Improving Perennial Bunchgrass Seeding Success in Annual Grass Invaded Areas Using Pre-Emergent Herbicide and Furrowing Techniques

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Improving Perennial Bunchgrass Seeding Success in Annual Grass Invaded Areas

Using Pre-Emergent Herbicide and Furrowing Techniques

Spencer Chad Camp

A thesis submitted to the faculty of
Brigham Young University
in partial fulfillment of the requirements for the degree of

Master of Science

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ABSTRACT

Improving Perennial Bunchgrass Seeding Success in Annual Grass Invaded Areas Using Pre-emergent Herbicide and Deep Furrowing Techniques

Spencer Chad Camp
Department of Plant and Wildlife Sciences, BYU
Master of Science

Exotic annual weeds have transformed western North America, particularly in sagebrush-steppe systems. Restoration of these invaded sites has been met with low levels of success. Pre-emergent herbicide provides a means to control annual weeds, but typically, this treatment does not allow for the concurrent seeding of desired species. Seeding within a deep, U-shaped furrow following herbicide application may be a method to reduce pre-emergent herbicide effects by transferring the herbicide away from the seed at the time of planting. We tested this potential planting technique by spraying plots with or without the pre-emergent herbicide imazapic, and planting bunchgrass seeds either with or without a deep furrow. Treatments (i.e. spraying and furrowing) were applied using mechanical equipment within a single pass, at six sites. In plots without imazapic, we found that deep furrows generally had higher seedling emergence, density of juvenile plants, and above-ground biomass when compared to no furrows. For plots with imazapic, deep furrows also generally improved measured plant metrics for the seeded species compared to plots without furrows. For example, the density of juvenile plants in deep furrows ranged, by study site, between 62% – 97% and 41% – 89% higher than the no furrow treatment, for plots with and without imazapic, respectively. Plots with imazapic and deep furrows was not always as effective as plots without imazapic and deep furrows. Deep furrows also reduced exotic annual weeds in the first year after planting, but weed reduction was generally more effective when this treatment was applied with imazapic. Overall, this research provides evidence that in most instances, the use of deep furrows alone is sufficient to improve seeding success. However, in areas with high weed cover, the application of herbicide followed by the creation of deep furrows in a one-pass system should be considered.

Keywords: furrow, imazapic, invasion, restoration, cheatgrass
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INTRODUCTION

Exotic annual grasses are restructuring dryland ecosystems in western North America (D’Antonio and Vitousek 1992; Evans et al. 2001) by displacing native plants and animals (Baker et al. 2009), limiting resources, promoting erosion, colonizing open spaces, and altering fire regimes (Brooks et al. 2004; D’Antonio 2000; Leffler 2016). As exotic annual grasses increase, disturbances and fluctuations in resource availability increase as well, creating a cyclical pattern of invasion and disturbance (Davis 2001; Davis et al. 2000; Pilliod et al. 2017). Cheatgrass (Bromus tectorum L.) is the most dominant and wide-spread of the exotic annual grass invaders. Since its introduction in the late 1800s (Mack 1981), this species has rapidly expanded to cover over 210,000 km² in North America (Bradley et al. 2018).

Reestablishing perennial grasses is one of the most crucial steps to excluding exotic annual species from a site (Parkinson et al. 2013; Svejcar et al. 2017). Perennial grasses increase the site's biotic resistance to the invasion of exotic annual plants by their fine roots, reducing soil nutrient concentrations and competing for limited soil moisture resources (Blank et al. 2020; Davies 2010; Grman and Suding 2010; Rowe and Leger 2011). Unfortunately, direct seeding efforts in dryland regions commonly fail to produce perennial grass densities that are sufficient to limit exotic annual grass invasion. Fewer than 10% of seeds deployed in restoration efforts typically produce a mature plant (James et al. 2011; Merritt et al. 2011), with rates often much lower (Chambers 2000; Larson et al. 2015).

Perennial seedlings' inability to compete with invasive annual weeds is a major reason for a lack of restoration success in areas with high weed pressure (Blank 2010; Humphrey and Schupp 2004). The ability of exotic annual weeds to achieve dominance over perennial seedings is associated with many physiological traits, including high plasticity in response to variable site
conditions (Upahyaya 1986), prolific production of seeds that can remain viable for more than five years (Beckstead et al. 1996; Hull 1974; Sebastian et al. 2017), and high competitive ability for moisture and nutrients, due to early germination and rapid life cycle, which limits the recruitment of native plants (DiTomaso 2000; Monsen 1994). Due to the aggressive nature of exotic annual species, emerged perennial grasses struggle to compete for limited resources and seedings often fail (Blank et al. 2020).

