Cheatgrass Die-Offs: A Unique Restoration Opportunity in Northern Nevada

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On the Ground

- The phenomenon of cheatgrass die-off is a common and naturally occurring stand failure that can eliminate the presence of this annual grass for a year or more, affecting tens of thousands of hectares in some years.
- We designed a study to determine if the temporary lack of cheatgrass caused by die-offs is a restoration opportunity. We seeded native perennial species at three die-offs in the Winnemucca, Nevada, area.
- Native grass establishment in die-offs was almost three times higher in the first season at all sites, relative to adjacent areas without die-off. Establishment was five times higher in the die-off at two sites in the second season, and plants produced dramatically more culms in the die-off at the third site in the third season.
- Increasing seed rates led to more seedlings establishing in both die-offs and controls, with the strongest effect in the second season.
- We suggest that landowners and managers consider targeting die-offs as efficient locations to focus native restoration efforts and that restoration practitioners should consider increasing seeding rates to maximize success.

Keywords: Great Basin, revegetation, *Bromus tectorum*, cheatgrass, die-off, restoration.

Cheatgrass (*Bromus tectorum*) is one of North America's most ecologically significant invasive species, growing in impressively dense near-monocultures across many parts of the West. Because it is highly competitive, it is a severe barrier to the survival of seedlings of perennial plants, especially in sagebrush steppe communities.[1] Cheatgrass "die-off," or stand replacement failure, is a naturally occurring phenomenon in which a seemingly healthy stand of cheatgrass fails to replace itself.[2] Die-offs result in the complete elimination of cheatgrass at a site for one or more growing seasons (Fig. 1). The cause of this phenomenon is under investigation[4] and likely involves one or more pathogens reaching epidemic levels under certain conditions. Only actively growing seeds are affected, so dormant cheatgrass seeds remain in the soil during and after the die-off, often resulting in a return to cheatgrass dominance within a year or two.[2,5]

Because these die-offs occur in remote areas, it can be difficult to understand how common they are. However, their distinct color and patterns make them perfect for detection with aerial or satellite imagery. In a recent remote sensing study focused on a highly invaded region of north-central Nevada centered on Winnemucca, we found that over 100,000 hectares of die-off have occurred over the last 31 years (Fig. 2).[6] Throughout the 1.7 million hectare study area, some years produced no die-off, around one-third of years produced 4,800 ha or more, and three years each produced over 40,000 ha of die-off. This study also found that certain areas (totaling around 15,000 ha) are "hotspots" that have experienced die-off four to nine times during the 31-year period. Cheatgrass die-off has also been observed in other arid shrublands in the west, including Washington, Utah, Idaho, and Oregon (O. Baughman, personal observation), and areas of unexpectedly low productivity of cheatgrass that could be die-offs have been remotely sensed throughout much of the northern Great Basin.[7] These die-offs can cause problems for land users because these areas may experience increased soil erosion, invasions of other weed species, and a sudden loss of spring forage. However, die-offs may also represent excellent opportunities for establishing seedlings of perennial plants, which is what we investigate here

Can Die-offs Increase Restoration Success in Areas Where There Are Few Options?

