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Authors: Johnston, Danielle B., and Garbowski, Magda

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Responses of Native Plants and Downy Brome to a Water-Conserving Soil Amendment☆

Danielle B. Johnston [a, b, *], Magda Garbowski [a, b, c]

[a] Colorado Parks and Wildlife, Grand Junction, CO 81505, USA
[b] Bioagricultural Sciences and Pest Management, Fort Collins, CO 80523-1062, USA
[c] Graduate Degree Program in Ecology, Colorado State University, Fort Collins, CO 80523-1062, USA

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ABSTRACT

Restoring native plants in rangelands threatened by downy brome (*Bromus tectorum* L.) presents a serious challenge to land managers. Higher, more consistent soil moisture, as well as slightly compacted soils, may reduce the competitive abilities of downy brome. We manipulated these factors with three treatments: superabsorbent polymer (SAP), a soil-binding agent, and roller compaction at two restoration sites, Wagon Road Ridge (WRR) and Sagebrush (SGE), in northwestern Colorado. SAPs absorb water when soils are wet and then gradually release it, often reducing plant water stress. The binding agent we used is purported to increase water infiltration while reducing soil movement. In Experiment 1, we crossed an SAP, a binding agent, and rolling and found that SAP benefitted perennial grass establishment at the WRR site only. SAP also decreased downy brome cover and biomass at WRR. The binding agent increased soil moisture at both sites, and the highest level of binding agent reduced downy brome cover in the absence of SAP at the SGE site. In Experiment 2, we examined only SAP, with larger plots and a more complex seed mix. Again, SAP benefitted perennial grass establishment at WRR only. SAP reduced initial perennial forb density at both sites but did not affect forb cover in subsequent years. SAP effects on downy brome were site-specific. There was a trend for reduced downy brome cover with SAP at WRR, but SAP caused a large increase in downy brome cover in yr 3 at SGE. Granulated SAP can be applied easily along with drill seeding, making it potentially applicable for dryland restoration. However, site specific factors may influence whether perennial grasses or downy brome most benefit from SAP application.

Introduction

When arid lands are disturbed, restoring desirable species is often constrained by irregular precipitation (Hardegree et al. 2012) and invasion by exotic species (Smith et al. 2008; Chambers et al. 2014). While exotic species often germinate rapidly in response to favorable conditions, native species may require longer periods of adequate soil moisture to germinate successfully (Wainwright and Cleland 2013). Successful restoration may occur in years with average to above-average moisture, but land managers have little or no ability to predict seasonal precipitation (Bernstein et al. 2014).

In western North America, the non-native annual grass downy brome (*Bromus tectorum* L.) has invaded > 2 million ha of rangeland and is expected to continue to expand in range (Bradley and Mustard 2005; Abatzoglou and Kolden 2011). Downy brome invasion reduces forage for livestock and wildlife (Knapp 1996; Ielmini et al. 2015), changes soil nutrient cycles (Norton et al. 2004), and increases fire frequencies (Knapp 1996; Balch et al. 2013). Part of the reason downy brome is successful is because it competes effectively when summer soil moisture is low (Bradley 2009) and when it is more variable from year to year (Chambers et al. 2007). Downy brome also has highly flexible phenology (Young et al. 1987) and is able to germinate at lower temperatures and water potentials than native perennial grass species (Harris 1967; Hardegree et al. 2013). These traits allow downy brome seedlings to develop extensive root systems throughout fall, winter, and early spring

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* Correspondence: Danielle B. Johnston, Colorado Parks and Wildlife, Grand Junction, CO 81505, USA. 970-420-8374
E-mail address: Danielle.bilyeu@state.co.us (D.B. Johnston).

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before native grass seedlings germinate and grow (Harris 1967). However, when summer soil moisture is increased, later-growing natives may be better able to establish, grow, and outcompete downy brome (Harris 1967; Prevey and Seastedt 2015). Creating conditions that reduce water stress throughout the growing season may be one way to help native plants compete effectively with downy brome.

Soil density is another factor that may be manipulated to reduce the competitive advantage of downy brome. Downy brome germinates less readily (Thill et al. 1979) and is less competitive (Beckstead and Augspurger 2004; Kyle et al. 2007) in denser soils. In a laboratory study of shallowly buried downy brome seeds, seedling emergence was reduced by 28%, 52%, and 60% at soil bulk densities of 1.1 $g \cdot cm^{-3}$, 1.2 $g \cdot cm^{-3}$, and 1.3 $g \cdot cm^{-3}$, respectively, values that permit growth of many desirable plants (Thill et al. 1979).

