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Rough Surface and High-Forb Seed Mix Promote Ecological Restoration of Simulated Well Pads

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Because of disturbance and exotic plant invasions, ecological restoration is necessary for maintaining functional big sagebrush ecosystems in western North America. Downy brome control is often necessary in restoring this ecosystem type; however, many brome control measures hinder ecological restoration by limiting the types of plants which can be established. Microtopography manipulation may aid weed control by entrapping undesirable seeds. We undertook a field experiment at four sites in the Piceance Basin of western Colorado, USA to test the effects of microtopography (rough with brush mulch or flat with straw mulch), seed mix (high-forb or balanced), and herbicide (140 g ai ha^{-1} imazapic ammonium salt or none) on downy brome control and perennial plant establishment following disturbance. Three years post-treatment, downy brome had become established at two of the four sites, one each with high (GVM) and low (MTN) downy brome seed rain. At GVM, the rough/brush treatment augmented the effectiveness of imazapic, reducing downy brome biomass six-fold. At MTN, the rough/brush surface reduced downy brome biomass 10-fold in the absence of imazapic. Across all four sites, forb and shrub biomass were higher with the high-forb mix, and there was no effect of seed mix on downy brome or annual forb biomass. Restoring a full complement of plant functional groups in big sagebrush ecosystems may be aided by increasing forbs in seed mixes, and manipulating soil microtopography.

Nomenclature: imazapic ammonium salt; big sagebrush, *Artemisia tridentata* Nutt. ARTR2; downy brome, *Bromus tectorum* L. BROTE.

Key words: Cheatgrass, microcatchment, microtopography, propagule supply, oil and gas development, sage-grouse, seed dispersal.

Disturbance and degradation of ecosystems has prompted the development of the field of ecological restoration (Shackelford et al. 2013). A restored ecosystem is one with a characteristic, largely native species assemblage, containing all functional groups necessary for self-sustaining populations, ecosystem functions, and resiliency (Society of Ecological Restoration International Science and Policy Working Group 2004). Ecological restoration is a key strategy for limiting or offsetting losses in ecosystem services, biodiversity, and wildlife habitat when landscapes are impacted (Montoya et al. 2012; Wassenaar et al. 2013). The restoration of plant functional group diversity is a core goal of ecological restoration, as functional group diversity underlies restoration of function, stability, and ecosystem services (Montoya et al. 2012). Yet, restored ecosystems often do not reach pre-disturbance levels of function (Benayas et al. 2009). This is in part because of a need for better plant establishment techniques, especially in arid areas (Shackelford et al. 2013).

For instance, techniques for restoring big sagebrush (*Artemisia tridentata* Nutt.) communities in western North America are needed (Davies et al. 2011). Big sagebrush plant communities are often dominated by weedy annuals or competitive rhizomatous grasses following disturbance and restoration, rather than the diversity of native shrubs, forbs, and grasses present prior to disturbance (Newman and Redente 2001; Redente et al. 1984). Anthropogenic disturbances have fragmented and degraded sagebrush ecosystems, and these losses, in addition to those incurred by annual grass and conifer invasion, have reduced sagebrush to only 56% of its former extent (Davies et al. 2011; Schroeder et al. 2004). This has led to dramatic declines in sagebrush-obligate species, such as greater sage-grouse (*Centrocercus urophasianus* Bonaparte; Aldridge et al.

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Management Implications

Big sagebrush ecosystems in western North America are threatened by many factors, including downy brome invasion, conifer encroachment, and disturbance. Restoring downy brome-invaded ecosystems is difficult because many effective downy brome control measures, such as seeding competitive grasses or applying herbicides, impair the growth of desirable forbs and shrubs. Previous work has shown that downy brome seeds disperse more readily when the soil surface is flat or when vegetation is removed, such as following a fire or after the creation of an oil and gas well pad. In this study, we examined whether creating obstructions to seed dispersal could improve restoration. We tested three factors: (1) a rough soil surface, comprised of pothole-sized holes and mounds with brush mulch vs. a flat soil surface with straw mulch, (2) a high-forb seed mix, containing nearly 75% forbs by seed number, vs. a mix containing roughly equal numbers of forb, grass, and shrub seeds, and (3) imazapic herbicide at 140 g ai ha^{-1} vs. no herbicide. Downy brome established at two of the four sites, and at both of these, the rough surface helped to control downy brome. The rough surface combined with imazapic was most effective at a site that had some downy brome prior to disturbance, while the rough surface alone was effective at another site which was not invaded prior to disturbance. It is possible that the rough surface makes downy brome less competitive because the seeds get trapped in the holes, which have higher soil moisture, as downy brome is typically less competitive in wetter environments. The high-forb seed mix resulted in higher forb and shrub establishment, and lower grass establishment, than the balanced mix. Even so, grass cover was still higher than forb cover at most sites, and was higher than in the undisturbed communities. There was no difference in downy brome or weedy annual forbs due to seed mix, and the high forb cover produced by the high-forb mix is beneficial for sage-grouse habitat restoration. Seeding mostly forbs and shrubs at a high rate, 1600 seeds m^{-2}, should be considered in areas where erosion is not a concern. The imazapic treatment did control downy brome, but it also had a negative impact on grasses, forbs, and shrubs. The lack of perennial plant establishment led to higher annual forb cover in imazapic plots three years post-treatment. Extending the plant-back interval, applying at a lower rate, and restricting application to areas with downy brome presence prior to disturbance are recommended.

2008; Rowland et al. 2006; Schroeder et al. 2004). Restoring a full complement of plant functional groups is essential for sage-grouse conservation, as sage-grouse rely on grasses for nesting cover, on forbs for brood-rearing nutrition, and on shrubs for cover and winter forage (Aldridge and Brigham 2002; Crawford et al. 2004; Hagen et al. 2008; Huwer et al. 2008).

Restoration of big sagebrush ecosystems is complicated by the presence of downy brome or cheatgrass (*Bromus tectorum* L.), an invasive annual grass which has infested over 22 million ha in the western United States (Duncan et al. 2004). Downy brome may create monocultures, alter fire cycles (Balch et al. 2013; Davies and Nafus 2013), and change soil nutrient dynamics (Norton et al. 2004). Downy brome presents a serious obstacle to restoration (Davies et al. 2011) because of its phenology and life history traits. Downy brome often germinates in the fall and is capable of extending roots at temperatures as low as 3 C (37 F) (Harris 1967). By the time most native species germinate, downy brome will have already depleted soil water and nutrients (Harris 1967), limiting native seedling recruitment (Young et al. 1987). Downy brome is also an enormously prolific seed producer; stands can produce as many as 20,000 seeds m^{-2} (Hempy-Mayer and Pyke 2008). This is problematic because as few as 40 seeds m^{-2} can hinder growth of perennial grasses (Evans 1961).

While downy brome control is often necessary for restoration, finding control measures that do not compromise ecological restoration is challenging. One technique that has proven effective for brome control is planting highly competitive, non-native perennial grasses, such as pubescent wheatgrass (*Thinopyrum intermedium* Host. Barkworth & Dewey) or crested wheatgrass (*Agropyron desertorum* L.) (Davies et al. 2010; Whitson and Koch 1998). However, grass competition, particularly from competitive non-natives, hinders the establishment of other plant functional groups, such as forbs and shrubs (Hild et al. 2006; Redente et al. 1984). Another technique which has some effectiveness is the use of imazapic herbicide, an acetolactate synthase inhibitor that impedes plant growth (Cox 2003). Imazapic has been shown to reduce annual grasses with little effect on some perennials (Kyser et al. 2007). However, imazapic has a narrow selectivity window (Kyser et al. 2007), and injury to non-target species is a concern (Baker et al. 2009; Owen et al. 2011; Sbatella et al. 2011). Downy brome control by imazapic is inconsistent, and several studies have concluded that without other management actions, a single application of imazapic is not sufficient for restoration of native plant communities (Elseroad and Rudd 2011; Morris et al. 2009; Owen et al. 2011).

Clearly, additional tools are needed to improve ecological restoration of big sagebrush ecosystems when downy brome is present. Recently, it has been suggested that manipulating seed dispersal within restoration areas may be an additional tool for practitioners working in weedy areas (Johnston 2011; Monty et al. 2013). Manipulations may occur via microtopography, which has been shown to have a large influence on determining where seeds settle (Chambers 2000). For instance, obstructions such as shrub mimics or large holes effectively entrap many kinds of seeds (Chambers 2000). In the absence of any such obstructions, such as following a fire or a ground disturbance, downy brome seeds travel one to two orders of magnitude farther than in intact ecosystems (Johnston 2011; Monty et al. 2013). Manipulating microtopography may be an important component of restoration when disturbances are bordered by downy brome, as dispersal from the disturbance edge can provide a sufficient number of downy brome seeds to compromise restoration (Johnston 2011).

