Rangeland Ecology & Management 71 (2018) 298–308

Contents lists available at ScienceDirect

Rangeland Ecology & Management

journal homepage: http://www.elsevier.com/locate/rama

Original Research

Evaluating Mechanical Treatments and Seeding of a Wyoming Big Sagebrush Community 10 Yr Post Treatment☆

Daniel D. Summers [a], Bruce A. Roundy [b,*]

[a] Habitat Coordinator, Utah Division of Wildlife Resources, Ephraim, UT 84627, USA
[b] Professor, Department of Plant and Wildlife Sciences, Brigham Young University, Provo, UT 84602, USA.

ARTICLE INFO

Article history:
Received 7 November 2017
Received in revised form 25 January 2018
Accepted 31 January 2018

Key Words:
aerating
chaining
habitat restoration
harrowing
imprinting
rangeland revegetation
sagebrush steppe

ABSTRACT

Increased cover of perennial grasses and forbs would increase the wildlife and forage value of many Wyoming big sagebrush (*Artemisia tridentata* ssp. *wyomingensis* Beetle & Young) communities, as well as increase their resistance to weeds. We compared six mechanical treatments in conjunction with seeding a Wyoming big sagebrush community in northern Utah over a 10-yr period. The treatments included disk plow followed by land imprinter, one-way Ely chain, one- and two-way pipe harrow, all applied in fall, and meadow aerator applied in fall and spring. A mixture of native and introduced grasses and forbs was broadcast seeded at 18.3 kg PLS ha^{-1} after the disk and before the imprinter and all other treatments. The experiment was installed in three randomized blocks, and density and cover data were collected before treatment in 2001 and 1, 2, 5, and 10 yr after treatment. All treatments initially reduced sagebrush and residual herbaceous cover and increased seeded species cover compared with the untreated control. By 10 yr after treatment, sagebrush cover was 24.5% ± 0.35% on the control, 1.6% ± 0.28% on the disk imprinter treatment, and 11.7% ± 0.79% on all other treatments. At that time, seeded grass cover was 16.5% ± 1.22% on the disk imprinter treatment and an average of 2% ± 0.1% on all other mechanical treatments. Sagebrush seedlings were recruited in all of the mechanical treatments, but least in the disk imprinter treatment. After 10 yr, the untreated control was dominated by decadent sagebrush and rabbitbrush, the disk imprinter treatment was dominated by seeded perennial grasses, and the other mechanical treatments shared dominance of sagebrush and native perennial grasses. Mechanical treatments changed the composition of this community while retaining sagebrush, but greatest understory increases were associated with greatest control of sagebrush and establishment of seeded species by disk imprinting.

Introduction

Sagebrush (*Artemisia* L.) steppe vegetation covers millions of hectares in western North America in seven floristic provinces (Wisdom et al., 2005; Pyke et al., 2015). Sagebrush communities typically include shrubs, perennial grasses, and forbs (Miller et al., 2011). However, sagebrush species and cover, as well as that of associated perennial and annual herbs, vary greatly across the sagebrush steppe in relation to environmental potential and disturbance (Davies et al., 2006; Miller et al., 2011; Pyke et al., 2015). Wyoming big sagebrush (*Artemisia tridentata* Nutt. ssp. *wyomingensis* Beetle & Young) is the dominant shrub on lower elevation and drier cold desert alluvial fans and valleys (Miller et al., 2011). This vegetation type provides important forage and habitat for wildlife, as well as livestock grazing (Davies et al., 2006). Wyoming big sagebrush communities are more easily degraded than those of other big sagebrush subspecies and probably need active management to increase herbaceous understories (Miller and Eddleman, 2001; Davies et al., 2012b; Davies and Bates, 2014). State and transition successional models portray the relative abundance of Wyoming big sagebrush and perennial grass mainly as a function of fire, livestock grazing, and interaction of the two (Stringham et al., 2003; Briske et al., 2008; Chambers et al., 2014). Heavy livestock grazing supports sagebrush while moderate-severity fire supports perennial grass dominance (Miller et al., 2013; Chambers et al., 2017). In addition to depleting perennial grasses, heavy grazing may also reduce fire frequency and further support sagebrush dominance (Miller and Heyerdahl, 2008). West (1983) estimated that about 25% of the sagebrush steppe had become stagnant due to dense, competitive stands of sagebrush, which prevents the recovery of perennial herbaceous species even when grazing is reduced or removed (Blaisdell et al., 1982; West et al., 1984; Bork et al., 1998; Davies et al., 2014).

Managing composition of big sagebrush communities has evolved from sagebrush reduction and seeding grasses for improvement of herbaceous forage production for livestock to promoting mixed shrub, grass, and forb communities to support wildlife habitat or ecosystem

☆ Research was funded by the Utah Division of Wildlife Resources through Federal Aid Project W-82-R and Brigham Young University Professional Development Funds.
* Correspondence: Bruce A. Roundy, Dept of Plant and Wildlife Sciences, Brigham Young University, Room 5023 LSB, Provo, UT, 84602, USA. Tel.: +801-422-8137.
E-mail address: bruce_roundy@byu.edu (B.A. Roundy).

https://doi.org/10.1016/j.rama.2018.01.006
1550-7424/

conservation (Young et al., 1979; Blaisdell et al., 1982; Roundy, 1996; Davies et al., 2011; Miller et al., 2011; Pyke et al., 2015). Big sagebrush communities with higher cover of deeper-rooted perennial grasses are considered to be more resistant to dominance by cheatgrass (*Bromus tectorum* L.), which is considered the greatest threat to this ecosystem (D'Antonio and Vitousek, 1992; Chambers et al., 2007; Miller et al., 2011; Chambers et al., 2014, 2017). Because big sagebrush and perennial grass roots use the same soil depth for water and nutrient uptake for growth, they are competitive for resources (Ryel et al., 2008, 2010; Lefler and Ryel, 2012). This can make finding techniques that retain Wyoming big sagebrush plants but restore depleted perennial grass understories a challenge. Compared with prescribed fire, mechanical shrub reduction has the advantages of easier and more flexible implementation, potentially lower mortality of perennial species, especially sagebrush, and less risk in urban-wildland interface areas (Davies et al., 2012b). Although mechanical sagebrush control generally increases perennial herbaceous vegetation, results can be highly variable depending on the amount of control, as well as the site, residual species, and subspecies of sagebrush (Watts and Wambolt, 1996; Davies et al., 2012a, 2012b; Hess and Beck, 2012; Pyke et al., 2014).

Wyoming big sagebrush communities that lack a perennial grass understory may end up dominated by cheatgrass after mechanical shrub reduction (Davies et al., 2012b). When perennial grasses are lacking, mechanical brush control may be used to help establish seeded species (Davies et al., 2012b). Mechanical treatments vary in amount of sagebrush control but may also help disturb the soil and bury seeds, thereby promoting establishment of seeded species or invasive weeds (Skousen and Brotherson, 1989). Treatments need to be tested across a range of sites and environmental potential. Sagebrush steppe located more northerly than Great Basin or semidesert sagebrush was recognized by Kuchler (1964) as having less sagebrush dominance and greater perennial herbaceous potential (West, 1983; West and Young, 2000; Miller et al., 2011). Because of the competitive relationships of sagebrush and perennial herbs, longer-term effects of treatments should be considered.

Treating big sagebrush communities can have negative consequences. Reductions in Wyoming big sagebrush could lead to declines in wildlife populations (Beck et al., 2009; 2012; Rhodes et al., 2010). Hess and Beck (2012) found that sagebrush canopy cover recovered quicker after mowing than burning, but there were few differences in grass canopy cover between treated and untreated sites, suggesting that mowing was ineffective in increasing perennial grass structure. While seeding may be required in addition to sagebrush reduction to increase understory cover, the desired cover could be limited by insufficient establishment or time for established plants to mature (Davies and Bates, 2014). Resilience to management treatments and resistance to annual exotic invasion are associated with soil temperature/moisture regimes, with warmer and drier Wyoming big sagebrush sites showing less resilience or resistance than upper elevation mountain big sagebrush (*Artemisia tridentata* Nutt. ssp. *vaseyana* [Rybd.] Beetle) sites (Chambers et al., 2014).

The objective of this study was to evaluate over a 10-yr period the effects of six mechanical treatments and seeding in a Wyoming big sagebrush steppe community in the Wyoming Basin area of northern Utah. There are a variety of implements for sagebrush thinning and control. This study was initiated to compare the Lawson aerator used for sagebrush thinning, with other mechanical treatments that have been commonly used for this purpose (Stevens and Monsen, 2004). We evaluated the response and recovery rate of sagebrush, the response of residual understory plants, and the establishment of seeded grasses and forbs in relation to the mechanical treatments.

Methods

Study Area

The study site is located in Rich County (lat 41°20′N, long 111°9′W, elevation 2 000 m), in northern Utah on private land owned by Deseret Land & Livestock and public lands managed by the US Department of the Interior Bureau of Land Management. The study site is located about 2.5 km south of Neponset Reservoir. The major land resource area is 034A—Cool Central Desertic Basins and Plateaus. The ecological site description is semidesert loam (Wyoming big sagebrush/bluebunch wheatgrass *(Pseudoroegneria spicata)* (R034AA220UT) (US Department of Agriculture — Natural Resources Conservation Service unpublished draft ecological site description). The study plots are on soils from the Lariat series and classified as coarse-loamy, mixed frigid Xerollic Calciorthids. The typical pedon is Lariat fine sandy loam, moderately deep, well drained, and derived from sandstone. Average annual precipitation is about 230 − 300 mm (USDA, 1981).

The study area is characterized by rolling hills covered by Wyoming big sagebrush. Western wheatgrass (*Pascopyrum smithii* [Rydb.] A. Löve), Sandberg bluegrass (*Poa secunda* J. Presl), longleaf phlox (*Phlox longifolia* Nutt.), carpet phlox (*Phlox hoodii* Richardson), and yellow rabbitbrush (*Chrysothamnus viscidiflorus* [Hook] Nutt. ssp. *viscidiflorus.*) are all common species. Perennial bunchgrasses such as bluebunch wheatgrass and needle and thread (*Hesperostipa comata* [Trin. & Rupr.] Barkworth) were rare.

