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Postfire Drill-Seeding of Great Basin Plants: Effects of Contrasting Drills on Seeded and Nonseeded Species☆,☆☆

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ABSTRACT

Objectives of postfire seeding in the Great Basin include reestablishment of perennial cover, suppression of exotic annual weeds, and restoration of diverse plant communities. Nonconventional seeding techniques may be required when seeding mixes of grasses, forbs, and shrubs containing seeds of different sizes. We conducted an operational-scale experiment to test the effectiveness of two rangeland drills (conventional and minimum-till) for seeding native plant mixes following wildfire in Wyoming big sagebrush (*Artemisia tridentata* Nutt. ssp. *wyomingensis* Beetle & Young) communities. Both drills were configured to place small and large seeds in alternate rows. We hypothesized that the minimum-till drill's advanced features would improve establishment compared with the conventional drill. We also hypothesized that the minimum-till drill would cause less damage to residual perennials, whereas the conventional drill would have a greater impact on annual weeds. The experiment was replicated at three burned sites and monitored for 2 yr at each site. Seeded plant establishment was lowest at a low-precipitation site that became dominated by exotic annuals. Another site had high perennial grass establishment, which effectively suppressed exotic annuals, while a third site attained high diversity of seeded species and life forms but became invaded by exotic annuals in plant interspaces. Small-seeded species generally established better with the minimum-till drill equipped with imprinter wheels than the conventional drill with drag-chains. However, large-seeded species frequently established better with the conventional drill despite its lack of depth bands and press wheels. Soil disturbance associated with the conventional drill had a negative effect on residual perennials and exotic annuals at some sites. Results indicate that different drill features are advantageous in different ways, but that either of the tested drills, if properly used, can be effective for seeding native plant mixes provided site conditions are otherwise favorable for seedling establishment.

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Introduction

Shrub-steppe communities of the Great Basin have been heavily affected by wildfire and annual weed invasion, resulting in ecosystem degradation, species endangerment, and loss of resource values (Crawford et al., 2004; Brunson and Tanaka, 2011; Pierson et al., 2011). Wyoming big sagebrush (*Artemisia tridentata* Nutt. ssp. *wyomingensis* Beetle & Young) communities are particularly vulnerable to these impacts because of their low resilience to fire and low resistance to invasion by exotic annuals such as cheatgrass (*Bromus tectorum* L.) (Chambers et al., 2014). With the exception of sites with an abundance of fire-tolerant perennials, Wyoming big sagebrush communities readily become dominated by exotic annuals following fire (Davies et al., 2007; Chambers et al., 2014; Miller et al., 2015), setting the stage for a recurring wildfire-weed invasion cycle (Balch et al., 2013; Davies and Nafus, 2013). However, exotic annual populations often require a year or more to expand and fill available space after their seed banks have been partially consumed by sagebrush fires (Young and

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Evans, 1978; Ott et al., 2003). The first year following wildfire thus provides a window of opportunity for establishing perennial species and breaking the trajectory toward exotic annual dominance and site degradation (Ott et al., 2003; Pyke et al., 2013).

Crested wheatgrass (*Agropyron* Gaertn. spp.) and other introduced perennials have been widely seeded to meet rehabilitation objectives of erosion control, weed suppression, and forage production on public lands administered by the US Department of the Interior, Bureau of Land Management (DOI-BLM) (Richards et al., 1998; Pyke et al., 2013; Knutson et al., 2014). However, policy shifts and expanded management objectives have led to the increased use of native species for postfire seeding on public lands (Pellant and Monsen, 1993; Richards et al., 1998; DOI-BLM, 2008; Leger and Baughman, 2015). Diverse plant communities containing native grasses, forbs, and shrubs are increasingly recognized as providing a broader range of resource values and ecosystem services than low-diversity crested wheatgrass stands (McAdoo et al., 1989; Pellant and Monsen, 1993; Christian and Wilson, 1999; Arkle et al., 2014). As demand has grown, collaborative efforts between government agencies and private growers have increased seed availability for many Great Basin plant species (Shaw et al., 2012).

The trend toward broader use of native plants in postfire seedings has been dampened by a mixed record of establishment success (Dalzell, 2004; Thompson et al., 2006; Wirth and Pyke, 2011; Knutson et al., 2014). Native plants often have less reliable establishment, especially in low-precipitation zones, compared with commonly seeded introduced perennials (Asay et al., 2001; Robins et al., 2013; Davies et al., 2015). Native perennials may also have lower competitiveness against exotic annuals (Harris and Wilson, 1970; Aguirre and Johnson, 1991; Davies et al., 2015), particularly in the seedling stage (Humphrey and Schupp, 2004; McGlone et al., 2011; Orloff et al., 2013). Addressing these issues requires strategies to improve the odds of native plant establishment, including careful selection of seeding technique (James and Svejcar, 2010; Madsen et al., 2013). In this paper we consider the effectiveness of rangeland drills for seeding native plants following fire.

Rangeland drills were initially designed for planting species that respond favorably to seed burial in furrows created by rotating disks (Hull, 1970; Young and McKenzie, 1982). Early rangeland drill-seedings were focused on introduced forage grasses (Young and McKenzie, 1982), although native grasses such as bluebunch wheatgrass (*Pseudoroegneria spicata* [Pursh] Á. Löve) and Indian ricegrass (*Achnatherum hymenoides* [Roem. & Schult.] Barkworth) have also been seeded using rangeland drills (Young et al., 1994; Thompson et al., 2006). Rangeland drill-seeding has been found to improve seedling establishment compared with aerial broadcasting, presumably because drill furrows capture water and seed burial enhances germination and survival (Hull, 1970; Nelson et al., 1970). However, seed losses due to suboptimal or irregular burial by drilling equipment have also been reported (Monsen and Stevens, 2004; Kees, 2006; James and Svejcar, 2010). Furthermore, standard drill-seeding techniques have been ineffective for species such as big sagebrush whose small seeds cannot tolerate deep seed burial (Jacobson and Welch, 1987; Boltz, 1994).

Some newer drill models have been designed to overcome limitations of older models with regard to seed placement and accommodation of smaller seeds. For example, the Truax Roughrider drill (Truax Co, Inc., 2015) uses hydraulic disk arms in combination with depth bands to modulate furrow depth and press wheels to cover seeds with a uniform amount of firmed soil (Monsen and Stevens, 2004; Truax Co, Inc., 2015). For small seeds, disks can be replaced with imprinter wheels that press seeds into the soil surface without creating a furrow (Monsen and Stevens, 2004; Truax Co, Inc., 2015), imitating cultipacker techniques previously found to be effective for seeding sagebrush (Boltz, 1994). By placing disks and imprinters in separate rows and using partitioned seed boxes, large and small seeds can be seeded simultaneously (Monsen and Stevens, 2004; Lambert, 2005). Drills possessing these features have been successfully used to seed Great Basin native plants (e.g., Hulet et al., 2010; Porensky et al., 2014, Brabec et al., 2015), but their effectiveness in comparison with conventional alternatives is poorly known. Conventional drill models might prove adequate for seeding native mixes if strategically modified (e.g., by retrofitting them with partitioned seed boxes and raising their disks above ground level to avoid creating furrows on small-seed rows). Furthermore, effects comparable with those of press wheels and imprinter wheels might be achieved using drag chains, a common feature of conventional rangeland drills (Monsen and Stevens, 2004; P & F Services, 2015).

Minimum-till drills, which use vertically oriented disks to create narrow furrows with minimal soil displacement (Truax Co, Inc., 2015), are potentially advantageous in postfire settings where conventional drills may damage residual perennial plants (Ratzlaff and Anderson, 1995; Knutson et al., 2014). Mechanical soil disturbance has been linked to soil erosion risks (Pierson et al., 2007; Ravi et al., 2011) and soil carbon loss (Kettler et al., 2000; Norton et al., 2012) but can be beneficial as a means of weed control (Stewart, 1950; Evans et al., 1970; Kettler et al., 2000). Some studies have suggested that exotic annuals can be reduced through the mechanical action of conventional rangeland drills (Stewart, 1950; Evans et al., 1970; Jessop and Anderson, 2007). However, the degree to which weed control benefits of conventional drills outweigh costs of damaging established perennials has not been closely examined.

We conducted an operational-scale experiment in Wyoming big sagebrush communities to 1) evaluate effectiveness of drill-seeding techniques for establishing diverse native seed mixes, 2) compare effects of different drill features on seeded plant establishment, and 3) assess impacts of conventional and minimum-till drills on exotic annuals and residual perennials following fire. On the basis of the expectation that equipment would function properly and conditions would be favorable for plant growth, we hypothesized that 1) seeded plant establishment would be higher in seeded treatments than nonseeded controls, 2) higher seeded plant establishment should correspond with lower abundance of exotic annuals, 3) drill features designed to improve seed placement (hydraulics, depth bands, press wheels) should lead to better establishment of large seeds in drill furrows, 4) imprinter wheels should improve establishment of small seeds relative to an alternative seed coverage technique involving drag chains; and 5) both residual native perennials and exotic annuals should have lower abundance when disturbed with the conventional drill compared with the minimum-till drill. Because the experiment was replicated across different sites and treatment years, we were able to examine the degree to which these hypotheses were supported under contrasting conditions.