Compared with other forms of temporary cheatgrass control, such as herbicide or targeted grazing, the die-off phenomenon is not costly or labor intensive, but it still provides conditions that
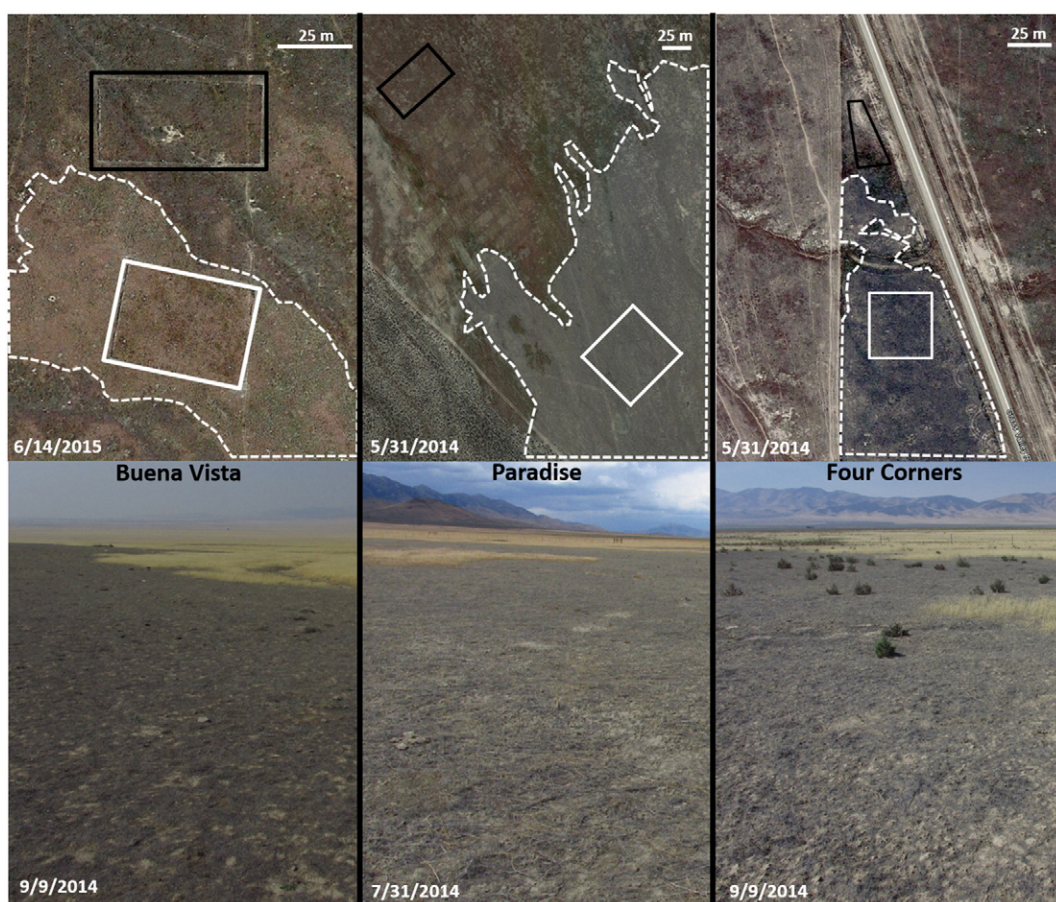
Figure 1. Many cheatgrass die-offs are so devoid of vegetation that they can be seen from far away, as well as in satellite imagery. Photos are satellite imagery[3] (top images) and ground-level views (bottom images) of the three sites used in this experiment. Satellite images show the die-off boundary (dashed outline) and experimental fields in the die-off (light boxes) and control (dark boxes), all of which were fenced soon after seeding. In the ground-level views, the characteristic gray litter of a recent die-off in the foreground contrasts with the light yellow of dried cheatgrass in the background. Note that the date (lower left of each panel) and scale (upper right of each satellite panel) vary.

may help native plants grow. For example, soil moisture, plant-available nitrogen, and other essential nutrients are higher in recent die-off soils than soils of nearby areas that did not experience die-off.[8–10] We conducted a precision seeding study to test how die-offs affected perennial grass seeds at a die-off in Pershing County, Nevada, in 2012.[5,8] We planted Sandberg bluegrass (*Poa secunda*) and bottlebrush squirreltail (*Elymus elymoides*) into a recent die-off as well as an adjacent intact cheatgrass stand (control). The die-off supported more bluegrass and squirreltail through 2 years of monitoring, and seedlings in the die-off had significantly greater growth and vigor late in the growing season than those in the control. These findings were promising, especially considering the competitive pressure exerted on these native seedlings by cheatgrass, which was common and returning to dominance during the study.

These promising results suggested that cheatgrass die-offs can increase restoration success in highly invaded areas, but our seeding was limited to only one site and two native species and used a nontypical method of hand-seeding. Therefore, researchers at the University of Nevada, Reno and managers at the Bureau of Land Management initiated this follow-up study to determine if similar results would be found across multiple die-off sites, seeding a greater diversity of native

species and using typical drill-seeding methods. Additionally, we were interested in whether simply increasing the seeding rate could improve native establishment. The questions of our study were as follows:

1. Do recent cheatgrass die-offs support higher establishment of native grass, forb, and shrub seeds after mechanical seeding?
2. Do higher seed rates result in higher establishment of native grass, forb, and shrub seeds, in or out of cheatgrass die-offs?