The use of soil-active (pre-emergent) herbicides, such as imazapic, provide land managers a tool for controlling invasive weeds (Mangold et al. 2013; Morris et al. 2009). Once exotic annual weeds are controlled, a window is then opened allowing desired perennial vegetation to establish (Davies et al. 2017). However, in addition to controlling exotic weed species, soil-active herbicides can limit the success of direct seeding efforts (Wilson et al. 2010; Sbatella et al. 2011, Hirsch et al. 2012). To address this issue, land managers will postpone seeding for approximately one year following an herbicide treatment to reduce non-target herbicide impacts on seeded species (Clements et al. 2017). Waiting until the following year may lead to reduced effectiveness of herbicide and give the invasive species enough time to reestablish on the site (Sebastian et al. 2017). Technologies that provide land managers with the ability to apply herbicide and plant desired species concurrently may be more effective at reclaiming sites invaded by exotic annual grasses.

Removing herbicide-treated soil away from the desired seedbed may be an effective approach to neutralize herbicidal effects to sown seeds (Eckert et al. 1974; Terry 2021). Through the implementation of furrows, it is possible to side cast and bury weed seeds away from the seeded species and concentrate herbicide in between the furrows (Eckert 1974; Humphries et al. 2018; Ogg Jr et al. 1994). Furthermore, direct seeding success rates are often higher if the seed is
deposited within a furrow or “safe-site,” which has increased shade (Eckert et al. 1986), greater humidity (Harper et al. 1965), sustained moisture (Winkel et al. 1991a), and reduced temperature fluctuations (Winkel et al. 1991b). Anderson et al. (In Review) demonstrated that deep furrows could improve water availability and reduce temperature fluctuations, which in some cases increased seedling emergence by almost 3-fold. Over a two-year study, Terry et al. (2021) showed that combining herbicide and furrowing treatments led to a decrease in cheatgrass cover and improved establishment of a native perennial grass. In these two aforementioned studies by Anderson et al. (In Review) and Terry et al. (2021), the furrows were implemented using hand tools to create wide bottoms to prevent sloughing of soil that may prevent seedling emergence. Creation of similar deep, “U-shaped” furrows may be possible using modified furrowers in-line with a rangeland drill’s planter disks. Additionally, attaching a boom sprayer on the front of the tractor, may make it possible to efficiently spray preemergent herbicide while planting desired species (Asher and Eckert 1973; Kay and Owen 1970).

The objectives of our study were to 1) investigate the efficacy of using mechanical equipment to spray pre-emergent herbicide, create U-shaped furrows, and plant desired species, all within one-pass, and 2) quantify how this one-pass system influences emergence, survival, and biomass of seeded species, and the reduction of exotic annual weed cover. We predicted that 1) the creation of U-shaped furrows alone will improve the performance of seeded species and reduce annual weed cover, and 2) when pre-emergent herbicide is applied, the furrow will reduce toxicity to seeded species and enhance the control of exotic annual weeds.
MATERIALS AND METHODS

**Study Sites**

Our study took place over two years with plantings in the fall of 2018 and 2019 (Figure 1). In 2018, research was implemented at three sites in Nevada, USA, near the towns of Tuscarora (41.696060, -116.534200), Battle Mountain (40.846000, -116.551000), and Paradise Valley (41.635251, -117.277930); and one site in Utah, USA, near Fountain Green (39.609189, -111.616850) (Fig. 1). In 2019, research occurred at two sites in Utah, USA, near Moroni (39.547306, -111.603537) and Mayfield (39.141216, -111.750989). These sites had a wide range of soil pH (7-8.5), mean precipitation (30-year average, 231-408 mm), and elevation (1433-1730 m) (Table 1; Soil Survey Staff, 2020). All sites had minimal slope (1.2-4.8 %) Fountain Green is characterized as an Upland Stony Loam (R028AY334UT) ecological site, which at the time of the study was primarily dominated by cheatgrass and tansy mustard (*Descurania pinnata* (Walter) Britton). The Mayfield site is a Semidesert Loam (R028AY220UT) invaded with cheatgrass, tansy mustard, and field bindweed (*Convolvulus arvensis* L.). Moroni is an Upland Loam (R028AY310UT) ecological site located within agricultural land that had been out of production for 10 years and was invaded by whitetop (*Cardaria draba* (L.) Desv.). Battle Mountain was in a Loamy 5-8 P.Z. ecological site (R024XY002NV), dominated by cheatgrass and prickly Russian thistle (*Salsola tragus* L.). The Paradise Valley and Tuscarora sites are classified as Loamy 8-10 (R025XY019NV) and Loamy Bottom (R025XY003NV) ecological sites, respectively. These locations were burned in early July of 2018, approximately five months before the implementation of this study, in the Martin fire. This fire was the largest fire in the history of Nevada, burning over 176,000 ha.
Seeded Species

This study used two different species, ‘Vavilov II’ Siberian wheatgrass (*Agropyron fragile* [Roth] P. Candargy) and ‘Anatone’ bluebunch wheatgrass (*Pseudoroegneria spicata* [Pursh] Á. Löve). Both of these species are commonly incorporated into rangeland seed mixes in the western United States. Siberian wheatgrass is a non-native perennial bunchgrass and one of the most drought-resistant, competitive plant materials available for seeding in dryland areas (Asay et al. 1995). (Jensen et al. 2009). This species is a top choice for droughty sites with at least 203 mm of precipitation (Ogle et al. 2008; Jensen et al. 2009). Due to Siberian wheatgrasses’ drought tolerance and competitive nature, we chose to plant this species at Fountain Green, Mayfield, and Battle Mountain, which had relatively high annual weed competition and low precipitation. Bluebunch wheatgrass is a native perennial bunchgrass that is less drought tolerant than Siberian wheatgrass, requiring at least 250 mm of precipitation (Monsen et al. 2003; Tilley and St. John 2013). We utilized this species in our trials at Moroni, Paradise Valley, and Tuscarora, which had less weed competition and relatively higher precipitation than the other study sites.