In this study, we examined the effects of three treatments intended to alter soil moisture and/or soil compaction on downy brome and native species establishment in restoration. The treatments we examined were 1) addition of a superabsorbent polymer (SAP) to the soil, 2) addition of a soil-binding polymer to the soil surface, and 3) rolling with a static drum roller. Each of these treatments has the potential to influence the establishment of downy brome and native species in restoration, is reasonably economical, and may be applied using commercially available equipment.

SAPs are large molecules, often potassium salts of cross-linked polymers of acrylic acid and/or acrylate, with the ability to absorb up to 400 times their weight in water. When incorporated into a soil medium, their rapid absorption of water after wetting events followed by gradual release results in increased soil water holding capacity (Akhter et al. 2004; Parvathy et al. 2014), decreased evaporative losses (Akhter et al. 2004), and reduced plant water stress (Huttermann et al. 2009; Ashkiani et al. 2013). SAPs can also increase nutrient uptake (Orikiriza et al. 2009; Islam et al. 2011b). They have been shown to increase growth of containerized seedlings (Liu et al. 2013), improve survival of tree transplants (Agaba et al. 2010), and increase crop yields (Akhter et al. 2004; Moslemi et al. 2011; Ashkiani et al. 2013). Even with their many demonstrated benefits in horticulture and agriculture, SAPs have received little attention in the field of native plant dryland restoration. Exceptions include a study that found that SAP promoted growth of a sand-dune-stabilizing reed (Hong and Lee 2016), and two studies that found that SAP increased short-term survival of seedling transplants (Minnick and Alward 2012; Werden et al. 2018).

In areas of severe soil disturbance, unconsolidated soil material can result in erosion and create a need for dust mitigation (Pointing and Belnap 2014). Soil binding agents, tackifiers, and chemical dust control agents are employed to stabilize soil and reduce dust in construction (Raskin et al. 2005), mining (Chen et al. 2016), transportation (Naeimi and Chu 2017), and agricultural (Piccolo et al. 2018) applications. Recently, some such products have been marketed as environmentally friendly, and their use in restoration has increased (Chen et al. 2015; Kuttner and Thomas 2017). However, data about how these products affect plant growth are extremely limited. Recent research indicates that products made with lignosulfonates, a paper industry byproduct, may reduce herbaceous plant germination and establishment, possibly because of reduced water infiltration and increased runoff (Kuttner and Thomas 2017). The product DirtGlue (Global Environmental Solutions, LLC, Salem, NH) differs from those with lignosulfonates in that the manufacturer claims that the product increases water infiltration, while also increasing bonds between soil particles. Because of its potential to increase soil moisture and promote soil particle aggregation, we were interested in this product for controlling downy brome.

Finally, we were interested in static drum rolling because of its ability to increase soil compaction at the soil surface. Unlike vibratory drum rollers, which increase soil density both at the soil surface and at deeper soil layers, static rolling compacts only soil at the soil surface, providing the potential to impede surface emergence of density-sensitive species like downy brome without impeding deep root development.

In this paper we report on two experiments. Experiment 1 was seeded in 2009 and had three fully crossed factors: addition of granulated SAP, addition of the binding agent DirtGlue, and rolling with a static drum roller. Experiment 2 was seeded in 2012 and examined only SAP application, using larger plots and a more complex seed mix than that in Experiment 1. The propagule pressure of downy brome was controlled in both experiments, and both experiments were conducted following disturbances that mimicked the creation and restoration of natural gas well pads at two sites in Rio Blanco County, Colorado. Rio Blanco County is part of the geologic Piceance Basin, which is rich in both wildlife and natural gas. As of June 2019, the 1.8 $\times$ 10^6 ha Piceance Basin contained 27 000 natural gas wells (Colorado Oil and Gas Conservation Commission 2019). Rio Blanco County also supports the largest migratory mule deer herd in the contiguous United States and contains native sagebrush ecosystems, which are threatened by the synergistic effects of disturbance and downy brome.