Sites, Seeding, and Monitoring

Three sites that contained an area of complete stand failure (die-off) as well as an immediately adjacent stand of cheatgrass (control) were selected for seeding (Fig. 1). Buena Vista and Paradise were formerly dominated by Wyoming sagebrush (*Artemisia tridentata* ssp. *wyomingensis*), while Four Corners was likely dominated by a mix of Wyoming sagebrush and salt desert scrub species. At the time of seeding, all sites had been dominated by cheatgrass for over a decade, with a mix of other exotic and native species existing at much lower levels. Die-off and control
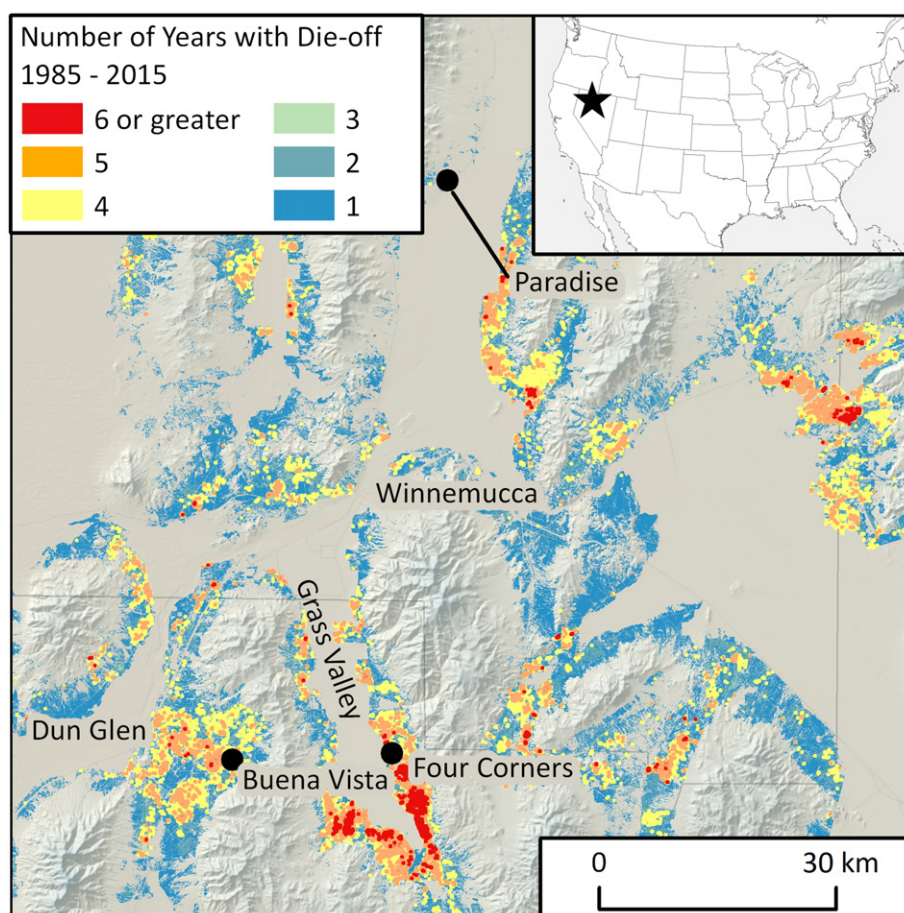
Figure 2. In this region of Northern Nevada, over 100,000 hectares of cheatgrass-infested rangelands have experienced cheatgrass die-off over the past 31 years. This map summarizes the number of times areas have experienced the die-off phenomenon over that time, with warmer colors indicating hot-spots of die-off activity, where the phenomenon is most frequent. The locations for the three sites used in this study are also shown.

fields were less than 400 m from one another and were each enclosed with barbed wire fences constructed after seeding.

An approximately 0.2 ha area within each die-off and control area at each site was designated as the study field, and

Table 1. Seeded species, source information, and seed rates in both PLS/ft^2 and lbsPLS/ac for the single rate[*]				
Species	**Germplasm origin**	**Production location**	**Single rate (PLS[†]/ft^2)**	**Single rate (lbsPLS/ac)**
Fourwing saltbrush	Humboldt County, Nevada	Wild	2.9	2.0
Spiny hopsage	Humboldt County, Nevada	Wild	4.2	0.9
Bottlebrush squirreltail	Klamath, Klamath County, Oregon	Warden, Washington	6.9	2.2
Sandberg bluegrass	Hanford, Benton County, Washington	Connell, Washington	13.9	0.5
Yarrow	Umatilla County, Oregon	Lincoln County, Washington	4.5	0.1
Royal penstemon	Douglas County, Nevada	Wild	2.5	0.2
Desert globemallow	Utah	Fresno, California	9.4	0.7
		Total	**44.3**	**6.5**