The area is used by pronghorn *(Antilocapra americana),* mule deer *(Odocoileus hemionus),* elk *(Cervus elaphus),* and greater sage grouse *(Centrocercus urophasianus)* during different periods of the year. Domestic livestock also graze the area as part of Deseret Land & Livestock's short-duration, high-intensity grazing system, but cattle grazing was excluded from the study site for the duration of this experiment.

Experimental Design

In October 2001, five mechanical treatments were applied including 1) disk plow followed by a land imprinter, 2) one-way chaining using an Ely chain, 3) one-way pipe harrow, 4) two-way pipe harrow, and 5) meadow aerator (fall). In April 2002, the meadow aerator was applied as a spring treatment. The experiment was a randomized complete block with three blocks. Each treatment plot in each block was a 1.1-ha strip (61 × 183 m) surrounded by a 15-m buffer of untreated sagebrush. Blocks were separated by 40-m strips to allow adequate space for equipment to move from plot to plot.

Revegetation

Each treatment plot except the undisturbed control plot was seeded with a mixture of native and introduced grasses, forbs, and four-wing saltbush (*Atriplex canescens* [Pursh] Nutt.) (Table 1). The same seed mix and seeding rate (18.3 kg PLS ha^{-1}) were used on each plot. Seed was applied using a broadcast seeder mounted on the back of a tractor and was applied before the treatments with the exception of the disk plow and land imprinter. Seed on the disk treatment was applied using a seed box on the imprinter, which dropped seed directly in front of the imprinter after the soil had been disked. The two-way pipe harrow treatment was seeded after the first pass and before the second pass of the harrow. All treatment plots were seeded in the fall, except the spring meadow aerator plots, which were seeded in the spring.

Vegetation Sampling

We conducted pretreatment vegetation sampling during the summer of 2001. Post-treatment sampling was completed in the summers of 2002, 2003, 2006, and 2011. Each treatment was sampled using a permanently marked 150-m transect divided into five 30-m baseline transects. One 30-m cross transect was placed perpendicular to each baseline transect at a random number along the baseline transect. Twenty evenly spaced 0.25 m^2 quadrats were read on the same side of each 30-m cross transect for a total of 100 quadrats. Aerial cover was ocularly estimated, and density was counted for all species occurring within each quadrat. Cover values were also determined for total

Table 1
Seeded species and pure live seed (PLS) seeding rates for seed mix broadcast into a Wyoming big sagebrush community prior to mechanical treatment in fall 2001 and spring 2002 (aerator only) in northern Utah.

Species		PLS kg ha^{-1}
Bluebunch wheatgrass	*Pseudoroegneria spicata* (Pursh) Á. Löve	0.6
Crested wheatgrass - Hycrest	*Agropyron cristatum* (L.) Gaertn.	0.6
Intermediate wheatgrass	*Thinopyrum intermedium* (Host) Barkworth & D.R. Dewey	1
Hybrid wheatgrass - NewHy	*Elymus hoffmannii* K.B. Jensen & K.H. Asay	1
Orchard grass - Paiute	*Dactylis glomerata* L.	1.3
Russian wildrye - Bozoisky	*Psathyrostachys junceus* (Fisch.) Nevski	1.2
Smooth brome	*Bromus inermis* Leyss.	2
Thickspike wheatgrass - Bannock	*Elymus lanceolatus* (Scribn. & J.G. Sm.) Gould	0.3
Alfalfa - Ladak	*Medicago sativa* L.	2.6
American vetch	*Vicia americana* Muhl. ex Willd.	0.4
Blue flax	*Linum perenne* L.	0.5
Rocky Mountain penstemon	*Penstemon strictus* Benth.	0.1
Sainfoin	*Onobrychis viciifolia* Scop.	2.3
Small burnett - Delar	*Sanguisorba minor* Scop.	2.4
Western yarrow	*Achillea millefolium* L.	0.4
Yellow sweet clover	*Melilotus officinalis* (L.) Lam.	0.9
Four-wing saltbush	*Atriplex canescens* (Pursh) Nutt.	0.7
Total		**18.3**

vegetation, litter, rock, pavement, cryptogams, and bare ground within each quadrat. Cover was estimated using slightly modified Daubenmire (1959) cover classes (Bailey and Poulton, 1968): 1) 0.01 − 1%, 2) 1.1 − 5%, 3) 5.1 − 25%, 4) 25.1 − 50%, 5) 50.1 − 75%, 6) 75.1 − 95%, and 7) 95.1 − 100%.

We measured cover of shrubs using the line intercept method for all cross transects (Bonham, 1989). Shrub density was measured using five 0.004-ha strips (1.34 m wide × 30 m long) centered over the length of each 30-m cross transect. All shrubs rooted within each strip were counted and placed into one of three classes: young (stem diameter < 1 cm), mature (stem diameter ≥ 1 cm), decadent (> 25% of crown is dead) (USDI, BLM, 1996).

Statistical Analysis

Cover data were logit transformed before analysis (Warton and Hui, 2011). Data were analyzed using mixed model analysis (Proc GLIMMIX in SAS version 9.4) with year considered as a repeated measure and using autoregressive of order 1 or AR(1) as the covariance structure. This accounts for stronger correlations for nearby times than far-apart times (Littell et al., 2006). Block was considered a random effect, while treatment was a fixed effect. Mean separation was done using Tukey's honestly significant difference multiple comparison procedure. Differences were considered statistically significant at $P < 0.05$. All statistical analyses and comparisons were conducted on transformed data, but means and standard errors reported in the text are from untransformed data, across blocks. In addition, herbaceous cover variables were regressed on sagebrush cover using data from blocks and years for all treatments.

Results

The main effects of treatment and year, as well as the two-way interaction of these factors was significant for all variables tested ($P < 0.01$), except for annual forb cover and cheatgrass cover.

Shrubs

All treatments significantly ($P < 0.05$) reduced sagebrush cover compared with the control after initial treatment (Fig. 1), but the disk imprinter reduced sagebrush cover lower than all other treatments (Table 2). By 10 yr after treatment, only fall aerator and disk-imprinter treatments had significantly lower sagebrush cover than the untreated control (see Fig. 1). Sagebrush cover on the disk-imprinter plots 10 yr after treatment was only 1.6% ± 0.28% compared with 24.5% ± 0.35% on the untreated control. The other treatments had average sagebrush

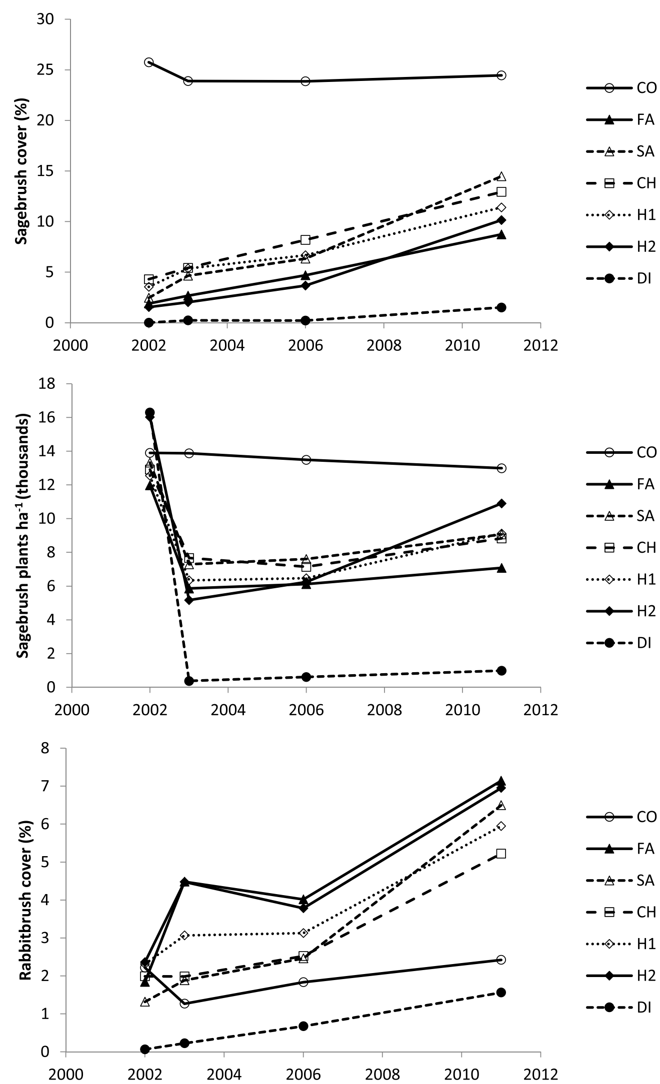

Figure 1. Big sagebrush cover (top) and density (middle) and rabbitbrush cover (bottom) for up to 10 yr after mechanical treatments and seeding. See Table 2 for treatment abbreviations and significant differences.

Table 2
Cover and density significant differences (P< 0.05) after mechanical treatments as indicated by different letters in columns for treatment within years and within rows for years within treatment.