Materials and Methods

Study Area

In the Piceance Basin, downy brome cover and dominant big sagebrush (*Artemisia tridentata* L.) subspecies vary with elevation. Downy brome is prevalent at elevations < ~1 800 m and common at higher elevations where ground disturbances have occurred. Wyoming big sagebrush (*Artemisia tridentata* ssp. *wyomingensis*) dominates at lower elevations up to ~2 100 m, and mountain big sagebrush (*Artemisia tridentata* ssp. *vaseyana*) dominates at higher elevations (Cottrell and Bonham 1992). We selected two study sites near the transition between Wyoming big sagebrush and mountain big sagebrush. Sites in this elevation range typically lack downy brome in the absence of disturbance but commonly become invaded once the ground is disturbed. Criteria for site selection included: slope < 5%, downy brome cover < 20%, sagebrush cover > 15%, and no obvious evidence of recent fire such as charred wood. The Sagebrush (SGE) site (39.83°N, 108.30°W) has an elevation of 2 004 m and is on sandy loam soils in the Piceance soil series. Dominant species include Wyoming big sagebrush, western wheatgrass (*Pascopyrum smithii* [Rydb.] Á. Löve), needle-and-thread grass (*Hesperostipa comata* Trin. & Rupr.), Sandberg bluegrass (*Poa secunda* J. Presl), prairie junegrass (*Koeleria macrantha* [Ledeb.] Schult.), and scarlet globemallow (*Sphaeralcea coccinea* [Nutt.] Rydb.). The Wagon Road Ridge (WRR) site (39.82°N, 108.46°W) has an elevation of 2 216 m and is on sandy loam soils in the Piceance soil series. Dominant vegetation includes mountain big sagebrush, 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.), spreading phlox (*Phlox diffusa* Benth.), hawksbeard (*Crepis acuminata* Nutt.), and silvery lupine (*Lupinus argenteus* Pursh). Precipitation information for each site is included in Table 1, and soil test information is included in Table S1 (available online at https://doi.org/10.1016/j.rama.2019.10.001).

Disturbance Simulation

Simulated natural gas well pads measuring 31 m $\times$ 52 m were created in September 2008 by clearing vegetation and then stripping and stockpiling the top 15 cm of topsoil. The subsoil was then

Table 1
Precipitation recorded using RG3-M data logging rain gauges (Onset Computer Corporation, Bourne, Massachusetts) installed on guyed posts at each site: Sagebrush (SGE) and Wagon Road Ridge (WRR). Summer data are June–August, fall data are September–November, and winter/spring data are December–May.

	Season	Site	
		SGE (mm)	WRR (mm)
2010	Summer	111.4	106.2
	Fall	69.2	66
2011	Winter/spring	102.6	189
	Summer	84	110.8
	Fall	44.6	81
2012	Winter/spring	8.6	44.4
	Summer	48.8	77
	Fall	39.4	57.8
2013	Winter/spring	109	121
	Summer	93.2	76.6
	Fall	151.4	142.8
2014	Winter/spring	102.8	88.4
	Summer	89.2	103.4
	Fall	145.2	125.4
2015	Winter/spring	167.8	180.8
	Summer	86.2	107.8
AVG	Winter/spring	98.2	124.7
	Summer	85.5	97.0
	Fall	90.0	94.6
Percent of total precipitation	Winter/spring	35.9%	39.4%
	Summer	31.2%	30.7%
	Fall	32.9%	29.9%

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% ($v \cdot v^{-1}$) glyphosate isopropylamine salt. In August 2009, sites were recontoured and stockpiled topsoil was redistributed evenly across the surface. All sites were fenced with 2.4 m fencing in late fall 2009. Standardized, ungrazed conditions were desirable because temporal and spatial variability in herbivory could not otherwise be controlled.

Downy Brome Seed Collection

Downy brome seed was collected using a lawnmower with a bagging attachment from monocultures or near-monocultures in four locations, each within 80 km of the study sites. Collections were made in late June or early July 2009 for Experiment 1 and late June or early July 2012 for Experiment 2. Most or all of the downy brome in a location had fully ripened seed heads at the time of seed collection. Seed was allowed to dry and after-ripen in shallow containers in a dry, warm location for approximately 3 mo. The purity of apparently viable downy brome seeds was determined by taking five subsamples of 5 g of bulk material from each collection and then counting and weighing all of the fully developed, hard-coated downy brome seeds for each subsample. We calculated the seed purity per bulk weight for each collection and then combined collections either equally in terms of number of apparently viable seeds (Experiment 1) or by preferentially using collections from sites nearer the study area (Experiment 2). We then recalculated seed purity for the combined seed material and determined the weight of bulk material necessary to hit target seeding rates for each plot. The target downy brome seeding rates were 300 seeds$\cdot$m^{-2} (Experiment 1), and 600 seeds$\cdot$m^{-2} (Experiment 2). The 300 seeds$\cdot$m^{-2} rate was 25% of the seed production in a heavily downy brome–invaded area near the study location and was considered a reasonable propagule pressure for sites in the initial phase of invasion. The rate was doubled in the second experiment because of low downy brome establishment at one of the two study sites in Experiment 1.

Experiment 1

Experiment 1 was a split-split plot study with completely randomized whole plots. The whole-plot factor was rolling (two levels: rolled or not rolled), the subplot factor was SAP (two levels: SAP or no SAP), and the sub-subplot factor was binding agent (three levels: none, low, or high; Fig. 1). There were five replicates at each site, and sub-subplots measured 2.4 m × 2.4 m (see Fig. 1). Unlike most split plot designs, the degrees of freedom for whole plots and subplots were the same because there was no blocking at the whole plot level (Table S2, available online at https://doi.org/10.1016/j.rama.2019.10.001).

