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RESEARCH ARTICLE

Establishing Cool-Season Grasses on a Degraded Arid Rangeland of the Colorado Plateau

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Abstract

Reestablishing cool-season (C3) grass communities on low elevation rangelands of the Colorado Plateau is notoriously difficult, raising questions about the viability of restoring native species and continuing to actively graze these landscapes. We conducted a seeding experiment on an arid (15.4 cm rain/year), historically heavily-grazed rangeland in Northern Arizona to test the effects of seeding technique and simulated seasonal climate scenarios on germination and recruitment of four species of native, cool-season bunchgrasses: *Achnatherum hymenoides, Hesperostipa comata, Poa secunda, and Elymus elymoides*. Initial results indicated that C3 grasses germinated significantly more in drill-seeded treatments under simulated high precipitation years than in other treatment types. Five years post-treatment, *P. secunda* and *E. elymoides* were not observed but simulated drill-seeded treatments, had significantly higher densities of *A. hymenoides* and *H. comata* recruits relative to most other treatment types. Simulated drill seeding also increased soil disturbance which increased the establishment of the invasive weed *Salsola tragus* in year 1, but not thereafter. Although it appears critical to coordinate effective seeding techniques with high winter–spring precipitation, predicting such events may not be possible at some sites, suggesting that seeding low elevation, arid rangelands of the Colorado Plateau may not always be realistic under a future climate that is drier and less predictable.

Key words: ***Achnatherum hymenoides*, climate change, cool-season, drill-seeding, grasses.**

Introduction

The ecological degradation of arid public rangelands is a pervasive problem that has concerned agency managers and conservationists in North America for nearly a century. In the United States, 133 million hectares of public rangelands comprise approximately 70% of the land area of the 11 western states, and are principally managed by the United States Department of the Interior (USDI) Bureau of Land Management and United States Department of Agriculture (USDA) Forest Service (Bryner 1998). A recent USDA assessment found that "a majority of the West's public rangelands are degraded" and "two-thirds of these rangelands are not responding to current management practices" (Peters et al. 2006). Most western rangelands are arid or semiarid, receiving less than 25.4 cm of annual precipitation (U.S. General Accounting Office 1988). Although it is commonly accepted that many of these rangelands have been historically overgrazed (Curtin 2002; Milchunas 2006) and have suffered losses of biodiversity and degradation of ecological function (Fleischner 1994; Donahue 1999), consensus on how to restore these landscapes is lacking.

In the arid Southwestern United States, resting degraded ecosystems from grazing has typically resulted in slow recovery (McLean & Tisdale 1972) or, in some cases, a failure to reestablish historic conditions (Valone et al. 2002). Conditions for plant establishment occur infrequently and irregularly. Studies of desert ecosystems suggest that without intervention it may take 100–200 years for the recovery of native species diversity on overgrazed, compacted soils (Prose & Metzger 1985). Because degraded arid ecosystems can be slow to recover even when negative disturbances are removed (Neff et al. 2005) and because of the pressure to improve forage, proactive restoration methods such as the seeding of desired plant species are now commonly recommended (Monsen et al. 2004).

A significant challenge for managers is that landscape-scale heterogeneity of arid rangeland plant communities and soil types, extreme temperatures, intense sun, high winds, limited moisture, and the low fertility of desert soils, limits the

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germination and recruitment of reintroduced plant material (Stohlgren et al. 1999; Milchunas 2006). Seeding has been more successful early in the degradation process, but even then the financial costs of restoration can be high (Milton et al. 1994; Barrow & Havstad 1995). As a result, arid grasslands have proven to be some of the most difficult ecosystems in which to reestablish native species (Eckert et al. 1986; Palmer et al. 1997; Monsen et al. 2004). In a review of restoration successes across different grassland ecosystems, ecological conditions varied widely, reinforcing the importance of developing site-specific restoration techniques (Wilson & Tilman 2002).

