alone. Backwards model selection was used on the full model to predict survival with the treatments wood (W), gel (G), mycorrhizae (M), and all combinations of these treatments. β parameters are given and an asterisk indicates $P < 0.05$, ** $P < 0.01$, and *** $P < 0.001$.

	Intercept	W	G	M	W × G	W × M	G × M	W × G × M
Fall 2005								
All species	1.52***	0.22*	0.18*		0.02			
Artemisia tridentata	0.84***	0.04*	0.10		0.12			
Atriplex canescens	2.62***							
Ericameria nauseosa	2.69***		0.48*					
Spring 2006								
All species	1.82***	0.08	0.28**		0.73			
A. tridentata	0.95***	0.31*	0.27		0.16			
A. canescens	1.92***							
E. nauseosa	2.96***							
Fall 2006								
All species	2.08***							
A. tridentata	1.09***							
A. canescens	2.52***							
E. nauseosa	3.24***							
Fall 2009								
All species	2.33***							
A. tridentata	1.42***							
A. canescens	2.62***							
E. nauseosa	3.72***							

Overall, *E. nauseosa* transplant survival was much lower than the other two species even though the literature suggests that this species establishes frequently (Monsen and Stevens 1987; Stevens 2004). In addition, we observed *E. nauseosa* plants naturally seeding into the edges of the disturbed area. Herbivory may have contributed to low transplant survival since *A. canescens* and *E. nauseosa* are reportedly more palatable and more susceptible to grazing than *A. tridentata* (Monsen and Christensen 1975; Mozingo 1987; Schuman et al. 1990; Shaw and Monsen 1990). Grasshopper herbivores, in particular, would not have been excluded by the plastic mesh placed around the seedlings. In addition, *E. nauseosa* seedling roots grow rapidly, but mortality is common in the summer months due to water-stress (Donovan et al. 1993).

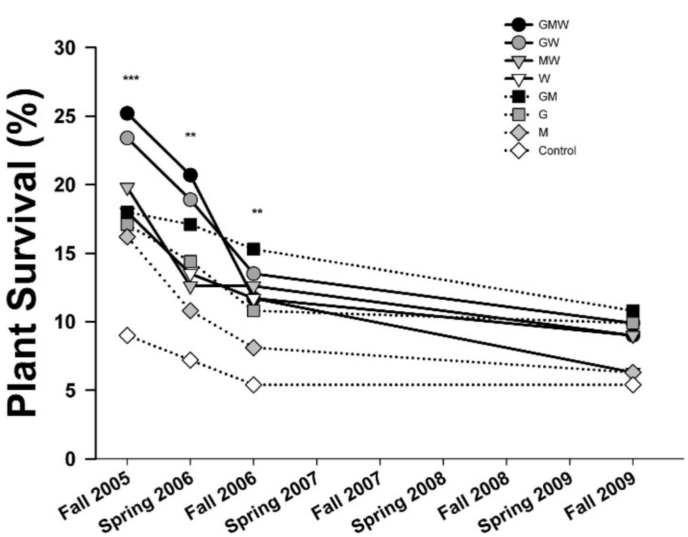

Figure 3. Initial survival over all species was higher with any treatment combination compared to the control; however, there was no significant difference in this contrast by 4.5 yr after planting. An asterisk indicates significant differences in the odds ratio analyses in transplant survival for all species with any treatment compared to the control at $P < 0.05$, ** $P < 0.01$, and *** $P < 0.001$. See Figure 2 for treatment abbreviations.

Four years following transplanting, the differences among treatments and the control were no longer detectable (Fig. 4). After the first growing season, mortality rates were highest for *A. canescens*; there was little further mortality in the either *A. tridentata* or *E. nauseosa* during the first 16 mo. However, in the final measurements, higher *A. tridentata* mortality was detected. This may be due to another dry growing season in 2008. These results suggest that more years of additional management intervention, including water supplements and herbivore protection, may be necessary in order to promote revegetation success during subsequent drought years.

IMPLICATIONS

Bypassing the germination phase of revegetation by using shrub transplants in arid and semi-arid environments is useful since soil water dynamics in the upper layer of the soil where seeds are found makes it a very harsh environment for germination (Van Epps and McKell 1980). However, transplant success and continued survival may still be very dependent on precipitation patterns in the following growing seasons, perhaps for years after. In arid environments such as where this experiment took place, we recommend planning either a multiyear revegetation attempt or having supplemental water available, even when

Table 2. Odds ratio analysis was used to determine significance of odds of survival of transplants with any treatment compared to the control. The odds ratio (ϕ) is the odds of survival for all treatment combinations divided by the odds of survival of the control. The odds ratio and variance are compared to a *Z* distribution.