In October 2009, soils were ripped to 30 cm and then disked to break up large soil clods using a Plotmaster 400 (Tecomate Wildlife Systems, Inc., San Antonio, TX). Downy brome seed was hand-broadcast and then raked lightly to incorporate seed into the soil. A mixture of native wheatgrasses (Table 2) was drill-seeded using the Plotmaster 400. Seed was mixed 1:1 by volume with rice hulls to maintain suspension of the seed mixture. For SAP plots, Luquasorb 1280 RM granulated superabsorbent polymer (a cross-linked copolymer of potassium acrylate and acrylic acid in granulated form; BASF Corporation, Ludwigshafen, Germany) was added to the seed/rice hull mixture. At SGE, 67 kg$\cdot$ha^{-2} of polymer were added, and at WRR, 310 kg$\cdot$ha^{-2} were added.

No recommended SAP application rates for dryland restoration were available at this time of this study. In containerized studies, rates are typically given as a percentage by weight, with positive effects reported in the ranges of 0.1% to 1.0% SAP (Bakass et al. 2002; Agaba et al. 2010). These rates would translate to between 600 kg$\cdot$ha^{-2} and 6 000 kg$\cdot$ha^{-2} after accounting for incorporation to 5-cm depth. As these rates are prohibitively expensive, most field crop studies have focused on localized applications within furrows at rates of 10–60 kg$\cdot$ha^{-2} (Islam et al. 2011a; Islam et al. 2011c; Ashkiani et al. 2013). The rate used at SGE (67 kg$\cdot$ha^{-2}) was near the upper end of the field crop recommendations, while the rate used at WRR (310 kg$\cdot$ha^{-2}) approached recommendations for containerized studies.

After seeding and SAP application, rolled plots were rolled 10 times with a static roller supplying a linear load of 36.5 N$\cdot$cm^{-1}. Binding agent (BA) sub-subplots were then treated by sprinkling plots using hand watering cans. High-BA plots received 4 100 li$\cdot$ha^{-1} (440 gal$\cdot$acre^{-1}) of soil binding agent diluted 6:1 with water. Low-BA plots received 1 600 li$\cdot$ha^{-1} of binding agent, diluted 17:1 with water. No-BA plots received 21 000 li$\cdot$ha^{-1} of plain water, a volume equivalent to the total amount of liquid applied to other plots.

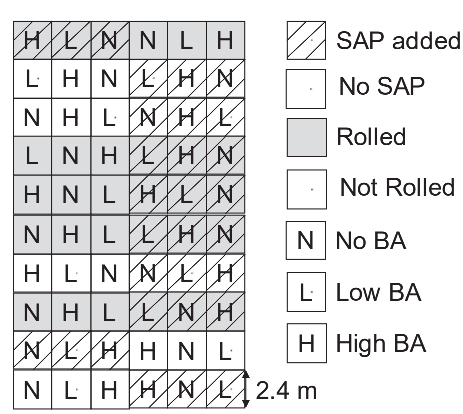

Figure 1. Layout of Experiment 1 at the Wagon Road Ridge Site. Whole plots were either rolled or not rolled, and the experiment was completely randomized at this level ($n = 5$). Superabsorbent polymer (SAP) treatment was applied to subplots with two levels: SAP or no SAP. Binding agent (BA) treatment was applied to sub-subplots with three levels: No BA, Low BA, or High BA.

Table 2
Seed mix of grasses used in Experiment 1. Downy brome *(Bromus tectorum)* was seeded simultaneously at 300 seeds·m^{-2}.

Scientific name	Common name	Variety	Seeds·m^{-2}	PLS (kg·ha^{-1})	seeds·ft^{-2}	PLS (lb·$acre^{-1}$)
Elymus lanceolatus spp. *lanceolatus*	Thickspike wheatgrass	Critana	150.7	4.5	14	4.0
Elymus trachycaulus spp. *trachycaulus*	Slender wheatgrass	San Luis	150.7	5.1	14	4.5
Pascopyrum smithii	Western wheatgrass	Rosana	150.7	5.8	14	5.2
		TOTAL	452.1	15.3	42	13.7

Downy brome and perennial seedling density was assessed in late July/early August 2010 within a 1 m × 1 m area centered within each plot. Cover was quantified 2011–2013 between 25 June and 8 August using a 1 m × 1 m sampling grid containing 36 intersections; point-intercept hits were measured at each intersection using a laser point-intercept sampling device (Synergy Resource Solutions, Bozeman, MT). All layers of vegetation were identified to species at each hit. When calculating percent cover of a particular functional group (e.g., perennial grasses), overlapping hits of different species within the functional group were counted as a single instance of the functional group. Aboveground biomass was quantified by clipping current-year growth to the ground level in July 2013 in one 0.5 m × 1 m frame centered in each plot. The current-year growth of the entire plant was clipped if the plant was rooted in the plot. Plant material was dried at 105°C for 36–48 h and weighed to the nearest 0.1 g.