Moreover, finding practical approaches for restoring rangelands that continue to be grazed is another challenge, as federal public lands policy attempts to balance a history based on production of commodities, including livestock, with growing demands for recreation, conservation, and other non-extractive uses across these landscapes (Davis 2006). "Range improvement," which historically involved introduction of non-native forage plants, has more recently developed techniques for restoring native rangeland communities and utilizing livestock for restoration. Testing multiple seedbed cultivation techniques across a simulated precipitation gradient, Winkel and Roundy (1991) demonstrated that subsurface seeding improves germination in arid environments (Bakker et al. 2003). Hypothetically, cattle might be employed in seeding treatments by trampling seeds into the soil (increasing seed to soil contact) to improve germination success (Dagget 2005). However, the soil disturbance associated with seeding treatments can promote colonization by invasive weeds, such as *Salsola tragus* (Sauer 1988; Rutledge & McLendon 1996).

The reestablishment of cool-season (C3) grasses is a restoration priority where historic heavy grazing of fragile, winter pastures has degraded native grassland communities (Allen 1995; NRCS 2007). Because C3 grasses break winter dormancy in late winter and grow slowly through the spring, they are valuable and nutritious forage when little else is growing. It is believed that in the late nineteenth and early twentieth centuries they were heavily grazed and quickly depleted when railroad expansion brought record numbers of livestock into the Colorado Plateau ecoregion (Bohrer 1975).

Our experimental site is generally representative of rangelands across Southwestern United States landscapes: extreme aridity, infertile soils, reduced native species richness, increasing dominance by exotic species, and a history of heavy grazing. In recent decades, annual stocking rates have been low, with approximately 800–2,400 animals ranging seasonally over the 20,234 ha management unit surrounding our experimental site. By comparison, in the early twentieth century, an estimated 60,000–100,000 heads were using this area as their primary winter pasture (Rider & Paulsen 1985).

Our research aims were to (1) compare establishment success of four C3 grasses (*Achnatherum hymenoides*, *Hesperostipa comata* spp. *comata*, *Poa secunda*, and *Elymus elymoides*) under irrigated and non-irrigated conditions (to explore the effect of climate), testing broadcast versus drilling techniques, and the effect of (pre-sowing) trampling by cattle on seeding success, and (2) evaluate, based on these results, the viability of reestablishing of native grasses, given changing climate and administrative constraints of rangeland management.

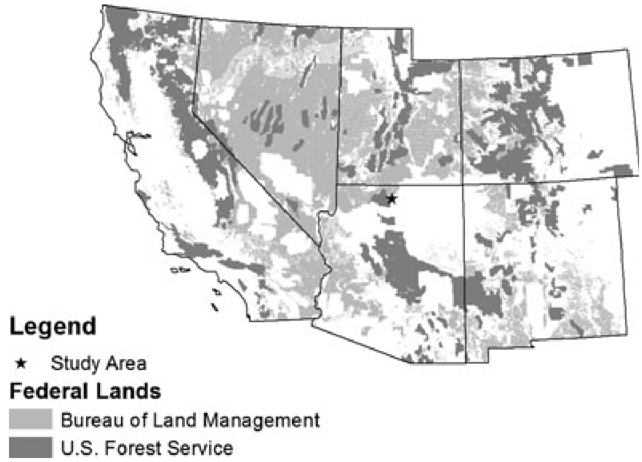

Figure 1. Map of the Southwestern United States region and location of the House Rock Valley study site.

Methods

Our restoration experiment was conducted on a Northern Arizona site characterized as Kaibab Formation Limestone/Sandstone Upland-Ecological Site Description R035XB233AZ (NRCS 2012). Soils are gravelly sandy loam in texture, shallow, alkaline, and slightly saline. *Achnatherum hymenoides* is the dominant C3 grass species for the associated plant community (Community Phase 2.2; NRCS 2012). The site is located at latitude: $36^\circ 33' 40.497''$N and longitude: $111^\circ 55' 58.225''$W, 1500 m elevation, in the House Rock Valley (HRV; Fig. 1). The valley covers the area immediately north of the Colorado River on the Arizona Strip, on the Colorado Plateau. Because of its low elevation, position in the rainshadow of the Kaibab Plateau, scarce monsoonal rainfall, and remoteness from either the Gulf of California or Pacific Coast where regional storm systems are generated, it is exceedingly dry, averaging just 15.4 cm of rain per year. Total annual precipitation patterns are weakly bi-modal, with 30% of rain falling in the months of July and August and another 55% falling between September and February.