	Odds Ratio (ϕ)	Z	*P* value
Fall 2005			
All species	2.48	3.46	< 0.001
Artemisia tridentata	4.99	3.94	< 0.001
Atriplex canescens	1.35	0.68	0.250
Ericameria nauseosa	3.45	1.93	0.027
Spring 2006			
All species	2.35	2.96	0.002
A. tridentata	4.43	3.57	< 0.001
A. canescens	1.20	0.34	0.365
E. nauseosa	2.34	1.13	0.130
Fall 2006			
All species	2.38	2.69	0.004
A. tridentata	5.69	3.99	< 0.001
A. canescens	0.87	−0.20	0.420
E. nauseosa	1.73	0.64	0.261
Fall 2009			
All species	1.68	1.41	0.079
A. tridentata	3.77	2.72	0.003
A. canescens	0.77	−0.37	0.356
E. nauseosa	0.85	−0.14	0.444

working with transplants. Both the obstruction and hydrogel treatments were effective at increasing initial survivorship of transplants; we recommend either of these treatments, or the combination, if time and resources are available. The obstruction treatment is especially valuable to consider since it significantly increased *A. tridentata* survival, the focus of revegetation efforts in this ecosystem. Additionally, there is often wood slash available on or near disturbed areas that require revegetation.

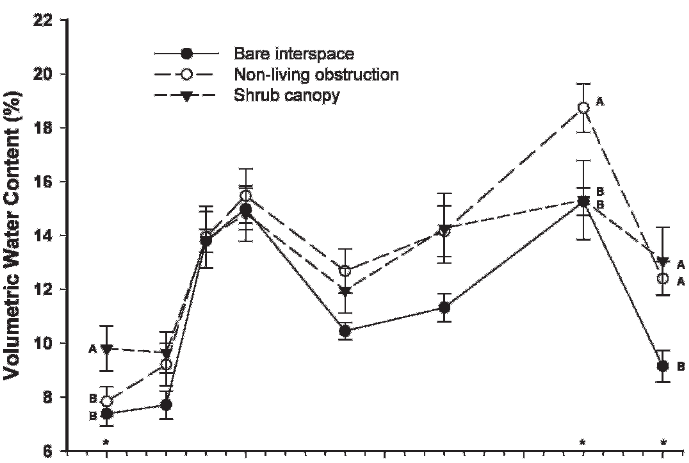

Figure 4. During the first transplanting season in April 2004, soil water content data were collected using time domain reflectometry for a depth of 0–15 cm in three treatment areas: a bare interspace, next to a nonliving obstruction (rock or log), or beneath a shrub canopy. Dates in which soil water content differed across treatments are indicated with an asterisk on the *x* axis, and letters indicate differences among treatments at $P < 0.05$.

ACKNOWLEDGMENTS

Undergraduates from the Environmental Science and Technology program at Colorado Mesa University aided in the design and performance of this research for Structured Research credit: Julia Christiansen, Kay Lambert, Kate Burden, and Brett Fletcher. We are heavily indebted to other students and staff volunteers from Colorado Mesa University, as well as volunteers from the community, for help with the transplanting process. In addition, Chief of Natural Resources Dave Price (retired), as well as Rangers Pete Larson (deceased), Lisa Claussen, and Liz Rogers from the Colorado National Monument, were critical in the success of the project. Frank Kelsey at the Colorado State University Western Colorado Research Center, Grand Junction, generously provided greenhouse space for rearing of transplants. Three anonymous reviewers provided valuable comments on earlier drafts of this manuscript.

LITERATURE CITED

Abedi-Koupai, J., F. Sohrab, and G. Swarbrick. 2008. Evaluation of hydrogel applications on soil water retention characteristics. *Journal of Plant Nutrition* 31:317–331.

Aldon, E. F., D. Cavazos, and J. Rafael. 1995. Growing and harvesting fourwing saltbush (*Atriplex canescens* [Pursh] Nutt.) under saline conditions. *In*: B. A. Roundy, E. D. McArthur, J. S. Haley, and D. K. Mann [comps.]. Proceedings: Wildland Shrub and Arid Land Restoration Symposium. Ogden, UT, USA: USDA Forest Service. INT-GTR-315. p. 299–304.