Experimental Design

Plantings were implemented within a randomized complete block split-split-plot design with six replicates at each site, in each planting year. Blocks were split in half, into sub-plots, with each sub-plot randomly assigned to a furrow treatment (no furrow or u-shaped deep furrows). Each sub-plot was further divided into two sub-plots, with each sub-sub-plot randomly assigned to an herbicide treatment (no herbicide and herbicide). Sub-sub-plots were comprised of four 9.1 m long seeded rows. This design gave us the following treatments applied to the seeded rows 1) no furrows without herbicide (CONTROL), 2) deep furrows without herbicide (DEEP
FURROWS), 3) no furrows plus herbicide (HERBICIDE), and 4) deep furrows plus herbicide (DEEP FURROWS + HERBICIDE). In total, there were 24 sub-sub-plots at each field site in each planting year (4 unique sub-sub-plot treatments \( \times \) 6 replications/site/year).

Planting and Herbicide Application

During the first year of the study, planting occurred on 8, 9, 10, and 20 November 2018 at Tuscarora, Winnemucca, Battle Mountain, and Fountain Green, respectively. The following year planting occurred on 1 and 6 November 2019 at Mayfield and Moroni, respectively.

We chose to use imazapic (Panoramic 2SL, Alligare, Opelika, AL, USA) as the pre-emergent herbicide in this study. Imazapic was applied at 87.6 g ae \( \cdot \) ha\(^{-1} \) using a 95 L boom-sprayer (Fimco, North Sioux City, SD, USA) fastened to the front of the tractor pulling the seeding implement (Figure 2). There was negligible wind or rain events at the time of herbicide application. A buffer zone of 1.2 m surrounded sub-blocks to prevent the herbicide from affecting neighboring treatments.

Deep U-shaped furrows were made with 40 cm wide modified furrowers (Johnson Tractor and Implement, Spanish Fork, Utah, USA) attached to a plow bar immediately in front of the individual cone seeders (Figure 2). The furrowers were modified by cutting off 12 cm of the leading edge of the furrower, to produce a furrow that was \(~12\) cm wide at the bottom. While planting, the tool bar was adjusted so the bottom of the furrow went to a depth of \(~20\) cm into the soil (Figure 2). When treatments were not applied in deep furrows, furrowers were not used in the planting process.

Seeds were sown just below the soil surface (6 mm) within four rows 9.1 m in length, with 45 cm between each row (Fig. 2). This was done using a single-pass approach with a 4-row cone
planter (ALMACO, Nevada, IA, USA) attached to a Kubota M6060 tractor (Kubota, Grapevine, TX, USA). Rows were seeded at a rate of 118 pure live seed (PLS) · m.

Field Measurements

Total annual weed cover was comprised of a variety of exotic annual species, including cheatgrass, prickly Russian thistle, tansy mustard, field bindweed, and whitetop. Ocular annual weed species cover estimates were made in October of both years following plantings (2019, 2020) using a circular metal hoop (1 m in diameter) that was laid over the planting rows every 2.5 m. (Bonham et al. 2004). Hoops were placed to include two of the planted rows and the interspace between all four rows. The percentage of total ground area occupied by the species of exotic annual weeds within the hoop was estimated visually to the nearest percentage.

Treatments were systematically sampled at four sections in each row for all seeded species parameters (seedling emergence, plant survival, and above-ground plant biomass). The sampling sections were 0.5 m long and 2 m apart, with a 1.5 m buffer at the beginning of the row to avoid any edge effects. Seedling emergence was monitored the spring following planting, during mid-late May. Plant survival was assessed in October 2020, allowing us to collect one-year survival for sites planted in 2019 and two-year survival for sites planted in 2018. However, only plants at Tuscarora and Paradise Valley had measurable biomass. Biomass at the other sites was limited due to livestock and wildlife grazing. Biomass was collected by clipping all seeded species’ biomass, at ground level. The biomass sampling area was comprised of the area used to sample seedling emergence and plant density as described above.