Taylor et al. (2014) presented complementary results showing effects of experimental treatments on plant biomass and microbial community composition at one of our study sites. Additional comparisons of different sagebrush seeding rates and broadcast seeding at different dates will be presented in a companion paper.

Methods

Study Area

Treatments were installed in the fall following summer wildfires at three sites in the northern Great Basin: Mountain Home (2007), Scooby (2008), and Saylor Creek (2010) (Table 1). Sites were selected from accessible, relatively flat areas where fires had burned with sufficient intensity to consume most of the litter layer exposing mineral soil. The Mountain Home site had noticeable residual litter but nevertheless fit within the limits of our site selection criteria. On the basis of evidence from burn halos and charred shrub remains, as well as sagebrush-dominated vegetation in nearby unburned areas, we inferred that these sites had been occupied by mature sagebrush stands before burning. We focused on sites that have been formally assigned to Wyoming

Table 1
Attributes of postfire seeding study sites in the northern Great Basin

	Mountain Home	Scooby	Saylor Creek
Location	42°58'42"N, 115°37'57"W	41°51"16"N, 113°2'46"W	42°39'43"N, 115°28'18"W
County, state	Elmore, ID	Box Elder, UT	Elmore, ID
Wildfire date	6 July 2007	22 September 2008	29 June 2010
Seeding date	29-30 October 2007	18-19 November 2008	27-28 October 2010
Elevation	911 m	1 422-1 475 m	1 204 m
Ecological site name[1]	LOAMY 8-12" ARTRW8/PSSPS-ACTH7	Semidesert Gravelly Loam (Wyoming Big Sagebrush) North; Semidesert Sandy Loam (Wyoming Big Sagebrush)	LOAMY 8-12" ARTRW8/PSSPS-ACTH7; SLICKSPOT-SODIC 8-14" ARTRW8/ACTH7
Soil map unit[1]	Scism silt loam, 0-4% slopes	Hiko Peak-Sheeprock-Rock outcrop association, 3-25% slopes	Purdam-Sebree-Owsel complex, 0-8% slopes
Soil classification[1]	Coarse-silty, mixed, mesic Haploxerollic Durorthids	Loamy-skeletal, mixed, mesic Xerollic Calciorthids; sandy-skeletal, mixed, mesic Xeric Torriorthents	Fine-silty, mixed, mesic Haploxerollic Durargids, Durixerollic Haplargids, and Xerollic Natridurids

[1] USDA-NRCS Web Soil Survey (2015).

big sagebrush community types (see Table 1) (USDA-NRCS Web Soil Survey, 2015). Site elevations range from 911 to 1 475 m, and soils are composed of silty, loamy, and sandy aridisols and entisols (see Table 1). Sites are located on BLM allotments designated for winter/early spring cattle grazing, although grazing in the immediate vicinity of each site has reportedly been moderate to absent in recent years (Carl Rudeen, personal communication; Danelle Ostolasa-Mendiola, personal communication; Dylan Tucker, personal communication). Perimeter fences were installed around each site to exclude livestock but not wild ungulates during the course of the experiment.

Baseline soil chemistry and texture were determined from 12.5-cm cores taken from each site (Table 2). Soils at Mountain Home were relatively high in N and P but low in K and clay; Scooby had relatively high K, pH, and cation-exchange capacity (CEC) but low P; and Saylor Creek had relatively low N and CEC and a high percentage of silt and clay compared with sand (see Table 2).

Interpolated weather data obtained for the 2-yr study period at each site (Wang et al., 2012; CFCG, 2014) revealed site-specific precipitation (Fig. 1) and temperature patterns that frequently deviated from 30-yr normals. Annual precipitation (from October to September) during the year of seeding was 127 mm at Mountain Home, 259 mm at Scooby, and 285 mm at Saylor Creek; 30-yr normals for these sites were 219 mm, 223 mm, and 248 mm, respectively. Monthly precipitation was below average at Mountain Home during nearly all months of the study period (see Fig. 1). Monthly precipitation was near average at Scooby during the winter and early spring following seeding (November 2008 to April 2009) and then spiked to 73 mm (292% above average) in June 2009, followed by mostly below-average precipitation through the spring of 2010 (see Fig. 1). Scooby also had lower temperatures and more precipitation as snow during the study period compared with other sites (data not shown). At Saylor Creek, precipitation was near or above average during most months of the study, including peaks exceeding 180% of normal in December and May of the first year (2010 — 2011) and January of the second year (2012) (see Fig. 1).

Table 2
Soil properties at postfire seeding study sites in the northern Great Basin (see Table 1). Means are followed by ranges in parentheses

	Mountain Home	Scooby	Saylor Creek
Sand (%)	42 (32-64)	35 (9-54)	11[1]
Silt (%)	44 (28-56)	38 (15-73)	54[1]
Clay (%)	14 (6-16)	28 (13-42)	35[1]
N (ppm)	27 (9-49)	13 (6-22)	8 (4-22)
K (ppm)	362 (176-512)	561 (315-1092)	409 (304-560)
P (ppm)	35 (14-75)	10 (5-14)	20 (12-27)
CEC	13.7 (5.3-21.7)	14.8 (11.4-19.2)	12.5 (5.9-17.9)
pH	7.4 (6.9-8.0)	8.2 (8-8.5)	7.5 (6.8-8.1)
OM (%)	2.1 (1.3-3.2)	2.1 (0.9-3.4)	2.1 (1.2-3.2)

[1] Soil texture was determined from one composite sample at Saylor Creek.

Experimental Treatments

The experimental design was a randomized complete block with treatments allocated to 30 × 70 m plots within each of five blocks at each site. Treatments included rangeland drill-seedings plus nonseeded control treatments where drilling was carried out with empty seed boxes (mimicking failed seedings), as well as a nondrilled/nonseeded control (Table S1; available online at doi:10.1016/j.rama.2016.05.001). Drill rows were parallel to the long axis of each plot. Plots were separated by 3.05-m wide buffer strips that were drill-seeded with a mix containing Anatone bluebunch wheatgrass and "Rimrock" Indian ricegrass. We seeded the buffer strips to reduce their likelihood of becoming corridors for movement of invasive annuals into study plots.

Drilling treatments were applied using two drill models, a Kemmerer rangeland drill from P & F Services, Kemmerer, Wyoming (P & F Services, 2015), and a Roughrider minimum-till drill from Truax Co, Inc., New Hope, Minnesota (Truax Co, Inc., 2015), hereafter "conventional drill" and "minimum-till drill," respectively (Fig. 2). Both drills had 10 seed drops with accompanying boxes for dispensing separate seed mixes in rows spaced 30.5 cm apart. A mix containing large seeds (drill mix) was drill-seeded in five rows, alternating with five rows where small seeds were broadcast onto the soil surface (broadcast mix). Disks were removed (minimum-till drill) or raised (conventional drill) in broadcast rows so that these rows lacked furrows. The minimum-till drill had 50.8-cm diameter disks with 45.7-cm diameter depth bands, resulting in an expected seeding depth of 2.5 cm. Hydraulic controls on the minimum-till drill were adjusted to provide sufficient pressure to penetrate soils encountered at each site. Press wheels and wire-loop drags installed behind disks on the minimum-till drill were used to enhance seed-soil contact and seed burial in drill rows, while patterned imprinter wheels were used to enhance seed-soil contact in broadcast rows (see Fig. 2). Disks of the conventional drill had a diameter of 50.8 cm and lacked depth bands. The conventional drill used drag chains on both drill and broadcast rows (see Fig. 2) but did not have press wheels or imprinter units. Broadcasting from the conventional drill was accomplished by pulling the seed tube from the disk assembly and installing aluminum pipes 165 cm long and 7.6 cm in diameter to channel seeds closer to the soil surface (see Fig. 2).

Seed mixes were formulated to match site conditions and seed availability from commercial sources (Table 3). Rice hulls were added to both the drill and broadcast mixes to maintain seeds of different weights, prevent bridging, and simplify drill calibration (St. John et al., 2005). Within sites, identical seed mixes and seeding rates were used