Two to three soil moisture readings were made in random locations within each plot on 21 May 2010, 7 June 2010, 3 June 2011, 19 July 2011, 15 May 2012, and 28 June 2012. Readings were taken to 12 cm using a Hydro Sense Soil Water Measurement System (Campbell Scientific, Inc, Logan, UT) and were averaged for each plot on each date.

Experiment 2

Experiment 2 was a completely randomized study with three replications at each of two sites (WRR and SGE). There was one factor with two levels (SAP or no SAP), and plot size measured 6.4 m × 8.1 m. It was implemented in 2012 on simulated well pad disturbances created in 2008. Vegetation was removed by ripping and disking to 15 cm in early September 2012. Plots were rolled with a Plotmaster to create a firm, level surface. Next, we simulated a drill seeding by creating 2 cm-deep furrows with the Plotmaster, hand-sprinkling seed (Table 3) into these furrows, and pressing soil over them. In plots randomly selected for the polymer treatment, Tramfloc 1001 granulated polymer (a cross-linked copolymer of acrylamide and potassium acrylate; Tramfloc, Inc, Tempe, AZ) was applied at 450 kg·ha^{-2} to furrows before covering seed with soil. The same SAP rate was applied at both sites. The Tramfloc product was chosen for its similarity to Luquasorb 1280 RM, which was no longer available. The two products have similar swelling capacities, bulk densities, decomposition rates, particle size distributions, and application recommendations (Gomez 2015; Tramfloc, Inc. 2019). Immediately after desirable species were seeded, downy brome seed was hand-broadcast at 600 seeds·m^{-2} and then lightly raked to incorporate it into the soil in all plots. In mid-November, 2012, locally collected Wyoming big sagebrush seed was hand-broadcast over snow at 270 seeds·m^{-2}.

Vegetation was assessed by seedling density in 2013 and percent cover in 2014 and 2015, using similar methods to Experiment 1, except that five 0.5 m × 1.0 m systematically placed miniplots per plot were used and averaged for each plot. Soil moisture was measured in 2013–2014 using the same sampling locations as vegetation data collection. At each location, one soil moisture reading was taken within a drill-seeded row and one reading was taken between rows on each of these dates: 19 June 2013, 21 August 2013, 16 May 2014, 23 June 2014, 19 July 2014, and 21 August 2014. Readings were taken to 12 cm using a Hydro Sense Soil Water Measurement System and were averaged for each plot on each date.

Analysis

For Experiment 1, perennial grass and downy brome density, cover, and biomass data were analyzed using analysis of variance (ANOVA) in SAS PROC MIXED for a split-split plot structure with completely randomized whole plots, and sites were considered fixed. Significant site by treatment interactions occurred for all responses (cutoff $\alpha = 0.10$); therefore, analyses were conducted separately by site. Data were transformed as needed to improve normality, and residual plots were inspected to ensure adherence to ANOVA assumptions [downy brome density: arcsine (square root [x]); perennial grass density: no transformation; downy brome and perennial grass cover: arcsine (square root [x]); downy brome biomass: log + constant; perennial grass biomass: no transformation]. Cover data 2011–2013 were analyzed similarly, with the addition of repeated measures with an autoregressive covariance structure (lag = 1).

For Experiment 2, density and cover data were analyzed using ANOVA in SAS PROC MIXED for a completely randomized design, with sites fixed. Again, significant site by treatment interactions occurred for nearly all responses; therefore, separate analyses were conducted by site. Species were grouped by functional group for analysis (perennial grass, perennial forb, annual forb, and downy brome). There were insufficient shrubs for analysis. Data were transformed to improve normality. and residual plots were inspected to ensure adherence to ANOVA assumptions (all functional group densities: log [x]; perennial grass cover and perennial forb cover: arcsine [square root {x}]; annual forb cover and downy brome cover: square root [x]). Cover data 2013–2014 were analyzed as repeated measures.

For both experiments, a significance level of $\alpha = 0.05$ was used to determine significantly different means, and a level of $\alpha = 0.10$ for interactions was used to determine which means to compare. Some mean comparisons associated with interactions of borderline significance ($\alpha = 0.05$ to $\alpha = 0.10$) were not significant themselves; discussion of these interactions was omitted. The order of results presented was guided by *F* values in the ANOVA tables (Tables S2–S6, available online at https://doi.org/10.1016/j.rama.2019.10.001), such that main effects are discussed first where main effects had higher *F* values than interactions and vice versa. Means are presented ± standard of error, and significantly different means are reported with their associated *t* statistic. Soil moisture data were analyzed similarly to vegetation data, except that date, date × site interaction, treatment × date, and treatment × date × site were also included as potential fixed effects.