Anderson, B. W., R. D. Ohmart, and J. Disano. 1979. Revegetating the riparian floodplain for wildlife. *In*: R. R. Johnson and J. F. McCormick [tech. coords.]. Strategies for Protection and Management of Floodplain Wetlands and Other Riparian Ecosystems: Proceedings of the Symposium. Washington, DC, USA: USDA Forest Service. GA. Gen. Tech. Rep. WO-12. p. 318–331.

Austin, M. P., and O. Williams. 1988. Influence of climate and community composition on the population demography of pasture species in semi-arid Australia. *Vegetatio* 77:43–49.

Bainbridge, D. A. 2007. A guide for desert and dryland restoration. Washington, DC, USA: Island Press. 391 p.

Barrow, J. R., K. M. Havstad, J. Hubstenberger, and B. D. McCaslin. 1997. Seed-borne fungal endophytes on fourwing saltbush, *Atriplex canescens. Arid Soil Research and Rehabilitation* 11:307–314.

Bethlenfalvay, G. J., and S. DaKessian. 1984. Grazing effects on mycorrhizal colonization and floristic composition of the vegetation on a semiarid range in northern Nevada. *Journal of Range Management* 37:312–316.

Booth, D. T. 1985. The role of fourwing saltbush in mined land reclamation: a viewpoint. *Journal of Range Management* 38:562–565.

Borman, M. M., W. C. Krueger, and D. E. Johnson. 1991. Effects of established perennial grasses on yields of associated annual weeds. *Journal of Range Management* 44:318–326.

Callaghan, T. V., D. K. Lindley, O. M. Ali, H. Abd El Nour, and P. J. Bacon. 1989. The effect of water-absorbing synthetic polymers on the stomatal conductance, growth and survival of transplanted *Eucalyptus microtheca* seedlings in the Sudan. *Journal of Applied Ecology* 26:663–672.

Castro, J., R. Zamora, J. A. Hodar, and J. M. Gomez. 2002. The use of shrubs as nurse plants: a new technique for reforestation in Mediterranean mountains. *Restoration Ecology* 10:297–305.

Connelly, J. W., E. T. Rinkes, and C. E. Braun. 2011. Characteristics of greater sage-grouse habitats: a landscape species at micro- and macroscales. *In*: S. T. Knick and J. W. Connelly [eds.]. Ecology and conservation of greater sage-grouse: a landscape species and its habitat. Berkeley, CA, USA: University of California Press. p. 69–84.

DONOVAN, L. A., J. MAUSBERG, AND J. R. EHLERINGER. 1993. Seedling size and survival for *Chrysothamnus nauseosus*. *Great Basin Naturalist* 53:237–245.

FENCHEL, G. A., D. R. DREESEN, AND J. FRASER. 2002. Progress Report 2002: Tall pot transplants established with hydrogel: a revegetation technique without using intensive irrigation for the arid Southwest. Los Lunas, NM, USA: USDA-NRCS Los Lunas Plant Materials Center. 22 p.

FIELD, A. P. 2009. Discovering statistics using SPSS. 3rd ed. London, UK: Sage Publications Ltd. 856 p.

FROST, S. M., G. E. SCHUMAN, P. D. STAHL, AND S. E. WILLIAMS. 1998. Arbuscular mycorrhizae and water stress tolerance of Wyoming big sagebrush seedlings. *Soil Science Society of America Proceedings* 62:1309–1313.

GRANTZ, D. A., D. L. VAUGHN, R. J. FARBER, B. KIM, L. ASHBAUGH, T. VANCUREN, R. CAMPBELL, D. BAINBRIDGE, AND T. ZINK. 1998. Transplanting native plants to revegetate abandoned farmland in the western Mojave Desert. *Journal of Environmental Quality* 27:960–967.

HALVORSON, J. J., H. BOLTON, JR., J. L. SMITH, AND R. E. ROSSI. 1994. Geostatistical analysis of resource islands under *Artemisia tridentata* in the shrub-steppe. *Great Basin Naturalist* 54:313–328.

HARPER, J. L., AND R. A. BENTON. 1966. The behavior of seeds in soil: II. The germination of seeds on the surface of a water supplying substrate. *Journal of Ecology* 54:151–166.

HARRINGTON, G. N. 1991. Effects of soil moisture on shrub seedling survival in a semi-arid grassland. *Ecology* 72:1138–1149.

HOLLIMAN, P., J. A. CLARK, J. C. WILLIAMSON, AND D. L. JONES. 2005. Model and field studies of the degradation of cross-linked polyacrylamide gels used during the revegetation of slate waste. *Science of the Total Environment* 336: 13–24.