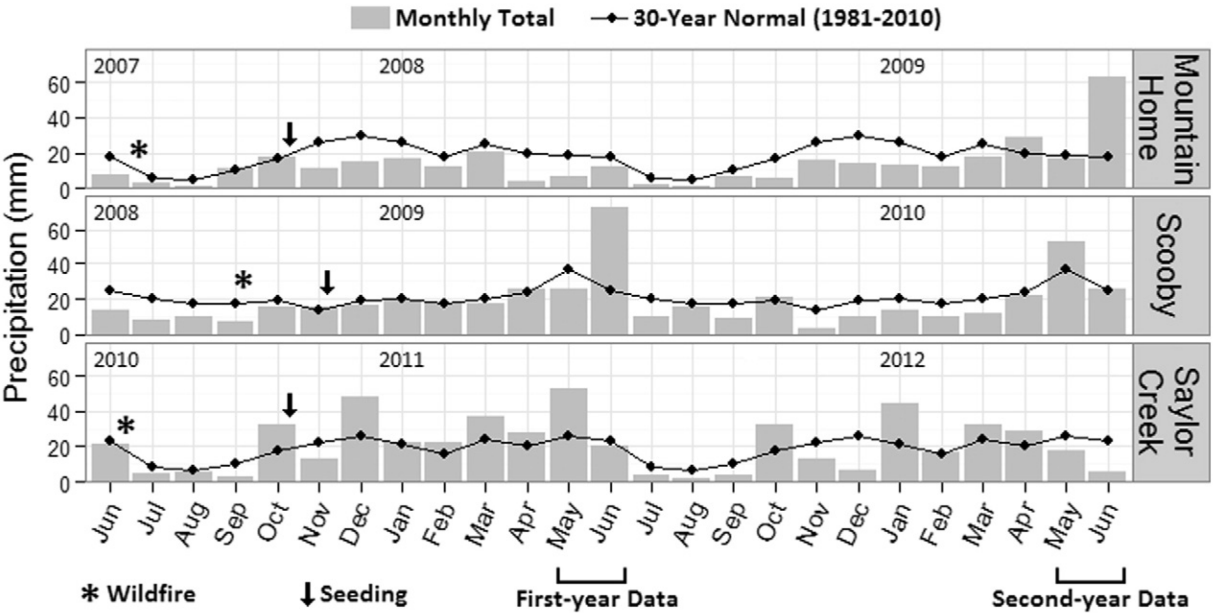

Figure 1. Monthly precipitation at study sites in the northern Great Basin spanning the time of wildfire through second-year data collection.
Source: CFCG (2014).

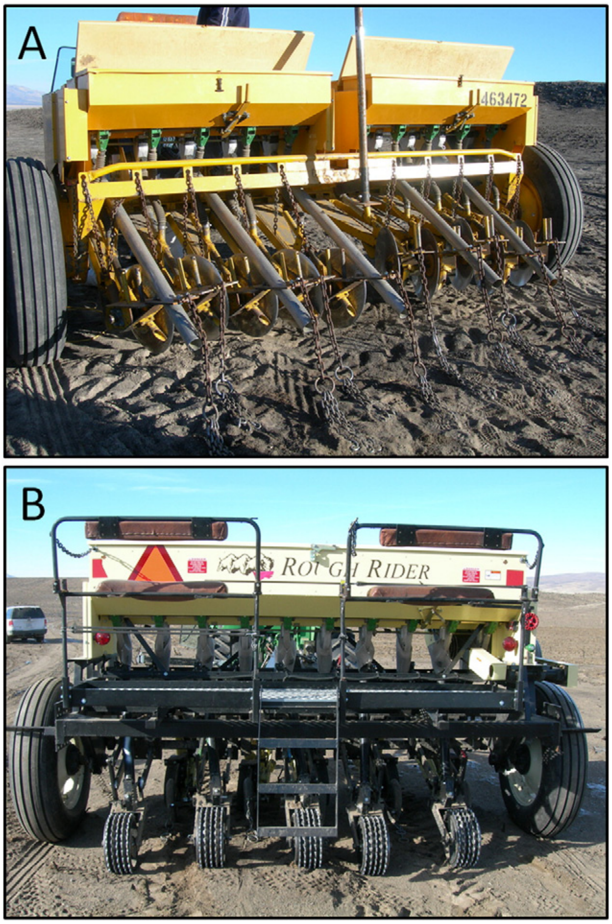

Figure 2. Photos of rangeland drills used for postfire seeding at study sites in the northern Great Basin. A, Conventional drill (P & F Services Kemmerer) with aluminum pipes installed on alternate rows. B, Minimum-till drill (Truax Roughrider) with imprinter wheels installed on alternate rows.

with each drill type. Seeding rates roughly followed standard recommendations listed by Lambert (2005) except for Wyoming big sagebrush, which was seeded at approximately 1, 5, and 10 times the standard recommendations in separate plots (see Table 3). Each block contained one plot for each sagebrush seeding rate for each drill type (six drill-seeded plots total per block; see Table S1).

Data Collection and Analysis

Vegetation data were collected at each site from May to June of the first 2 yr following seeding using protocols modified from Herrick et al. (2005) and Wirth and Pyke (2007). Five 20-m transects were established 10 m apart, perpendicular to the long axis of each plot. Density of seed-mix species was recorded in each of four quadrats along each transect. We used 0.5 m^2 (0.5 × 1 m) quadrats except at Saylor Creek, where 1.0 m^2 (1 × 1 m) quadrats were used the first year. Quadrats were placed along transects at 6-m intervals beginning at a randomly selected starting point and were adjusted so that each quadrat always included exactly two drill rows and two broadcast rows. Foliar cover by species (seed-mix species plus others) was recorded by line point intercept at 20 points along each transect, with a random starting point followed by additional points at 1-m intervals. Starting points were re-randomized during the second year of data collection.

Density and cover values were summed across quadrats or points within plots before analysis. Summed density counts from 1.0-m^2 quadrats (Saylor Creek Yr 1) were divided by two so that density unit area would match 0.5-m^2 quadrats. Cover was analyzed as the percentage of points within a plot striking a given species or group. Indian ricegrass, Thurber needlegrass (*Achnatherum thurberianum* [Piper] Barkworth), and needle-and-thread (*Hesperostipa comata* [Trin. & Rupr.] Barkworth) could not readily be differentiated during the first year at Saylor Creek and were merged for that year. New seedlings and residual adult plants were treated separately in density analyses for the first year but not the second year when they became difficult to distinguish.

Using density data for seeded species, we calculated species diversity and life form diversity within each plot, thereby quantifying the degree to which the seeded communities attained full and equal representation of seed mix components. Seeded species were placed in four life form categories: shallow-rooted grasses, deep-rooted grasses, forbs, and shrubs (see Table 3). We used the inverse of Simpson's Index (Krebs, 1999) to quantify diversity using the "Vegan" package in R (R Core Team, 2012).

Density, cover, and diversity were analyzed at one or both of two tiers of statistical tests. Both tiers employed the GLIMMIX and LSMEANS procedures in SAS 9.3 (SAS Institute, Inc., 2011) to implement statistical tests and estimate means and standard errors. We used the negative binomial as the reference distribution for density, the beta distribution for cover, and the Gaussian distribution for diversity. Cover values were transformed by adding 0.001 to each value (to remove zeros) and then back-transformed following analysis.

Our first tier of statistical tests compared seeded (seeding) and nonseeded (control) treatments across sites and years, implemented by grouping original treatments into these two classes (see Table S1). By focusing on seeding effects, averaged across other treatment variables, we highlighted differences in seeding efficacy arising from differing site conditions. Seeding analyses were carried out for five plant cover groups (drill-mix species, broadcast-mix species, non-seed-mix perennials, cheatgrass, and exotic annual forbs), two plant density groups (drill-mix species, broadcast-mix species), and the two diversity measures described earlier. Note that drill-mix and broadcast-mix labels were applied to all encountered individuals of species in Table 3, irrespective of whether they actually originated from the mixes. We tested main effects and three-way interactions of treatment (seeding vs. control), year (1 vs. 2), and site. Block interactions with these three fixed effects were included as random effects only if their variance estimates were higher than the error variance for a given model. Tukey's HSD was used for mean separation at $P < 0.05$.

Our second tier of statistical tests examined effects of drilling (drilled vs. nondrilled) and drill type (conventional versus minimum-till) within the treatment classes used in our first tier. Analyses were carried out as independent contrasts within each combination of site, year, and seeding treatment (seedings and controls) to detect where and when drilling and drill-type differences resulted in different amounts of density or cover for a given species or group. Contrasts comparing drilled versus nondrilled treatments were applicable only within the controls, whereas drill-type comparisons were applicable within both controls and seedings (see Table S1). When comparing drill types within seedings, we used plots representing all three sagebrush seeding rates and thereby averaged out sagebrush seeding rate effects (see Table S1). We were able to ignore sagebrush seeding rate in these analyses because plots with different rates were distributed in equal proportions in the two drill types, and these plots did not differ with respect other species' seeding rates (see Table 3).

Results

Seeding, Site, and Year Effects

Analyses comparing seeding and control treatments across sites and years revealed significant effects of treatment, site, year, and treatment × site × year for most species groups analyzed. The non-seed-mix perennial cover group was an exception that had a significant site effect only. Differences between treatment × site × year combinations obtained from these analyses are depicted in Figs. 3 to 5.