[*] **The double rate treatment consisted of the single rate applied twice.**
[†] **Pure live seed (PLS) is % purity multiplied by % germination of the seed lot.**
Multiply PLS/ft^2 by 10.76 for seed rate per square meter, and multiply lbsPLS/ac by 1.12 for kgPLS/ha.
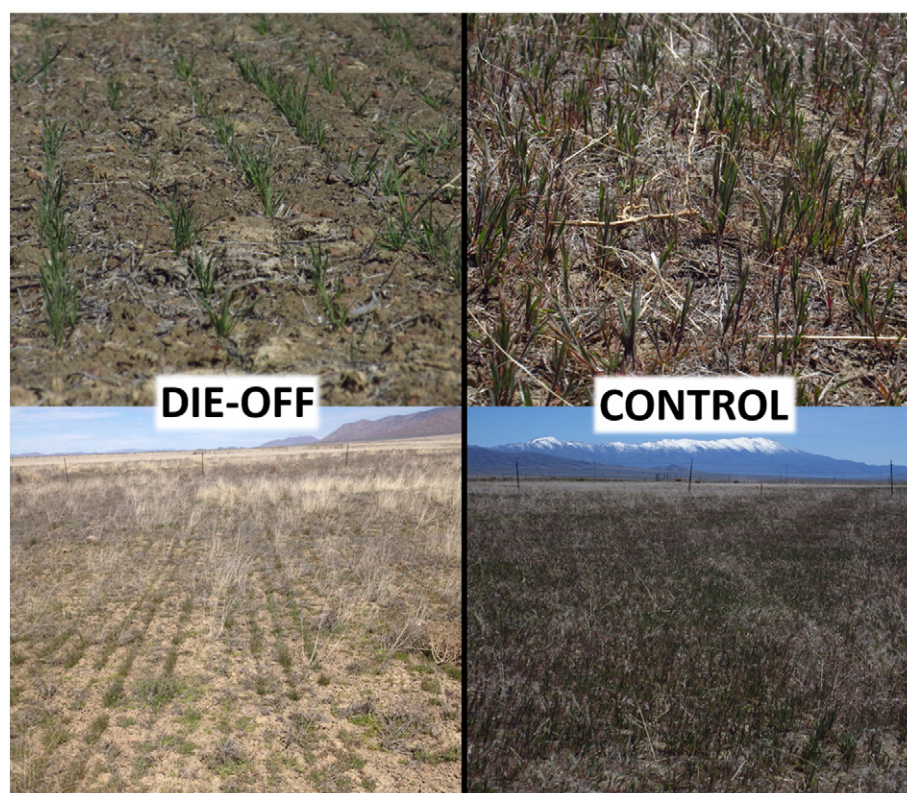
Figure 3. These images from the Four Corners site in April 2015 (top images) and March 2016 (bottom images) show reduced cheatgrass in the areas that experienced die-off (left images) compared to unaffected controls (right images). In the first season, large and vigorous seeded native grass seedlings could be seen in the die-off drill rows, while smaller seedlings were hidden in dense cheatgrass seedlings in the control. By the second year, these differences were even more dramatic as seeded grasses began to fill the drill rows in the die-off and grow together. While the control still supported seedlings, they were of a much smaller stature and grew amid much higher cheatgrass density.

three treatment areas were established in each field: unseeded, single seed rate, and double seed rate.

Six perennial native species of grasses, forbs, and shrubs were selected for the seed mix used in the experiment due to their commercial availability and likely suitability to one or more of the sites (Table 1): scarlet globemallow (*Sphaeralcea ambigua)*, royal penstemon (*Penstemon speciosus)*, yarrow *(Achillea millefolium)*, Sandberg bluegrass (*P. secunda)*, bottlebrush squirreltail (*E. elymoides)*, spiny hopsage (*Grayia spinosa),* and four-wing saltbrush (*Atriplex canescens)*. We selected collections or cultivars that originated from sites that were as similar as possible to the planting sites to maximize the benefit from any locally adapted traits.

All sites were seeded the third week of November 2014 using a minimum-till Truax Flex II 86 drill mounted on a tractor. The unseeded treatment was left completely undisturbed to represent site conditions that would occur with no management intervention. The single rate treatment received a total of approximately 44 pure live seeds per square foot (PLS/ft^2) applied with one seeder application, and the double rate treatment received approximately 89 PLS/ft^2 applied in two applications of 44 PLS/ft^2 each (Table 1). At the time of planting in November 2014, cheatgrass seedlings were just beginning to green up in all sites except the die-off field at Four Corners.