Treatment		Treatment within year					Year within treatment				
Big sagebrush cover											
	Abbrev.	2001	2002	2003	2006	2011	2001	2002	2003	2006	2011
Control	CO		A	A	A	A		A	A	A	A
Fall aerator	FA		B	B	B	B		C	BC	AB	A
Spring aerator	SA		B	B	B	AB		C	BC	B	A
Chain	CH		B	B	B	AB		B	B	AB	A
1-way harrow	H1		B	B	B	AB		B	B	AB	A
2-way harrow	H2		B	B	B	AB		C	BC	B	A
Disk imprinter	DI		C	C	C	C		C	B	B	A
Big sagebrush density											
		2001	2002	2003	2006	2011	2001	2002	2003	2006	2011
Control	CO		A	A	A	C		A	A	A	A
Fall aerator	FA		B	B	A	BC		B	B	B	A
Spring aerator	SA		AB	AB	A	AB		B	B	B	A
Chain	CH		AB	AB	A	A		B	B	B	A
1-way harrow	H1		B	B	A	AB		B	B	B	A
2-way harrow	H2		B	B	A	BC		C	C	B	A
Disk imprinter	DI		C	C	B	D		B	B	B	A
Rabbitbrush cover											
		2001	2002	2003	2006	2011	2001	2002	2003	2006	2011
Control	CO		A	A	AB	AB		A	A	A	A
Fall aerator	FA		A	A	A	A		B	AB	AB	A
Spring aerator	SA		A	A	AB	AB		B	B	B	A
Chain	CH		A	A	AB	AB		B	B	AB	A
1-way harrow	H1		A	A	A	AB		B	AB	AB	A
2-way harrow	H2		A	A	A	A		B	AB	AB	A
Disk imprinter	DI		B	B	B	B		C	B	A	A
Residual grass cover											
		2001	2002	2003	2006	2011	2001	2002	2003	2006	2011
Control	CO	A	A	A	BC	AB	A	A	A	A	A
Fall aerator	FA	A	AB	A	AB	A	B	B	A	A	A
Spring aerator	SA	A	AB	A	A	A	C	C	AB	A	BC
Chain	CH	A	AB	A	AB	A	C	BC	AB	A	AB
1-way harrow	H1	A	AB	A	AB	A	B	B	A	A	A
2-way harrow	H2	A	B	A	AB	A	B	B	A	A	A
Disk imprinter	DI	A	C	B	C	B	A	B	A	A	A
Seeded grass cover											
		2001	2002	2003	2006	2011	2001	2002	2003	2006	2011
Control	CO	A	C	C	C	C	B	B	B	AB	A
Fall aerator	FA	A	B	B	B	B	C	B	A	A	A
Spring aerator	SA	A	B	B	B	B	C	B	A	A	A
Chain	CH	A	B	B	B	B	C	B	AB	AB	A
1-way harrow	H1	A	B	B	B	B	C	B	AB	A	A
2-way harrow	H2	A	B	B	B	AB	C	B	AB	AB	A
Disk imprinter	DI	A	A	A	A	A	B	A	A	A	A
Perennial grass cover											
		2001	2002	2003	2006	2011	2001	2002	2003	2006	2011
Control	CO	A	A	B	B	C	A	A	A	A	A
Fall aerator	FA	A	A	AB	AB	BC	B	B	A	A	A
Spring aerator	SA	A	A	AB	A	BC	C	C	AB	A	BC
Chain	CH	A	A	B	AB	BC	B	B	A	A	A
1-way harrow	H1	A	A	B	A	BC	B	B	A	A	A
2-way harrow	H2	A	A	AB	A	AB	B	B	A	A	A
Disk imprinter	DI	A	A	A	A	A	B	B	A	A	A
Residual forb cover											
		2001	2002	2003	2006	2011	2001	2002	2003	2006	2011
Control	CO	A	A	A	A	A	A-C	C	BC	A	AB
Fall aerator	FA	A	A	A	A	A	AB	C	BC	A	AB
Spring aerator	SA	A	B	B	A	AB	A	B	B	A	A
Chain	CH	A	A	A	A	A	A	BC	C	A	AB
1-way harrow	H1	A	AB	B	A	AB	A	B	B	A	A
2-way harrow	H2	A	AB	AB	A	A	AB	C	BC	A	AB
Disk imprinter	DI	A	C	C	B	B	A	C	D	C	B
Seeded forb cover											
		2001	2002	2003	2006	2011	2001	2002	2003	2006	2011
Control	CO	A	C	C	D	C	A	A	A	A	A
Fall aerator	FA	A	BC	BC	BC	BC	B	AB	AB	A	A
Spring aerator	SA	A	BC	BC	CD	BC	A	A	A	A	A
Chain	CH	A	A-C	BC	CD	B	B	AB	AB	AB	A
1-way harrow	H1	A	A-C	AB	BC	BC	B	AB	A	A	A

(continued on next page)

Table 2 *(continued)*

Treatment		Treatment within year					Year within treatment				
2-way harrow	H2	A	AB	AB	AB	AB	B	A	A	A	A
Disk imprinter	DI	A	A	A	A	A	C	B	AB	A	AB
Annual forb cover											
		2001	2002	2003	2006	2011	2001	2002	2003	2006	2011
Control	CO	A	BC	B	A	A	B	D	CD	BC	A
Fall aerator	FA	A	A-C	AB	A	A	B	B	B	B	A
Spring aerator	SA	A	C	AB	A	A	B	C	B	B	A
Chain	CH	A	AB	AB	A	A	B	B	B	B	A
1-way harrow	H1	A	A	AB	A	A	B	B	B	B	A
2-way harrow	H2	A	A	AB	A	A	B	B	B	B	A
Disk imprinter	DI	A	A	A	A	A	B	B	B	B	A
Perennial forb cover											
		2001	2002	2003	2006	2011	2001	2002	2003	2006	2011
Control	CO	A	A	A	A	A	B	B	B	A	A
Fall aerator	FA	A	A	A	A	A	A	C	BC	A	AB
Spring aerator	SA	A	B	B	A	A	A	B	B	A	A
Chain	CH	A	A	A	A	A	A	B	B	A	A
1-way harrow	H1	A	AB	B	A	A	A	B	B	A	A
2-way harrow	H2	A	AB	A	A	A	AB	C	B	A	A
Disk imprinter	DI	A	B	B	A	A	A	B	B	A	A
Western wheatgrass cover											
		2001	2002	2003	2006	2011	2001	2002	2003	2006	2011
Control	CO	A	A	BC	C	B	A	A	A	A	A
Fall aerator	FA	A	A	A	AB	A	B	A	A	A	A
Spring aerator	SA	A	A	A	A	A	C	B	AB	A	B
Chain	CH	A	A	AB	A-C	A	B	A	A	A	A
1-way harrow	H1	A	A	A	AB	A	C	B	AB	A	AB
2-way harrow	H2	A	A	A	A-C	AB	C	B	AB	A	AB
Disk imprinter	DI	A	B	C	BC	AB	BC	D	CD	A	AB
Sandberg bluegrass cover											
		2001	2002	2003	2006	2011	2001	2002	2003	2006	2011
Control	CO	A	A	A	A	A	A	A	A	A	A
Fall aerator	FA	A	B	A	AB	A	AB	B	A	AB	AB
Spring aerator	SA	A	AB	A	A	AB	A	B	A	AB	B
Chain	CH	A	AB	A	A	A	A	A	A	A	A
1-way harrow	H1	A	B	A	AB	A	A	B	A	AB	AB
2-way harrow	H2	A	B	A	A	A	A	B	A	AB	AB
Disk imprinter	DI	A	C	B	B	B	A	C	B	B	B
Cryptobiotic cover											
		2001	2002	2003	2006	2011	2001	2002	2003	2006	2011
Control	CO	A	A	A	A	A	A	AB	BC	C	BC
Fall aerator	FA	A	AB	A	B	AB	A	AB	BC	C	BC
Spring aerator	SA	A	AB	A	AB	BC	A	AB	B	BC	C
Chain	CH	A	A	A	B	B	A	AB	BC	C	C
1-way harrow	H1	A	BC	B	B	AB	A	BC	C	BC	B
2-way harrow	H2	A	D	B	C	BC	A	C	C	C	B
Disk imprinter	DI	A	CD	B	C	C	A	B	BC	C	BC
Litter cover											
		2001	2002	2003	2006	2011	2001	2002	2003	2006	2011
Control	CO	A	DC	BC	BC	BC	A	A	A	A	A
Fall aerator	FA	A	A-C	A-C	A-C	A-C	B	A	A	A	AB
Spring aerator	SA	A	A-C	A-C	AB	AB	B	AB	A	A	A
Chain	CH	A	AB	AB	A	A	B	A	A	A	A
1-way harrow	H1	A	A	A	A-C	A-C	C	AB	A	BC	BC
2-way harrow	H2	A	BC	C	A-C	A-C	A	A	A	A	A
Disk imprinter	DI	A	D	D	C	C	AB	BC	C	A	A
Bare ground cover											
		2001	2002	2003	2006	2011	2001	2002	2003	2006	2011
Control	CO	A	D	B	C	A	A	A	A	A	A
Fall aerator	FA	A	BC	B	A-C	A	BC	A	A-C	AB	C
Spring aerator	SA	A	BC	B	A-C	A	A	AB	BC	BC	C
Chain	CH	A	CD	B	BC	A	A	A	A	A	A
1-way harrow	H1	A	CD	B	A-C	A	C	A	BC	AB	C
2-way harrow	H2	A	B	B	AB	A	C	A	BC	B	C
Disk imprinter	DI	A	A	A	A	A	C	A	B	B	C

cover of 11.7% ± 0.79%, about half of the untreated control. Sagebrush cover recovery on these treatments averaged 1% per year.

Initially, all but the spring aerator and chain treatments reduced sagebrush density below that of the control (see Fig. 1, Table 2). By 5 yr after treatment, all but the disk-imprinter treatment had similar density as the control. Even after 10 yr, the disk-imprinter treatment only had 27% as much sagebrush density as the control. By then, all other treatments had similar or greater sagebrush density than the control. At that time, over half of the sagebrush plants in the mechanical treatments were young, while < 5% were considered decadent compared with 34% ± 1.07% decadent in the control (Fig. 2).

Disk imprinting decreased rabbitbrush cover initially and over the 10-yr measurement period (see Fig. 1, Table 2). All other treatments had statistically similar cover as the control, but averages were higher. Rabbitbrush cover increased for all mechanical treatments between 1 and 10 yr after treatment. By 10 yr after treatment, rabbitbrush cover averaged 2.8% ± 0.98% on the control, 1.6% ± 0.28% on the disk imprinter treatment, and 6.5% ± 0.3% on all other treatments.

Residual Herbaceous Cover

The first year after treatment, residual perennial grass cover was lower on the disk-imprinter and two-way harrow treatments than on the control. Residual grass cover on all treatments except the disk imprinter was either similar to or exceeded that on the control by 2 and 5 yr after treatment (see Fig. 3, Table 2). By 10 yr after treatment, residual grass cover was statistically similar for all treatments compared with the control but averaged lower on the disk imprinter (5.8% ± 0.95%) than other mechanical plots (11.7% ± 1%, see Fig. 3 and Table 2). Sandberg bluegrass was a major residual grass, with 4.1% ± 0.18% cover before treatment. The first year after treatment, its cover was decreased compared with the control by all treatments except the spring aerator and chain treatments (see Fig. S1 [available online at https://doi.org/10.1016/j.rama.2018.01.006], Table 2). However, by the second yr after treatment it had recovered to equal that of the control on all but the disk imprinter treatment. Even 10 yr after disk-imprinting, Sandberg bluegrass cover was only 1.1% ± 0.33% compared with 3.0% ± 0.15% for all other treatments, including the control. By 10 yr after treatment, Sandberg bluegrass was 51% of the total residual grass cover on the control and 22% on the mechanical treatments. Another important residual grass was western wheatgrass, which had 1.8% ± 0.25% pretreatment cover. Western wheatgrass cover was decreased initially and even after 10 yr by the disk imprinter. In contrast, its cover increased on all other treatments to be greater than the control by 10 yr after treatment (see Fig. S1). By that time, cover averaged 2.2% ± 0.78% for the control, 3.3% ± 0.68% for the disk imprinter, and 5.8% ± 1.18% for all other treatments. At 10 yr after treatment, western wheatgrass was 23% of total residual perennial grass on the control and 49% on the mechanical treatments. Cheatgrass had < 1% cover for all treatments and years except that it was 1.4% ± 0.77% for the disk imprinter and 1.9% ± 0.26% for the one-way harrow 10 yr after treatment.