Density and Diversity of Seed-Mix Species

Within the first year, drill-mix species established in the seeding treatment with densities of 23 plants m^{-2} at Scooby, 13 plants m^{-2} at Mountain Home, and 12 plants m^{-2} at Saylor Creek (Fig. 3). Drill-mix densities in the seeding treatments remained stable between the first and second year at Scooby but decreased at the other two sites (see Fig. 3). Drill-mix species were nearly absent from the control

Table 3

Seed mixes and seeding rates applied at postfire seeding study sites in the Northern Great Basin (see Table 1). Nomenclature follows USDA-NRCS Plants (2013)

Species (life form[2])	Cultivar/germplasm	Seeding rate[1]		
		Mtn. Home	Scooby	Saylor Creek
Drill mix				
Bluebunch wheatgrass, *Pseudoroegneria spicata* (G1)	Anatone germplasm	67	67	60
Squirreltail, *Elymus elymoides* (G1)	Toe Jam Creek germplasm	47	47	–
	Emigrant germplasm	–	–	35
Indian ricegrass, *Achnatherum hymenoides* (G1)	"Rimrock"	51	51	50
Thurber's needlegrass, *Achnatherum thurberianum* (G1)	Snake River Plain—pooled	–	–	30
Needle-and-thread, *Hesperostipa comata* (G1)	Millard Co, UT	–	–	20
Munro's globemallow, *Sphaeralcea munroana* (F)	Utah Co, UT (1 470 m)	93	–	–
	Uintah Co, UT (1 550 m)	–	93	40
Sulphur-flower buckwheat, *Eriogonum umbellatum* (F)	Northern Great Basin—pooled	8	11	–
Basalt milkvetch, *Astragalus filipes* (F)	Deschutes Co, OR (1 330 m)	–	–	14
Broadcast mix				
Sandberg bluegrass, *Poa secunda* (G2)	Mountain Home germplasm	91	91	100
Western yarrow, *Achillea millefolium* (F)	Eagle germplasm	–	100	100
Scabland penstemon, *Penstemon deustus* (F)	Northern Great Basin—pooled	76	–	–
Blue penstemon, *Penstemon cyaneus* (F)	Lincoln Co, ID (1370 m)	–	76	–
Royal penstemon, *Penstemon speciosus* (F)	Northern Great Basin—pooled	–	–	15
Rubber rabbitbrush, *Ericameria nauseosa* (S)	Uinta Co, WY (2 060m)	86	–	–
	Sanpete Co, UT (1 460 m)	–	86	–
	Utah Co, UT (1 650 m)	–	–	85
Wyoming big sagebrush, *Artemisia tridentata* ssp. *wyomingensis* (S)	Lincoln/Blaine/Jerome Co, ID (1 230 m)	1X[3]: 52	–	–
		5X: 262	–	–
		10X: 525	–	–
	Sanpete Co, UT (1 460 m)	–	1X[3]: 52	–
		–	5X: 234	–
		–	10X: 495	–
	Power Co, ID (1 390 m)	–	–	1X[3]: 50
		–	–	5X: 250
		–	–	10X: 500

[1] Seeding rate in pure live seed (PLS) m^{-2}.

[2] Life forms: F indicates forb; G1, deep-rooted perennial grass; G2, shallow-rooted perennial grass; S, shrub.

[3] Wyoming big sagebrush was seeded at three different rates (1X, 5X, 10X), each rate applied in an equal number of plots at each site.

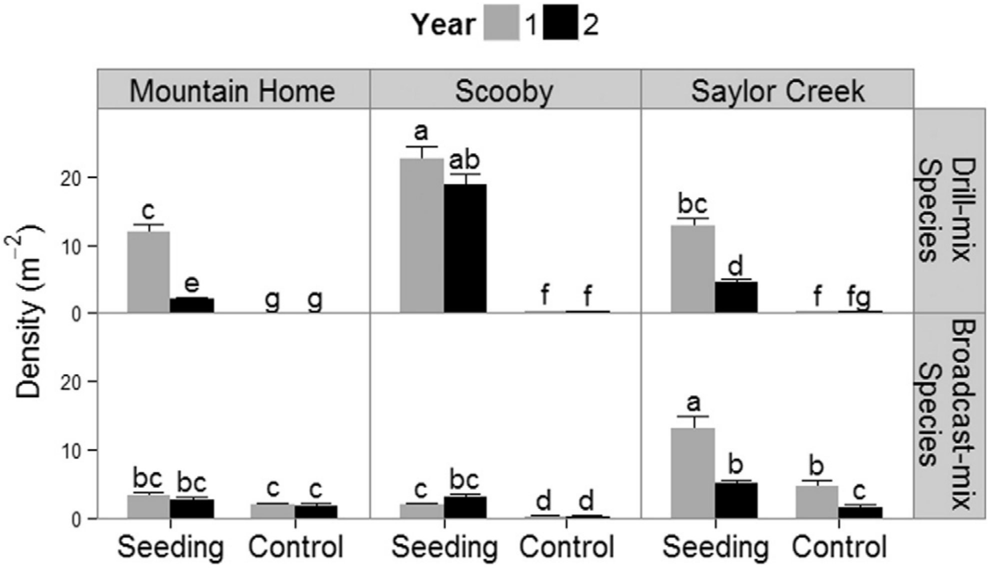

Figure 3. Density by site, treatment, and postfire year for seed-mix species groups at three study sites in the northern Great Basin (see Table 1). Density values for drill-mix and broadcast-mix groups include all species in respective seed mixes (see Table 3) regardless of whether individuals encountered were actually seeded. Bars are means; error bars are standard errors. Within groups (horizontal panels), means with the same letter are not significantly different ($P < 0.05$).

treatments at all three sites, although broadcast-mix species (primarily residual Sandberg bluegrass) were present in control treatments at Saylor Creek and Mountain Home (see Fig. 3). At Mountain Home, broadcast-mix density in the seeding treatment was not significantly higher than the control (see Fig. 3). Broadcast-mix density was highest at Saylor Creek in Yr 1 (13 plants m^{-2}) but decreased to the level of the other sites by Yr 2 (5 plants m^{-2}) (see Fig. 3).

Species and life form diversity of seed mix species differed by site and treatment but were otherwise stable across years (Fig. 4). Both measures of diversity attained their highest value in the seeding treatment at Saylor Creek (see Fig. 4).

Cover by Species Group

Cover patterns of the seed-mix groups (Fig. 5) were similar to density patterns (see Fig. 3) except that cover increased between years in some instances. Drill-mix cover in the seeding treatment increased to 41% at Scooby and 24% at Saylor Creek by Yr 2 (see Fig. 5). At Mountain Home, drill-mix cover remained at low levels (<3%) in both seeding and control treatments during both years (see Fig. 5). Broadcast-mix cover did not differ between treatments within sites or within treatments across sites during the first year (see Fig. 5). At Scooby and Mountain Home, broadcast-mix cover did not change significantly between years (see Fig. 5). At Saylor Creek, however, broadcast-mix cover increased in both treatments and was higher in the seeding treatment (22%) than the control (13%) by Yr 2 (see Fig. 5).

Perennial species beyond those included in the seed mixes were relatively uncommon, but those encountered were composed of native species such as western wheatgrass (*Pascopyrum smithii* [Rydb.] Á. Löve), yellow rabbitbrush (*Chrysothamnus viscidiflorus* [Hook.] Nutt.), and Nevada onion (*Allium nevadense* S. Watson). Cover of non-seed-mix perennials did not differ between treatments or years within sites, but the site mean at Saylor Creek (3%) was slightly higher than

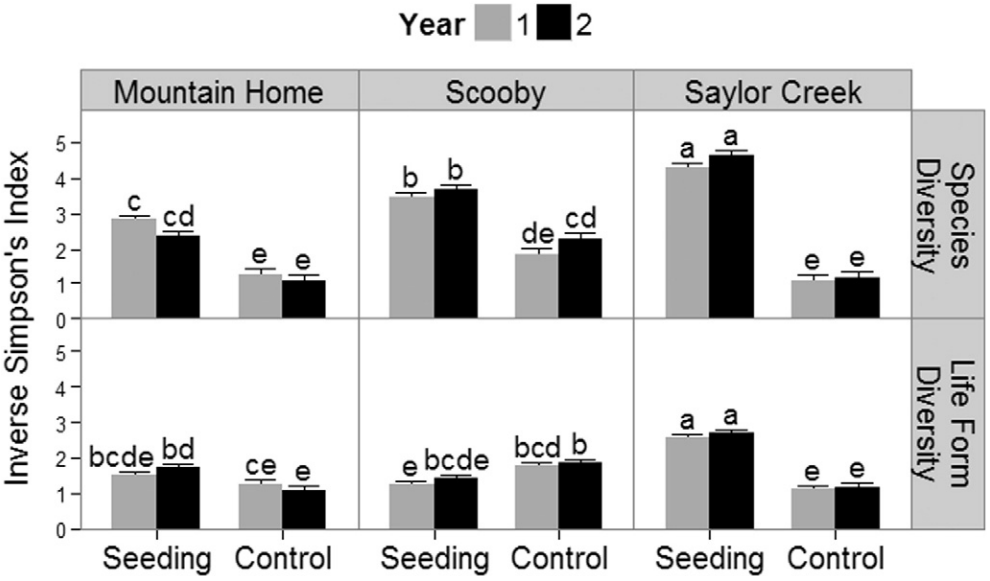

Figure 4. Community diversity by site, treatment, and postfire year at three study sites in the northern Great Basin (see Table 1). Diversity values are based on measured densities of species/life forms included in seed mixes (see Table 3) regardless of whether individuals encountered were actually seeded. Bars are means; error bars are standard errors. Within diversity types (horizontal panels), means with the same letter are not significantly different ($P < 0.05$).

Mountain Home (1%) and the site mean at Scooby (2%) did not differ from either (see Fig. 5).