All fields were monitored through two growing seasons, at 5 months (April 2015) and 16 months (March 2016) after seeding. We sampled 20 randomly placed 1 m^2 quadrats in each treatment to record densities for seeded and resident grasses, forbs, and shrubs, as well as cheatgrass and other weeds. In June 2017, the Four Corners site was monitored for the number of flowering culms, following up on patterns observed in 2016. On a field-by-field basis, the sampled area was scaled down to a smaller area (e.g., 10 cm × 10 cm for annual weeds) to reduce counting fatigue if counts were likely to exceed several hundred. Additionally, 25 randomly selected cheatgrass plants in each field were measured in the first season for leaf number and maximum leaf height.

A fully factorial analysis of variance model was used to analyze the results separately for each sampling period, with site (Buena Vista, Four Corners, Paradise), die-off condition (control, die-off), and seeding treatment (unseeded, single-rate, double-rate) as main effects.[11] Significance was assessed at the **P** = 0.05 level.

Our Findings: Seeding Was More Successful in Die-offs

Estimated precipitation for the three sites was 97% to 101%, 116% to 126%, and 144% to 158% of the 30-year
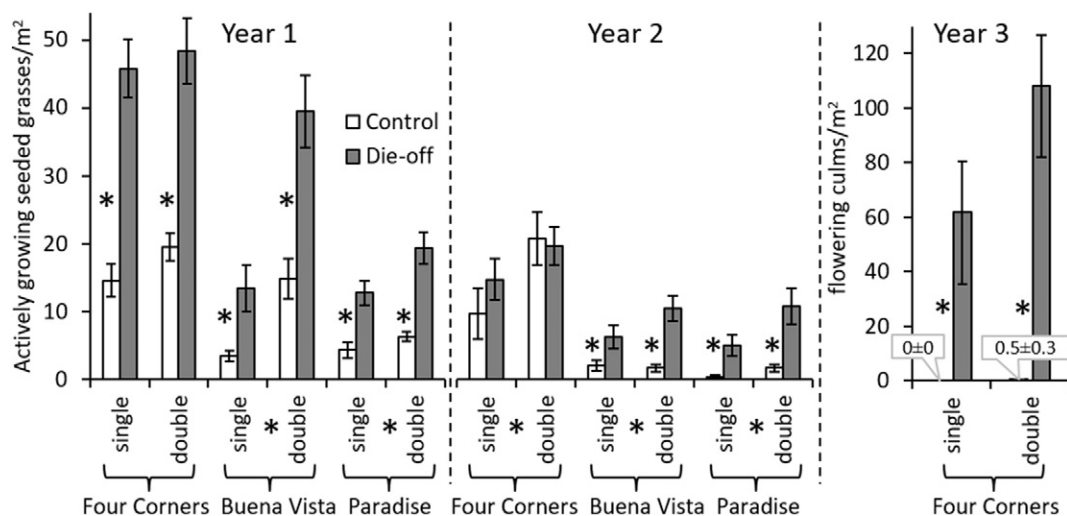
Figure 4. Means and standard errors for number of live seedlings (left and middle) and number of flowering culms (right) of both squirreltail and Sandberg bluegrass per square meter for each seed rate treatment (single, double) in areas that did not recently die off (control), as well as recent die-offs across three study sites (Four Corners, Buena Vista, Paradise). Third-year data were only taken at the Four Corners site to clarify patterns observed in the second year. Asterisks indicate significant ($P < 0.05$) differences between control and die-off fields (asterisks among the bars) and between single and double seed rate treatments (asterisks below the bars) in analysis of variance models.

average for each growing season, respectively.[12] We found absolutely no seeded shrubs and an insignificantly small number of seeded forbs surviving in our treatments, which supports the notion that these kinds of species are particularly challenging to establish, especially in highly invaded systems.[13] However, our perennial grass species, Sandberg bluegrass and bottlebrush squirreltail, did establish in significant numbers, ranging from 3 to 48 seedlings/m² in the first growing season to 0 to 20 seedlings/m² in the second growing season (Figs. 3 and 4). In the second growing season, the Four Corners site supported the highest establishment, averaging 10 to 20 seedlings/m², with the other two sites showing similar densities of 0 to 11 seedlings/m². Due to the lack of forb and shrub establishment, the rest of this text is focused only on the response of the seeded native grasses, although we recommend future work be conducted to understand the poor response of these species.