Microtopography manipulations may also benefit perennial plant establishment by providing microsites of higher soil moisture. In arid ecosystems, microcatchments can increase soil moisture and improve survival of transplants (Gupta et al. 1999; Li et al. 2006). Such treatments may decrease the competitive advantage of downy brome, which has been shown to compete more effectively when summer moisture is lower (Bradley 2009) and when soil moisture is more variable (Chambers et al. 2007). They may also improve the establishment of desirable perennials, whether or not downy brome is present. A potential disadvantage of using microtopography manipulation is that it precludes the use of techniques requiring a flat surface, such as drill seeders and straw mulch crimpers. Drill seeders provide precise seed placement and increased germination of many native grass species (Natural Resource Conservation Service 2011). Crimping straw mulch into the soil increases water infiltration and soil moisture (Wilson et al. 2004). Whether or not the potential benefits of mictrotopography manipulation outweigh those of a flat surface is unknown.

Ecological restoration is needed in the Piceance Basin of northwestern Colorado, USA. The Piceance Basin provides habitat for a threatened population of greater sage-grouse and winter range for the largest migratory mule deer (*Odocoileus hemionus* Rafin.) population in North America. The Piceance Basin is also rich in natural gas; as of April 2013, the 1.8 by 10^6 ha area contained about 24,000 gas wells (Colorado Oil and Gas Conservation Commission 2013). Downy brome is patchily prevalent, and ongoing disturbances may accelerate its invasion (Bradford and Lauenroth 2006). Overlapping critical habitats, resource development, and invasive plants create a need for effective ecological restoration in the area.

The main objective of this study is to examine the effects of microtopography, seed mix, and imazapic application on downy brome control and establishment of desirable perennial plants in disturbed areas of the Piceance Basin. Specific goals included addressing these questions: (1) does a roughened surface composed of brush mulch over pothole-sized holes aid in downy brome control? (2) does a high-forb seed mix promote habitat characteristics beneficial for sage-grouse, while controlling downy brome as well as a mix balanced by functional group? 3) how does imazapic application interact with microtopography to influence downy brome control and desirable plant establishment?

Materials and Methods

Site Description. In the Piceance Basin downy brome cover and dominant big sagebrush subspecies vary with elevation. Downy brome is prevalent at elevations less than ~ 1,800 m (6000 ft), and common at higher elevations where ground disturbances have occurred. Wyoming big sagebrush (*Artemisia tridentata* ssp. *wyomingensis* Beetle & Young) dominates at lower elevations up to ~2,100 m, and mountain big sagebrush (*Artemisia tridentata* ssp. *vaseyana* (Rydb.) Beetle) dominates at higher elevations (Cottrell and Bonham 1992). We selected four study sites ranging from 1,662 m to 2,216 m for this experiment: Grand Valley Mesa (GVM; 39.46°N, 108.06° W), Sagebrush (SGE; 39.83°N, 108.30°W), Mountain Shrub (MTN; 39.78°N, 108.33°W), and Wagon Road Ridge (WRR; 39.82°N, 108.46°W). Criteria for site selection included: slope < 5%, downy brome cover < 20%, sagebrush cover > 15%, and no evidence of recent fire. The GVM site is at 1662 m on loam soils in the Potts-Ildefonso soil complex. Dominant species include Wyoming big sagebrush, Utah juniper (*Juniperus osteosperma* Torr.), downy brome, needle-and-thread grass (*Hesperostipa comata* Trin. & Rupr.), and western wheatgrass [*Pascopyrum smithii* (Rydb.) Á. Löve]. The SGE site is at 2004 m on sandy loam soils in the Piceance soil series. Dominant species include Wyoming big sagebrush, western wheatgrass, needle-and-thread grass, Sandberg bluegrass (*Poa secunda* J. Presl), prairie junegrass [*Koeleria macrantha* (Ledeb.) Schult.], and scarlet globemallow [*Sphaeralcea coccinea* (Nutt.) Rydb.]. The MTN site is 2182 m on sandy clay soil in the Piceance soil series. Vegetation contains a mixture of mountain and Wyoming big sagebrush, green rabbitbrush [*Chrysothamnus viscidiflorus* (Hook.) Nutt.], Saskatoon serviceberry [*Amelanchier alnifolia* (Nutt.) Nutt. ex M. Roem.], western wheatgrass, needle-and-thread grass, Sandberg bluegrass, prairie junegrass, Indian ricegrass [*Achnatherum hymenoides* (Roem. & Schult.) Barkworth], bulbous bluegrass (*Poa bulbosa* L.), and spreading phlox (*Phlox diffusa* Benth.). The WRR site is at 2216 m on sandy loam soils in the Piceance soil series. Dominant vegetation includes mountain big sagebrush, Saskatoon serviceberry, and a similar understory to the MTN site, with the addition of a wider diversity of native forbs, including hawksbeard (*Crepis acuminata* Nutt.) and silvery lupine (*Lupinus argenteus* Pursh). Precipitation information for each site is included in Table 1.

Disturbance Simulation. Well pad disturbances measuring 31 m by 52 m were simulated in September 2008 by clearing vegetation then stripping and stockpiling the top 15 cm (5.9 in.) of topsoil. The subsoil was then cut and filled to create a level surface. The simulated well pad surface was kept weed-free through the 2009 growing season by spot treatment of emerging plants with 2% (v/v) glyphosate isopropylamine salt. In August 2009, sites were recontoured and stockpiled topsoil respread evenly across the surface.

Treatments. In October 2009, soils at all sites were ripped to 30 cm then disked to break up large soil clods using a

Table 1. Precipitation information recorded using RG3-M data logging rain gauges (Onset® Computer Corporation, Bourne, MA) installed on guyed posts at each site: Grand Valley Mesa (GVM), Sagebrush (SGE), Mountain Shrub (MTN), and Wagon Road Ridge (WRR). Summer data are June through August, fall data are September through November, and winter/spring data are December through May.

	Precipitation (mm)									
	2009		2010			2011			2012	
Site	Summer	Fall	Winter/spring	Summer	Fall	Winter/spring	Summer	Fall	Winter/spring	Summer
GVM	88.6	38.2	151.6	68.4	95.8	85.2	198.4	98.0	88.4	28.6
SGE	NA	NA	NA	111.4	69.2	102.6	84.0	44.6	†[a]	48.8
MTN	NA	NA	NA	91.4	75.4	169.6	110.8	74.0	50.2	47.0
WRR	62.3	57.9	†	106.2	66.0	110.8	189.0	81.0	44.4	77.0

[a] † = Data not available because of logger failure.

Plotmaster™ 400 (Tecomate Wildlife Systems, Inc.). Eight treatments were implemented, representing all combinations of three factors, each with two levels:

(1) surface (rough/brush or flat/straw)
(2) seed mix (high-forb or balanced)
(3) herbicide (imazapic or none).

Treatment assignment was completely randomized with three replications per site and a plot size of 9.1 m by 6.0 m (Figure 1). Due to space constraints resulting from a concurrent experiment, the herbicide treatment was only implemented at GVM and MTN.

The two surface treatments were chosen to allow comparison of contrasting and mutually exclusive strategies in oilfield restoration. The flat/straw treatment is similar to most restoration in the Piceance Basin area. In flat plots, lighter seeds were hand broadcasted then lightly raked, while heavier seeds were drill seeded approximately 1 cm deep using a Plotmaster 400 (Table 2). Flat plots were mulched with 4.0 metric tons ha^{-1} (1.7 tons ac^{-1}) weed-free straw which was crimped in place using a custom-built mini crimper pulled behind an all-terrain vehicle. The rough surface was created with a 331 Bobcat® compact excavator. Each hole measured approximately 130 cm by 80 cm by 50 cm deep. Eighteen holes were dug per plot, with removed material mounded next to each hole. In rough/brush plots, all planted species (Table 2) were hand-broadcasted, then lightly raked, and finally mulched with approximately 2 m^3 (70 ft^3) of brush per plot. The brush consisted of native shrub skeletons that had been grubbed off of the disturbed areas during the well pad simulation.

The high-forb seed mix contained nearly 75% forbs by seed number. Of the grasses included, 90% were bunchgrass species (Table 2). In the balanced mix, roughly equal numbers of forbs, shrubs and grasses were used. Both seed mixes contained exclusively native seeds. All species except big sagebrush were planted in mid-October, 2009. Big sagebrush seed was collected within 100 m of each site in November 2009 and hand-broadcasted on top of snow in all plots in December of 2009.

Imazapic plots were sprayed with 140 g ai ha^{-1} (8 oz. ac^{-1}) of imazapic (Plateau™, BASF Corporation, Ludwigshafen, Germany) applied with 550 L ha^{-1} (60 gal ac^{-1}) of water using a backpack sprayer shortly before seeding. In imazapic, flat/straw plots, the amount of water used in herbicide application was tripled to aid the herbicide in penetrating the straw mulch. In imazapic, rough/brush plots, imazapic was applied before application of brush mulch. All sites were fenced with 2.4 m fencing after experiments were implemented. This eliminated variability from site to site in the degree of browsing and grazing pressure from wildlife and livestock.