Results

Experiment 1

Across sites, years, and treatments, 100% of perennial grass cover was native. Perennial grasses at both sites consisted of a

Table 3
Seed mix used in Experiment 2. Downy brome *(Bromus tectorum)* was seeded simultaneously at 600 seeds$\cdot$m^{-2}.

Scientific name	Common name	Variety	Seeds$\cdot$m^{-2}	PLS (kg$\cdot$ha^{-1})	Seeds$\cdot$ft^{-2}	PLS (lbs$\cdot$acre^{-1})
Forbs						
Eriogonum umbellatum	Sulphur flower buckwheat	VNS	130	3.5	12.1	3.1
Hedysarum boreale	Utah sweetvetch	Timp	26	3.5	2.4	3.1
Linum lewisii	Lewis flax	Maple Grove	91	1.4	8.5	1.2
Penstemon palmeri	Palmer penstemon	Cedar	104	0.8	9.7	0.7
Grasses						
Pascopyrum smithii	Western wheatgrass	Arriba	39	1.6	3.6	1.4
Achnatherum hymenoides	Indian ricegrass	Nezpar	130	4.1	12.1	3.6
Bouteloua gracilis	Blue gramma	Hachita	65	0.4	6.0	0.4
Elymus elymoides	Bottlebrush Squirreltail	Toe Jam Creek	65	1.5	6.0	1.4
Elymus trachycaulus	Slender wheatgrass	San Luis	52	1.8	4.8	1.6
Poa sandbergii	Sandberg bluegrass	Cedar	182	0.9	16.9	0.8
Pseudoroegneria spicata	Bluebunch Wheatgrass	Anatone	104	3.4	9.7	3.0
Shrubs						
Atriplex canescens	Fourwing saltbush	Colorado source	195	32.2	18.1	28.7
Artemisia tridentata[1]	Big sagebrush	Local collection	150	0.6	13.9	0.5

[1] Collected from plants adjacent to each site. Subspecies *wyomingensis* was used at the Sagebrush site, and subspecies *vaseyana* was used at the Wagon Road Ridge site.

heterogeneous mix of slender wheatgrass (*Elymus trachycaulus* [Link] Gould ex Shinners), western wheatgrass, bluebunch wheatgrass (*Pseudoroegneria spicata* [Pursh] Á. Löve), and needle-and-thread grass.

At SGE, we found no significant treatment effects on perennial grass density, although there was a trend for higher perennial grass density in rolled plots ($F = 4.005$, $P = 0.085$, see Table S2). At WRR, SAP increased perennial grass density from 48.4 seedlings$\cdot$m^{-2} to 67.0 seedlings$\cdot$m^{-2} ($F = 13.814$, $P = 0.006$; Fig. 2a). The effect was modulated by a 3-way interaction involving rolling, binding agent, and SAP ($F = 5.600$, $P = 0.008$) and a 2-way interaction between rolling and SAP ($F = 5.560$, $P = 0.046$). In the presence of SAP, there was no effect of binding agent on perennial grass seedling density ($P > 0.1081$). In the absence of SAP, binding agent had different effects depending on level of rolling ($F = 5.08$, $P = 0.0196$). Without rolling, perennial grass density was 55.4 ± 11.9 seedlings$\cdot$m^{-2} in the high-binding agent treatment, significantly higher than either the low-binding agent treatment (33.4 ± 9.6 seedlings$\cdot$m^{-2}, $t = 2.56$, $P = 0.015$) or the no-binding agent treatment (35.0 ± 9.9 seedlings$\cdot$m^{-2}; $t = 2.38$, $P = 0.024$). With rolling, perennial grass density was 45.4 ± 4.7 seedlings$\cdot$m^{-2} in the high-binding agent treatment, which was significantly lower than the low-binding agent treatment (66.8 ± 9.3 seedlings$\cdot$m^{-2}; $t = 2.49$, $P = 0.018$) but similar to the no-binding agent treatment (54.2 ± 3.3 seedlings$\cdot$m^{-2}). When averaged over binding agent, SAP effects were more pronounced in rolled plots than no-roll plots.

Across years and treatments, perennial grass cover averaged 46.7% ± 1.0% at SGE and 60.9% ± 1.0% at WRR (see Fig. 2c), and there were no significant contrasts of means for treatments ($P > 0.18$; see Table S3). Across years and treatments, perennial grass biomass in 2013 averaged 22.8 g$\cdot$m^{-2} ± 1.2 g$\cdot$m^{-2} at SGE and 48.4 g$\cdot$m^{-2} ± 1.7 g$\cdot$m^{-2} at WRR (see Fig. 2e) and was not influenced by treatments ($P > 0.10$; see Table S4) at either site.