Our results strongly confirm what our previous case study suggested, which is that die-offs significantly improve our ability to establish native grasses from seed. We observed an average of 280% more establishment of seeded native grasses in the first season in die-off areas relative to controls, and this pattern was consistent across all sites and seed rates (Fig. 4). In the second growing season, this difference increased to over 500% more seedlings in die-offs at two of the three sites, while the third site, Four Corners, did not show such a pattern. The Four Corners site visually supported the trend for improved success in die-offs (Fig. 3), and the likely explanation for the lack of a difference in density is that large seeded grasses in the die-off had grown together and were difficult to differentiate from one another, leading to an underestimation of seeded grass density in the die-off. In the third growing season, counts of flowering culms of seeded grasses at Four Corners were over 100-fold higher in the die-off than in the control (Fig. 4), confirming greater success in the die-off, despite the lack of difference in density in the second year.

Another important finding is that the patterns of native grass establishment described were observed despite generally intense competition with cheatgrass and/or other weeds in die-off fields in both seasons (Fig. 3, Appendix A). Additionally, our results were observed in exclosures that prevented livestock from accessing seedings over the study period. Although this rest from grazing is standard practice for post-fire seedings, it remains to be seen if exclosures affect seeding in die-off areas. Because fences are expensive and time consuming to construct, we suggest that future research determine how this practice affects restoration success in die-off areas.

Our Findings: Increasing Seed Rates Can Pay Off

Our results strongly suggest that increasing seeding rates directly increased establishment. In the first growing season, doubling the seed rate significantly increased the number of seeded grasses in die-off as well as control fields at the Buena Vista and Paradise sites by 145% to 437% (average 235%), with no effect at Four Corners (Fig. 4). In the second growing season, the double-rate treatment supported 133% to 425% (average 175%) more seedlings than the single-rate treatment across all sites and fields, with the exception of the control field at Buena Vista, where there was no difference.

The double-rate treatment in our experiment was achieved by applying the single rate twice. This is important to consider because the extra cutting and packing of the soil or disturbance to the thatch layer caused by an additional pass of the tractor and seeder likely affected the seedbed conditions. These effects may have been positive and may explain some or all of the benefits of increased seeding rate, as well as why the Buena Vista site supported three to four times more grasses due to a mere doubling of the seed rate. Ideally,

the double rate treatment would have been applied in a single pass rather than a double pass, but this was not feasible at the time of seeding.

The two seed rates used in our experiment, 21 and 42 PLS/ft^2 for grasses, are both higher than the recommended rate for a mixed stand involving these two species (~14 PLS/ft^2).[14] Our findings suggest that the single rate was likely too low to expect maximum success at our semi-arid, 203 to 254mm (8 to 10-in) annual precipitation sites, even in areas with reduced cheatgrass competition. This is contrary to a more exhaustive synthesis of restoration in this region, which found no benefit to increasing similar seed rates for grasses.[15] However, James and Svejcar[16] identified a need to research better seeding technologies by demonstrating that the low success of drill seeding methods may be because they do not place enough seed at the best depth or into ideal seedbed conditions. Although we support the need for improved seeding technologies, our results suggest that in the meantime, increasing seeding rates of traditional drill seeding may be an easy way to increase success by exposing more seeds to appropriate conditions.

Moving Forward with Die-off Restoration

Previous work has shown that die-offs are common, although localized and unpredictable, and can affect tens of thousands of hectares in some years.[6] These die-offs are short-lived, with over 80% returning to cheatgrass dominance in the next year. Die-offs also experience increases in the densities of other annual forb weeds. However, despite this seemingly hostile situation for native species, our research has repeatedly shown that seeding of native perennial grasses in the fall after a die-off results in greater success. Considering that die-offs occur in highly invaded, low-diversity, low-productivity ecosystems (commonly characterized as hopeless candidates for restoration), the prospect of any dependable method for increasing the success of native species at these sites is welcome news. We propose that cheatgrass die-off represents a large and underutilized opportunity to improve establishment of native seedlings.

Cheatgrass die-offs can be thought of as one of several tools in the revegetation toolbox and present a great opportunity to focus restoration efforts. Because they are visible in freely available satellite imagery as early as April/May, managers could have 4 to 5 months to plan and prepare for seeding in years with extensive die-offs, a considerable improvement on post-fire seeding timelines. Prioritizing restoration in "hotspots" of frequent die-off may further improve restoration success, and optimizing seed mixes to suit these arid sites might result in even greater establishment. For example, our work clearly suggests that we need to do more to understand barriers to shrub and forb restoration, as we had no success with these seeds. Though more costly than seedings, die-offs may be an area where transplanting forb and shrub seedlings could establish islands within die-off hot-spots,[17] which could increase natural recruitment when climatic conditions are good for these species. Finally,

post-seeding management may further benefit these seedings. Pre-emergent herbicide or targeted grazing may be useful for reducing annual weed densities in the years following seeding, and these factors could be tested in future experiments.