Vegetation Characterization. Ambient downy brome seed rain was quantified for 2009 to 2011 using 0.1 m^2 seed rain traps covered with Tree Tanglefoot (The Tanglefoot Company, Grand Rapids, MI), which is a sticky resin (Gage and Cooper 2004). Eight traps were set in systematically chosen locations in undisturbed vegetation surrounding each site. Downy brome seeds were counted and removed from traps mid-May to late September a mean of every 12 days.

Undisturbed vegetation cover at all sites was characterized in late June 2011 by six point-intercept transects 10 m in length placed systematically in undisturbed vegetation 10 m from the edge of the disturbed area. Fifty hits per transect were recorded to species following the method outlined by Herrick (Herrick et al. 2005).

Vegetation cover on treatment plots was measured in July of 2011 and 2012 using five systematically-placed 1 m^2 miniplots per plot. A grid containing 36 intersections was held over each miniplot, and point-intercept hits were measured at each grid intersection using a laser point-intercept sampling device (Synergy Resource Solutions, Bozeman MT). When calculating percent cover of a given

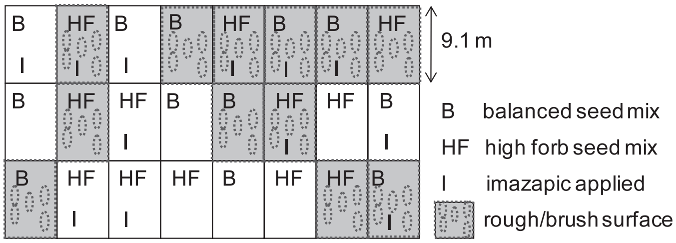

Figure 1. Layout of study plots at one of two sites where the full experiment was implemented. At two additional sites, an abbreviated form, omitting the imazapic treatment, was implemented.

functional group, such as perennial grasses, overlapping hits of different species within a functional group were counted as a single instance of the functional group.

Biomass was assessed in late July or early August 2012 using a double-sampling technique (Ahmed et al. 1983). Sixteen 0.25 m^2 subplots were arrayed systematically within each plot; 42% of these were clipped as well as estimated ocularly and 58% were estimated only. Ocular estimates were corrected using regressions based on sub life-form species groups with similar morphology (Ebrahimi et al. 2008). The average R^2 of these regressions was 0.84 (Appendix 1). Clipping and estimates included all standing aboveground biomass, live or dead, and the values therefore reflect a cumulative assessment of treatments on available wildlife forage.

Statistical Analysis. Response variables cover (2011 and 2012) and biomass (2012) of perennial grasses, perennial forbs, annual forbs, annual grasses, and shrubs were analyzed using a four–factor (site, seed mix, surface, and imazapic treatment) model in SAS PROC MIXED, Version 9.3 (SAS Institute 2012). Biennial forbs were combined with annual forbs for analysis. All factors were considered fixed effects. Transformations of response variables were performed to achieve approximately homogeneous variance and normality when the need was indicated by residual plots. Annual grass cover and biomass varied so greatly with both site and imazapic treatment that variance was not homogeneous, even after transformation. Therefore, separate variance estimates by site and imazapic were used in the models for these variables (in addition to transformation), a choice justified by lower Akaike information criterion values. No annual grass cover was detected at the SGE site in 2012; this site was excluded from the analysis for 2012 annual grass cover. A full model including all main effects and interactions was first considered, and a backwards model selection process was used to simplify the model. A significance level of $\alpha = 0.1$ was used to retain interaction terms, and a significance level of $\alpha = 0.05$ was used to retain main effects, subject to the restriction that a main effect was not a candidate for removal if it was involved in an interaction still in the model. Statistical comparisons of means associated with significant main effects and interactions were made in the transformed scale, but means are presented in graphs in the original scale. Where site by treatment interactions occurred, results are presented on a site-by-site basis. Because the imazapic treatment was only conducted at two of the four sites (GVM and MTN), separate backwards model selection processes were conducted for models with the imazapic treatment versus those without. Models excluding imazapic plots, but including all four sites, are summarized in the sections labeled ''in the absence of herbicide''. Models including imazapic plots, but excluding the SGE and WRR sites, are summarized in sections labeled ''interactions with herbicide treatment.'' Significant effects not involving the herbicide treatment are not discussed for this latter set of models, as they are addressed more comprehensively by the analysis including all four sites. In a few cases, significant interactions occurred which, when broken down by site, did not reveal significant lower-level interactions or main effect comparisons. Discussion of these interactions is omitted.

Results

The growing season of 2012 was exceptionally dry. Summer precipitation was 50 mm (2.0 in), while the prior years were 145 mm (2011) and 94 mm (2010), and the 30-year average (1981 to 2010) at the nearest long-running weather station is 129 mm (Western Regional Climate Center Little Hills, Colorado station, 1868 m in elevation, located ~20 km NW of the SGE site). Throughout the study area, unusual vegetation patterns were noted in 2012, including lower than normal prevalence of annuals and low productivity of perennials.

Ambient downy brome seed rain in 2009 to 2011 was 50–300 times higher at GVM than at any of the other three sites (Table 3).

Undisturbed vegetation varied by site (Figure 2). The lowest elevation site, GVM, was dominated by woody vegetation, with very little perennial grass or forb understory. At the other three sites, SGE, MTN, and WRR, cover of perennial grasses and shrubs was roughly equal at about 25%. Cover of perennial forbs was limited to 5% at SGE and 7% at MTN, but reached 20% at WRR (Figure 2).

Across sites, perennial vegetation cover on experimental plots was nearly synonymous with native cover, and annual cover was nearly synonymous with non-native cover. In 2011, 100% of perennial grass cover was native, 99% of perennial forb cover was native, and 100% of shrub cover was native. Shrub cover was primarily big sagebrush at SGE (63%), MTN (83%), and WRR (74%). At GVM, four-winged saltbush [*Atriplex canescens* (Pursh) Nutt.] comprised 60% of shrub cover, and big sagebrush comprised

Table 2. Seed mixes used. Species noted as "drill seeded" were drill seeded in plots with a flat/straw surface. In plots with a rough/brush surface, all seed was broadcast.

					Balanced mix		High-forb mix	
	Common Name	Variety	Scientific Name	Type	Seeds m^{-2}	PLS[b] ($kg\ ha^{-1}$)	Seeds m^{-2}	PLS ($kg\ ha^{-1}$)
Drill Seeded	Bluebunch wheatgrass	Anatone	*Pseudoroegneria spicata* ssp. *spicata*	grass	—	—	22	0.8
	Galleta grass	Viva	*Pleuraphis jamesii*	grass	75	2.2	—	—
	Indian ricegrass	Rimrock	*Achnatherum hymenoides*	grass	65	1.8	11	0.3
	Muttongrass	VNS	*Poa fendleriana*	grass	—	—	54	0.1
	Slender wheatgrass	San Luis	*Elymus trachycaulus* ssp. *trachycaulus*	grass	75	2.5	11	0.4
	Thickspike wheatgrass	Critana	*Elymus lanceolatus* ssp. *lanceolatus*	grass	65	1.9	—	—
	Western wheatgrass	Rosana	*Pascopyrum smithii*	grass	65	2.5	5	0.2
	Utah sweetvetch	Timp	*Hedysarum boreale*	forb	22	2.1	22	2.1
	Fourwing saltbush	VNS CO	*Atriplex canescens*	shrub	11	1.1	11	1.1
Broadcast seeded	Prairie junegrass	VNS	*Koeleria macrantha*	grass	—	—	54	0.1
	Bluestem penstemon*[a]	VNS	*Penstemon cyanocaulis*	forb	108	0.7	108	0.7
	Hairy false goldenaster*	VNS	*Heterotheca villosa*	forb	—	—	215	1.3
	Lewis flax	Maple Gr.	*Linum lewisii*	forb	54	0.8	54	0.8
	Lobeleaf groundsel*	VNS	*Packera multilobata*	forb	—	—	215	1.3
	Aspen fleabane*	VNS	*Erigeron speciosus*	forb	—	—	323	0.9
	Sulphur flower buckwheat*	VNS	*Eriogonum umbellatum*	forb	108	2.3	108	2.3
	Western yarrow*	VNS	*Achillia millefolium*	forb	129	0.2	129	0.2
	Winterfat	VNS	*Krascheninnikovia lanata*	shrub	22	0.8	22	0.8
	Big sagebrush	VNS	*Artemisia tridentata*	shrub	253	0.6	253	0.6
Grass total					344	9.8	156	1.7
Forb total					420	5.6	1173	8.7
Shrub total					285	2.2	285	2.2
Overall total					1049	17.6	1614	12.6

[a] Species denoted with an * are local ecotype.