Cheatgrass cover did not differ between seeding and control treatments within sites during Yr 1 but was higher at Mountain Home (averaging ca. 29% across treatments) than at the other sites (<5%) (see Fig. 5). By the second year, cheatgrass cover had approximately doubled at Mountain Home to ca. 60%, while Saylor Creek was not far behind at ca. 49% due to a proportionally large increase relative to its first-year cover (see Fig. 5). At Scooby, cheatgrass cover increased to 18% in the control treatment by Yr 2 but remained near first-year levels of 5% in the seeding treatment, resulting in a significant difference between treatments by the second year (see Fig. 5).

Cover patterns of exotic annual forbs (see Fig. 5) were driven primarily by four species: tumblemustard (*Sisymbrium altissimum* L.), tansymustard (*Descurainia sophia* [L.] Webb ex Prantl), Russian thistle (*Salsola tragus* L.), and halogeton (*Halogeton glomeratus* [M. Bieb.] C.A. Mey.). First-year cover of exotic annual forbs did not differ between treatments within sites but differed by site: highest at Mountain Home (ca. 36%), lowest at Saylor Creek (ca. 1%), and intermediate at Scooby (ca. 5%) (see Fig. 5). Exotic annual forb cover did not change significantly between years except in the control treatments at Saylor Creek (1% in Yr 1 to 12% in Yr 2) and Scooby (5% in Yr 1 to 39% in Yr 2) (see Fig. 5). Because of increases in control treatments, exotic forb cover differed significantly between seeding and control treatments at Saylor Creek and Scooby by Yr 2 (see Fig. 5).

Drilling and Drill-Type Effects

Statistical tests comparing conventional and minimum-till drilling treatments within seedings revealed the relative effectiveness of the two drill types for establishing seed-mix species. Analogous tests comparing drill types or drilling treatments (drilled vs. nondrilled) within nonseeded controls were designed to show effects of differing levels of drill-induced soil disturbance on residual perennials and exotic annuals, independent of the effects of the seed-mix species. However, the raw effects of drilling on residual perennials and exotic annuals were evident even within seeding treatments, especially at Mountain Home, where seeded plant establishment was low. Furthermore, tests involving seeding treatments had greater statistical power because of the greater number of experimental plots (see Table S1). For these reasons, we focus primarily on results from statistical tests applied within seeding treatments (Tables 4 and 5), while secondarily referring to control treatment test results available as supplementary material (Tables S2, S3; available online at doi:10.1016/j.rama.2016.05.001).

Seeded Species

Seed-mix species frequently had similar density and cover when seeded with the minimum-till drill compared to the conventional drill (Tables 4 and 5). However, significant differences between drill types were also detected, mostly at Saylor Creek and Scooby. In cases where significant differences were detected, density and cover tended to be higher in the conventional drill treatment for drill-mix species and higher in the minimum-till treatment for broadcast-mix species (Tables 4 and 5).

Each drill-mix species except basalt milkvetch showed evidence of differences in establishment due to drill type, at least in site-specific or year-specific cases. Indian ricegrass density and cover were consistently higher in the conventional than minimum-till treatment at Saylor Creek during both years; the same was true for Indian ricegrass density but not cover at Scooby (see Tables 4 and 5). The largest drill-type differences of any seeded species were attained by Indian ricegrass at Saylor creek, where first-year densities (which included minor amounts of Thurber's needlegrass and needle-and-thread) differed by 5 plants m^{-2} (see Table 4) and second-year cover differed by 8% (see Table 5). Bluebunch wheatgrass, squirreltail, Thurber's needlegrass, needle-and-thread, and Munro's globemallow also had significantly higher cover and/or density in the conventional drill treatment at Saylor Creek one or both years (see Tables 4 and 5). Higher establishment with the conventional drill was observed at Mountain Home for first-year cover of bluebunch wheatgrass (see Table 5) and second-year densities of bluebunch wheatgrass, squirreltail and Indian ricegrass (see Table 4). On the other hand, the opposite pattern (higher establishment with minimum-till) was observed at Scooby for squirreltail (see Table 5) and sulphur-flower buckwheat (see Table 4).

Most species in the broadcast-mix group had higher seedling densities in the minimum-till than conventional drill treatments during one or both years at Saylor Creek and Scooby (see Table 4). Cover of these species also differed between drill types at these sites, but the differences were only statistically significant for western yarrow and total broadcast-mix cover (see Table 5). At Mountain Home, broadcast-mix density and cover differed by drill type in only two cases, both during the first year: Wyoming big sagebrush density was higher in minimum-till while Sandberg bluegrass (seedling) density was higher in the conventional drill treatment (see Table 4).

Residual Perennials

Residual perennials generally did not differ in abundance between drill types (conventional vs. minimum-till; see Tables 4, 5, and S2) or drilling treatments (drilled vs. nondrilled; Table S3), but in cases where differences were detected they were always more abundant in treatments characterized by lower soil disturbance (i.e., nondrilled and minimum-till). Residual squirreltail had higher Yr 2 cover in the nondrilled/nonseeded treatment than the drilled/nonseeded treatment at Scooby (see Table S3). Yr 1 density of residual Sandberg bluegrass was higher in the minimum-till than conventional drill treatment in seedings at Saylor Creek (see Table 4). Although residual Sandberg bluegrass was not differentiated from new seedlings in Yr 2, residuals may partly account for the higher Sandberg bluegrass density in the minimum-till treatment at Saylor Creek that year (see Table 4). Sandberg bluegrass residuals may have also contributed to the high Yr 2 broadcast-mix species cover in the minimum-till treatment at Saylor Creek (see Table 5).

Exotic Annuals

Drill-type effects on exotic annuals were readily apparent at Mountain Home, where first-year cover values of cheatgrass and tumblemustard were, respectively, 9% and 16% higher in the minimum-till than conventional drill-seeded treatment (see Table 5). By the second year, tumblemustard and cheatgrass cover at Mountain Home no longer differed significantly between drill types (see Table 5). Russian thistle showed the opposite pattern, with higher cover in the conventional drill treatment (see Tables 5 and S2), as well as higher cover in drilled than nondrilled treatments during Yr 1 (see Table S3).

At Scooby and Saylor Creek, significant differences in exotic annual cover between drill types and drilling treatments were limited to a few cases in Yr 2 only (see Tables 5, S2, and S3). These cases showed that cheatgrass and tumblemustard had higher cover in lower-disturbance treatments (minimum-till drill and non-drilled) while tansymustard cover was higher in higher-disturbance treatments (conventional drill and drilled) (see Tables 5, S2, S3).

Discussion

Seeding Effectiveness by Site and Year

Postfire seeding success is commonly judged by how quickly seeded plants establish with sufficient density and cover to stabilize the soil and suppress invasive weeds (Pyke et al., 2013). Increasingly, restoration of native plant diversity is also a criterion for success. Assessments of seeding success can be difficult because of complicating details: Seeded plants may have delayed germination and require multiple years to reach maturity, nonseeded residual perennials can contribute to postfire recovery (Ratzlaff and Anderson, 1995; Wirth and Pyke, 2011),