In an area of HRV where soil and vegetation conditions are most representative of the valley as a whole, we established a 1-ha grazing exclosure, subdivided into (100) 3×3 m plots. We randomly located 10 replicates of 10 treatments in the 100-plot grid, with 3 m buffers between all plots. Five seeding treatments were applied: control (unseeded), control + cattle trampling, broadcast seeding, broadcast seeding + cattle trampling, and drill seeding. Each of these five seeding treatments was also applied with supplemental irrigation to simulate a 90th percentile wet year, for a total of 10 treatments (Table 1).

Table 1. The total number of seedlings germinated in 10 plots for four native C3 grasses seeded in each of 10 treatments over 5 years (2007–2011) and recruiting over 4 years (2008–2011).

	Number of Plants Germinated					*Number of Plants Recruited*			
	2007	*2008*	*2009*	*2010*	*2011*	*2008*	*2009*	*2010*	*2011*
Achnatherum hymenoides									
B	0	0	0	2	0	0	0	0	2
BI	0	0	0	0	0	0	1	5	3
C	0	0	—	2	0	0	—	0	1
CI	0	0	—	11	0	0	—	5	16
D	17	152	1	3	0	3	2	5	8
DI	536	70	5	6	0	51	6	4	18
T	0	0	—	0	0	0	—	0	3
TI	0	4	0	0	0	0	0	0	3
TB	2	0	0	1	0	0	1	0	5
TBI	0	0	—	23	0	0	—	0	2
Elymus elymoides									
B	0	0	0	0	0	0	0	0	0
BI	0	0	0	0	0	0	0	0	0
C	0	0	—	0	0	0	—	0	0
CI	0	1	—	0	0	0	—	0	0
D	0	476	2	0	0	2	1	0	0
DI	390	378	0	0	0	7	1	0	0
T	0	1	—	0	0	0	—	0	0
TI	0	1	0	0	0	0	0	0	0
TB	3	0	0	0	0	0	0	0	0
TBI	0	0	—	0	0	0	—	0	0
Hesperostipa comata									
B	0	0	0	0	0	0	0	0	1
BI	0	0	0	0	0	0	1	0	0
C	0	0	—	0	0	0	—	0	0
CI	0	0	—	0	0	0	—	0	0
D	12	371	6	0	0	27	4	6	10
DI	184	417	5	2	0	14	3	2	7
T	0	0	—	0	0	0	—	2	0
TI	0	1	0	0	0	0	0	0	0
TB	4	0	0	1	0	0	0	0	1
TBI	0	0	—	0	0	0	—	0	3
POSE (*Poa secunda*)									
B	0	0	0	0	0	0	0	0	0
BI	0	0	0	0	0	0	0	0	0
C	0	0	—	0	0	0	—	0	0
CI	0	0	—	0	0	0	—	0	0
D	0	19	0	0	0	0	0	0	0
DI	0	31	0	0	0	0	0	0	0
T	0	0	—	0	0	0	—	0	0
TI	0	0	0	0	0	0	0	0	0
TB	0	0	0	0	0	0	0	0	0
TBI	0	0	—	0	0	0	—	0	0
Total	1148	1922	19	51	0	104	—[a]	29	83

B, broadcast; BI, broadcast + irrigation; C, control; CI, control + irrigation; D, drill; DI, drill + irrigation; T, trampling; TI, trampling + irrigation; TB, trampling + broadcast; TBI, trampling + broadcast + irrigation.
[a]Total not reported because not all treatment types were sampled.

Prior to seeding treatments, we conducted a soil seed bank study, using standard protocols for soil seed bank germination (Warr et al. 1993) to analyze differences in community composition across plots and to confirm that the seeded C3 grasses were not present in the soil seed bank prior to initiation of the study. In the summer of 2006, one 20 cm^3 soil sample was collected for seed bank analysis from each of the 100 experimental plots. In the winter of 2006–2007, we germinated soil seed bank samples in a greenhouse at Northern Arizona University. Community composition among plots was analyzed using Analysis of Similarity (ANOSIM) in Primer software (Clarke 1993).