We suggest that landowners or managers experiencing cheatgrass die-offs consider experimenting with seeding these areas as a means of reintroducing native perennial species to highly invaded, low-diversity lands, and we would be interested in hearing reports of any successes or failures with die-off seeding. Ongoing and future research should lead to improved understanding of what causes die-offs and can hopefully lead to useful predictions of when and where die-off will occur, or even the ability to create new die-offs. In the meantime, naturally occurring cheatgrass die-offs provide a rare opportunity for active restoration in some of our most degraded lands where, until recently, the potential for improving rangeland resources and values has been considered a lost cause.

## Appendix A. Weed Recovery after Die-off

Because the die-off phenomenon does not affect dormant cheatgrass seeds, many sites return to cheatgrass dominance in the next growing season. Additionally, many forb weeds are excellent seed dispersers and appear to do well in areas recovering from cheatgrass die-off. Here, we report results of cheatgrass and other weeds in our treatment plots.

In the first season, all sites supported significantly greater densities of cheatgrass in the control than the die-off fields (Fig. A1). In the second year, Four Corners still strongly showed this trend, Paradise weakly showed this trend in only two treatments, and Buena Vista had uniform cheatgrass density across die-off and control fields. The lower-density cheatgrass in the die-off in the first season had significantly more culms per plant and was significantly taller than in the control at all sites (Fig. A2). These findings show that the cheatgrass present in die-offs the year after the event is at a lower density but has higher individual vigor than in adjacent areas that did not die off and that these differences persist or fade away by the second year, depending upon the site, all of which corroborates previous findings.[8–10] Because of this quick recovery, the window for restoration benefits after die-off may be short.

Other weedy species responded to the die-off as well (Table A1). All three sites had significantly higher densities of other weed species in the die-off fields in the first year,
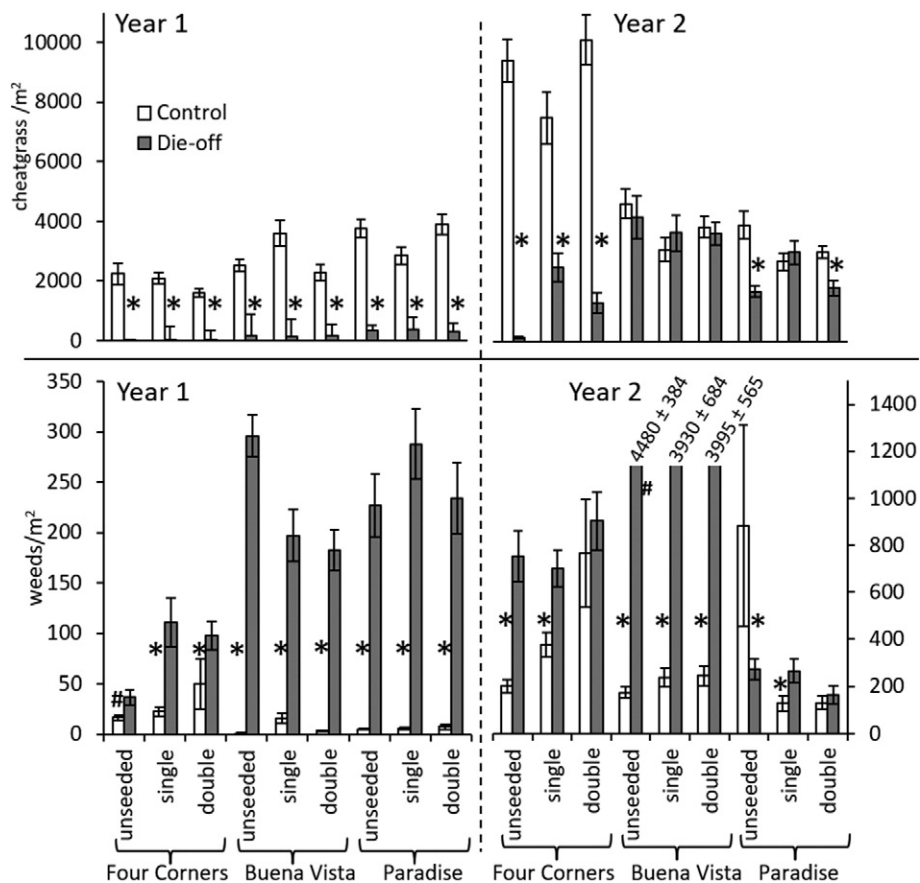
Appendix Figure A1. Means and standard errors for cheatgrass (top two panels) and weed (bottom two panels) density per square meter across seeding treatments (unseeded, singlerate, double-rate) in areas that have not died-off (control, white bars) as well as recent die-offs (die-off, dark bars) across sites (Four Corners, Buena Vista, Paradise) for both the first (left two panels) and second season (right panels). Values from the die-off field at the Buena Vista site were exceptionally high and are noted above the bars. Note the difference in scale between the first and second year weed panels. Significant differences between control and die-off fields in ANOVA models are indicated with asterisks (*P<0.05) and hashes (#P=0.05-0.06).
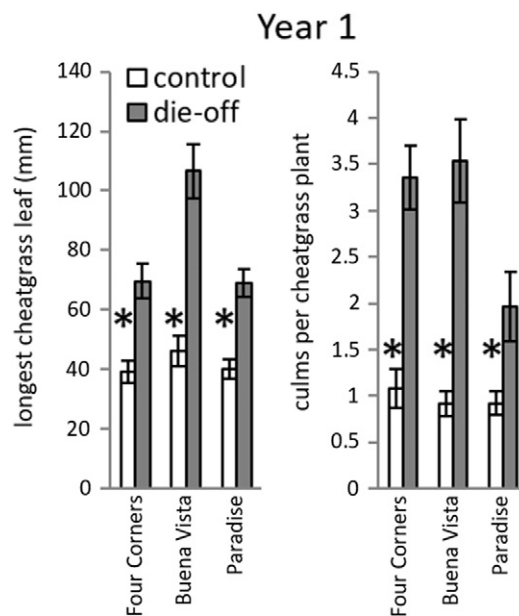
Appendix Figure A2. Longest leaf (left) and number of culms per plant (right) for cheatgrass for the first season in areas that have not died-off (control, white bars) as well as recent die-offs (die-off, dark bars) across sites (Four Corners, Buena Vista, Paradise). Significant differences between control and die-off fields in ANOVA models are indicated with asterisks (*P<0.05).