Residual forb cover averaged 4.2% ± 0.1% before treatment in 2001 (Fig. 4). Compared with the control, the spring aerator treatment decreased residual forb cover the first 2 yr after treatment while the disk imprinter decreased it over the 10-yr measurement period (see Fig. 4, Table 2).

Seeded Species Cover

Disk imprinting had the highest seeded grass cover initially and over the 10-yr measurement period (see Fig. 3). All other treatments also increased seeded grass cover compared with the control, but not as much as the disk imprinter (see Fig. 3, Table 2). By 10 yr after disk imprinting, seeded grass cover was 16.5% ± 1.22%, compared with 0.08% ± 0.05% on the control and 2% ± 0.1% on all other treatments. Across all the mechanical treatments and by 10 yr after treatment, wheatgrass (*Agropyron cristatum* [L.] Gaertn. X *Agropyron desertorum* [Fisch. ex Link] J. A. Schultes-'Hycrest' and *Elymus repens* [L.] Gould X *Pseudoroegneria spicata* [Pursh] Á. Löve–'Newhy'), intermediate wheatgrass (*Thinopyrum intermedium* [Host] Barkworth & D. R. Dewey), and Russian wildrye (*Psathyrostachys junceus* [Fisch.] Nevski-'Bozoisky-Select') were 73%, 10%, and 13% of seeded grass cover.

Seeded forb cover was < 1% on all except the disk imprinter treatment (see Fig. 4). On that treatment, maximum cover was 3.5% ± 0.39% 5 yr after treatment and 2.4% ± 0.14% 10 yr after treatment. Although the Lawson aerator and one-way harrow treatments increased seeded forb cover compared with the control on some years, the disk imprinter, chain, and two-way harrow were the only treatments to have significantly higher seeded forb cover than the control by 10 yr after treatment, and the disk imprinter had significantly higher cover than the chain treatment (see Table 2). Blue flax (*Linum perenne* L.) was the main seeded forb species that established (95% of total seeded forb cover across all years) and the only one that persisted 10 yr after treatment.

Forb Cover

Annual forb cover was significant for year and the two-way interaction but was not significant for treatment ($P > 0.349$). Annual forb cover was similar for all treatments for most years (see Fig. 4, Table 2). The disk imprinter treatment consistently had the highest annual forb cover across the measurement years, but cover was similar for all treatments by 10 yr after treatment. Cover significantly increased ($P < 0.05$) for all treatments from 0.6% ± 0.09% pretreatment to 5.6% ± 0.35% 10 yr after treatment. Total perennial forb cover was initially decreased below that of the control by the spring aerator and disk imprinter treatments, but cover was similar for all treatments by 5 and 10 yr after treatment (see Fig. 4, Table 2).

Annual Grass Cover

Cheatgrass was the only annual grass encountered. Cheatgrass cover was significant for year ($P < 0.001$) but only marginally significant for treatment ($P = 0.1$) and the interaction of year and treatment ($P = 0.055$). Cover was especially low on the control for all years measured (< 0.03% ± 0.01%) and for all mechanical treatments from 2002 through 2006 (< 0.3% ± 0.22%). However, by 2011 it increased to an average of 1.3% ± 0.41% for all mechanical treatments in 2011. Highest cover was for the one-way harrow (1.9% ± 0.26%).

Perennial Grass Cover

Perennial grass cover generally followed the same pattern as residual grass cover for all but the disk-imprinter treatment (see Fig. 3, Table 2). The spring aerator, harrow, and disk-imprinter treatments all had greater perennial grass cover than the control at 5 yr after treatment (see Table 2). Because of higher seeded grass cover, the disk imprinter had higher perennial grass cover than the control and some of the other treatments 3, 5, and 10 yr after treatment. By 10 yr after treatment, the disk imprinter treatment had higher perennial grass cover (22.3% ± 1.41%) than all other treatments (12.4% ± 0.71%) except the two-way harrow treatment (15.9% ± 2.07%).

Ground Cover

Total herbaceous vegetation cover was decreased compared with the control (36.4 ± 1.66) by all treatments (16.0% ± 0.47%) the first yr after treatment. By the second yr after treatment, total herbaceous cover had recovered to equal that of the control on the harrow treatments. By 5 yr after treatment, herbaceous cover was similar on all treatments and similar to pretreatment percentages. Cryptobiotic soil cover was decreased compared with the control by the disk imprinter and two-way harrow treatments for all measurement years (see Fig. 5, Table 2). Other treatments had lower cryptobiotic cover than the control on some years, but 10 yr after treatment the spring aerator, chain, disk imprinter, and two-way harrow all had lower cover than the control. At that time, cryptobiotic cover was 7.4% ± 0.75% for the control and averaged 0.9% ± 0.1% for all other treatments. Litter cover was

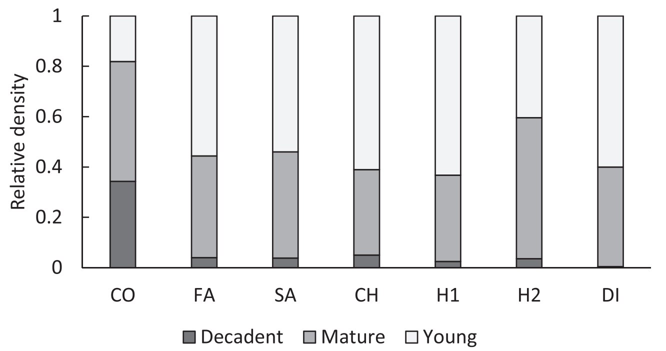

Figure 2. Relative density of big sagebrush in three categories and 10 yr after mechanical treatments (see Table 2 for abbreviations). Young = stem diameter < 1 cm, mature = stem diameter ≥ 1 cm, decadent (> 25% of crown is dead).

high for all treatments (> 20%) for most years. It was initially increased relative to the control by all but the disk imprinter and two-way harrow treatments (see Fig. 5, Table 2). By 10 yr after treatment, litter cover was still higher on the spring aerator (43.2% ± 1.92%) and chain (43.8% ± 0.64%) treatments than on the control (32.9% ± 0.54%), while litter cover on all other treatments was similar to the control. Bare ground was increased relative to the control the first year after treatment by all but the chain and one-way harrow treatments (see Fig. 5, Table 2). Most treatments had greater bare ground than the control the second yr after treatment, but by the fifth yr, only the disk imprinter (49.7% ± 2.54%) and two-way harrow (45.4% ± 4.59%) had greater bare ground than the control (33.8% ± 0.73%). By 10 yr after treatment, all treatments had similar bare ground (31.5% ± 1.13%).

Cover Group Relationships

The various mechanical treatments and subsequent plant succession resulted in an array of functional group or species associations 10 yr after treatment. Although there were a number of independent variables that were significantly either positively or negatively correlated with sagebrush cover, only three of them were significant ($P < 0.05$) when the control and disk imprinter treatments were omitted. For the dependent variables that had a significant correlation with sagebrush cover with the control and disk imprinter data included, but not when those data were excluded, the main inference is about the effect of the disk imprinter: The disk imprinter treatment most negatively affected sagebrush, cryptobiotic, Sandberg bluegrass, annual forb, residual forb, and rabbitbrush cover while this treatment positively affected seeded grass and seeded forb cover. The three variables that were significantly correlated with sagebrush cover without the control and imprinter treatments were litter ($r = 0.62$), western wheatgrass ($r = -0.60$), and perennial grass cover ($r = -0.51$).

Community and Surface Cover Composition

By 10 yr after treatment, the mechanical treatments and seeding resulted in different community compositions (Fig. 6). Sagebrush ranged from a low of 4.5% ± 0.68% relative cover for the disk imprinter to a high of 49.5% ± 2.56% for the control. The other mechanical treatments ranged from 22.8% ± 3.92% to 33.4% ± 3.37% relative cover of sagebrush. The control had the least relative cover of perennial grass (18.7% ± 1%), while the disk imprinter had the most relative cover of perennial grass (67.4% ± 0.71%) and the least cover of rabbitbrush (4.6% ± 0.7%). The other treatments had generally less relative cover of rabbitbrush and more perennial grass cover than the control. By 10 yr after treatment, most treatments had similar relative cover of annual forbs (11.2% ± 0.75% to 15% ± 0.94%), which was much higher than previous years (0.3% ± 0.2% to 10% ± 4.7%). Relative cover of perennial forbs was more consistent over the years and ranged from a low of 7.0% ± 0.95% for the spring aerator to a high of 11.8% ± 2.26% for the control 10 yr after treatment.

Sagebrush was retained in all of the mechanical treatments, but its cover and density varied among the treatments. All mechanical treatments reduced the number of decadent big sagebrush shrubs compared with the control (see Fig. 2). With major sagebrush control from disk-imprinting, sagebrush cover recovered to only 6% of the control, while density recovered to 29% of the control 10 yr after treatment. Over half of the sagebrush plants in most of the mechanical treatments were young (stem diameter < 1 cm, see Fig. 2) and all treatments except the disk imprinter had > 1.3 times the sagebrush density and 35 − 59% as much cover as the control. Thus, all the mechanical treatments except disk imprinting changed the sagebrush population to more and smaller plants, with less cover than the control. While reducing sagebrush cover, all mechanical treatments increased perennial grass cover.