[b] PLS = pure live seed.

Table 3. Ambient cheatgrass seed rain at Grand Valley Mesa (GVM), Sagebrush (SGE), Mountain Shrub (MTN), and Wagon Road Ridge (WRR) sites. No data were collected at SGE and MTN in 2009. Means are given ± SE for eight seed rain traps installed in undisturbed vegetation near each site.

	Seeds m^{-2}		
Site	*2009*	*2010*	*2011*
GVM	334.7 ± 8.9	127.8 ± 4.8	1297.2 ± 30.5
SGE	—	0.0 ± 0.0	4.2 ± 0.3
MTN	—	0.0 ± 0.0	*1.4 ± 0.1*
WRR	6.9 ± 0.5	1.4 ± 0.1	4.2 ± 0.3

13%. In 2011, 97% of annual forb cover was non-native, and 100% of annual grass cover was non-native. Downy brome comprised 98% of annual grass cover. Dominant annual forbs differed by site: at GVM 91% of annual forb cover was Russian thistle (*Salsola tragus* L.), at SGE 77% of annual forb cover was desert madwort (*Alyssum desertorum* Stapf), at MTN annual forb cover was 48% prickly lettuce (*Lactuca serriola* L.) and 21% desert madwort, and at WRR 79% of annual forb cover was tumble mustard (*Sisymbrium altissimum* L.).

Perennial Grasses in Absence of Herbicide. Perennial grass cover and biomass were significantly affected by seed mix (Table 4). Plant cover averaged across sites for the high-forb vs. balanced mixes were: 29.9% vs. 41.9% (2011) and 26.6% vs. 39.4% (2012). Biomass in 2012 was 65.6 g m^{-2} for the high-forb mix and 91.8 g m^{-2} for the balanced mix (see Figure 3 for site-specific effects). The effect of surface on perennial grasses depended on site (Table 4). The use of a rough/brush surface increased 2011 perennial grass cover from 23.7% to 41.3% at MTN [$t(39) = 3.77$, $p = 0.0005$] and from 31.8% to 41.5% at SGE [$t(39) = 2.06$, $p = 0.046$], and did not have significant effects at other sites ($p > 0.086$). In 2012, the rough/brush surface *reduced* perennial grass cover at WRR from 58.5% to 34.1% [$t(38) = 5.21$, $p < 0.0001$] but did not significantly affect other sites ($p > 0.1237$). In 2012, the rough/brush surface increased perennial grass biomass at MTN from 56.8 g m^{-2} to 122.5 g m^{-2} [$t(32) = 5.12$, $p < 0.0001$; Figure 4f, 'no imazapic' bars] and at SGE from 51.5 g m^{-2} to 74.7 g m^{-2} [$t(32) = 2.56$, $p = 0.015$], but reduced it at WRR from 166.3 g m^{-2} to 79.4 g m^{-2} [$t(32) = 4.97$, $p < 0.0001$]. A three way interaction between site, surface treatment, and seed mix for 2012 perennial grass biomass was also significant (Table 4). It may have been caused by a two way interaction that occurred at GVM but not at other sites. At GVM, the effect of the rough/brush treatment on biomass depended on seed mix; the rough/brush treatment reduced biomass from 53.1 g m^{-2} to 21.8 g m^{-2} in plots with the high-forb mix [$t(8) = 3.44$, $p = 0.0089$], but didn't have a detectible effect in plots with the balanced mix.

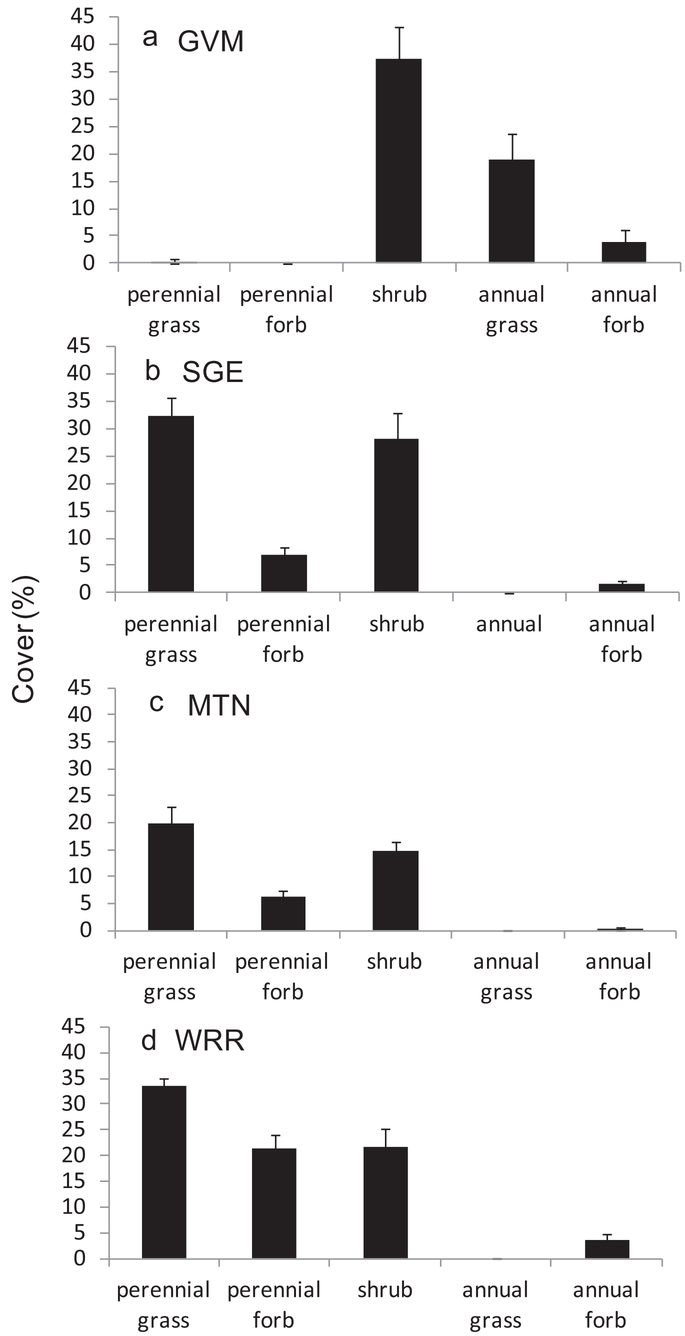

Figure 2. Percent cover by functional group in 2011 for undisturbed (control) vegetation near a) Grand Valley Mesa (GVM), b) Sagebrush (SGE), c) Mountain (MTN), and d) Wagon Road Ridge (WRR) study sites.

Perennial Grass Interactions with Herbicide Treatment. The effect of imazapic on perennial grasses depended on site for all responses measured (Table 5), with more detrimental effects at MTN than at GVM. In 2011,

Table 4. F-values and significance of the linear model for surface and seed mix treatments at all sites.

	Perennial grass[a]	Perennial forb[a]	Shrub[a]	Annual grass[b]	Annual forb[b]
2011 Cover					
Surface	6.23*	0.12	4.29*	5.78*	0.04
Seed mix	26.20***	28.79***	2.75	1.06	0.04
Site	10.46***	33.83***	4.31*	60.46***	13.34***
Surface by seed mix	1.97	0.69	1.15	0.09	2.49
Site by surface	5.45**	1.23	1.58	15.35***	0.45
Site b seed mix	0.36	0.51	1.87	0.65	0.91
Site by surface by seed mix	1.43	2.17	2.22	0.56	0.32
2012 Cover					
Surface	6.25*	9.52**	4.01*	1.59	—[c]
Seed mix	35.11***	33.89***	0.90	0.19	—
Site	30.73***	113.36***	1.59	1.91	—
Surface by seed mix	2.91	0.06	1.35	0.79	—
Site by surface	8.28***	1.04	1.70	4.30*	—
Site by seed mix	0.70	3.21*	0.78	1.85	—
Site by surface by seed mix	1.32	6.95**	9.49***	0.86	—
2012 Biomass					
Surface	0.55	1.09	2.37	1.14	1.22
Seed mix	14.48***	6.09*	4.60*	0.71	0.01
Site	38.19***	56.93***	3.76*	11.32***	1.03
Surface by seed mix	1.09	2.20	0.01	1.15	0.00
Site by surface	19.49***	2.17	0.26	3.12	0.73
Site by seed mix	0.89	0.37	1.03	1.09	0.05
Site by surface by seed mix	6.95**	1.01	2.98*	0.56	0.16

[a] Transformations: arcsin [sqrt (*cover*)] or log (*biomass*+15).

[b] Transformations: sqrt (*cover*) or log (*biomass*+0.01).

[c] — analysis omitted due to low annual forb cover.