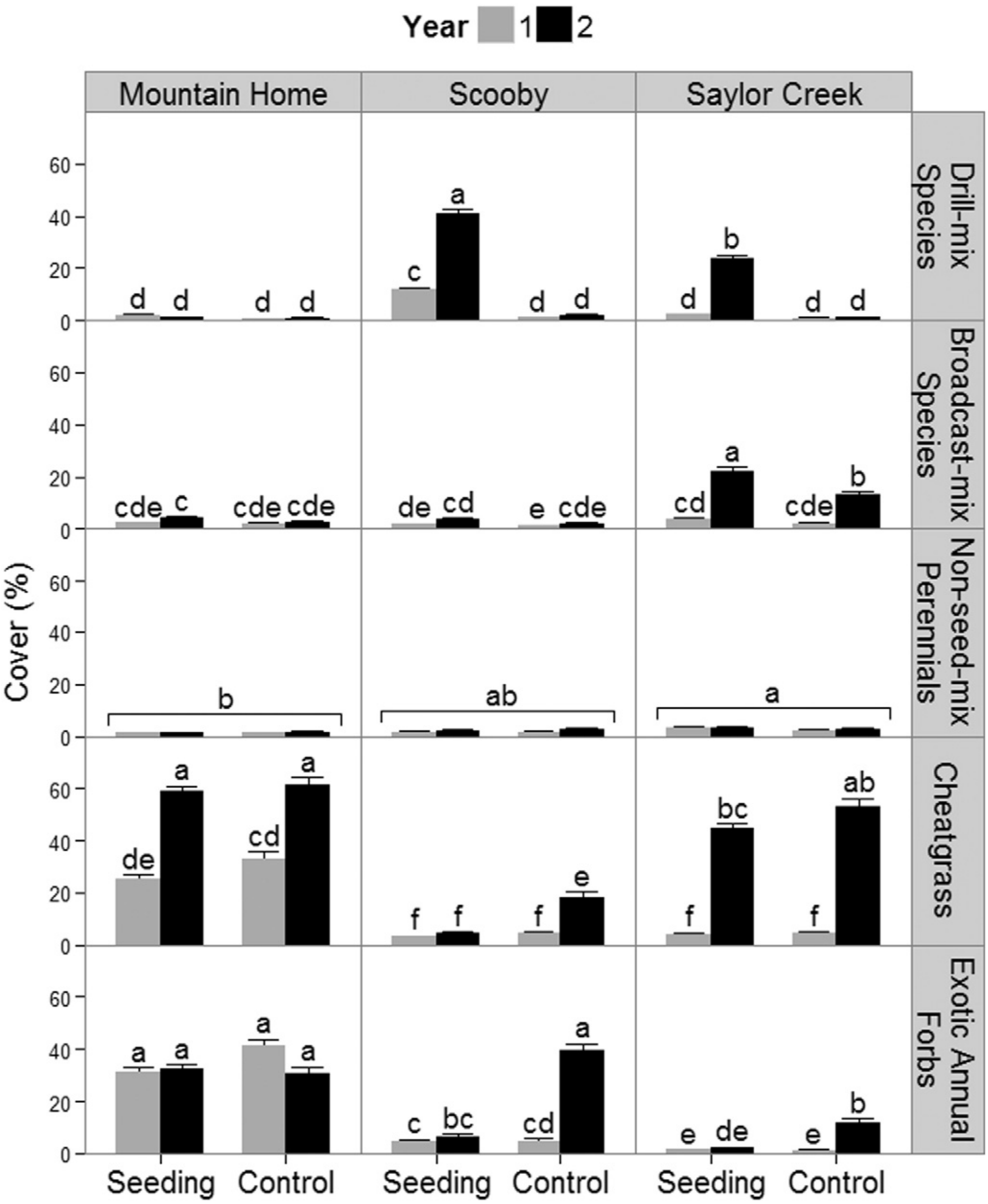

Figure 5. Foliar cover by site, treatment, and postfire year for plant species groups at three study sites in the northern Great Basin (see Table 1). Cover values for drill-mix and broadcast-mix groups include all species in respective seed mixes (see Table 2) regardless of whether individuals encountered were actually seeded. Bars are means; error bars are standard errors. Within groups (horizontal panels), means with the same letter are not significantly different ($P < 0.05$).

invasive annuals can contribute to soil stability (Pierson et al., 2007; Miller et al., 2012), and soil disturbance associated with seeding treatments can impact erodibility (Brown et al., 1985; Pierson et al., 2007), residual perennials (Ratzlaff and Anderson, 1995), and weed establishment (Evans et al., 1970; Jessop and Anderson, 2007). Our results suggest that objectives of reestablishing perennial cover, suppressing exotic annuals, and restoring native plant diversity may or may not be achievable during the first 2 yr following fire and seeding, depending on site conditions.

A combination of drought conditions and competition from exotic annuals likely contributed to low seeding success at Mountain Home. Although drill-mix species had promisingly high densities at Mountain Home during the first year, they experienced high mortality between the first and second years and had minimal cover during both years. Density and cover of broadcast-mix species were also minimal, while exotic annual cover was high even during the first year at Mountain Home. Exotic annuals were probably abundant in the prefire understory, and the fire at Mountain Home may have burned with lower intensity than the other sites, leaving sufficient seed for cheatgrass and other exotic annuals to regain dominance within one growing season. The site also had relatively high levels of soil nitrogen, which could have further favored cheatgrass over perennial seedlings (Beckstead and Augspurger, 2004; Orloff et al., 2013).

Conditions at the Scooby site, including anomalously high precipitation during the first summer, proved favorable for the drill-mix grasses that established with high cover and density during the first year and did not decline significantly between years (see also Taylor et al., 2014). In the first year, drill-seeded grasses at Scooby exceeded the 5 plants m^{-2} density threshold suggested by Lambert (2005) and Boyd and Davies (2012) as a measure of seeding success, and by the second year these grasses had sufficient cover to suppress cheatgrass and exotic annual forbs. Scooby thus demonstrated successful achievement of perennial establishment and weed suppression objectives, although the objective of restoring plant diversity was less successful due to limited establishment of broadcast-mix species and drill-mix forbs. Low establishment of the latter groups could have been due to competition from

Table 4

Density of plants m^{-2} (mean ± standard error) of seed-mix species in treatments seeded using a conventional drill (conv.) or minimum-till drill (min.-till) at three sites (see Table 1) and 2 postfire years. Wherever the difference between conv. and min.-till for a given species, site and year was significant ($P < 0.05$), values are shown in bold and the higher value is indicated with underlined text

	Mountain Home		Scooby		Saylor Creek	
	conv.	min.-till	conv.	min.-till	conv.	min.-till
Yr 1						
Drill mix						
Bluebunch wheatgrass (seedl.)[1]	6.7 ± 0.8	5.4 ± 0.6	8.6 ± 1.1	7.3 ± 0.9	5.5 ± 0.6	3.9 ± 0.5
Squirreltail (resid.)	0	0	0	0	0.1 ± < 0.1	0.1 ± < 0.1
Squirreltail (seedl.)	4.2 ± 0.7	4.8 ± 0.8	7.8 ± 0.8	7.0 ± 0.7	**2.2 ± 0.9**	**1.6 ± 0.7**
Indian ricegrass[2] (seedl.)	1.3 ± 0.2	1.3 ± 0.2	**9.1 ± 0.7**	**4.3 ± 0.4**	**7.5 ± 0.8**	**2.5 ± 0.3**
Munro's globemallow (seedl.)	0	<0.1	0.4 ± 0.1	0.5 ± 0.1	0.4 ± 0.1	0.2 ± < 0.1
Sulphur-flower buckwheat (seedl.)	0.2 ± < 0.1	0.2 ± 0.1	0.1 ± 0.1	0.1 ± < 0.1	Not seeded	Not seeded
Basalt milkvetch (seedl.)	Not seeded	Not seeded	Not seeded	Not seeded	0.3 ± 0.1	0.3 ± 0.1
Broadcast mix						
Sandberg bluegrass (resid.)	1.1 ± 0.6	1.2 ± 0.7	0	0	**4.3 ± 0.6**	**7.7 ± 1.1**
Sandberg bluegrass (seedl.)	**1.4 ± 0.3**	**0.4 ± 0.1**	**0.4 ± 0.1**	**1.0 ± 0.2**	2.2 ± 0.2	2.7 ± 0.3
Western yarrow (seedl.)	Not seeded	Not seeded	**0.4 ± 0.1**	**1.2 ± 0.2**	**1.0 ± 0.2**	**2.0 ± 0.4**
Penstemon[3] (seedl.)	<0.1	<0.1	<0.1	0.1 ± < 0.1	1.4 ± 0.2	1.5 ± 0.2
Wyoming big sagebrush (seedl.)	**0.2 ± 0.1**	**0.7 ± 0.2**	0.1 ± 0.1	0.3 ± 0.1	**0.7 ± 0.2**	**2.0 ± 0.6**
Rubber rabbitbrush (seedl.)	<0.1	<0.1	<0.1	0.2 ± 0.1	0.3 ± 0.1	0.3 ± 0.1
Yr 2						
Drill mix						
Bluebunch wheatgrass	**1.3 ± 0.3**	**0.7 ± 0.2**	8.3 ± 1.7	7.6 ± 1.5	2.3 ± 0.5	2.1 ± 0.5
Squirreltail	**0.6 ± 0.1**	**0.3 ± 0.1**	4.2 ± 0.3	5.1 ± 0.4	0.7 ± 0.1	0.5 ± 0.1
Indian ricegrass	**0.7 ± 0.1**	**0.2 ±** < **0.1**	**6.4 ± 0.5**	**3.7 ± 0.3**	**1.5 ± 0.2**	**0.3 ± 0.1**
Thurber's needlegrass	Not seeded	Not seeded	Not seeded	Not seeded	**0.1 ±** <**0.1**[4]	**0.1 ±** <**0.1**[4]
Needle-and-thread	Not seeded	Not seeded	Not seeded	Not seeded	**0.3 ±** <**0.1**	**0.1 ±** <**0.1**
Munro's globemallow	0	0	0.4 ± 0.1	0.7 ± 0.1	**0.2 ±** < **0.1**	**0.1 ±** < **0.1**
Sulphur-flower buckwheat	0	<0.1	<**0.1**	**0.1 ±** < **0.1**	Not seeded	Not seeded
Basalt milkvetch	Not seeded	Not seeded	Not seeded	Not seeded	0.1 ± < 0.1	0.1 ± < 0.1
Broadcast mix						
Sandberg bluegrass	2.4 ± 0.7	2.1 ± 0.6	**0.6 ± 0.1**	**1.0 ± 0.2**	**2.1 ± 0.3**	**3.6 ± 0.5**
Western yarrow	Not seeded	Not seeded	0.9 ± 0.2	2.8 ± 0.6	**0.5 ± 0.1**	**0.9 ± 0.2**
Penstemon[3]	0	0	**0.1 ±** < **0.1**	**0.3 ± 0.1**	**0.4 ± 0.1**	**0.7 ± 0.1**
Wyoming big sagebrush	0.1 ± <0.1	0.1 ± 0.1	**0.1 ±** < **0.1**	**0.4 ± 0.1**	**0.4 ± 0.1**	**1.0 ± 0.3**
Rubber rabbitbrush	0	0	<0.1	0.1 ± < 0.1	0.1 ± < 0.1	0.1 ± < 0.1

[1] Residual adult plants (resid.) and new seedlings (seedl.) were differentiated in Yr 1 but not Yr 2.