Ten yr after treatment, the control community was dominated by big sagebrush (24.5% ± 0.35%) and rabbitbrush (2.7% ± 1%), with an understory of residual perennial grasses (9.2% ± 0.81%), annual (7.1% ± 1.12%), and perennial forbs (6% ± 1.41%). All mechanical treatments, except the disk imprinter had similar cover of sagebrush (9 ± 1.68% to 14.6 ± 1.36%) and residual native perennial grasses (9.2% ± 0.81%

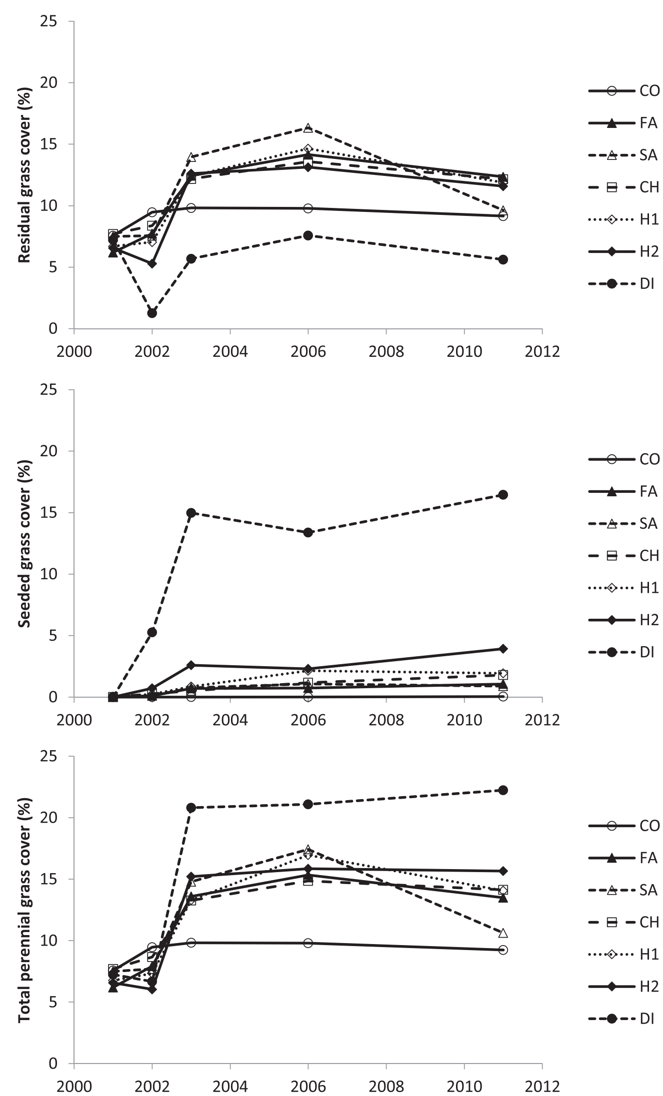

Figure 3. Residual (top), seeded (middle), and total (bottom) perennial grass cover for up to 10 yr after mechanical treatments. See Table 2 for treatment abbreviations and significant differences.

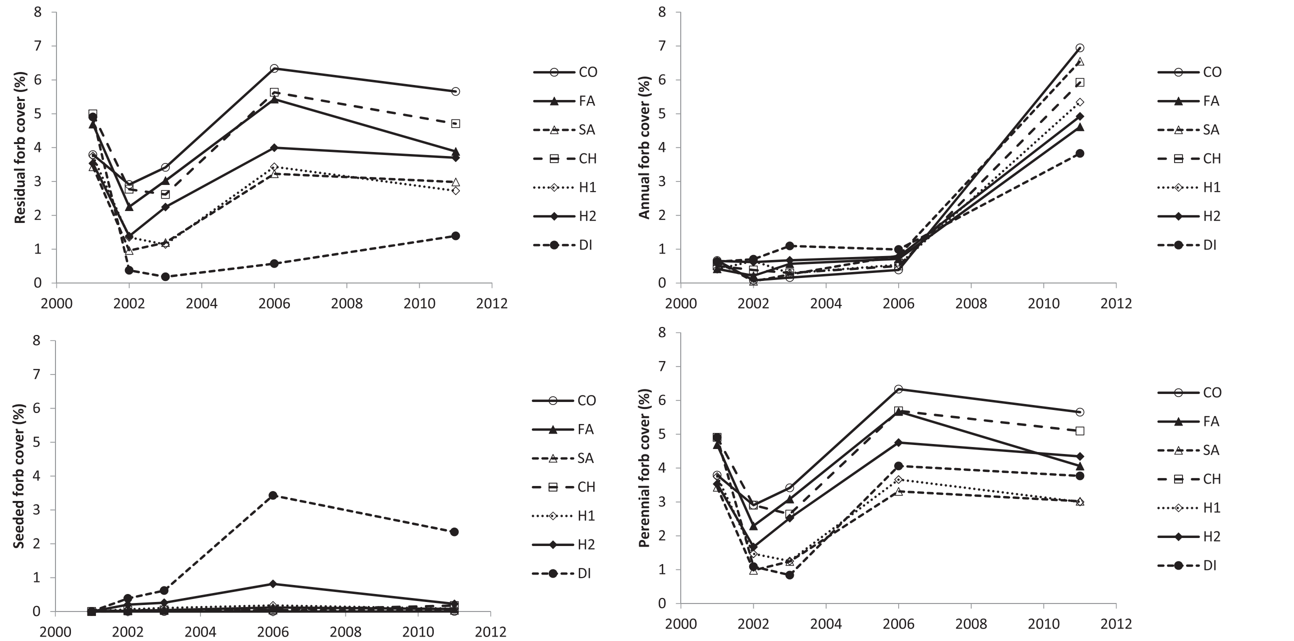

Figure 4. Residual (top left), seeded (bottom left), annual (top right), and perennial (bottom right) forb cover for up to 10 yr after mechanical treatments. See Table 2 for treatment abbreviations and significant differences.

to 12.4% ± 0.38%) with rabbitbrush (5.4% ± 1.04% to 7.3% ± 1.2%) and annual (4.7% ± 0.71% to 6.6% ± 0.46%) and perennial forbs (3.1% ± 0.41% to 5.2% ± 0.74%) as subdominants. Disk imprinting resulted in the greatest change in composition. Perennial grasses were dominant (22.3% ± 1.41%) with residual grasses (5.8% ± 0.95%) comprising much lower cover than seeded grasses (16.5% ± 1.22%), which were mainly introduced and hybrid wheatgrasses. Sagebrush (1.6% ± 0.28%) and rabbitbrush (1.6% ± 0.28%) were minor components, with perennial forbs (3.8% ± 0.21%—mainly seeded blue flax) and annual forbs (3.9% ± 0.44%) making up the rest of the community. Annual cheatgrass was < 2.2% ± 1.39% cover across all mechanical treatments.

Relative surface cover of bare ground was highest for the disk imprinter (50.8% ± 0.19%) and two-way harrow treatments (48% ± 6.34%) and lowest for the spring aerator (40.4% ± 1.27%), chain (40% ± 2.30%), and one-way harrow treatments (40% ± 1.76%) (see Fig. 5). Lower relative surface cover of bare ground for these three treatments was associated with higher relative litter cover (> 58%) compared with the other treatments (< 49%). Absolute surface cover of bare ground was similar for the control (32.5% ± 2.79%) and disk imprinter (33.7% ± 2.31%), but relative cover of bare ground was lower for the control (44.5% ± 2.71%). Relative and absolute cryptobiotic surface cover were highest for the control (10.2% ± 1.23% and 7.3%) and much lower for the other treatments (< 2.6% ± 1.17% and < 1.3%).

Discussion

Greater soil and root disturbance associated with the disk imprinter treatment resulted in more reduction in residual perennial grass and shrub species but greater establishment and cover of seeded perennial grasses than the other mechanical treatments. Some of the other mechanical treatments temporarily reduced residual species and increased seeded species cover, but these effects did not persist or were limited compared with those of the disk imprinter 10 yr after treatment. Competition between big sagebrush and bunchgrass seedlings or mature plants has long been observed (Robertson and Pearse, 1945; Cook and Lewis, 1963; Frischknecht, 1963; Rittenhouse and Sneva, 1976). Shrub control studies in sagebrush steppe report limited to major increases in perennial herbs depending on amount of invasive species response, residual shrub survival, associated revegetation success, soil depth, and climatic conditions that support subsequent natural seedling establishment of both herbs and sagebrush (Cook and Lewis, 1963; Hedrick et al., 1966; Harniss and Murray, 1973; Davis, 1979; Blaisdell, 1982; Davies et al., 2007, 2012b; Boyd and Svejcar, 2011; Pyke et al., 2014). Sagebrush varies in the time of its recovery from major reduction in the absence of subsequent disturbance (Blaisdell 1982; Sturges, 1993; Watts and Wambolt, 1996; Ellsworth et al., 2016). Seeded sagebrush establishment can be limited by concurrently seeded perennial grasses (Richardson et al., 1986; Schuman et al., 1998; Hild et al., 2006). Seedlings transplanted into even highly competitive crested wheatgrass have successfully established (Davies et al., 2013), but transplant survival is greatly increased by reducing competition (McAdoo et al., 2013).

The shallow and deep roots of big sagebrush allow it to extract soil water from winter and spring precipitation, while its deep tap roots maintain it through summer drought (Dobrowolski et al., 1990; Inouye, 2006; Ryel et al., 2010). Competition between big sagebrush and mature bunchgrasses results from overlapping roots in the upper 30 cm of soil, where nitrogen is most available for growth during spring and early summer (Lefler and Ryel, 2012). Bunchgrasses are competitive with big sagebrush for soil nitrate (Leonard et al., 2008). Interactions of big sagebrush with associated bunchgrasses can vary, depending on soils and soil water dynamics associated with precipitation inputs (Holthuijzen and Veblen, 2015). For example, negative effects of big sagebrush on bunchgrass growth are especially exacerbated where restrictive soil layers limit shrub tap roots (Frischknecht, 1963). Sagebrush is also directly competitive with bunchgrasses for phosphorus (Caldwell et al., 1985, 1987). On the other hand, bunchgrasses can benefit from phosphorus taken up through mycorrhizal associations with sagebrush roots (Allen and Allen, 1990), deeper soil water lifted by sagebrush tap roots (Richards and Caldwell, 1987), and moderated environmental conditions, as well as higher soil nutrient concentrations under sagebrush canopies (Davies et al., 2007). These beneficial effects may help explain why sagebrush reduction does not always increase herbaceous growth.