Statistical Analysis
All data were analyzed using JMP® version 15 (SAS Institute Inc., Cary, NC). Mixed model analysis was used to analyze total cover of annual exotic weeds (%) and total above-ground biomass (kg \cdot ha^{-2}). Prior to analysis, exotic annual weed cover data was square-root transformed. Seedling density and biomass data were also transformed using a log(x)+1 transformation. Blocks were considered random factors while year of planting, site, furrowing treatment, and herbicide treatment were considered fixed factors. Mean estimates were separated using the Tukey-Kramer honestly significant difference multiple-comparison method. Differences were considered significant when \( P < 0.05 \). In the text and figures, arithmetic means are reported either with unique letters to denote significances or with associated standard error. Seedling density data was analyzed using repeated-measures mixed-model analysis in the same manner described above using year of sampling as a repeated measure. For exotic annual weed cover, seedling emergence, seedling survival and above-ground biomass, three- and four-way interactions between year of planting, site, furrowing treatment, and herbicide treatment were included in all initial models, but in order to form simpler models, insignificant three- and four-way interactions were not included in the model.

RESULTS

Precipitation and Temperature

Precipitation was highly variable in the two seeding years of the study (Table S1; Figure 3). In the first year (October 2018 – September 2019), precipitation at most sites was above average, ranging between 107% and 149% of normal, while precipitation the following year (October 2019- September 2020) ranged between 50% and 93% of normal (Table S1; Figure 3). In the second year of the study (October 2019 – September 2020), all sites were under extreme drought
conditions with precipitation averaging between 24% and 48% less than normal from January 2020 – April 2020, and between 24% and 92% less than normal, from May 2020 – September 2020. Temperature also varied between sites and planting years. Average temperatures during 2018-2019 were below or near normal at all sites, ranging between 80% and 101%. Temperatures during 2019-2020, were higher than the previous year ranging of between 93% and 113% from normal (Table 2).

**Exotic Annual Weed Control**

Total weed cover sampled in fall 2019 showed that site, furrows, herbicide applications, and time after treatment influenced exotic annual weed cover for the sites that had an appreciable level of exotic annual weeds (i.e. Battle Mountain, Tuscarora, and Fountain Green) ($P < 0.001$; Table 2). There were also interactions among these effects, which indicate that the furrow and herbicide treatments responded differently by site ($P \leq 0.002$) and time after treatment ($P \leq 0.166$). At Battle Mountain, DEEP FURROWS reduced weed cover by 30% (13 percentage points) in comparison to the CONTROL ($P = 0.003$; Figure 4). The HERBICIDE and DEEP FURROW + HERBICIDE treatments were similar to each other ($P = 0.375$) and had improved control over DEEP FURROWS, with a 71% (30 percentage points) and 85% (36 percentage points) reduction in weed cover in comparison to the CONTROL ($P < 0.001$), respectively. By the second year, at Battle Mountain, weed cover had declined in the CONTROL, which is most likely due to the severe drought at the site, and all other treatments had similar weed cover to the CONTROL.

At Fountain Green, DEEP FURROW + HERBICIDE treatments decreased exotic annual weed cover by 69% (37 percentage points; Figure 4) compared to the CONTROL ($P < 0.001$).
The other treatments failed to limit annual weed cover at this site, on this year. The other treatments did not significantly reduce exotic annual weed cover. However, during the second year, in addition to the DEEP FURROW + HERBICIDE treatment showing a decline in weed cover, the DEEP FURROW treatment showed an equal ability to reduce weed cover ($P = 0.779$). The Tuscarora site had less weed cover than the other sites and showed in the first year that weed cover was decreased by the HERBICIDE and DEEP FURROW + HERBICIDE treatments by approximately 1% (~5 percentage points) compared to the CONTROL ($P < 0.001$).

In the second year of the trial (fall 2020), weed cover was minimal at Mayfield and Moroni (Figure 4). At Mayfield in the HERBICIDE and DEEP FURROW + HERBICIDE treatments reduced weed cover by 83% (12 percentage points) and 73% (11 percentage points), respectively compared to the CONTROL ($P < 0.001$). Weed control at Moroni was similar among the treatments ($P \geq 0.213$).

**Seedling Emergence and Survival**

During the first year of our study, the impact of the type of furrow and herbicide treatment applied varied by site and year of sampling (Table 2). In non-herbicide treated soils, DEEP FURROWS only improved seedling emergence at the Tuscarora site, with an increase over the CONTROL of 46% ($P < 0.001$; Figure 5). In contrast, enhanced survival of the seedlings in the DEEP FURROWS resulted in higher plant densities at all sites with an increase in plant density ranging between 42 – 89% ($P < 0.037$; Figure 5). HERBICIDE treatment effects varied across sites and years of sampling (Table 2). Seedling emergence was reduced by the HERBICIDE treatment at Paradise Valley ($P < 0.001$) but increased emergence at Battle Mountain compared to the CONTROL ($P < 0.001$; Figure 5). The HERBICIDE treatment substantially reduced the
Plant density of seedlings that had survived to the second year at Tuscarora ($P < 0.001; 75\%$) and Paradise Valley ($P < 0.001; 97\%$), but at Fountain Green, this treatment dramatically improved plant densities ($P < 0.001; 97\%$). DEEP FURROWS + HERBICIDE was relatively consistent at improving seedling emergence and survival into the second year compared to HERBICIDE, except at Fountain Green ($P = 0.037$; Figure 5).