HOWARD, J. L. 2003. *Atriplex canescens*. *In*: Fire Sciences Laboratory [PRODUCERS]. Fire effects information system. Ft Collins, CO, USA: USDA Forest Service Rocky Mountain Research Station. Available at: http://www.fs.fed.us/database/feis. Accessed 10 August 2010.

HUTTERMANN, A., M. ZOMMORODI, AND K. REISE. 1999. Addition of hydrogels to soil for prolonging the survival of *Pinus halepensis* seedlings subjected to drought. *Soil and Tillage Research* 50:295–304.

LAYCOCK, W. A. 1991. Stable states and thresholds of range condition on North American rangelands: a viewpoint. *Journal of Range Management* 44: 427–433.

LUDWIG, J. A. 1986. Primary production variability in desert ecosystems. *In*: W. G. Whitford [ED.]. Pattern and process in desert ecosystems. Albuquerque, NM, USA: University of New Mexico Press. p. 5–17.

LUDWIG, J. A., AND D. J. TONGWAY. 1996. Rehabilitation of semiarid landscapes in Australia. II. Restoring vegetation patches. *Restoration Ecology* 4:398–406.

LYSNE, C. R. 2005. Restoring Wyoming big sagebrush. *In*: N. L. Shaw, M. Pellant, and S. B. Monsen [COMPS.]. Sage-grouse habitat restoration symposium proceedings; 4–7 June 2001; Boise, ID, USA. Ft. Collins, CO, USA: USDA Forest Service Rocky Mountain Research Station. Proc. RMRS-P-38. p. 19–35.

MANGOLD, J. M., AND R. L. SHELEY. 2007. Effects of soil texture, watering frequency, and a hydrogel on the emergence and survival of coated and uncoated crested wheatgrass seeds. *Ecological Restoration* 25:6–11.

MILTON, S. J., W. R. J. DEAN, M. A. DUPLESSIS, AND W. R. SIEGFRIED. 1994. A conceptual model of arid rangeland degradation. *BioScience* 44:70–76.

MINNICK, T. J., AND D. P. COFFIN. 1999. Geographic patterns of simulated establishment of two *Bouteloua* species: implications for distributions of dominants and ecotones. *Journal of Vegetation Science* 10:343–356.

MONSEN, S. B., AND D. R. CHRISTENSEN. 1975. Woody plants for rehabilitating rangelands in the Intermountain Region. *In*: H. C. Stutz [ED.]. Wildland shrubs: Proceedings: symposium and workshop; 5–7 November 1975. Provo, UT, USA: Brigham Young University. p. 72–119.

MONSEN, S. B., AND R. STEVENS. 1987. Seed and seeding characteristics of rabbitbrush. *In*: K. L. Johnson [ED.]. Proceedings of the Fourth Utah Shrub Ecology Workshop: The Genus *Chrysothamnus*; 17–18 September 1986. Logan, UT, USA: Utah State University. p. 41–49.

MOZINGO, H. N. 1987. Shrubs of the Great Basin: a natural history. Reno, NV, USA: University of Nevada Press. 342 p.

OWENS, M. K., AND B. E. NORTON. 1992. Interactions of grazing and plant protection on basin big sagebrush (*Artemisia tridentata* subsp. *tridentata*) seedling survival. *Journal of Range Management* 45:257–262.

RAMSEY, F. L., AND D. W. SCHAFER. 2002. Statistical sleuth: a course in methods of data analysis. 2nd ed. Pacific Grove, CA, USA: Thomson Learning. 742 p.

RICHTER, B. S., AND J. C. STUTZ. 2002. Mycorrhizal inoculation of big sacaton: implications for grassland restoration of abandoned agricultural fields. *Restoration Ecology* 10:607–616.

SAS INSTITUTE INC. 2009. JMP 9 Modeling and Multivariate Methods. Cary, NC, USA: SAS Institute Inc.

SAVÉ, R., M. PERY, O. MARFA, AND L. SERRANO. 1995. The effect of a hydrophilic polymer on plant water status and survival of transplanted pine seedlings. *HortTechnology* 5:141–143.

SAWYER, H., R. M. NIELSON, F. LINDZEY, AND L. L. MCDONALD. 2006. Winter habitat selection of mule deer before and during development of a natural gas field. *Journal of Wildlife Management* 70:396–403.