Four species of C3 grasses, *A. hymenoides*, *Hesperostipa comata* spp. *comata*, *Poa secunda* and *Elymus elymoides*, were seeded in November 2006 (Table 2). We calculated seeding rates for each species (each grass given an equal

Table 2. Seed ecotypes, seeding densities, price, seed source, and estimated above-ground production for four species of native cool-season grasses seeded at HRV experiment site.

	ACHY (Achnatherum Hymenoides)	HECO (Hesperostipa Comata)	POSE (Poa Secunda)	ELEL (Elymus Elymoides)	A C3 Grasses
Ecotype	Nezpar', seed/lb: 161,920	No ecotype information, seed/lb: 137,857	Sandberg bluegrass seed/lb: 1,046,960	Sand hollow, seed/lb: 192,000	(See above)
PLS kg/ha	13.5 (broadcast), 7 (drill)	16 (broadcast), 11 (broadcast)	4.5 (broadcast), 2 (drill)	13.5 (broadcast), 8 (drill)	13.5 (broadcast), 8 (drill)
Price/kg	\$9/kg	\$103/kg	\$15/kg	\$55/kg	\$45/kg
Source	Granite seed (Idaho, Idaho)	Granite seed (Iron, Utah)	Granite seed (Sanders, Montana)	Granite seed (Jim, Idaho)	Granite seed
ESD prod/yr	20.2–39.2 kg/ha	na	na	0–4.5 kg/ha	20.2–48.3 kg/ha

ESD prod/yr, ecological site description-production/year; PLS, pure live seed; na, not available.

percent of the total seed mix) by increasing bulk pure live seed (PLS) to commonly recommended rates (Monsen et al. 2004). Broadcast seeding was done by hand at 3.3 kg/ha and we simulated drill seeding with a hand hoe, scratching furrows to the depth of a typical range-drill (0.64 cm for all species except *A. hymenoides*, which was seeded at 10.16 cm), spacing (approximately 40 cm apart), and at the rate (2.2 kg/ha) (Monsen et al. 2004).

All seeding treatments were conducted in November 2006. Within the 1-ha experimental block, plots not slated for trampling were protected with temporary fencing. Six cows were gently herded throughout the unfenced portion of the experimental block for 4 hours. Immediately following trampling, soil surface disturbance was estimated visually for all plots. The intent was to create moderate trampling of plots in order for cows to imprint seeds lightly into the soil, as determined by previous trampling studies (Winkel & Roundy 1991; Finch 2004). Soil surface disturbance averaged 49% across all plots with a standard deviation of 19%. This disturbance is equivalent to approximately 15 hoof prints/m^2.

Irrigation treatments implemented in the spring of 2007 supplemented that year's ambient rainfall (2.1 cm) during the winter–spring germination period to a level representing 90% of the precipitation from the wettest spring on record over the last 30 years. Weekly irrigation (0.64 cm) was delivered by overhead oscillator between March and May 2007, totaling 7.7 cm over the 12-week period, the critical C3 germination period. Coincidentally, during the following winter–spring (2007–2008) ambient precipitation was 10.11 cm, 145% above the historical average, making for two consecutive years of historically wet winter–spring periods for all irrigated treatments.

We surveyed all plots for the number of germinated and recruited individuals of the four-seeded grass species as well as *Salsola tragus* in May of 2007, 2010, and 2011 and in March of 2008. In May 2009, counts were conducted in a subset of plots (Table 1). Counts were converted to densities and the effects of year, treatment, and a year × treatment interaction were analyzed using a repeated measures analysis of variance (Neter et al. 1996) using the MIXED procedure in SAS (v. 9.2; SAS Institute, Cary, NC, U.S.A.).