Appendix Table A1. List of exotic invasive (weeds), resident native, and introduced exotic species found to be actively growing in samples at the three sites at the time of seeding (S) and in the first (1) and second (2) year of monitoring.

Exotic invasive (weeds)	Four Corners	Buena Vista	Paradise
Cheatgrass (*Bromus tectorum*)	S, 1, 2	S, 1, 2	S, 1, 2
Field chickweed (*Cerastium arvense*)	-	2	2
Crossflower (*Chorispora tenella*)	-	-	1
Herb sophia (*Descurainia sophia*)	2	2	1
Redstem filaree (*Erodium cicutarium*)	-	-	2
Clasping pepperweed (*Lepidium perfoliatum*)	1	1, 2	-
Burr buttercup (*Ranunculus testiculata*)	1, 2	1, 2	2
Russian thistle (*Salsola tragus*)	S, 1, 2	1	-
Tall tumblemustard (*Sisymbrium altissimum*)	1, 2	S, 1, 2	S, 2
Resident native			
Bottlebrush squirreltail (*Elymus elymoides*)	-	-	S
Slender phlox (*Microsteris gracilis*)	1	1	-
Sandberg bluegrass (*Poa secunda*)	S, 1, 2	S	S, 1, 2
Gooseberryleaf globemallow (*Sphaeralcea grossulariifolia*)	S, 1, 2	-	-
Small fescue (*Vulpia microstachys*)	-	1, 2	-
Introduced exotic			
Crested wheatgrass (*Agropyron cristatum*)	-	S, 1	S, 1, 2

ranging from 37 to 296 plants/m^2 in the die-offs and from 1 to 50 plants/m^2 in the controls (Fig. A2). The density of other weed species was generally higher when cheatgrass densities were lower, suggesting that die-off events release other weed species from the competitive dominance that cheatgrass otherwise maintains. While the effect of the die-off on cheatgrass densities began to fade at some sites in the second growing season, this effect of die-offs on other weed densities was stronger and consistent for both years at all sites.

The use of an undisturbed area for the unseeded treatment prevented us from separating the physical effects of tractor and seeder-related soil disturbance on weed densities from the ecological effects (competition, facilitation, etc.) of the grass seedlings on the dynamics of cheatgrass and other weeds; this could be included in future experimental designs.

In summary, despite a complex interplay of cheatgrass and weeds, the bottom line is that recent die-offs supported dramatically increased establishment of seeded native grasses, even though they were still infested with weeds and were quickly returning to cheatgrass dominance.

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