Failure of seeded species to establish well without control of competing species that use similar resources led to the principle of competition control (Roundy and Call, 1988; Roundy, 1996; Monsen et al. 2004; Pyke et al., 2017) or designed disturbance (Krueger-Mangold et al., 2006; Mangold, 2012) in successful rangeland revegetation and

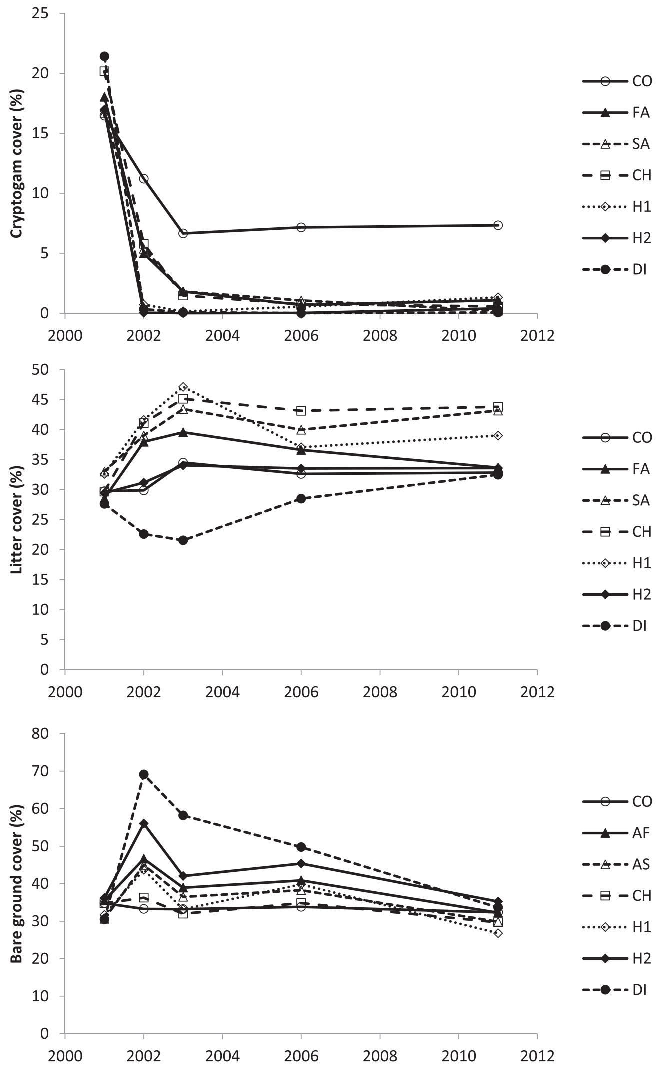

Figure 5. Cryptogam (top), litter (middle), and bare ground (bottom) cover for up to 10 yr after mechanical treatments. See Table 2 for treatment abbreviations and significant differences.

restoration. For example, resprouting rabbitbrush can limit establishment of other species (West, 1999). Our results support the concept that major shrub reduction is needed for successful establishment of perennial grasses. The Lariat soil series where our study was conducted has a depth to sandstone parent material of 0.8 m. This depth should have been sufficient to avoid exacerbated sagebrush-grass competition, which occurred in the study of Frischknecht (1963). Huber-Sannwald and Pyke (2005) reviewed potentially beneficial effects of sagebrush on seedling establishment and reported high survival of both crested and bluebunch wheatgrass seedlings in intact big sagebrush stands. However, such plantings have not been tested beyond small-plot experimental scales. Holthuijzen and Veblen (2015) found positive associations of Sandberg bluegrass and bottlebrush squirrel tail with sagebrush canopies. Such positive associations may be a function of beneficial environmental conditions that outweigh competitive effects or protection from livestock grazing, or both (Boyd and Davies, 2010; Reisner et al., 2013; Holthuijzen and Veblen, 2015).

By 10 yr after treatment, the control continued to be dominated by sagebrush with perennial grasses and annual and perennial forbs as subdominants. Most of the mechanical treatments had dominance equally shared by big sagebrush and residual native perennial grass with lesser amounts of seeded grasses and annual and perennial forbs. In contrast, the disk imprinter community was dominated by seeded perennial grasses (mainly introduced and hybrid wheatgrasses), with residual grasses and annual and perennial forbs (mainly seeded blue flax) as subdominants. Big sagebrush and rabbitbrush were minor components of the disk imprinter community. These successional outcomes may each support different management goals with shrub dominance supporting endangered species and perennial grass dominance supporting large herbivores, weed resistance, and soil conservation (Hoelzle et al., 2012). Studies of chemical thinning of big sagebrush in Wyoming (Baxter, 1998) indicated that reduction from 36% to 15% cover increased plant and small mammal diversity and that sagebrush density did not increase over the 10-yr period since treatment. However, in our study, community composition varied over time. Based on statistical differences between 2006 and 2011, residual and seeded grass cover was similar for most treatments while annual and perennial forb cover increased for most treatments and the control (see Table 2). The spring aerator treatment had a downward trend for residual grasses and an upward trend for sagebrush and rabbitbrush cover. The two-way harrow and disk imprinter treatments also had an upward trend in sagebrush cover, and all of the mechanical treatments had an upward trend in sagebrush density. Sagebrush will probably continue to increase on all of the treatments but may be slower on the disk imprinter treatment due to greater abundance of perennial grasses (Boyd and Svejcar, 2011). Wyoming big sagebrush is known to recover from both chemical (McDaniel et al., 2005) and mechanical (Wambolt and Payne 1986) control, even in conjunction with seeding perennial grasses. Although crested wheatgrass interferes with Wyoming big

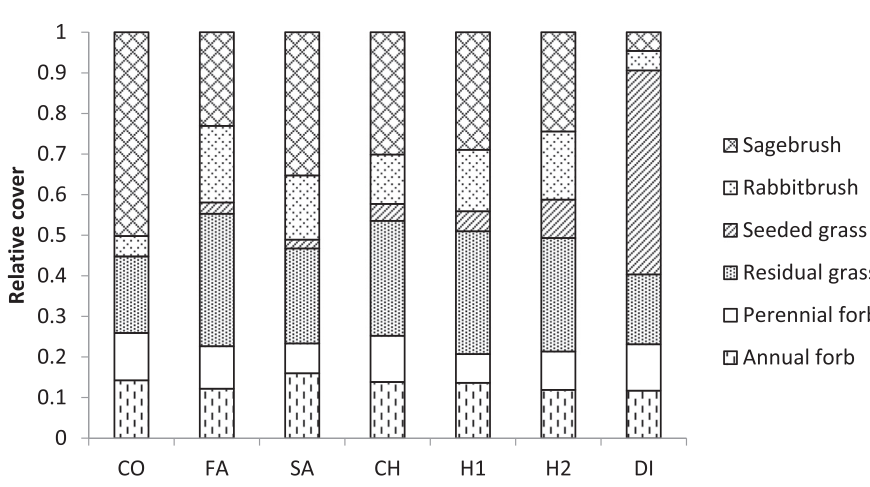

Figure 6. Relative cover of plant groups 10 yr after mechanical treatments. SB indicates big sagebrush; RB, rabbitbrush; SG, seeded grass; RG, residual grass; PF, perennial forb; AF, annual forb. For treatment abbreviations, see Table 2.

sagebrush seedling establishment (Gunnell et al., 2010), sagebrush still has the ability to reestablish and codominate stands of crested wheatgrass (Rittenhouse and Sneva, 1976; Williams et al., 2017).

The highest-disturbance treatments, two-way harrow and disk-imprinting, were the only treatments that resulted in greater perennial grass cover 10 yr after treatment than the control (see Fig. 3, Table 2). Disk-imprinting had lower residual grass, sagebrush, and rabbitbrush cover than the two-way harrow treatment, which had higher residual grass cover (see Figs. 1 and 3). However, most of the seeded grass cover was from introduced and hybrid wheatgrasses. Greater soil disturbance may not only reduce competition from associated plants but also help bury seeds and improve germination and establishment (Roundy, 1996; Ott et al., 2003, 2017; Hardegree et al., 2016). Introduced grasses have often been used preferentially to native grasses due to establishment ability, seed availability, and cost (Roundy et al., 1997; Davies et al., 2011). Current emphasis on use of native species in rangeland restoration for wildlife may require advanced approaches to improve their consistent establishment (James et al., 2012; Knutson et al., 2014; Hardegree et al., 2017), although successful native species revegetation at the operational scale has been reported by Thompson et al. (2006) and Ott et al. (2016, 2017).

Dominance by cheatgrass and other invasive weeds after fire and other vegetation disturbances has been a major concern in the sagebrush ecosystem. Cheatgrass had very limited cover in our study but increased to a maximum of 1.9% $\pm$ 0.26% in the one-way harrow 10 yr after treatment. Maintaining high perennial grass cover is critical for resisting cheatgrass, especially on Wyoming big sagebrush sites (Chambers et al., 2017). Longer-term effects of our mechanical treatments on cheatgrass cover should be followed.

Management Implications

Big sagebrush vegetation treatments resulted in different community compositions or states over time. These compositions could favor different management objectives. Leaving the Wyoming big sagebrush community untreated resulted in its continued dominance by decadent sagebrush with limited cover of perennial grasses (< 10%). This community might favor some wildlife species but be least resistant to cheatgrass dominance after wildfire. The disk imprinter treatment best controlled big sagebrush and also best established and maintained seeded perennial grasses, even though the majority of this cover was from introduced or hybrid wheatgrasses. This community would best favor grazers and should best resist weed invasion. The other mechanical treatments reduced sagebrush cover by about half but did not significantly increase perennial grass cover by 10 yr after treatment. The dominant native grass on most of these treatments was Sandberg bluegrass. These treatments would favor wildlife species dependent on greater structural diversity but would not maximize herbaceous forage production. Big sagebrush recruited on all mechanical treatments but least on the disk imprinter treatment. In this study, greater control of sagebrush and residual herbs was necessary to best establish seeded species and increase the perennial grass component.

Supplementary data to this article can be found online at https://doi.org/10.1016/j.rama.2018.01.006.

References

Allen, E.B., Allen, M.F., 1990. The mediation of competition by mycorrihizae in successional and patchy environments. In: Tilman, D., Grace, J.B. (Eds.), Perspectives in plant competition. Academic Press, San Diego, CA, USA, pp. 367–389.