Results

Soil Seed Bank Study

Seedlings emerged in soil samples from 41 of the 100 plots. ANOSIM indicated no differences in community composition among treatment types (global $r = -0.018$, $p = 0.604$). *Plantago patagonica* was the most abundant of 10 species germinating from the soil seed bank (52% of all seedlings) and the invasive weed *Salsola tragus* represented 2% of seed bank germinants. None of the four-seeded C3 grass species were present in any of the soil seed bank samples.

Restoration Experiment

In spring 2007, a total of 1,148 C3 seedlings germinated across all plots, with 104 seedlings recruited into mature plants in 2008 (Table 1). However, the greatest annual germination (1,922 seedlings) occurred in March 2008. Germination and recruitment rates across the four C3 species declined dramatically after the second year following seeding, and have remained low since 2009 for *Achnetherum hymenoides* and *Hesperostipa comata*, the only two species with significant recruitment. Annual germination rates declined rapidly; in 2010 (4 years after seeding) only 51 total seeds germinated despite the occurrence of above average winter–spring precipitation (10.10 cm), and no germination occurred in 2011, a dry year. Only 11 *Elymus elymoides* recruits survived beyond 2009, and no *Poa secunda* recruitment occurred (Table 1).

Germination of seeded C3 grasses was dependent on both year and treatment effects (Table 1). Germination was significantly higher in the drill + irrigation treatment in 2007 ($t = 20.74$, $p < 0.0001$), and in both the drill treatment ($t = 19.02$, $p < 0.0001$) and drill + irrigation treatment ($t = 16.74$, $p < 0.0001$) in 2008 (Fig. 2). In drill-seeded treatments, we found a significant positive relationship between winter–spring (December to May) precipitation and germination ($F = 11.88$, $p = <0.0001$, $n = 40$).

Although germination and recruitment of C3 grasses declined significantly in 2009 and beyond, a treatment