[2] Yr 1 density values for Indian ricegrass at Saylor Creek include Thurber's needlegrass and needle-and-thread.

[3] Includes three penstemon species listed in Table 3.

[4] Rounding masks small but statistically significant difference between mean density in conv. (0.14) and min.-till (0.06).

the drill-mix grasses (Parkinson et al., 2013; Porensky et al., 2014), although for broadcast-mix species, segregation into different rows should have reduced this effect (Lambert, 2005). Seed origin could have influenced establishment success if the ecotypes we seeded were poorly adapted to weather or soil conditions they encountered (Meyer and Monsen, 1992; Meyer and Kitchen, 1994; Rowe and Leger, 2012).

At Saylor Creek, perennial establishment and plant diversity objectives were both achieved reasonably well but weed suppression was less successful. Although drill-mix species establishment was lower at Saylor Creek than Scooby, this was compensated by higher establishment of broadcast-mix species, which contributed to overall higher diversity. Relatively high precipitation at Saylor Creek during winter and spring of the first year appears to have favored plant establishment. Once established, seeded plants persisted at Saylor Creek despite subsequent summer drought and had a suppressive effect on exotic annual forbs, but they did not prevent second-year proliferation of cheatgrass. Limited cheatgrass suppression at Saylor Creek might have been due to insufficient establishment and growth of perennial grasses, which have been found to be especially important suppressors of annual plants in sagebrush systems (James et al., 2008; Sheley and James, 2010; Davies et al., 2014; Leffler et al., 2014). Functional diversity has also been found to be important for suppressing annual plants (Sheley and Half, 2006; Allen and Meyer, 2014; Leffler et al., 2014), but the effect of higher functional diversity (as measured by life forms) on cheatgrass suppression at Saylor Creek was not readily apparent, at least during the time frame of this study.

Assuming that drill rows dominated by deep-rooted perennial grasses contributed more to cheatgrass suppression than broadcast rows, it might have been advantageous to increase the number of rows dedicated to drill-mix species. Further experimentation with different proportions of drill and broadcast rows containing different species combinations and seeding rates is necessary to determine optimal seeding parameters for weed suppression and plant community restoration.

Due to site selection constraints and the small number of site replications included in our study, we cannot claim to have captured the full range of conditions likely to be encountered at Wyoming big sagebrush sites in the northern Great Basin. However, as we have discussed, our study sites illustrate contrasting postfire seeding responses that we attribute to differences in prefire vegetation, fire intensity, and postfire weather. These variables are recognized as important determinants of postfire successional pathways and should be evaluated when making decisions regarding treatment options (Miller et al., 2015). To a certain degree, variables such as elevation and long-term weather patterns can be used to predict the likelihood of seeding success for a given site (Chambers et al., 2014; Knutson et al., 2014), but our results highlight the value of basing treatment decisions on detailed information specific to the shorter-term seeding timeframe. For example, elevation and 30-yr precipitation normals could have been used to correctly predict higher seeded plant establishment at Saylor Creek than nearby Mountain Home but would not have predicted the magnitude of difference brought on by deviations from average conditions. Furthermore, the prediction might have proved incorrect had the year of seeding been reversed for the two sites.

Table 5

Percent cover (mean ± standard error) of species groups and dominant species in treatments seeded using a conventional drill (conv.) or minimum-till drill (min.-till) at three sites (see Table 1) and 2 postfire years. Wherever the difference between conv. and min.-till for a given group/species, site and year was significant ($P < 0.05$), values are shown in bold and the higher value is indicated with underlined text. NOTE: Because of overlapping canopies, cumulative cover of species within groups may exceed group totals

	Mountain Home		Scooby		Saylor Creek	
	conv.	min.-till	conv.	min.-till	conv.	min.-till
Yr 1						
Drill mix total	2.2 ± 0.4	1.5 ± 0.3	13.2 ± 1.7	11.7 ± 1.6	**2.5 ± 0.4**	**1.2 ± 0.2**
Bluebunch wheatgrass	**2.1 ± 0.4**	**1.1 ± 0.2**	5.3 ± 0.9	4.2 ± 0.8	0.1 ± < 0.1	<0.1
Squirreltail	0.1 ± < 0.1	0.2 ± < 0.1	3.3 ± 0.5	4.7 ± 0.6	0.1 ± < 0.1	0.1 ± < 0.1
Indian ricegrass[1]	0.2 ± < 0.1	0.1 ± < 0.1	5.7 ± 1.1	4.1 ± 0.9	**2.3 ± 0.3**	**1.1 ± 0.2**
Munro's globemallow	0	0	0.2 ± < 0.1	0.2 ± < 0.1	0	0
Broadcast mix total	2.3 ± 0.5	1.8 ± 0.4	**1.0 ± 0.2**	**1.9 ± 0.3**	3.3 ± 0.7	5.1 ± 1.0
Sandberg bluegrass	2.1 ± 0.5	1.8 ± 0.4	0.3 ± < 0.1	0.4 ± < 0.1	3.0 ± 0.7	4.0 ± 0.9
Western yarrow	Not seeded	Not seeded	0.7 ± 0.1	1.1 ± 0.2	0.3 ± < 0.1	0.4 ± < 0.1
Penstemon[2]	<0.1	<0.1	<0.1	0.1 ± < 0.1	0.2 ± < 0.1	0.2 ± < 0.1
Wyom. big sagebrush	0.1 ± < 0.1	<0.1	<0.1	0.1 ± < 0.1	0.1 ± < 0.1	0.3 ± < 0.1
Non-seed-mix perennials	0.5 ± < 0.1	0.3 ± < 0.1	2.4 ± 0.7	2.0 ± 0.6	2.9 ± 0.6	2.9 ± 0.6
Western wheatgrass	0	0	1.5 ± 0.5	1.3 ± 0.4	2.1 ± 0.5	1.8 ± 0.5
Cheatgrass	**20.6 ± 2.2**	**30.0 ± 2.6**	4.0 ± 1.1	3.4 ± 1.0	3.4 ± 0.7	3.3 ± 0.7
Exotic annual forbs	**24.9 ± 3.0**	**39.7 ± 3.5**	3.6 ± 0.7	5.2 ± 0.9	0.4 ± < 0.1	0.4 ± < 0.1
Tumblemustard	**11.1 ± 2.5**	**26.8 ± 3.9**	0.2 ± < 0.1	0.2 ± < 0.1	0.1 ± < 0.1	<0.1
Tansymustard	5.0 ± 1.4	9.4 ± 2.2	0.1 ± < 0.1	0.2 ± < 0.1	0.2 ± < 0.1	0.2 ± < 0.1
Russian thistle	**8.5 ± 1.4**	**2.7 ± 0.6**	1.3 ± 0.3	0.9 ± 0.2	0.1 ± < 0.1	0.1 ± < 0.1
Halogeton	0	0	1.6 ± 0.4	2.4 ± 0.5	0	0
Yr 2						
Drill mix total	1.1 ± 0.2	0.7 ± 0.1	38.9 ± 2.9	43.7 ± 2.9	**30.8 ± 1.7**	**18.0 ± 1.4**
Bluebunch wheatgrass	0.5 ± 0.1	0.4 ± < 0.1	22.3 ± 2.5	25.1 ± 2.6	**19.1 ± 1.5**	**13.6 ± 1.3**
Squirreltail	0.2 ± < 0.1	0.2 ± < 0.1	**8.9 ± 1.3**	**14.3 ± 1.7**	**2.9 ± 0.4**	**1.7 ± 0.3**
Indian ricegrass	0.3 ± < 0.1	0.2 ± < 0.1	13.7 ± 1.9	14.0 ± 1.9	**10.3 ± 1.5**	**2.3 ± 0.6**
Needle-and-thread	Not seeded	Not seeded	Not seeded	Not seeded	**1.2 ± 0.2**	**0.6 ± 0.1**
Munro's globemallow	0	0	0.8 ± 0.1	1.2 ± 0.2	0.6 ± 0.1	0.6 ± 0.1
Broadcast mix total	4.5 ± 0.9	4.2 ± 0.8	3.0 ± 0.6	5.0 ± 0.9	**18.5 ± 1.9**	**27.2 ± 2.2**
Sandberg bluegrass	4.5 ± 0.9	4.2 ± 0.8	0.8 ± 0.1	1.2 ± 0.2	15.4 ± 1.7	20.0 ± 1.9
Western yarrow	Not seeded	Not seeded	2.1 ± 0.5	3.6 ± 0.7	**2.8 ± 0.6**	**5.8 ± 1.0**
Penstemon[2]	0	0	0.1 ± < 0.1	0.1 ± < 0.1	0.8 ± 0.1	1.4 ± 0.2
Wyom. big sagebrush	<0.1	<0.1	0.1 ± < 0.1	0.1 ± < 0.1	0.5 ± 0.1	1.0 ± 0.2
Non-seed-mix perennials	0.1 ± < 0.1	0.1 ± < 0.1	3.6 ± 1.1	3.7 ± 1.1	6.8 ± 2.1	6.5 ± 2.0
Western wheatgrass	0	0	1.7 ± 0.6	1.5 ± 0.5	6.2 ± 2.1	5.4 ± 1.8
Cheatgrass	54.8 ± 3.1	62.5 ± 3.0	3.6 ± 0.9	5.6 ± 1.1	45.4 ± 2.4	43.5 ± 2.4
Exotic annual forbs	**35.3 ± 1.9**	**28.5 ± 1.8**	7.5 ± 1.6	7.6 ± 1.6	1.1 ± 0.2	1.9 ± 0.4
Tumblemustard	21.7 ± 1.8	20.7 ± 1.8	0.2 ± < 0.1	0.1 ± < 0.1	**0.2 ± < 0.1**	**0.5 ± < 0.1**
Tansymustard	10.8 ± 2.2	6.0 ± 1.5	1.2 ± 0.3	0.9 ± 0.2	0.8 ± 0.2	0.9 ± 0.2
Russian thistle	**5.7 ± 1.0**	**2.7 ± 0.6**	3.4 ± 0.8	3.2 ± 0.8	0.2 ± < 0.1	0.2 ± < 0.1
Halogeton	0	0	2.6 ± 0.7	3.5 ± 0.9	0	0

[1] Yr 1 cover values for Indian ricegrass at Saylor Creek include Thurber's needlegrass and needle-and-thread.