$*p < 0.05$; $**p < 0.01$; $***\ p < 0.001$.

imazapic reduced perennial grass cover from 32.5% to 7.0% at MTN [$t(32) = 10.64$, $p < 0.0001$] and from 28.3% to 16.9% at GVM [$t(32) = 4.06$, $p = 0.0003$]. In 2012, imazapic did not detectably effect perennial grass cover or biomass at GVM, but at MTN, imazapic reduced cover from 37.6% to 9.8% [$t(40) = 11.63$, $p < 0.0001$] and reduced biomass from 89.6 g m^{-2} to 44.3 g m^{-2} [$t(40) = 4.75$, $p < 0.0001$]. For 2012 cover, a two-way interaction also occurred between imazapic and surface treatment (Table 5). In the absence of imazapic, no effect of surface treatment was evident, but with imazapic, the rough/brush treatment increased grass cover from 10.0% to 14.6% [$t(40) = 2.79$, $p = 0.008$].

Perennial Forbs in Absence of Herbicide. Perennial forb cover and biomass were significantly affected by seed mix (Table 4; see Figure 3 for site-specific effects). Across sites, the averages for the high-forb vs. balanced mixes were as follows: 25.7% vs. 15.9% (2011 cover); 16.5% vs. 10.7% (2012 cover); and 32.8 g m^{-2} vs. 23.6 g m^{-2} (2012 biomass). The rough/brush treatment had an effect only on 2012 forb cover (Table 4), reducing it from 15.1% to 12.1%. A three-way interaction between site, surface treatment, and seed mix was significant for 2012 perennial forb cover (Table 4). This interaction was likely to due to a two-way interaction between surface and seed mix at WRR ($p = 0.0037$). In rough/brush plots at WRR, perennial forb cover was 13.5% with the balanced mix and 8.3% with the high-forb mix [$t(8) = 3.37$, $p = 0.045$]. For other combinations of sites and surfaces, perennial forb cover was either higher with the high-forb mix, or similar between the seed mixes.

Perennial Forb Interactions with Herbicide Treatment. Perennial forb cover values in 2011 and 2012 were influenced by imazapic, site, and their interaction (Table 5), but no significant effect of imazapic was found for 2012 perennial forb biomass (Figures 4b and 4g). In 2011, imazapic reduced perennial forb cover at MTN from 28.7% to 17.7% [$t(33) = 3.18$, $p = 0.0032$], but there

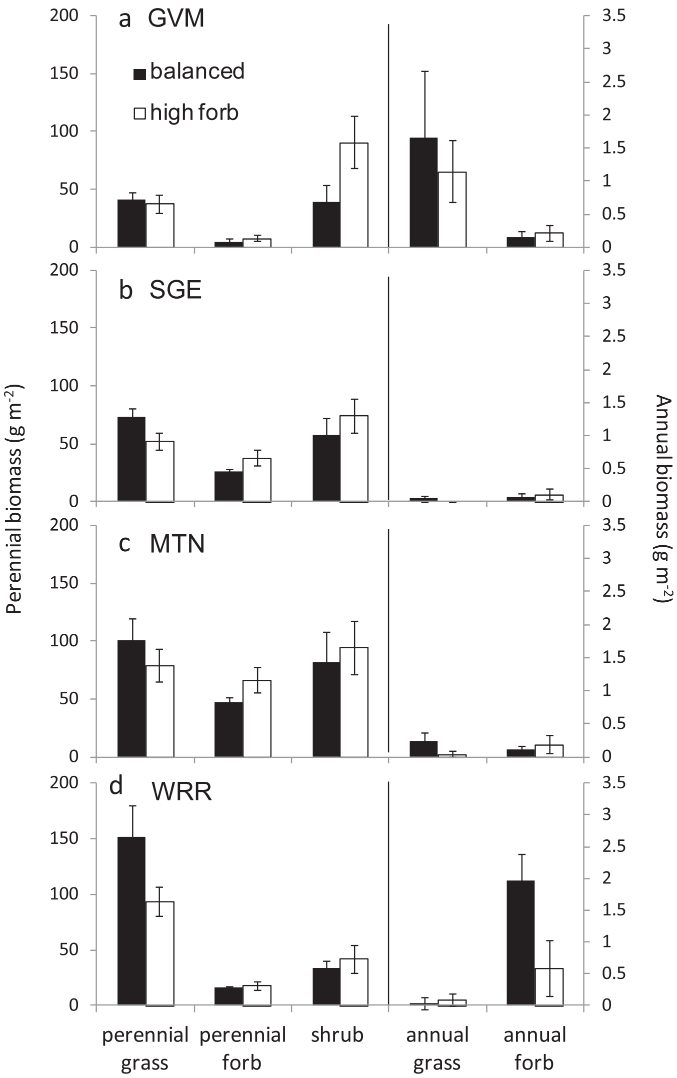

Figure 3. 2012 biomass of perennial grasses, perennial forbs, and shrubs (left axis) as well as annual grasses and annual forbs (right axis) in the absence of imazapic for plots with the balanced vs. high-forb seed mixes at 4 sites: a) Grand Valley Mesa (GVM); b) Sagebrush (SGE); c) Mountain Shrub (MTN); and d) Wagon Road Ridge (WRR). Error bars = standard error.

was no detectible effect at GVM. Similarly, in 2012, imazapic reduced perennial forb cover at MTN from 24.0% to 14.8% [$t(42) = 4.09$, $p = 0.0002$], but there was no effect detected at GVM.

Shrubs in the Absence of Herbicide. Although shrub cover was not affected seed mix, shrub biomass was higher with the high-forb mix. Shrub biomass was 42.0 g m^{-2} with the high-forb mix and 33.7 g m^{-2} with the balanced mix (Table 4; see Figure 3 for site-specific effects). Shrub cover was affected by surface in both years, but there was no main effect of surface on shrub biomass (Table 4). Shrub cover averages for rough/brush and flat/straw plots were: 5.8% and 8.5% (2011), and 7.4% and 9.8% (2012). A three-way interaction between site, surface treatment, and seed mix for also occurred for 2012 shrub cover. This was likely due to a two-way interaction between surface and seed mix which occurred at WRR ($p = 0.0009$) but was not evident at other sites. In flat/straw plots at WRR, shrub cover was 11.3% with the balanced mix and 2.4% with the high-forb mix [$t(8) = 4.28$, $p = 0.0027$]. In other combinations of site and surface, shrub cover was higher with the high-forb mix, or similar between the two mixes.

Shrub interactions with Herbicide Treatment. Shrub cover and biomass were influenced by the strong main effect of imazapic, and by a three-way interaction between site, imazapic, and surface for all responses (Table 5). At GVM, imazapic reduced all shrub responses, and did not interact with surface. In 2011, shrub cover was 2.9% in imazapic plots and 7.9% in no-imazapic plots [$t(32) = 4.25$, $p = 0.0002$]. In 2012, cover was 1.9% in imazapic plots and 8.5% in no-imazapic plots [$t(33) = 5.32$, $p < 0.0001$], and biomass was 33.54 g m^{-2} in imazapic plots and 65.3 g m^{-2} in no-imazapic plots [$t(40) = 2.63$, $p = 0.0121$; Figure 4c]. At MTN, imazapic and surface interacted for all three responses ($p < 0.006$). Without imazapic, surface had no significant effect ($p > 0.15$ for all three responses). In the presence of imazapic, 2011 shrub variables were higher in rough/brush plots: 2011 cover was 8.0% in rough/brush plots and 1.7% in flat/straw plots [$t(17) = 2.90$, $p = 0.0099$], 2012 shrub cover was 10.4% in rough/brush plots and 1.3% in flat/straw plots [$t(20) = 4.56$, $p = 0.0002$], and biomass was 273.3 g m^{-2} in rough/brush plots and 27.5 g m^{-2} in flat/straw plots [$t(20) = 4.56$, $p = 0.0002$; Figure 4h]. Shrub biomass was also influenced by an interaction between seed mix and imazapic (Table 5). Without imazapic, shrub biomass was influenced by seed mix as mentioned in the preceding paragraph; with imazapic, no effect of seed mix was evident.

Annual Grasses in the Absence of Herbicide. We detected no effect of seed mix on annual grasses for any response variable (Table 4). The effect of surface on annual grass cover and biomass depended on site (Table 4), with significant effects being detected only at MTN. At MTN in 2011, annual grass cover was 5.9% in rough/brush plots and 44.1% in flat/straw plots [$t(40) = 7.29$, $p < 0.0001$; Figure 5]. At MTN in 2012, annual grass cover was 0% in rough/brush plots and 7.0% in flat/straw plots [$t(40) = 6.51$, $p < 0.0001$], and annual grass biomass was 0.022 g m^{-2} in rough/brush plots and 0.27 g m^{-2} in flat/straw plots [$t(40) = 2.30$, $p = 0.027$; Figure 4i].