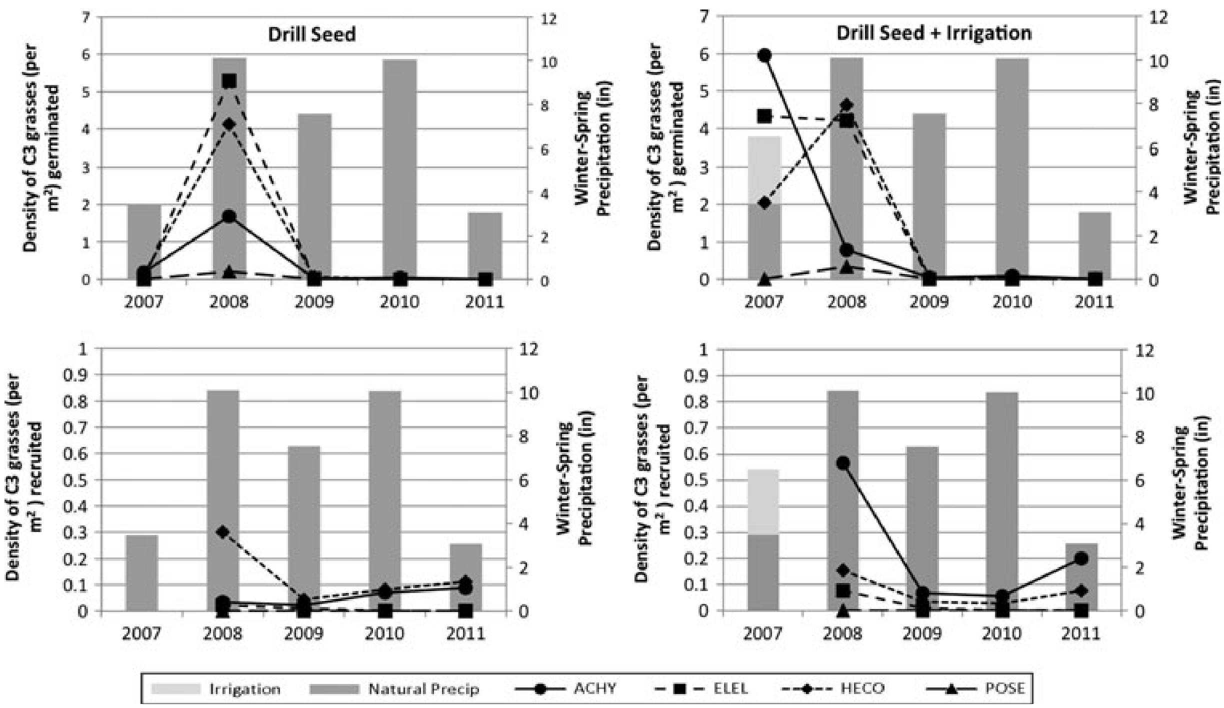

Figure 2. Density of C3 grasses germinated (above) and recruited (below) in drill seeded (left) and drill seeded + irrigation (right) treatments, over a 5-year period. Plant densities are plotted against total winter–spring (December to May) precipitation. The proportion of precipitation provided by irrigation treatments in 2007 is indicated by the lighter portion of precipitation bars; note that total seasonal precipitation is greater in 2008, without any supplementation.

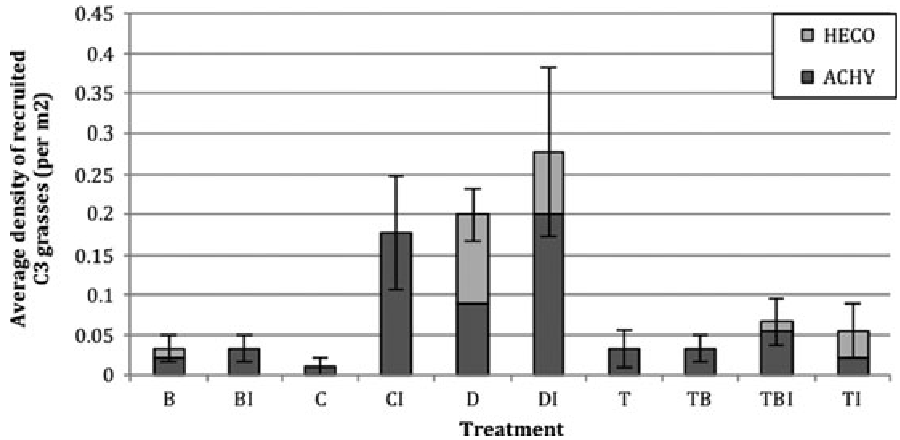

Figure 3. In 2011, 5 years following seeding, ACHY (*Achnatherum hymenoides*) and HECO (*Hesperostipa comata*) had significantly higher average recruited densities in drill-seeded (D; $t = 4.64$, $p < 0.0001$), drill-seeded + irrigation (DI; $t = 6.44$, $p < 0.0001$), and control + irrigation treatments (CI; $t = 4.12$, $p < 0.0001$) than in other treatments. See Table 1 for treatment abbreviations and descriptions.

effect was still detected in 2011 (Fig. 2), 4 years after the seeding occurred ($F = 4.53$, $p < 0.0001$). Recruitment of C3 grasses was significantly higher in drill + irrigation ($t = 6.44$, $p < 0.0001$), drill-only ($t = 4.64$, $p < 0.0001$), and control + irrigation ($t = 4.12$, $p < 0.0001$) treatments than other treatment types (Fig. 3). The control + irrigation treatment showed unexpectedly high recruitment, which we attribute to the presence of anthills, suggesting seed transport, in 2 of the 10 plots. These two plots each had five recruited individuals (*A. hymenoides*), most of which were growing on or adjacent to an anthill.

Notably, *A. hymenoides* and *H. comata* were the only seeded species still present in 2011 (Fig. 3). In total, 83 established plants were counted in the experimental plots (61 *A. hymenoides* and 22 *H. comata*) in 2011. Of these, 28% are located in treatment types that were not seeded. Dispersal was greater for *A. hymenoides*; in 2011, 38% of *A. hymenoides* were found in treatments that were not seeded while no

H. comata were observed outside of seeded treatment plots. Recruited individuals were also observed in the plot buffer areas, outside of the seeded plots; however, these were not enumerated. Ants appeared to be an important mechanism for dispersal and establishment, and *A. hymenoides* were anecdotally observed in high densities on anthills both inside and outside of the experimental plots.