Plantings in 2019, at Mayfield and Moroni, responded similarly to each other, but there were some differences in the degree of the response between the sites (Table 2). At Mayfield, DEEP FURROWS improved seedling emergence ($P < 0.001$) and the number of survived seedlings ($P < 0.001$) by 60% and 82%, respectively in comparison to the CONTROL (Figure 6). At Moroni, DEEP FURROWS increased the emergence ($P < 0.001$) and number of survived seedlings ($P < 0.001$) by 70% and 60%. The HERBICIDE treatment did not impact emergence but decreased the number of survived seedlings at Moroni ($P < 0.001$) by 92% compared to the CONTROL. At Mayfield and Moroni DEEP FURROWS + HERBICIDE improved seedling emergence ($P \leq 0.001; 24-51\%$) and the number of survived seedlings ($P < 0.001; 73-96\%$) over the HERBICIDE treatment. At Mayfield and Moroni in the DEEP FURROWS + HERBICIDE, the density of seedlings that emerged and number of plants that survived was higher than the CONTROL ($P < 0.001$).

**Biomass at Tuscarora and Paradise Valley**

Two years following planting, biomass did not differ between Tuscarora and Paradise Valley in CONTROL plots. The effect of DEEP FURROWS, HERBICIDE, and DEEP FURROWS + HERBICIDE differed between sites. Biomass in DEEP FURROWS at Paradise valley totaled $370 \pm 63 \text{ kg} \cdot \text{ha}^{-2}$ while biomass at Tuscarora was $161 \pm 48 \text{ kg} \cdot \text{ha}^{-2}$ in the same treatment. The
HERBICIDE treatment at Paradise Valley and Tuscarora reduced biomass weight by 95% and 84%, respectively, compared to the CONTROL ($P < 0.001$). At Paradise Valley, DEEP FURROWS + HERBICIDE reduced biomass when compared to DEEP FURROWS ($P = 0.007$), but still maintained 39% more weight than the CONTROL ($P = 0.049$; Figure 7). At Tuscarora, DEEP FURROWS + HERBICIDE were similar to the CONTROL ($P = 0.804$) and DEEP FURROW plots ($P = 0.181$) with biomass weighing $103 \pm 22$ kg · ha$^{-2}$.

DISCUSSION

*Review of Hypotheses*

In this study, we tested mechanical equipment's ability to spray pre-emergent herbicide, create U-shaped furrows, and plant desired species, all within a one-pass system, to improve emergence, survival, and biomass of seeded species, and to reduce exotic annual weed cover. Our data partially supported our first hypothesis, that the creation of deep, U-shaped furrows would improve the performance of seeded species with increased emergence, survival, and biomass at most sites and planting years (Figures 5 - 7). We also found that this treatment would generally reduce exotic annual weed cover (Figure 4). Pre-emergent herbicide application typically reduced weed cover in the first year after spraying, but its effectiveness was diminished by the second year (Figure 4). Additionally, this herbicide treatment affected plant recruitment of seeded species, mainly through a reduction in plant survival and above-ground biomass (Figure 6 and 8). As predicted in our second hypothesis, applying herbicide in combination with deep furrows generally had the highest reduction in exotic annual weed control compared to sites that were not furrowed or sprayed (Figures –4 - 7).
Furrows

Restoring perennial species back into dryland systems has low success rates (Duniway et al. 2015; Knutson et al. 2014), particularly in the presence of invasive species (DiTomaso 2000; Ledger et al. 2015). Successful restoration outcomes are generally limited to years with average or above-average precipitation (Hardegree et al. 2011). Seeding technologies that can improve site bed seed conditions, particularly with respect to soil moisture and temperature, could help improve the success of a restoration project. Creating “safe-sites” using furrowing techniques have been shown to minimize temperature fluctuations and enhance soil moisture availability (Anderson 2020; Eckert Jr and Evans 1967). Our data showed that deep furrow plantings led to increased seedling emergence in three of our six research sites (Figures 5 and 6). Except for Fountain Green, all research sites with a deep furrow treatment had a higher number of surviving plants in comparison to the control, with an increase ranging from 42% - 83% (Figures 5 and 6). For the two sites where above-ground biomass was obtained (Paradise Valley and Tuscarora), deep furrows had between 52% and 78% higher above-ground biomass than the control. It is our observation that the primary reason we did not see a positive treatment response from deep furrows at Fountain Green, was due to wildlife ungulate grazing, primarily from mule deer (*Odocoileus hemionus*) and elk (*Cervus Canadensis*). These wildlife species appeared to be targeting seeded species growing in the deep furrows. Wildlife may target plants in deep furrows because furrows remove annual grasses and forbs that provide a protective canopy layer, while the furrow displays locations of palatable seedlings to grazers (Oesterheld and Oyarzábal 2004). During the early stages of plant development, grazing can decrease plant survival and fitness due to seedlings being pulled up from their roots, trampled, and excess removal of plant biomass.
We anticipate that we would have seen a treatment effect from furrowing if Fountain Green was not grazed heavily by wildlife.