Across treatments, downy brome seedling density in 2010 averaged 11.1 ± 0.8 seedlings$\cdot$m^{-2} at SGE and 24.4 ± 1.9 seedlings$\cdot$m^{-2} at WRR (see Fig. 2b). Binding agent treatment was significant at SGE ($F = 5.11$, $P = 0.013$, see Table S2), where downy brome density in low-BA plots was 13.6 ± 2.8 seedlings$\cdot$m^{-2}, significantly higher than in no-BA plots (8.6 ± 2.9 seedlings$\cdot$m^{-2}, $t = 3.19$, $P = 0.004$) but not high-BA plots (10.8 ± 3.0 seedlings$\cdot$m^{-2}). At WRR, binding agent and SAP interacted to influence downy brome density ($F = 2.51$, $P = 0.097$), with significant effects only in the absence of SAP. Within no SAP plots, downy brome density was significantly lower with the high-BA treatment than with the no-BA treatment ($t = 2.28$, $P = 0.029$; see Fig. 2b).

Downy brome cover varied dramatically by year ($P < 0.0001$). In 2012, following an exceptionally dry winter, downy brome cover was low both regionally and in our study plots. At SGE, downy brome cover across plots was 11.2% ± 1.3% in 2011, only 2.0% ± 0.6% in 2012, and 5.4% ± 0.7% in 2013. At WRR, downy brome cover across plots was 28.1% ± 2.4% in 2011, only 1.7% ± 0.05% in 2012, and 19.1% ± 2.5% in 2013. SAP and binding agent interacted to influence downy brome cover at SGE ($F = 3.279$, $P = 0.051$) such that in the absence of SAP, the high-BA and low-BA treatments reduced downy brome cover about twofold relative to the no-BA treatment ($P < 0.0132$), but binding agent had no effect in the presence of SAP ($P > 0.4210$; see Fig. 2d). Downy brome biomass in 2013 averaged 0.58 g$\cdot$m^{-2} across treatments at SGE, and there were no treatment effects. Downy brome cover at WRR was lower in SAP than in no-SAP plots ($F = 5.733$, $P = 0.044$; see Fig 2d). An interaction between SAP and year ($F = 2.697$, $P = 0.073$) occurred because no SAP effect was discernible in 2012. SAP reduced downy brome cover by about half in 2011 ($t = 2.22$, $P = 0.028$) and again in 2013 ($t = 3.14$, $P = 0.002$). SAP reduced downy brome biomass in 2013 at WRR from 4.14 ± 0.73 g$\cdot$m^{-2} to 1.53 ± 0.41 g$\cdot$m^{-2} ($F = 8.450$, $P = 0.020$; see Fig. 2f, Table S4).

Soil moisture differed by site on every date measured ($P < 0.0001$; Fig. 3), with SGE averaging 24.3% ± 15.2% and WRR averaging only 13.7% ± 10.4% soil moisture across dates and treatments. Plots with the high level of binding agent had significantly higher soil moisture than no-binding agent plots. At SGE, high-BA plots had significantly higher soil moisture than no-BA plots on 21 May 2010 and 15 May 2012 ($P < 0.004$), and at WRR, high-BA plots had significantly higher soil moisture than no-BA plots on 21 May 2010, 2 June 2011, 18 July 2011, 15 May 2012, and 28 June 2012 ($P < 0.025$; see Fig. 3). On the highest soil moisture date measured, 21 May 2010, the high-BA treatment averaged 37.1% ± 9.4% across sites while the no-BA treatment averaged 32.9% ± 8.9%. On the lowest soil moisture date measured, 28 June 2012, the high-BA treatment averaged 2.1% ±1.3% across sites and the no-BA treatment averaged 1.9% ± 1.4%.

Experiment 2

Across sites and years, perennial grass cover was 99.8% native. Perennial grass density in 2013 was similar between sites, averaging 20.6 ± 3.1 seedlings$\cdot$m^{-2}, and there was no SAP effect at either site ($P > 0.14$; Fig. 4a; see Table S5). Perennial grass cover increased from 2014 to 2015 at SGE ($F = 17.26$, $P = 0.014$; see Fig. 4b and Table S6), and there was no SAP effect. At WRR, perennial grass cover did not change with time