In spring of 2007, there was a highly significant within-year treatment effect on *S. tragus* germination ($F = 35.24$, $p < 0.0001$). The drill + irrigation treatment had significantly higher densities of *S. tragus* germinants than other treatment types ($t = 18.91$, $p = <0.0001$). However, between 2008 and 2011, differences in *S. tragus* seedling densities across treatments did not show a consistent trend. Analysis of among-year effects showed that in 2011 *S. tragus* seedling densities were higher in all treatments than in any of the previous years ($F = 110.42$, $p < 0.0001$).

Discussion

Germination of seeded C3 grasses was significantly higher in drill-seeded plots, both irrigated and non-irrigated, as compared with other treatments. Broadcast seeding, with or without trampling, did not yield ecologically significant C3 germination, even under irritation. The fact that significant germination was only observed in 2007 in the drill + irrigation treatment, but in both drill and drill + irrigation treatments in 2008 (when all treatments received above average natural precipitation) suggests that together drill seeding and high winter–spring precipitation support the germination of C3 grasses. Our results largely corroborate previous findings that drill seeding is an effective seeding method in arid systems (Jacobs et al. 1998), and that precipitation is a principal factor for seeding success (Bakker et al. 2003). However, our data do not support the hypothesis that cattle trampling can facilitate germination and persistence of seeded species (Winkel & Roundy 1991).

Our results also confirm that species selection is of utmost importance for reestablishment of native cool-season grasses in arid environments (Hufford & Mazer 2003). Although *Elymus elymoides* is common a few hundred meters upslope of our study site, it is largely absent from adjoining areas of the HRV. Similarly, *Poa secunda* is a common species in arid rangelands in our region, but is nowhere abundant in the HRV. Both species failed to recruit at our study site. Conversely, *Achnatherum hymenoides* and *Hesperostipa comata*, present in HRV (albeit in low densities), showed more favorable germination and recruitment. It is possible that species-level results were related to genotypic variation in seed sources, but we are unable to evaluate the effects of local adaptation on differences in germination rates among species. Our goal was to utilize seeding treatments and seed sources commonly available to public land managers who are orchestrating restoration projects. The genotypes of the four C3 species seeded in this experiment were drawn from regional sources; at the time of this experiment no commercial sources offered local ecotypes (Table 2).

In evaluating whether observed recruitment rates represented restoration success/failure we needed to tackle the thorny question of how to set restoration objectives in these degraded landscapes. Reference conditions for arid public rangelands across the West are rare, due to the pervasiveness of livestock grazing over the last 150 years (Monsen et al. 2004). Additionally, increased aridity throughout the Southwest over the past two decades has already resulted in observed differential shifts in species distributions (Munson et al. 2011). This trend is likely to continue, given the predictions of most regional climate change models for warmer and drier conditions across the Southwest (Seager et al. 2007). In fact, climate warming could soon make restoration to historic or "reference" conditions difficult, if not impossible (Parmesan 2006), further confounding efforts to use present or historical conditions to inform rangeland restoration and management (Harris et al. 2006). Climatically induced shifts and future novel ecosystems make it difficult to judge whether our germination and recruitment results are likely lead to ecologically significant reestablishment of C3 grasses.

Acknowledging these uncertainties, we compared our recruitment data to NRCS (Natural Resource Conservation Service) ecological site description data. Because NRCS plant community species composition densities typical of our ecological site description are provided in average annual production lbs of dry weight/acre, we compared post-treatment plant densities on our drill-seeded plots to NRCS productivity data (NRCS 2012). We multiplied average C3 densities in our drill-seeded treatment types (0.244 plants/m^2) by the mean annual forage production for *A. hymenoides* "*Nezpar*"—11.3 g/plant, dry weight(Jones & Nielson 1992)—as *A. hymenoides* was by far the most successful recruited species. This resulted in an average production value of 2.72 g/m^2, which is within the productivity range (2.02–3.92 g/m^2 or 20.2–39.2 kg/ha) for C3 grasses in the historic climax plant community for this ESD (NRCS 2012). Although ESDs are valuable reference points they are also rough approximations of ecological steady states. Thus, we are cautious to conclude that seeded C3 grass densities are meeting ecological objectives. The recruited densities of seeded C3 grasses reported here may not justify the fiscal cost for many land managers, especially as compared with seeding wetter, upslope plant communities where conditions for germination and persistence are more favorable. However, these results should help managers make more predictive decisions, identifying both the least and most cost-effective sites for future seeding treatments.