SCHUMAN, G. E., D. T. BOOTH, AND J. W. WAGGONER. 1990. Grazing reclaimed mined land seeded to native grasses in Wyoming. *Journal of Soil and Water Conservation* 45:653–657.

SCHUMAN, G. E., L. E. VICKLUND, AND S. E. BELDEN. 2005. Establishing *Artemisia tridentata* ssp. *wyomingensis* on mined lands: science and economics. *Arid Land Research and Management* 19:353–362.

SHAW, N. L., AND S. B. MONSEN. 1990. Use of sagebrush for improvement of wildlife habitat. *In*: H. G. Fisser [ED.]. Wyoming shrublands: aspen, sagebrush and wildlife management. Ft. Collins, CO, USA: USDA Forest Service Rocky Mountain Research Station. RMRS-GTR-136-vol.3. p. 739–744.

SHELEY, R. L., J. S. JACOBS, AND D. E. LUCAS. 2001. Revegetating spotted knapweed infested rangeland in a single entry. *Journal of Range Management* 54:144–151.

STEVENS, R. 2004. Establishing plants by transplanting and interseeding. *In*: S. B. Monsen, R. Stevens, and N. L. Shaw [COMPS.]. Restoring western ranges and wildlands; Proceedings, 17th Wyoming Shrub Ecology Workshop; 21–22 June 1988. Laramie, WY, USA: University of Wyoming. p. 19–35.

STODDARD, M. T., D. W. HUFFMAN, T. M. ALCOVE, AND P. Z. FULE. 2008. Effects of slash on herbaceous communities in pinyon-juniper woodlands of northern Arizona. *Rangeland Ecology and Management* 61:485–495.

TAUSCH, R. J., P. E. WIGAND, AND J. W. BURKHARDT. 1993. Viewpoint: plant community thresholds, multiple steady states, and multiple successional pathways: legacy of the Quaternary? *Journal of Range Management* 46:439–447.

TIRMENSTEIN, D. 1999a. *Artemisia tridentata* spp. *tridentata*. *In*: Fire Sciences Laboratory [PRODUCERS]. Fire effects information system. Ft Collins, CO, USA: USDA Forest Service Rocky Mountain Research Station. Available at: http://www.fs.fed.us/database/feis. Accessed 10 August 2010.

TIRMENSTEIN, D. 1999b. *Chrysothamnus nauseosus*. *In*: Fire Sciences Laboratory [PRODUCERS].Fire effects information system. Ft Collins, CO, USA: USDA Forest Service Rocky Mountain Research Station. Available at: http://www.fs.fed.us/database/feis. Accessed 10 August 2010.

TONGWAY, D. J., AND J. A. LUDWIG. 1996. Rehabilitation of semiarid landscapes in Australia. I. Restoring productive soil patches. *Restoration Ecology* 4: 388–397.

USDA-NRCS. 2009a. The PLANTS database. Available at: http://plants.usda.gov. Accessed 10 August 2010.

USDA-NRCS. 2009b. Web soil survey. Available at: http://websoilsurvey.nrcs.usda.gov. Accessed 10 August 2010.

VAN EPPS, G. A., AND C. M. MCKELL. 1980. Revegetation of disturbed sites in the salt desert range of the Intermountain West. Logan, UT, USA: Utah Agricultural Experiment Station. Land Rehabilitation Series 5. 54 p.

VAN EPPS, G. A., AND C. M. MCKELL. 1983. Effect of weedy annuals on the survival and growth of transplants under arid conditions. *Journal of Range Management* 36:366–369.

VON ENDE, C. N. 1993. Repeated-measures analysis: growth and other time-dependent measures. *In*: S. M. Scheiner and J. Gurevitch [EDS.]. Design and analysis of ecological experiments. New York, NY, USA: Chapman and Hall. p. 113–137.

WALKER, B. L., D. E. NAUGLE, AND K. E. DOHERTY. 2007. Greater sage-grouse population response to energy development and habitat loss. *Journal of Wildlife Management* 71:2644–2654.

WHISENANT, S. G. 1999. Repairing damaged wildlands: a process-oriented, landscape scale approach. Cambridge, UK: Cambridge University Press. 312 p.

WILKINS, S. D., J. M. KLOPATEK. 1987. Plant water relations in ecotonal areas of pinyon-juniper. *In*: R. L. Everett [COMP.]. 1987. Proceedings: pinyon-juniper conference. Ogden, UT, USA: USDA Forest Service Intermountain Research Station. Gen Tech. Rep. INT-215. p. 412–417.