Annual Grass Interactions with Herbicide Treatment. In 2011, annual grass cover was significantly affected by imazapic (Table 5), with 4.8% cover in plots with

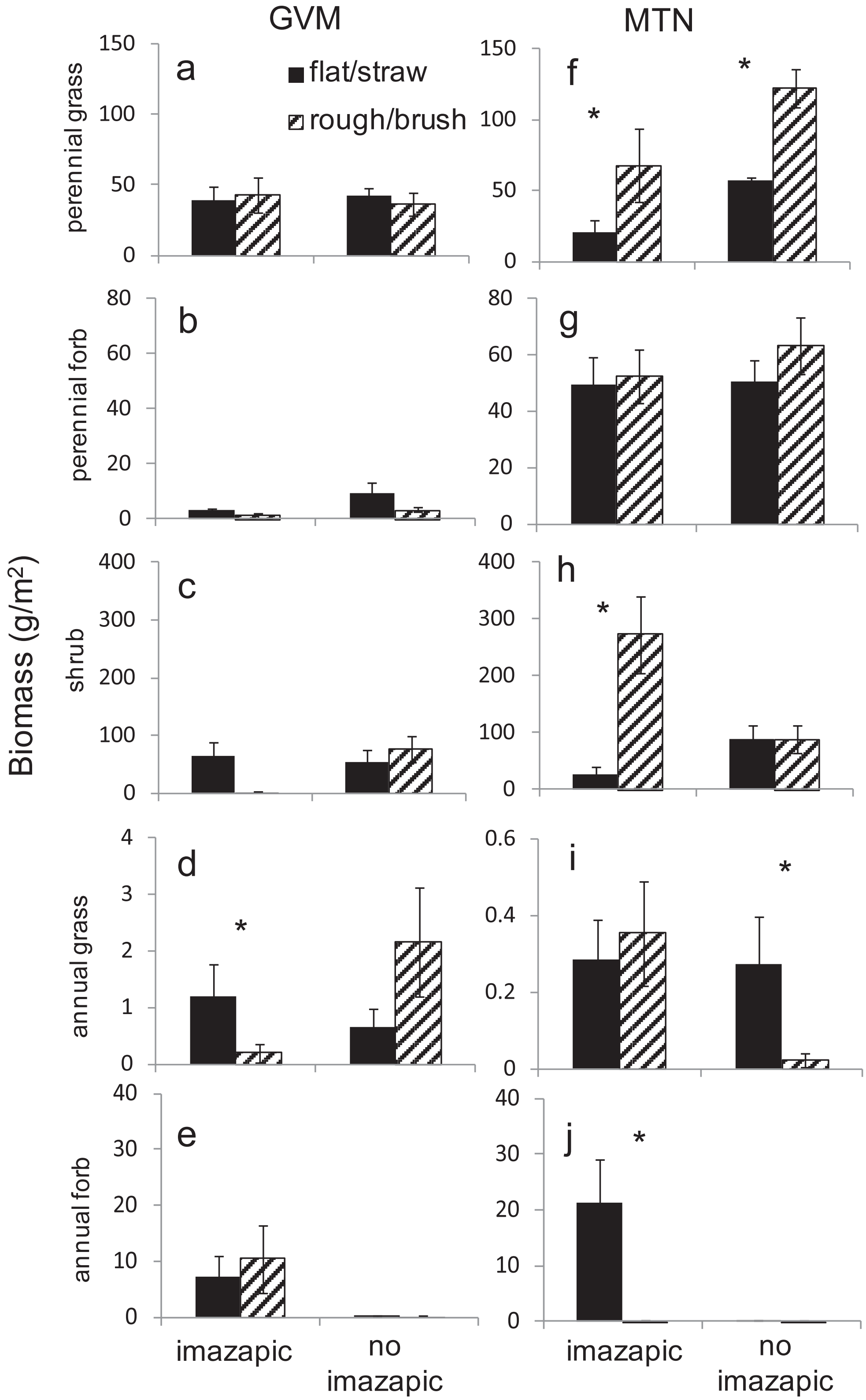

Figure 4. 2012 biomass of perennial grasses (a, f), perennial forbs (b, g), shrubs (c, h), annual grasses (d, i), and annual forbs (e, j) in response to imazapic and surface treatment at Grand Valley Mesa (GVM; a–e) and Mountain Shrub (MTN; f–j) sites. Data are averaged over seed mix treatment. Error bars = standard error of data in original scale. Asterisks denote significantly different ($p < 0.05$) means of data based on analysis in transformed scale.

Table 5. F-values and significance of the linear model for the analysis including herbicide effects.

	Perennial grass[a]	Perennial forb[a]	Shrub[a]	Annual grass[b]	Annual forb[b]
2011 Cover					
Imazapic	107.97***	6.46*	30.17***	52.52***	15.84***
Surface	21.98***	0.00	0.27	6.77*	2.38
Seed mix	18.71***	9.19**	5.12*	0.80	0.30
Site	8.35**	42.64***	10.46**	2.51	9.19**
Seed mix by imazapic	0.00	0.16	0.61	0.48	0.16
Surface by imazapic	0.00	0.38	8.14**	1.82	3.32
Surface by seed mix	0.50	1.19	0.47	1.31	0.10
Surface by seed mix by imazapic	0.25	0.28	0.21	2.64	3.51
Site by imazapic	21.64***	3.92	0.27	0.10	1.37
Site by surface	19.89***	9.32**	4.60*	3.98*	0.08
Site by seed mix	0.04	0.04	0.56	3.42	3.82
Site by seed mix by imazapic	0.00	1.69	0.00	4.44*	0.00
Site by surface by imazapic	2.48	1.73	5.93*	16.89***	0.72
Site by surface by seed mix	1.02	2.90	2.87	0.03	1.81
Site by surface by seed mix by imazapic	6.85*	1.28	4.40*	1.12	0.05
2012 Cover					
Imazapic	81.82***	2.97	36.69***	2.58	—[c]
Surface	1.43	3.98*	0.80	2.63	—
Seed mix	48.06***	12.92**	2.50	0.00	—
Site	10.68**	188.97***	6.13*	3.67	—
Seed mix by imazapic	0.08	0.50	0.00	2.38	—
Surface by imazapic	7.24*	0.87	9.39**	0.00	—
Surface by seed mix	0.98	1.83	3.78	0.02	—
Surface by seed mix by imazapic	0.49	0.15	0.45	2.92	—
Site by imazapic	51.10***	15.69***	3.22	1.71	—
Site by surface	4.40*	0.75	4.29*	2.05	—
Site by seed mix	0.66	0.31	0.10	4.91*	—
Site by seed mix by imazapic	0.24	0.24	0.01	2.59	—
Site by surface by imazapic	1.06	1.08	8.79**	6.77*	—
Site by surface by seed mix	1.75	2.11	4.14*	0.12	—
Site by surface by seed mix by imazapic	1.48	0.76	3.95	0.01	—
2012 Biomass					
Imazapic	11.88**	2.81	4.40*	0.04	56.36***
Surface	8.69**	0.12	1.41	1.52	9.96**
Seed mix	9.38**	2.63	0.05	0.24	0.05
Site	5.89*	224.85***	11.89**	4.76*	3.62
Seed mix by imazapic	3.34	0.66	4.63*	4.43*	0.01
Surface by imazapic	0.72	0.00	0.04	0.50	1.26
Surface by seed mix	2.58	0.22	2.56	0.24	0.34
Surface by seed mix by imazapic	1.15	0.03	0.40	2.31	1.69
Site by imazapic	10.27**	0.17	2.99	8.15**	0.15
Site by surface	12.06**	2.63	16.06***	0.32	13.08**
Site by seed mix	0.98	0.03	1.60	8.56**	0.45
Site by seed mix by imazapic	0.34	0.31	0.02	2.46	0.30
Site by surface by imazapic	0.00	0.46	23.93***	8.76**	8.93**
Site by surface by seed mix	0.13	0.93	0.95	0.02	0.13

Table 5. Continued.

	Perennial grass[a]	Perennial forb[a]	Shrub[a]	Annual grass[b]	Annual forb[b]
Site by surface by seed mix by imazapic	1.27	0.18	0.21	0.01	0.07

[a] Transformations: arcsin[sqrt(*cover*)] or log (*biomass*+15).

[b] Transformations: sqrt(*cover*) or log (*biomass*+0.01).

[c] — analysis omitted due to low annual forb cover.