Bailey, A.W., Poulton, C.E., 1968. Plant communities and environmental interrelationships in a portion of the Tillamook burn, Northwest Oregon. Ecology 49, 1–13.

Baxter, G., 1998. Thinning big sagebrush stands with Spike 20P. Rangelands 20, 14–16.

Beck, J.L., Connelly, J.W., Reese, K.P., 2009. Recovery of greater sage-grouse habitat in Wyoming big sagebrush following prescribed fire. Restoration Ecology 17, 393–403.

Beck, J.L., Connelly, J.W., Wambolt, C.L., 2012. Consequences of treating Wyoming big sagebrush to enhance wildlife habitats. Rangeland Ecology & Management 65, 444–455.

Blaisdell, J.B., Murray, R.B., McArthur, E.D., 1982. Managing intermountain rangelands-sagebrush-grass ranges. USDA Forest Service Intermountain Forest and Range Experiment Station, Ogden, UT, USA 41 p.

Bonham, R.J., 1989. Measurements for terrestrial vegetation. John Wiley and Sons, New York, NY, USA.

Bork, C.E., West, N.E., Walker, J.W., 1998. Three-tip sagebrush steppe responses to long-term seasonal sheep grazing. Journal of Range Management 51, 293–300.

Boyd, C.S., Davies, K.W., 2010. Shrub microsite influences post-fire perennial grass establishment. Rangeland Ecology & Management 63, 248–252.

Boyd, C.S., Svejcar, T.J., 2011. The influence of plant removal on succession in Wyoming big sagebrush. Journal of Arid Environments 75, 734–741.

Briske, D.D., Bestelmeyer, B.T., Stringham, T.K., Shaver, P.L., 2008. Recommendations for development of resilience-based state-and-transition models. Rangeland Ecology & Management 61, 359–367.

Bureau of Land Management, 1996. Utilization studies and residual measurements, Interagency Technical Reference, BLM/RS/ST-96/004 + 1730. BLM, Washington, DC, USA.

Caldwell, M.M., Eissenstat, D.M., Richards, J.H., Allen, M.F., 1985. Competition for phophorus: differential uptake from dual-isotope—labelled soil interspaces between shrub and grass. Science 229, 384–386.

Caldwell, M.M., Richards, J.H., Manwaring, J.H., Eissenstat, D.M., 1987. Rapid shifts in phosphate aquisition show direct competition between neighboring plants. Nature 237, 615–616.

Chambers, J.C., Roundy, B.A., Blank, R.R., Meyer, S.E., Whittaker, A., 2007. What makes Great Basin sagebrush ecosystems invasible by *Bromus tectorum?* Ecological Monographs 77, 117–145.

Chambers, J.C., Miller, R.F., Board, D.I., Pyke, D.A., Roundy, B.A., Grace, J.B., Schupp, E.W., Tausch, R.J., 2014. Resilience and resistance of sagebrush ecosystems: Implications for state and transition models and management treatments. Rangeland Ecology & Management 67, 440–454.

Chambers, J.C., Board, D.I., Roundy, B.A., Weisberg, P.J., 2017. Removal of perennial herbaceous species affects response of Cold Desert shrublands to fire. Journal of Vegetation Science 1–10, https://doi.org/10.1111/jvs.12548.

Cook, C.W., Lewis, C.E., 1963. Competition between big sagebrush and seeded grasses on foothill ranges in Utah. Journal of Range Management 16, 245–250.

D'Antonio, C.M., Vitousek, P.M., 1992. Biological invasions by exotic grasses, the grass/fire cycle, and global change. Annual Review Ecology and Systematics 23, 63–87.

Daubenmire, R., 1959. A canopy coverage method of vegetation analysis. Northwest Science 33, 43–66.

Davies, K.W., Bates, J.D., 2014. Attempting to restore herbaceous understories in Wyoming big sagebrush communities with mowing and seeding. Restoration Ecology 22, 608–615.

Davies, K.M., Bates, J.D., Miller, R.F., 2006. Vegetation characteristics across part of the Wyoming big sagebrush alliance. Rangeland Ecology & Management 59, 567–575.

Davies, K.M., Bates, J.D., Miller, R.F., 2007. The influence of *Artemisia tridentata* ssp. *wyomingensis* on microsite and herbaceous vegetation heterogeneity. Journal of Arid Environments 69, 441–457.

Davies, K.M., Boyd, C.S., Beck, J.L., Bates, J.D., Svejcar, T.J., Gregg, M., 2011. Saving the sagebrush sea: An ecosystem conservation plan for big sagebrush plant communities. Biological Conservation 144, 2573–2584.

Davies, G.M., Bakker, J.D., Dettweiler-Robinson, E., Dunwiddie, P.W., Hall, S.A., Downs, J., Evans, J., 2012a. Trajectories of change in sagebrush steppe vegetation communities in relation to multiple wildfires. Ecological Applications 22, 1562–1577.

Davies, K.M., Bates, J.D., Nafus, A.M., 2012b. Mowing Wyoming big sagebrush communities with degraded herbaceous understories: has a threshold been crossed? Rangeland Ecology & Management 65, 498–505.

Davies, K.M., Boyd, C.S., Nafus, A.M., 2013. Restoring the sagebrush component in crested wheatgrass-dominated communities. Rangeland Ecology & Management 66, 472–478.

Davies, K.W., Vavra, M., Schultz, B., Rimbey, N., 2014. Implications of longer term rest from grazing in the sagebrush steppe. Journal of Rangeland Applications 1, 14–34.

Davis, W.F., 1979. Mechanical control of sagebrush. The sagebrush ecosystem: a symposium. Logan, UT: Utah State University. pp. 49–53.

Dobrowolski, J.P., Caldwell, M.M., Richards, J.H., 1990. Basin hydrology and plant root systems. In: Osmond, C.B., Pitelka, L.F., Hidy, G.M. (Eds.), Plant biology of the basin and range. Springer, Berlin, Germany, pp. 243–292.

Ellsworth, L.M., Wrobleski, D.W., Kauffman, J.B., Reis, S.A., 2016. Ecosystem resilience is evident 17 years after fire in Wyoming big sagebrush ecosystems. Ecosphere 7, 1–12.

Frischknecht, N.C., 1963. Contrasting effects of big sagebrush and rubber rabbitbrush on production of crested wheatgrass. Journal of Range Management 16, 70–74.

Gunnell, K.L., Monaco, T.A., Call, C.A., Ransom, C.V., 2010. Seedling interference and niche differentiation between crested wheatgrass and contrasting native Great Basin species. Rangeland Ecology & Management 63, 443–449.

Hardegree, S.P., Jones, T.A., Roundy, B.A., Shaw, N.L., Monaco, T.A., 2016. Assessment of range planting as a conservation practice. Rangeland Ecology & Management 69, 237–247.

Hardegree, S.P., Abatzoglou, J.T., Brunson, M.W., Germino, M.J., Hegewisch, K.C., Moffet, C.A., Pilliod, D.S., Roundy, B.A., Boehm, A.R., Meredith, G.R., 2018. Weather-centric rangeland revegetation planning. Rangeland Ecology & Management 71, 1–11.

Harniss, R.O., Murray, R.B., 1973. 30 years of vegetal change following burning of sagebrush-grass range. Journal of Range Management 26, 322–325.

Hedrick, D.W., Hyder, D.N., Sneva, F.A., Poulton, C.E., 1966. Ecological response of sagebrush-grass range in eastern Oregon to mechanical and chemical removal of Artemisia. Ecology 47, 432–439.

Hess, J.E., Beck, J.L., 2012. Burning and mowing Wyoming big sagebrush: Do treated sites meet minimum guidelines for greater sage-grouse breeding habitats? Wildlife Society Bulletin 36, 85–93.

Hild, A.L., Schuman, G.E., Vicklund, L.E., Williams, M.I., 2006. Canopy growth and density of Wyoming big sagebrush sown with cool-season perennial grasses. Arid Land Research and Management 20, 183–194.