Deep furrows may also reduce weed cover due to seeds being buried to a depth that inhibits their growth by side-casting and “tipping” soil over (Clements et al. 2017). It has been suggested that furrowing may also create “safe-sites” for weedy species that may take advantage of the more conducive growing conditions that furrows provide (Ott et al. 2016). Ott et al. (2016) studied the differences between minimum-till drills to standard rangeland drills and their effects on invasive species. They showed that in some cases, standard rangeland drills (which increased disturbance versus minimum-till drills) actually increased the density of Russian thistle and tansy mustard. In this study, we saw no indication that deep furrows increased the recruitment of exotic annual weeds but reduced weed cover from 22% to 57% at four of six study sites (Figure 4). Increased disturbance from the furrowing may be necessary to remove standing biomass and bury the weed seed bank. At the two study sites where weed cover was not reduced by deep furrows (Moroni and Mayfield), there was a minimal amount of weeds in general at the sites, which was most likely due to precipitation in that year being well below normal (Figures 3 and 4). Had precipitation and subsequently weed cover been higher during the year Moroni and Mayfield were planted, we anticipate that we would have seen a reduction in annual weeds at these sites.

**Herbicide Treatments**

Exotic annual weed invasion often prevents the establishment of commonly seeded species (Monsen 1994; Young et al. 1987). Typically, weed control is most effective when it is combined with soil-active herbicides (Davison and Smith 2007; Young and Clements 2000). The
soil-active herbicide imazapic is a non-selective herbicide that can incur damage to seeded species (Morris et al. 2009; Sheley et al. 2007). In our study, herbicide reduced the emergence of seeded species at three of the six sites (Figures 5 and 6). Additionally, the number of plants that survived to the study's conclusion was reduced between 41% and 97% compared to the control at four of the six sites. Above-ground biomass was also negatively affected by imazapic application, limiting growth compared to the control by 95% at Paradise Valley and 84% at Tuscarora (Figure 7).

Fountain Green was the only location where we did not see a reduction to the seeded species from an herbicide application. At this site, the herbicide application had the highest amount of plant recruitment relative to the other treatments, with 97% more surviving plants than the control at the end of the study (Figure 5). The herbicide application at Fountain Green may not have impacted seeded species to the same degree as at other sites due to the leaching of the herbicide near the soil surface. Particularly in coarse-textured soils (Jursík et al. 2020), soil-active herbicides can be susceptible to leaching to lower depths beneath germinating seeds (Martini et al. 2013). Leaching of herbicide at Fountain Green could have been greater than at other sites due to the location's relatively higher sand content (Table 1), combined with above-average precipitation during the first five months after planting (Figure 3). It could also be presumed that we saw an increase in seeding success in the herbicide treatment because the herbicide reduced exotic annual weed cover, which improved growing conditions, and helped counter the deleterious effects of the herbicide. However, at Fountain Green, we did not see a significant reduction in weed cover from the herbicide application, which again may be due to the leaching of the product near the soil surface (Figure 4). While the reduction in weed cover at
Fountain Green may not have been significant, it may have been enough to be biologically significant to the seeded species.

There was evidence at Battle Mountain to suggest seedling emergence was improved by the herbicide reducing competition between seeded species and exotic annual weeds. The herbicide treatment had an 86% increase in seedling emergence (Figure 5) and an 71% decrease in weed cover (Figure 4). This response was not maintained into the second year, as exotic annual weeds returned to the same level as the control, and the number of surviving plants was reduced by 40% compared to the control (Figure 5). Potentially as herbicide effects wore off and exotic annual weeds returned, seedlings may not have been able to compete and subsequently died off. These results are consistent with previous studies showing that immature bunchgrass plants are highly susceptible to competition from exotic annual grasses (Aguirre and Johnson 1991; Humphrey and Schupp 2004).

As with Battle Mountain, herbicide activity appeared to also decline after the first year of planting at Tuscarora, as indicated by an increase in exotic annual weeds (Figure 4). The limited effect of herbicide during the second season following planting may result from high soil mobility or leaching of herbicide, as mentioned previously. Because herbicide effectiveness subsides in the second year, exotic annual weeds may establish quickly by taking advantage of the abundance of nutrient and water resources made available by clearing existing vegetation (Chambers et al. 2016; Perryman et al. 2020). Another factor that may have also reduced the long-term control of the exotic annual weeds could be associated with our small plot study design. Even when weed control was achieved with the herbicide, the plots had high weed propagule pressure from the surrounding area. Exotic annual weed reduction may be maintained more effectively when treatments are done over larger areas (Chambers et al. 2016).
At Paradise Valley, Mayfield, and Moroni, we cannot conclude what response imazapic herbicide has on weed control, because of a lack of weed cover at the sites (Figure 4). Paradise Valley most likely had a minimal weed presence before the study. Our observations at Mayfield and Moroni were that these sites would have had a high presence of weeds had the study not been implemented under severe drought conditions (Figure 3).