$*p < 0.05$; $**p < 0.01$; $*** \ p < 0.001$.

imazapic, and 27.1% cover in plots without imazapic. In 2012, there was no main effect of imazapic on annual grass cover or biomass (Table 5). For all annual grass responses, a three-way interaction occurred between site, imazapic, and surface treatment (Table 5). For 2011 and 2012 cover, this was due to a two-way surface treatment by imazapic interaction, which occurred only at MTN ($p < 0.001$). At MTN, in plots without imazapic, annual grass cover in 2011 and 2012 was influenced by surface, as described in the prior paragraph, and there was no effect of surface in plots with imazapic (Figure 5). For 2012 biomass, a two-way surface by imazapic interaction occurred only at GVM ($p = 0.02$). At GVM in 2012, there was no effect of surface in plots *without* imazapic, but in plots with imazapic, annual grass biomass was 0.20 g m^{-2} with the rough/brush surface and 1.19 g m^{-2} with the flat/straw surface [$t(18) = 2.15$, $p = 0.0456$].

Annual Forbs. Annual forb cover in 2012 was very low and we did not detect any annual forb cover in 78% of plots. Due to the high proportion of zeros in the 2012 cover dataset, we chose to limit our analysis to 2011 cover and 2012 biomass. In the absence of herbicide, there were no effects of any treatments on 2011 cover ($p > 0.13$) or 2012 biomass ($p > 0.27$). Imazapic increased 2011 annual forb cover from 11.4% to 27.5% at GVM ($t[37] = 3.76$, $p = 0.0006$) and from 7.0% to 14.1% at MTN ($t[37] = 2.05$, $p = 0.047$). In 2012, imazapic increased annual forb biomass from 0.19 g m^{-2} to 8.9 g m^{-2} at GVM ($t[40] = 5.97$, $p < 0.0001$; Figure 4e). At MTN, a two-way interaction between imazapic treatment and surface occurred for 2012 annual forb biomass ($p = 0.0052$). Without imazapic, annual forb biomass averaged 0.15 g m^{-2} and no effect of surface was evident. With imazapic, annual forb biomass was 0.21 g m^{-2} in rough/brush plots ($t[20] = 5.88$, $p < 0.0001$; Figure 4j) and 21.3 g m^{-2} in flat/straw plots.

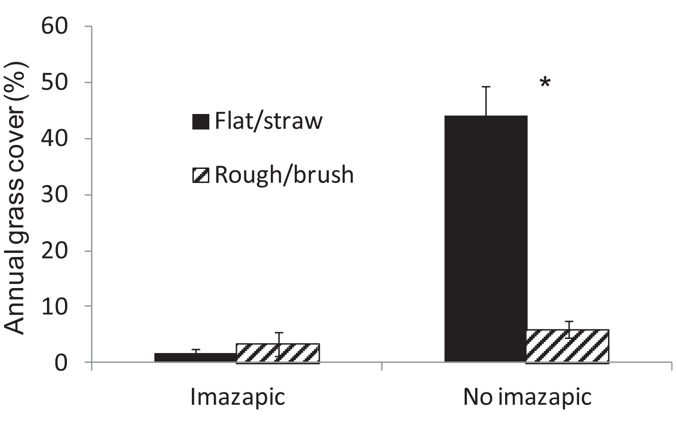

Figure 5. 2011 annual grass cover at the Mountain Shrub site in response to imazapic and surface treatment. Error bars= SE.

Discussion

The rough/brush treatment was successful at limiting cover and biomass of annual grasses, with the effects dependent on site. At SGE and WRR, very little annual grass established and there was no statistical effect of the surface treatment. Even so, annual grass biomass was detected in three plots at these sites in 2012, and all three were flat/straw plots. AT GVM and MTN, annual grass cover and biomass were higher. The surface treatment had significant effects and these depended on imazapic treatment in different ways at the two sites. At GVM, which had high downy brome seed rain, the rough/brush treatment was effective only when applied with imazapic, where it reduced 2012 annual grass biomass six-fold. At MTN, which had low downy brome seed rain, the rough/brush treatment was effective when applied without imazapic, lowering 2011 annual grass cover from 44% to 6% and 2012 annual grass biomass 12-fold (compare Figures 6e and 6f). The rough/brush treatment also reduced the biomass of weedy annual forbs 100-fold in plots with imazapic at MTN.

The effectiveness of the rough/brush treatment may be due to seed dispersal limitation and altered competitive dynamics. Prior work has shown that holes are effective at entrapping seeds (Chambers 2000); at sites with only a few downy brome seeds, the rough/brush treatment may be sufficient to limit downy brome to a small portion of the restoration area. Depressions or microcatchments also increase soil moisture (Gupta et al. 1999; Li et al. 2006), and several studies have shown downy brome to be a more effective invader with lower or more variable soil moisture (Bradford and Lauenroth 2006; Chambers et al. 2007; Shinneman and Baker 2009). The rough/brush treatment may control downy brome by trapping their seeds in an environment in which they are less competitive.

Effects of the rough/brush treatment on desirable perennial vegetation depended on functional group. Perennial forb cover in 2012, shrub cover in 2011, and shrub cover in 2012 were approximately 1/4 lower in rough/brush plots across sites, although no effect was seen on forb or shrub biomass. Higher forb and shrub cover in flat/straw plots could have been due to seeding method differences. In this study, soil surface type was coupled with compatible seeding techniques: in flat/straw plots, most grasses were drill seeded but most forbs and shrubs were broadcast seeded, while rough/brush plots were completely broadcast-seeded. There was some spatial separation of grass and forb/shrub seed in flat/straw plots, which may have aided shrub and forb establishment. The lack of difference in forb or shrub biomass between surface types suggests that those forbs and shrubs that did establish in rough/brush plots grew well. A comparison of photographs suggests that forbs and shrubs may have attained taller stature in rough/brush plots (Figure 6), which could explain why surface treatment affected cover but not biomass for forbs and shrubs.

The effect of the rough/brush treatment on perennial grasses was site-dependent: 2012 biomass was higher with the rough/brush treatment at SGE and MTN, but lower at WRR. At SGE and MTN, it appears that the microsites provided by the rough/brush treatment were helpful in aiding perennial grass establishment. At WRR, grass cover in flat/straw plots approached 60%; apparently, microsites were not needed for grass establishment. WRR is the highest elevation site with the least alkaline soils and highest average summer precipitation. At all sites, few plants established on the mounded soil between holes in rough/brush plots; therefore, a tradeoff between reduced cover on mounds and increased cover in holes occurs. Whether or not this tradeoff is worthwhile may depend on site conditions.

Overall the benefit of the rough/brush treatment in controlling weedy annuals appears to outweigh that of traditional flat surface restoration, which includes drill seeding and straw mulch application, at our study sites. It is worthwhile to note that the seeding rate between the two methods in this study was the same, even though the commonly given advice is that the seeding rate for broadcast seedings should be double that of drill seedings. In spite of this, desirable perennials established well in the rough/brush plots. At our sites, the loss of ability to drill seed and crimp in straw mulch does not seem sufficient to outweigh the benefits of microtopography manipulation.

The effect of seed mix was consistent across sites; the high-forb mix resulted in higher 2011 and 2012 forb cover, higher 2012 forb biomass, and higher 2012 shrub biomass than the balanced seed mix.

While both mixes resulted in good cover of all functional groups, the higher forb and shrub dominance with the high-forb mix may be especially beneficial for wildlife. Forbs and shrubs are critical for re-establishing ecological functions in big sagebrush ecosystems; for instance, greater sage-grouse brood-rearing success increases with forb cover values exceeding 10% (Connelly et al. 2000), and shrubs provide winter nutrition for sage-grouse and mule deer as well as other ungulates. The high-forb mix differed from the balanced mix in having a much lower density of rhizomatous grass and by including three additional species of perennial forbs: Shinners hairy false goldenaster (*Heterotheca villosa* Pursh), lobeleaf groundsel (*Packera multilobata* Torr. and A. Gray ex A. Gray) and aspen fleabane (*Erigeron speciosus* Lindl.). Other forbs, and all shrubs, were seeded at the same rate in both mixes (Table 2). Shinners hairy false goldenaster and lobeleaf groundsel established successfully; in high-forb plots in 2011, Shinners hairy false goldenaster cover was 1.0% and lobeleaf groundsel cover was 2.6%. Even so, these species account for less than half of the difference in forb cover between seed mixes. The rest of the difference in forb cover, and all of the difference in shrub biomass, is due to better establishment. Lessened grass competition is the most likely explanation for these responses.

The idea that seed mixes should limit the proportion of rhizomatous grasses in order to promote a mixed plant stand was proposed 30 years ago (Redente et al. 1984). However, seed mixes commonly used in reclamation continue to have a large proportion of rhizomatous grasses. This may occur because rhizomatous grasses are useful for erosion control, because appropriate forb seeds are expensive or unavailable, or out of a fear of weed invasion. We detected no effect of seed mix on annual forb cover in 2011 or 2012, annual forb biomass in 2012, or annual grass cover in 2011 or 2012. Studies in the North American tallgrass prairie have shown that high-forb seed mixes can inhibit weeds (Carter and Blair 2012; Dickson and Busby 2009), and our study shows a similar result for sites two and three years post-restoration in the Piceance Basin. High-forb seed mixes should be considered for areas where erosion is not a concern.