Hoelzle, T.B., Jonas, J.L., Paschke, M.W., 2012. Twenty-five years of sagebrush steppe plant community following seed addition. Journal of Applied Ecology 49, 911–918.
Holthuijzen, M.F., Veblen, K.E., 2015. Grass-shrub associations over a precipitation gradient and their implications for restoration in the Great Basin, USA. PLoS One https://doi.org/10.1371/journal.pone.0143170.
Huber-Sannwald, E., Pyke, D.A., 2005. Establishing native grasses in a big sagebrush-dominated site: an intermediate restoration step. Restoration Ecology 13, 292–301.
Inouye, R.S., 2006. Effects of shrub removal and nitrogen addition on soil moisture in sagebrush steppe. Journal of Arid Environments 65, 604–618.
James, J.J., Rinella, M.J., Svejcar, T., 2012. Grass seedling demography and sagebrush steppe restoration. Rangeland Ecology & Management 65:409–417. https://doi.org/10.2111/REM-D-11-00138.1.
Knutson, K.C., Pyke, D.A., Wirth, T.A., Arkle, R.S., Pilliod, D.S., Brooks, M.L., Chambers, J.C., Grace, J.B., 2014. Long-term effects of seeding after wildfire on vegetation in Great Basin shrubland ecosystems. Journal of Applied Ecology 51, 1414–1424.
Krueger-Mangold, J.M., Sheley, R.L., Svejcar, T.J., 2006. Toward ecologically-based invasive plant management on rangeland. Weed Science 54, 597–605.
Kuchler, A.W., 1964. Potential natural vegetation of the conterminous United States. American Geographical Society, New York, NY, USA.
Lefler, A.J., Ryel, R.J., 2012. Resource pool dynamics: conditions that regulate species interactions and dominance. In: Monaco, T.A., Sheley, R.L. (Eds.), Invasive plant ecology and management. Linking processes to practice. CAB International, Oxfordshire, UK, pp. 57–78.
Leonard, E.D., Monaco, T.A., Stark, J.M., Ryel, R.J., 2008. Invasive forb, annual grass, and exotic forb competition with three sagebrush-steppe growth forms: acquisition of a spring 15N tracer. Invasive Plant Science and Management 1, 168–177.
Littell, R.C., Milliken, G.A., Stroup, W.W., Wolfinger, R.D., Schabenberger, O., 2006. SAS for mixed models. SAS Institute, Inc., Cary, NC, USA.
Mangold, J.M., 2012. Revegetation: Using current technologies and ecological knowledge to manage site availability, species availability, and species performance. In: Monaco, T.A., Sheley, R.L. (Eds.), Invasive plant ecology and management. Linking processes to practice. CAB International, Oxfordshire, UK, pp. 176–195.
McAdoo, J.K., Boyd, C.S., Sheley, R.L., 2013. Site, competition, and plant stock influence transplant success of Wyoming big sagebrush. Rangeland Ecology & Management 66, 305–312.
McDaniel, K.C., Torell, L.A., Ochoa, C.G., 2005. Wyoming big sagebrush recovery and understory response with tebuthiuron control. Rangeland Ecology & Management 58, 65–76.
Miller, R.F., Eddleman, L.L., 2001. Spatial and temporal changes of sage grouse habitat in the sagebrush biome. Oregon State University Technical Bulletin 151, Corvallis, OR, USA 35 p.
Miller, R.F., Heyerdahl, E.K., 2008. Fine-scale variation of historical fire regimes in sagebrush-steppe and juniper woodland: an example from California, USA. International Journal of Wildland Fire 17, 245–254.
Miller, R.F., Knick, S.T., Pyke, D.A., Meinke, C.W., Hanser, S.E., Wisdom, M.J., Hild, A.L., 2011. Characteristics of sagebrush habitats and limits to long-term conservation. In: Knick, S.T., Connelly, J.W. (Eds.), Greater sage-grouse-ecology and conservation of a landscape species and its habitats. University of California Press, Berkeley, CA, USA, pp. 145–184.
Miller, R.F., Chambers, J.C., Pyke, D.A., Pierson, F.B., Williams, C.J., 2013. A review of fire effects on vegetation and soils in the Great Basin region—response and ecological site characteristics. General Technical Report RMRS-GTR-308. US Forest Service, Rocky Mountain Research Station, Fort Collins, CO, USA 126 p.
Monsen, S.B., Stevens, R., Shaw, N.L., (compilers. 2004. Restoring western ranges and wildlands. Gen. Tech. Rep. RMRS-GTR-136-vol-1. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station 294 p.
Ott, J.E., McArthur, E.D., Roundy, B.A., 2003. Vegetation of chained and non-chained seedings after wildfire in Utah. Journal of Range Management 56, 81–91.
Ott, J.E., Cox, R.D., Shaw, N.L., Newingham, B.A., Ganguli, A.C., Pellant, M., Roundy, B.A., Eggett, D.L., 2016. Postfire drill-seeding of Great Basin plants: effects of contrasting drills on seeded and nonseeded species. Rangeland Ecology & Management 69, 373–385.
Ott, J.E., Cox, R.D., Shaw, N.L., 2017. Comparison of postfire seeding practices for Wyoming big sagebrush. Rangeland Ecology & Management 70, 625–632.
Pyke, D.A., Shaff, S.E., Lindgren, A.I., Schupp, E.W., Doescher, P.S., Chambers, J.C., Burnham, J.S., Huso, M.M., 2014. Region-wide ecological responses of arid Wyoming big sagebrush communities to fuel treatments. Rangeland Ecology & Management 67, 455–467.
Pyke, D.A., Chambers, J.C., Pellant, M., Knick, S.T., Miller, R.F., Beck, J.L., Doescher, P.S., Schupp, E.W., Roundy, B.A., Brunson, M., McIver, J.D., 2015. Restoration handbook for sagebrush steppe ecosystems with emphasis on greater sage-grouse habitat—Part 1. Concepts for understanding and applying restoration. US Geological Survey Circular 1416. US Geological Survey, Reston, VA, USA Available at: https://doi.org/10.3133/cir1416. Accessed 12 June 2017.
Pyke, D.A., Chambers, J.C., Pellant, M., Knick, S.T., Miller, R.F., Beck, J.L., Doescher, P.S., Schupp, E.W., Roundy, B.A., Brunson, M., McIver, J.D., 2017. Restoration handbook for sagebrush steppe ecosystems with emphasis on greater sage-grouse habitat—Part 3: Site level restoration decisions. US Geological Survey. Available at, Reston, VA, USA https://doi.org/10.3133/cir 1426. Accessed 5 September 2017.
Reisner, M.D., Grace, J.B., Pyke, D.A., Doescher, P.S., 2013. Conditions favouring Bromus tectorum dominance of endangered sagebrush steppe ecosystems. Journal of Applied Ecology 50, 1039–1049.
Rhodes, E.C., Bates, J.D., Sharp, R.N., Davies, K.W., 2010. Fire effects on cover and dietary resources of sage-grouse habitat. Journal of Wildlife Management 75, 755–764.
Richards, J.H., Caldwell, M.M., 1987. Hydraulic lift: substantial nocturnal water transport between soil layers by *Artemisia tridentata* roots. Oecologia 73, 486–489.
Richardson, B.Z., Monsen, S.B., Bowers, D.M., 1986. Interseeding selected shrubs and herbs on mine disturbance in southeastern Idaho. In: McArthur, E.D., Welch, B.L. (Eds.), Proceedings symposium on the biology of *Artemisia* and *Chrysothamnus*. USDA Forest Service Intermountain Research Station, General Technical Report INT-200, pp. 134–139 Ogden, UT, USA.
Rittenhouse, L.R., Sneva, F.A., 1976. Expressing the competitive relationship between Wyoming big sagebrush and crested wheatgrass. Journal of Range Management 29, 326–327.
Robertson, J.H., Pearse, C.K., 1945. Artificial reseeding and the closed community. Northwest Science 19, 56–66.
Roundy, B.A., 1996. Revegetation for wildlife. In: Krausman, P.R. (Ed.), Rangeland wildlife. Society for Range Management, Denver, CO, USA, pp. 355–368.
Roundy, B.A., Call, C.A., 1988. Revegetation of arid and semiarid rangelands. In: Tueller, P.T. (Ed.), Vegetation science applications to rangeland analysis and management. Kluwer Academic Publishers, Boston, MA, USA, pp. 607–635.
Roundy, B.A., Shaw, N.L., Booth, D.T., 1997. Using native seeds on rangelands. In: Shaw, N.L., Roundy, B.A. (Eds.), Proceedings: using seeds of native species on rangelands. General Technical Report INT-GTR-372. USDA Forest Service Intermountain Research Station, Ogden, UT, USA, pp. 1–8.
Ryel, R.J., Ivans, C.Y., Peek, M.S., Leffler, A.J., 2008. Functional differences in soil water pools: a new perspective on plant water use in water-limited ecosystems. Progress in Botany 69, 397–422.
Ryel, R.J., Leffler, A.J., Ivans, C., Peek, M.S., Caldwell, M.M., 2010. Functional differences in water-use patterns of contrasting life forms in Great Basin steppelands. Vadose Zone Journal 9, 548–560.
Schuman, G.E., Booth, D.T., Cockrell, J.R., 1998. Cultural methods for establishing Wyoming big sagebrush on mined lands. Journal of Range Management 51, 223–230.
Skousen, J.G., Brotherson, J.D., 1989. Pinyon-juniper chaining and seeding for big game in central Utah. Journal of Range Management 42, 98–103.
Stevens, R., Monsen, S.B., 2004. Guidelines for restoration and rehabilitation of principal plant communities. In: Stevens, R.S., Monsen, S.B., Shaw, N.L. (Eds.), Restoring western ranges and wildlands, Volume 1 USDA Forest Service Rocky Mountain Research Station, Fort Collins, CO, USA, pp. 199–258.
Stringham, T.K., W. C. K., Shaver, P.L., 2003. State and transition modeling: an ecological process approach. Journal of Range Management 56, 106–113.
Sturges, D.L., 1993. Soil-water and vegetation dynamics through 20 years after big sagebrush control. Journal of *Range Management* 46, 161–169.
Thompson, T.W., Roundy, B.A., McArthur, E.D., Jessop, B.D., Waldron, B., Davis, J.N., 2006. Fire rehabilitation using native and introduced species: a landscape trial. Rangeland Ecology & Management 59, 237–248.
USDA Soil Conservation Service, 1981. Soil survey of Rich County. US Government Printing Office, Washington, DC, USA.
Wambolt, C.L., Payne, G.F., 1986. An 18-year comparison of control methods for Wyoming big sagebrush in southwestern Montana. Journal of Range Management 39, 314–319.
Warton, D., Hui, F.K., 2011. The arcsine is asinine: the analysis of proportions in ecology. Ecology 92, 3–10.
Watts, M.J., Wambolt, C.L., 1996. Long-term recovery of Wyoming big sagebrush after four treatments. Journal of Environmental Management 46, 95–102.
West, N.E., 1983. Great Basin-Colorado Plateau sagebrush semi-desert. In: West, N.E. (Ed.), Temperate deserts and semi-deserts. Elsevier, New York, NY, USA, pp. 331–349.
West, N.E., 1999. Synecology and disturbance regimes of sagebrush steppe ecosystems. In: Entewistle, P.G., DeBolt, A.M., Kaltenecker, J.H., Steenhof, K. (Eds.), Sagebrush steppe ecosystems symposium. Bureau of Land Management, Boise, ID, USA, pp. 15–26.
West, N.E., Young, J.A., 2000. Intermountain valleys and lower mountain slopes. In: Barbour, M.G., Billings, W.D. (Eds.), North American terrestrial vegetation. Cambridge University Press, Cambridge, UK, pp. 256–284.
West, N.E., Provenza, F.D., Johnson, P.S., Owens, M.K., 1984. Vegetation change after 13 years of livestock exclusion on sagebrush semidesert in west central Utah. Journal of Range Management 37, 262–264.
Williams, J.R., Morris, L.R., Gunnell, K.L., Johanson, J.K., Monaco, T.A., 2017. Variation in sagebrush communities historically seeded with crested wheatgrass in the eastern Great basin. Rangeland Ecology & Management 70, 683–690.
Wisdom, M.J., Rowland, M.M., Suring, L.H., 2005. Habitat threats in the sagebrush ecosystem: methods of regional assessment and applications in the Great Basin. Alliance Communications Group, Lawrence, KS, USA.
Young, J.A., Eckert Jr., R.E., Evans, R.A., 1979. Historical perspectives regarding the sagebrush ecosystem. The sagebrush ecosystem: a symposium. Utah State University, Logan, UT, USA, pp. 1–13.