[2] Includes three penstemon species listed in Table 3.

Because the Great Basin region is subject to wide fluctuations in interannual precipitation, weather forecasts for the upcoming year at the time of seeding (e.g., NOAA, 2016) may be equally or more valuable for predicting seeded plant establishment than long-term averages from previous years (Hardegree and Van Vactor, 2004).

Effects of Drilling Technique on Seeded Plant Establishment

As predicted, we found instances of small-seeded species establishing better when broadcast using the minimum-till drill, especially at Saylor Creek and Scooby. We suspect that imprinter wheels of the minimum-till drill enhanced germination and emergence by improving soil water retention (via firming) and increasing seed-soil contact without burying seeds too deeply (Hyder et al., 1955; Boltz, 1994). Drag chains of the conventional drill, in contrast, likely loosened rather than firmed the soil and may have buried seeds at irregular depths. Seeds broadcast from the conventional drill could have also been buried by soil displaced from adjacent drill furrows. Our novel use of pipes to channel broadcast seeds close to the soil surface likely reduced this straying tendency compared with the alternative of simply letting seeds fall from drop tubes.

For some species, the question of whether to place seeds in drill versus broadcast rows is not clearly resolved. Although we placed Sandberg bluegrass in broadcast rows, this species can reportedly emerge from depths of up to 3 cm (Evans et al., 1977) and has been successfully seeded in drill furrows (Douglas et al., 1960, Sheley et al., 2012). Higher establishment of Sandberg bluegrass in the conventional drill treatment at Mountain Home, unlike other sites where establishment was higher with the minimum-till, might reflect advantages of deeper burial for this species under conditions of lower soil moisture.

Surprisingly, we found that minimum-till drill features expected to improve seed placement in drill rows (hydraulics, depth bands, press wheels) did not lead to higher establishment of large-seeded species except in a few cases at Scooby. Instead, we found multiple instances of higher establishment using the conventional drill, which lacked these features. Higher establishment of large-seeded species with the conventional drill may be due to 1) more widely spaced seedlings in broader furrows, leading to reduced seedling competition; 2) broader and deeper furrows that were more effective at capturing water (Hull, 1970); 3) lower competition from exotic annuals in the vicinity of drill rows due to mechanical disturbance (see later section); and 4) suboptimal depth settings for the minimum-till drill, resulting in shallower seed burial than the conventional drill. The latter explanation in particular might explain the pronounced differences in Indian ricegrass establishment that we observed. Young et al. (1994) found that Indian ricegrass emergence increased with seed burial depth (up to a maximum tested depth of 15 cm), which they attributed to increased protection from desiccation and reduced exposure to granivores.

As a caveat, we note that there were many instances in which no difference was found between drill types, and even in cases where differences were statistically significant, the magnitude of differences was often small. Furthermore, variation in seeded plant establishment across sites was generally more pronounced than variation between drill types within sites, suggesting that site conditions such as available moisture and weed competition were generally more influential than seeding technique. This result differs from James and Svejcar (2010), who found that soil moisture and weed competition were relatively unimportant compared with seeding technique in explaining variation in seeding establishment, but they also noted that their experiment took place under favorable moisture conditions at locations with low weed abundance. The implication is that only under favorable conditions are the advantages of a given technique likely to be fully realized.

Drilling Impacts on Residual Perennials and Exotic Annuals

Because mechanical soil disturbance has the potential to disrupt established perennials (Douglas et al., 1960; Ratzlaff and Anderson, 1995), we hypothesized that residual native perennials would have higher abundance in the minimum-till treatment. This was found for Sandberg bluegrass at Saylor Creek and squirreltail at Scooby. Our field observations of uprooted Sandberg bluegrass plants in the vicinity of conventional drill furrows gave further credence to this hypothesis. Knutson et al. (2014) analyzed postfire seedings across the Great Basin and also concluded that conventional drills can lead to Sandberg bluegrass mortality. The shallow roots and small stature of Sandberg bluegrass may have made it particularly vulnerable to drill disturbance.

We also found evidence that conventional drill disturbance would have a greater impact on exotic annuals than the minimum-till drill, in this case primarily at Mountain Home, where exotic annuals were especially abundant. Reductions in cover of cheatgrass and tumblemustard associated with conventional drill disturbance could have arisen through multiple mechanisms, including seed burial beyond emergence depth in disturbed soil of drill rows (Wicks et al., 1971; Young et al., 2014), destruction of plants that had already emerged at the time of drilling (Kettler et al., 2000), and reduction of suitable microsites for annual seeds through removal of surface litter (Evans and Young, 1970).

Regardless of mechanism, the inhibitory effect of conventional drill disturbance at Mountain Home was temporary, as tumblemustard and cheatgrass began to occupy the conventional drill treatment more fully by the second year. This shift could have been facilitated by buildup of litter in conventional drill furrows or benefits of greater water availability in furrows where seeded plants had largely failed to establish. Our impression from field observations was that zones of displaced soil on ridges between conventional drill furrows were poor sites for cheatgrass establishment, but that the furrows themselves became favorable microsites as they accumulated litter and cheatgrass seeds over time.

In contrast to other exotic annuals at Mountain Home, Russian thistle responded positively to the greater disturbance of the conventional drill, likely because of its rapid germination on soil surfaces with low litter cover (Evans and Young, 1970) and/or its ability to emerge when buried as deep as 7.5 cm (Wallace et al., 1968). In the northern Great Basin, Russian thistle is recognized as an early-successional colonizer of disturbed areas that typically becomes subordinate to cheatgrass over time (Piemeisel, 1951). Conventional drill disturbance at Mountain Home appears to have shifted the competitive balance of exotic annuals toward Russian thistle.

Implications

Seeding mixtures of native grasses, forbs, and shrubs following fire can be accomplished using rangeland drills with features adapted for seeding large and small seeds in separate rows. The choice of conventional versus minimum-till drill will depend on circumstances and objectives because each drill type has its own set of advantages and drawbacks. We found that a minimum-till drill equipped with imprinter wheels tended to be more effective for establishing small-seeded (broadcast-mix) species while a conventional drill was often better for large-seeded (drill-mix) species. We recommend further testing of drill depth settings for large-seeded species. Our results indicate that minimum-till drills would be preferable at sites where retention of established residual perennials is a priority, although seeding may not be necessary at such sites because of their capacity for natural recovery (Ratzlaff and Anderson, 1995; Miller et al., 2015). The conventional drill may be preferable if weed control is a greater concern, although drilling is not as effective for mechanical weed control as disking or tilling with heavier implements (Stewart, 1950; Douglas et al., 1960; Kettler et al., 2000; Monsen and Stevens, 2004). Other concerns not addressed by our study are also relevant, including impacts of different drill types on soil properties, as well as costs and availability of drilling equipment. Regardless of drill type used, seeding mixes of large and small seeds in a one-pass operation using a rangeland drill is likely to offer considerable cost savings over the common strategy of drilling followed by aerial seeding (Dalzell, 2004; Monsen and Stevens, 2004).

Our three study sites exemplify different outcomes in relation to restoration objectives of perennial establishment, weed suppression, and native plant diversity. The Mountain Home site failed to meet these objectives and exemplified conditions that are especially challenging for seeding; successful restoration of such sites will likely require strategies beyond single-entry seeding following fire. To the extent that weather conditions can be predicted for a given year, seeding may best be delayed until a year when above-average precipitation is predicted (Hardegree and Van Vactor, 2004), and secondary means of controlling invasive annuals (e.g. herbicides) may also be necessary in consequence of the delay (Hardegree and Van Vactor, 2004; Davies et al., 2015). Seedings at Scooby and Saylor Creek fortuitously coincided with favorable weather conditions but differed in establishment of seeded grasses relative to forbs, shrubs, and exotic annuals. Results suggest a tradeoff between suppressing invasive annual weeds and establishing diverse communities containing forbs and shrubs. Further research is necessary to determine optimal strategies to concurrently achieve weed suppression and native plant community restoration following fire.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.rama.2016.05.001.

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