The imazapic treatment successfully controlled annual grasses, but caused an increase in annual forbs two and three years post-treatment and had either neutral or negative effects on perennials. A recent study has shown that increasing the plant-back interval to three months may minimize negative effects of imazapic on perennial grasses (Sbatella et al. 2011). A plant-back interval of one year has also been recommended for perennial bunchgrass seedings (Davies 2010). In this study, except for big sagebrush, species were seeded shortly after imazapic was applied; negative impacts may have been avoided if desirable plants had been seeded several months or more after imazapic application.

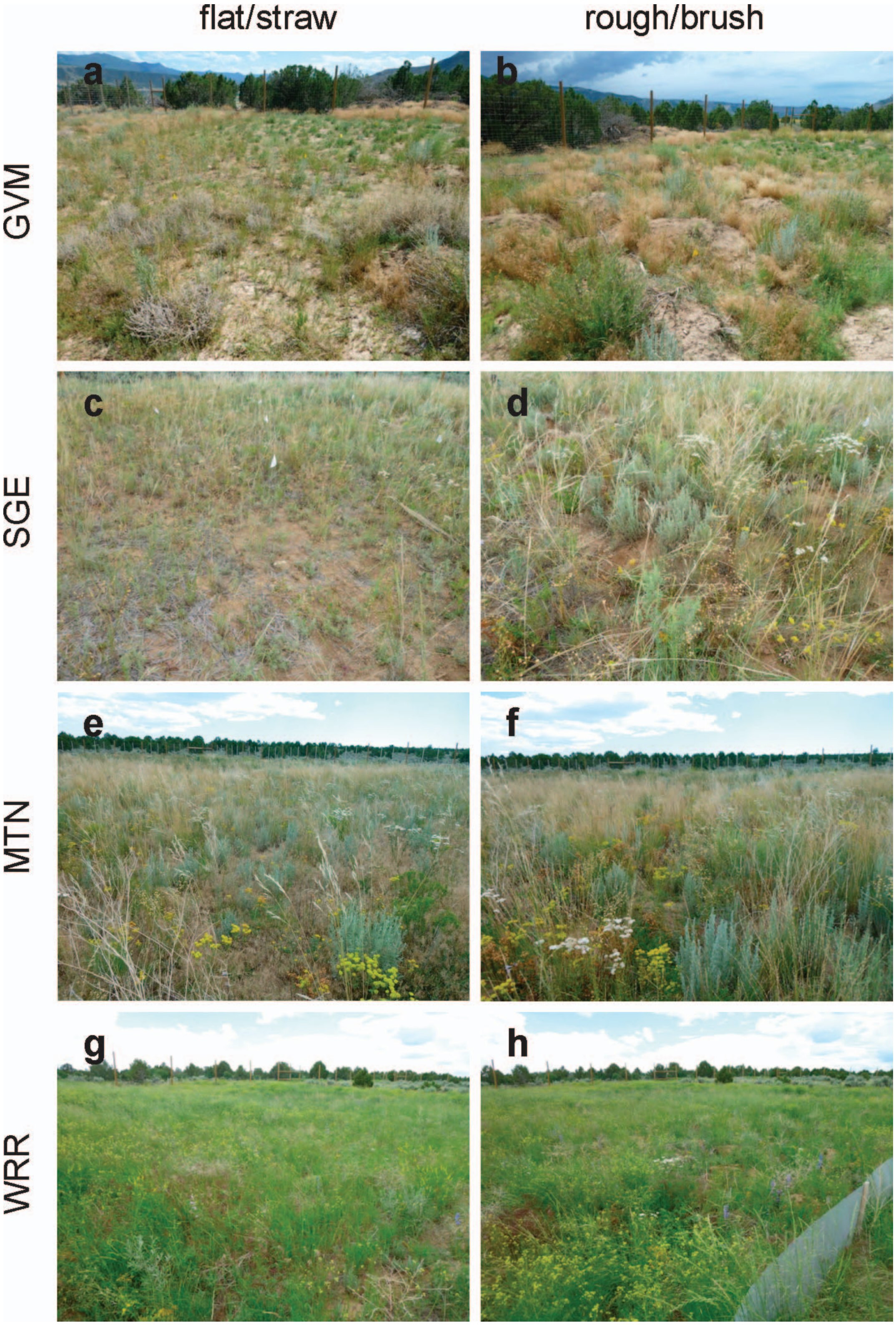

Figure 6. Comparison of flat/straw (a,c,e,g) and rough/brush (b,d,f,h) plots at the Grand Valley Mesa (GVM; a,b), Sagebrush (SGE; c,d), Mountain (MTN; e,f), and Wagon Road Ridge (WRR; g,h) sites. All plots were seeded with the high-forb mix and were not treated with imazapic. Except for GVM, all photos are of adjacent plots within a site.

Several studies have suggested that one-time imazapic treatment alone is not sufficient to restore big sagebrush communities dominated by downy brome (Elseroad and Rudd 2011; Morris et al. 2009; Owen et al. 2011). Combining imazapic with other control measures such as prescribed fire has been more effective (Barnes 2004; Davies and Sheley 2011). In this study, we found that combining imazapic with the rough/brush treatment led to better results. The rough/brush treatment plus imazapic caused a 10-fold decrease in weedy annual forb biomass at MTN, increased shrub cover and biomass at MTN, and lessened annual grass biomass three years post-treatment at GVM.

While the rough/brush treatment appears to have benefits, potential disadvantages must also be addressed. Injury to livestock and/or wildlife due to the holes may be a concern, therefore the minimum size of holes required to produce the desired results should be identified. Also, as fewer plants established on mounds between holes, further monitoring is needed to determine if these areas may eventually harbor weeds. Finally, implementing the rough surface treatment with a backhoe is expensive and time-consuming, which limits the practical scale of implementation. Creating a more efficient machine to produce the rough surface is the subject of ongoing research (Colorado Parks and Wildlife 2014).

Another ongoing research objective is to separate the contributions of brush mulch and rough surface to the results in this study. Brush and holes have similar impacts on some potential mechanisms, though the magnitude of those impacts may differ. Both brush and holes have been shown to entrap dispersing seeds, but the effect of holes appears to be larger than that of brush (Chambers 2000). Both brush (Roberts et al. 2005) and holes (Gupta et al. 1999) have been shown to create microsites of higher soil moisture, though it seems likely that holes may have the greater effect. Finally, brush mulch, or coarse woody debris, encourages habitat use by rodents (Greenberg 2002; McCay 2000; Planz and Kirkland 1992), and this effect may also occur to a lesser extent for pit/mound microtopography (Greenberg 2002). This could impact the plant community in complex ways because rodents select, disperse, and consume seeds (Sivy et al. 2011). Future work should determine the role of these and other potential mechanisms, and the importance of brush vs. holes to their action.

Ecological restoration entails restoring plant functional group diversity and minimizing the presence of invasive non-natives (Montoya et al. 2012; Society of Ecological Restoration International Science and Policy Working Group 2004). Undisturbed plant communities near the study sites were characterized by shrub cover that approached or exceeded that of perennial grasses, forb cover that increased at higher elevation sites, and low cover of weedy annual grasses and forbs. Overall, experimental plots had higher grass cover, higher forb cover, two to 10 times lower shrub cover, and higher annual cover than the undisturbed communities. Experimental treatments modified these proportions, however, and may influence whether or not the disturbed areas ever come to resemble the undisturbed community. The high-forb seed mix treatment increased the proportion of shrubs relative to grasses, which could prevent long-term grass domination, a common occurrence in disturbed big sagebrush ecosystems which have been seeded (Biondini et al. 1985; Hoelzle et al. 2012; Newman and Redente 2001). The rough/brush surface treatment helped reduce annual grass and annual forb cover, which may prevent long-term downy brome dominance. The imazapic treatment also helped reduce annual grass cover, although the undesirable effects of this treatment included lessened grass, forb, and shrub cover, which could lead to heightened susceptibility to future invasion. For the big sagebrush communities in this study, the high-forb seed treatment and the rough/brush surface treatment promoted ecological restoration, while the imazapic application was less successful. Limiting imazapic to a lighter application than that used here, with a longer plant-back interval, and restricting use to areas with apparent downy brome prior to disturbance is recommended.

Successful ecological restoration can help plant communities become more resistant to invasion by exotics (Bakker and Wilson 2004), can offset disturbance-related losses to biodiversity (Wassenaar et al. 2013), and can aid the sustainability of threatened wildlife populations (de Souza and Batista 2004). Current threats to the big sagebrush ecosystem come from many sources, including conifer encroachment, annual grass invasion, and anthropogenic disturbance (Davies et al. 2011). Maintaining function in the big sagebrush ecosystem will require identifying practical techniques which promote ecological restoration. Future work should also include defining spatial and climatic scopes of application for those techniques.

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