Our data provide mixed evidence whether seeded species will persist in our study area over the long term. Although germination rates strongly declined over the course of our study, the dispersal and establishment of plants outside of seeded areas suggest the possibility of effective seed dispersal, germination, and recruitment, and thus, continued persistence. Because our treatments have been excluded from livestock grazing over the past 5 years, it is not clear how seedling establishment would be affected by the continued winter grazing that occurs in the area surrounding our experimental site. Successful recruitment of C3 grasses is only one step in the restoration process on arid rangelands. Cumulatively, non-native plant invasions, climate change, and grazing management budgets will likely determine the long-term and real success of reestablishing native C3 grasses at this site.

In the first year following treatment, our results showed significantly higher densities of the invasive species *S. tragus* in the drill-seeded treatments, however, this treatment effect dissipated with time. Invasion by *Salsola* species has been associated with soil disturbance from restoration treatments over the short term (1 year; Banerjee et al. 2006) and longer term (>5 years) in certain soil types (Johnson & Fulbright 2008). Propagule pressure from *S. tragus* is high in our study area and although we only detected a short-term treatment effect of *S. tragus* invasion at our experimental site, the risk of promoting further invasion by this and other invasive species should be considered if seeding is to occur at larger scales or in different soil types.

Our results also suggest that in landscapes where precipitation is suboptimal for seeding, years with above average winter–spring precipitation represent "windows of opportunity" that will be critical to restoration success. While El Niño years are currently the most predictable periods of high winter precipitation in our region, for example, an Arizona statewide analysis showed a positive correlation ($r^2 = 0.54$) between El Niño years and the wettest years on record (Western Regional Climate Center 2008), annual precipitation was not significantly correlated with El Niño years at HRV over the last 30 years ($r^2 = 0.005$). Thus, predicting optimal seeding years may not be possible (or sufficiently precise) at specific sites or scales of analysis. Compounding this problem, there is considerable uncertainty regarding how El Niño patterns will shift under a changing climate, and how this in turn will influence both summer monsoonal and winter precipitation patterns (Castro et al. 2007).

On the Colorado Plateau, observed declines in C3 grasses have been attributed to both heavy winter grazing (Bohrer 1975) and increasing aridity (Munson 2011). This trend is likely to continue as the Southwest experiences increased evapotranspiration and depleted soil moisture under climatic warming and drying (Seager et al. 2007). Thus, in the face of continued livestock grazing and accelerated warming and drying across the region, the reestablishment of C3 grasses on arid rangelands will become increasingly challenging. Rangeland managers across the region may be forced to focus more on preventing and controlling exotic invasives and less on reestablishing natives in the coming years. If so, reestablishing native C3 grasses may be more successful in other locations where climatic conditions are more favorable and predictable.

Implications for Practice

- Predicting climatic windows of opportunity (years with high winter–spring precipitation) are as important as seeding methodology and seed selection in the reestablishment of cool-season plant species in arid rangelands. Without a highly confident prediction of ENSO (El Niño Southern Oscillation), seeding should not be implemented. In such predictably optimal years, drill seeding is the most promising method for reestablishing C3 grasses within low-elevation, arid rangelands on the Colorado Plateau.
- Seeding native C3 grasses in low-elevation, degraded rangelands on the Colorado Plateau is unlikely to be successful if future climate is, as predicted, marked by increasing aridity and more erratic precipitation. Therefore, preventing or controlling non-native, invasive species will be of higher priority to managers, in most years.
- Given the risk of promoting the spread of non-native species via soil disturbances associated with restoration treatments, land managers should prioritize restoration and grassland management that minimizes disturbance to soils and vegetation.

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