Combining Furrows and Herbicide

Many restoration approaches require treated areas to remain unseeded for at least a year following herbicide application to reduce the effects of herbicide on seeded species (Clements et al. 2017; Davies 2010; Evans and Young 1984). Leaving the area dormant prior to seeding may allow exotic annual weeds to opportunistically reestablish when residual herbicide effects wear off (Sebastian et al. 2017). By employing furrows in combination with an herbicide application we created a one-pass system that can effectively reduce exotic annual weeds but also allow perennial bunchgrasses to establish. A reduction in herbicide toxicity from furrowing is shown in our study, by the herbicide plus furrowing treatment having a higher final plant density at five out of the six sites (62% to 97% increase), in comparison to an herbicide treatment (Figures 5 - 6). The site that did not produce higher plant densities from the combinational treatment relative to just an herbicide treatment was at Fountain Green. As described previously, we anticipate that this site would have had a similar response to the other places had there not been impacts from wildlife grazing.

It appears that the herbicide plus furrowing treatment provides a similar enhanced microsite to seeded species as just a furrow treatment. In this study, the herbicide plus furrowing treatment generally produced the same final plant densities and above-ground biomass as a deep furrow
treatment without herbicide (Figures 5-7). In comparison to just furrowing, the furrow plus herbicide treatment had the greatest reduction in exotic annual weed cover after the first year following the first planting of the study, at Fountain Green, Battle Mountain, and Tuscarora (Figure 4). The reason for greater weed control from this treatment during the first year may be because 1) the treatment combines two different methods for weed control, the burial of weed seed and the chemical inhibition of plant growth, 2) weed seed and herbicide are brought together between the drill rows and presumable this higher concentration of herbicide is more effective at weed control, and 3) because the herbicide is mixed with the soil it enhances herbicide soil contact, which minimizes the issue of having the herbicide being bound to the surface litter layer (Applestein et al. 2018).

After the second year following planting, at Battle Mountain and Tuscarora, weed cover was not controlled by imazapic, which may be due to high soil mobility of the herbicide and high propagule pressure, as previously discussed. However, at Fountain Green combining herbicide and furrowing as a treatment did have reduced weed cover in comparison to the control plots, but this treatment did not show any difference compared to the plots with deep furrows. This result suggests that herbicide was ineffective during the second year at controlling weed cover, but the deep furrows provided continual control on weed cover at Fountain Green.

Implications and Management Recommendations

Our data suggest that a deep, U-shaped furrow, applied at the time of seeding, has the potential to improve seeding success by enhancing the plant seedbed and reducing exotic annual weeds and their seed bank. Our data also suggest that deep furrows can allow land managers to apply pre-emergent herbicide concurrently with seeding and see minimal to no impact from the
herbicide to the seeded species. However, our study generally indicated that in most instances, the use of deep furrows alone is sufficient to improve seeding success and pre-emergent herbicide may not be needed. However, in areas with high weed cover, the application of herbicide followed by the creation of deep furrows in a one-pass system may be required, as we found that this combinational treatment provided greater weed control in comparison to just using deep furrows.

Simply attaching furrowers or furrowing arms with disks to a rangeland drill would allow land managers to incorporate these methods into established restoration practices using standard seeding equipment (Larson 1980). Other single-entry approaches for restoring invaded sites have had limited effect at controlling exotic annual weed cover while establishing perennial grasses and often incur high costs and risks (Davies et al. 2014; Sheley et al. 2007; Sheley et al. 2012). The single-entry approaches shown in our study of furrowing as a stand-alone treatment or furrowing in combination with herbicide, may offer a practical method for land managers to restore perennial bunchgrasses in annual weed invaded areas and reduce the high risks and costs associated with restoration.

The furrowing technique presented in our research can prevent sidewalls from sloughing and covering seeds to a depth that limits their emergence. Our work was performed with large-seeded species that have relatively high vigor. The use of deep, U-shaped furrows may be especially useful for establishing smaller seeded species or species with shallow depth requirements, which are in danger of being buried too deep when they are sown in conventional V-shaped furrows. Additional research is required to evaluate this method with other species, herbicides, soil types, and climates before it can be recommended as a restoration treatment.
### Table 1. Site characteristics of research plots

<table>
<thead>
<tr>
<th>Site</th>
<th>Ecological Site Name</th>
<th>Soil Map Unit</th>
<th>Soil Texture (%)</th>
<th>Soil pH</th>
<th>Precip. (mm)</th>
<th>Aspect</th>
<th>Slope (%)</th>
<th>Elevation (m)</th>
</tr>
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<td>Semidesert Loam</td>
<td>Mayfield shaly loam</td>
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<td>43</td>
<td>40</td>
<td>8.5</td>
<td>300</td>
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<td>Upland Loam</td>
<td>Donnardo stony loam</td>
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<td>6</td>
<td>47</td>
<td>7.9</td>
<td>283</td>
<td>E</td>
</tr>
<tr>
<td>Fountain Green</td>
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<td>Mountainville cobbly fine sandy loam hardpan variant</td>
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<td>70.9</td>
<td>16.6</td>
<td>7.6</td>
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<td>NE</td>
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<tr>
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<td>9.3</td>
<td>66.1</td>
<td>7.0</td>
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<tr>
<td>Paradise Valley</td>
<td>Dry Floodplain</td>
<td>Hunton-Goosel-Connel association</td>
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<td>40.7</td>
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<td>Whirlo gravelly silt loam</td>
<td>8</td>
<td>34</td>
<td>58</td>
<td>7.9</td>
<td>231</td>
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Table 2. Results of mixed ANOVA models for final seedling density and exotic annual weed cover, by year, site, furrow treatment, and herbicide treatment and their interactions. *Significant factors ($P < 0.05$) are highlighted in bold.

<table>
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Figure 1. Map of study sites. Tuscarora, Paradise Valley, Battle Mountain and Fountain Green were planted in 2018. Sites planted in 2019 were Moroni and Mayfield.
Figure 2. The picture on the left is an example of a mechanical one-pass system that allows for the application of herbicide followed by furrowing to remove the herbicide-treated soil away from the planting discs. The picture on the right depicts the deep, U-shaped furrow created by this design. Because the bottom is relatively flat, it may help prevent the seeds and seedlings from being covered by sloughing soil from the furrow’s sidewall.
Figure 3. Precipitation and Temperature vs 30yr Normal. Precipitation was much higher in 2018-2019 than in 2019-2020. The temperature was lower in 2018-2019 compared to 2019-2020.
Figure 4. Change in exotic annual weed cover between 2019 and 2020 at Tuscarora, Battle Mountain, and Fountain Green. Mayfield and Moroni were limited to sampling only once due to being planted during the second year of the study. Paradise Valley is not represented due to a lack of exotic annual weeds (i.e., < 2% weed cover). Treatments included plots sown without furrows and without herbicide (CONTROL), deep furrows without herbicide (DEEP FURROWS), without furrows plus herbicide (HERBICIDE), and deep furrows plus herbicide (DEEP FURROWS + HERBICIDE). Differing lower case letters indicate a significant difference ($P < 0.05$) between treatments.
Figure 5. Seedling emergence and survival (mean ±SE) at sites planted in 2018 from plots sown without furrows and without herbicide (CONTROL), deep furrows without herbicide (DEEP FURROWS), without furrows plus herbicide (HERBICIDE), and deep furrows plus herbicide (DEEP FURROWS + HERBICIDE). Differing lower case letters indicate a significant difference ($P <0.05$) between treatments.
Figure 6. Seedling emergence and survival (mean ±SE) at sites planted in 2019 from plots sown without furrows and without herbicide (CONTROL), deep furrows without herbicide (DEEP FURROWS), without furrows plus herbicide (HERBICIDE), and deep furrows plus herbicide (DEEP FURROWS + HERBICIDE). Differing lower case letters indicated a significant difference ($P < 0.05$) between treatments.
Figure 7. Biomass collected at Tuscarora and Paradise Valley (mean ±SE) following two growing seasons produced from plots sown without furrows and without herbicide (CONTROL), deep furrows without herbicide (DEEP FURROWS), without furrows plus herbicide (HERBICIDE), and deep furrows plus herbicide (DEEP FURROWS + HERBICIDE). Differing lower case letters indicated a significant difference ($P < 0.05$) between treatments.
Table S1. Percentage of precipitation and temperature at each study site and planting year compared to the 30-year normal.

### Precipitation

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<thead>
<tr>
<th></th>
<th>Fountain Green</th>
<th>Mayfield</th>
<th>Moroni</th>
<th>Battle Mountain</th>
<th>Paradise Valley</th>
<th>Tuscarora</th>
<th>Average</th>
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<tr>
<td>2018-2019</td>
<td>149 %</td>
<td>135 %</td>
<td>146 %</td>
<td>144 %</td>
<td>107 %</td>
<td>129 %</td>
<td>135 %</td>
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<tr>
<td>2019-2020</td>
<td>64 %</td>
<td>83 %</td>
<td>50 %</td>
<td>60 %</td>
<td>71 %</td>
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### Temperature

<table>
<thead>
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<th>Moroni</th>
<th>Battle Mountain</th>
<th>Paradise Valley</th>
<th>Tuscarora</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>2018-2019</td>
<td>80 %</td>
<td>93 %</td>
<td>81 %</td>
<td>100 %</td>
<td>101 %</td>
<td>98 %</td>
<td>92 %</td>
</tr>
<tr>
<td>2019-2020</td>
<td>94 %</td>
<td>103 %</td>
<td>93 %</td>
<td>113 %</td>
<td>113 %</td>
<td>109 %</td>
<td>104 %</td>
</tr>
</tbody>
</table>
LITERATURE CITED


Kay, B.L., Owen, R.E., 1970. Paraquat for range seeding in cismontane California. Weed Science 18, 238–244.


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