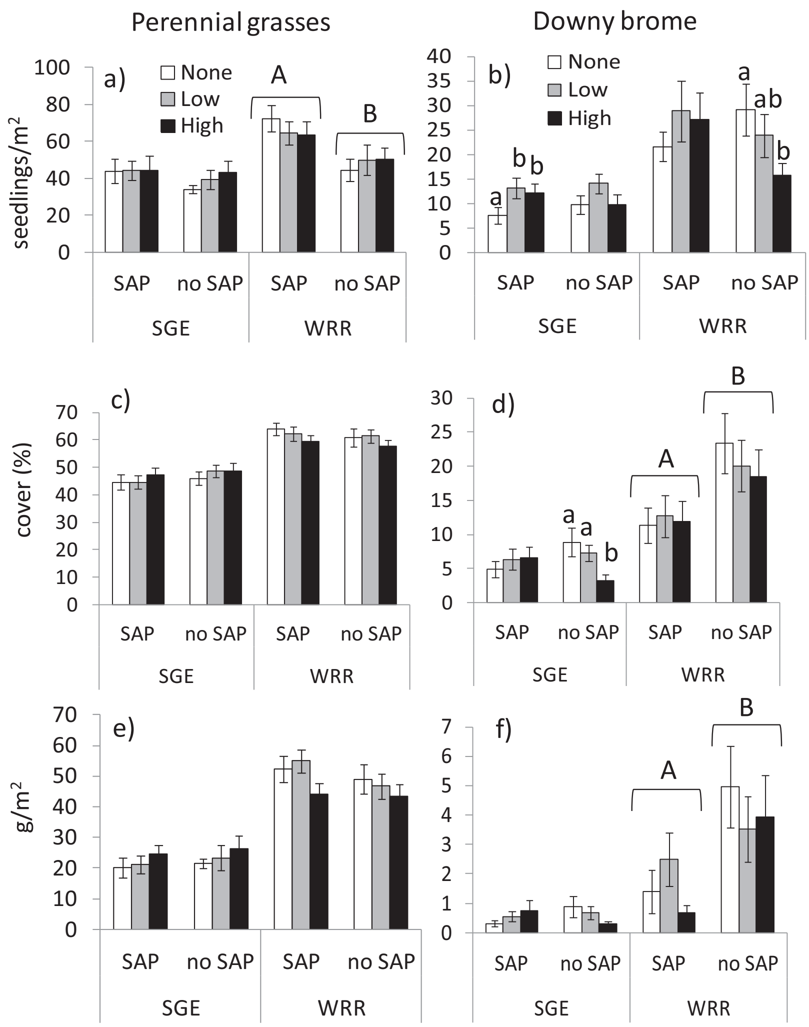

Figure 2. Experiment 1's 2010 seedling density (**a** and **b**), average of cover 2011–2013 (**c** and **d**), and 2013 biomass (**e** and **f**) of downy brome (*Bromus tectorum;* **a, c, e**) and of perennial grasses (**b, d, f**) in response to superabsorbent polymer addition (SAP) and DirtGlue soil binding agent (three levels: None, Low, or High) at two sites: Sagebrush (SGE) and Wagon Road Ridge (WRR). Data are averaged over 5 replicates and a static rolling treatment, which had no significant main effect for any responses. Error bars = standard of errors. Bars groups not sharing capital letters are significantly different at $\alpha = 0.05$. Bars not sharing lowercase letters represent significant effects within site and SAP treatment at $\alpha = 0.05$.

($P = 0.51$), but there was a large SAP effect; SAP increased perennial grass cover about threefold in both 2014 ($F = 27.5$, $P = 0.006$) and 2015 ($F = 24.82$, $P = 0.007$; see Fig. 4b). About 50% of perennial grass cover at SGE in 2014 was needle-and-thread, an unseeded native grass, while the other 50% was composed of the seeded species slender wheatgrass, western wheatgrass, Indian ricegrass, bottlebrush squirreltail (*Elymus elymoides* [Raf.] Swezey), and bluebunch wheatgrass. At WRR, needle-and-thread grass was not prevalent and about 80% of perennial grass cover was comprised of the seeded species Indian ricegrass, slender wheatgrass, and western wheatgrass.

Perennial forbs were entirely native at both sites. SAP reduced 2014 perennial forb density at both SGE ($F = 8.85$, $P = 0.041$) and WRR ($F = 18.66$, $P = 0.013$; see Fig. 4c). At SGE, SAP had no significant effect on perennial forb cover ($P = 0.357$) and cover increased from 2014 to 2015 ($F = 57.33$, $P = 0.002$; see Fig. 4d). At WRR, neither SAP nor time had a significant effect on perennial forb cover ($P > 0.13$). Overall, perennial forb cover was higher at SGE than at WRR ($F = 6.51$, $P = 0.034$; see Fig. 3d). The seeded species Lewis flax (*Linum lewsii* Pursh.) comprised about half of 2013 perennial forb density and 60% of forb cover in subsequent years at both sites.

Annual forbs were almost entirely non-native (97.4%) and averaged 15% cover across sites, years, and treatments. Annual forb density in 2013 was not affected by SAP at either site ($P > 0.13$; see Fig. 4e). At SGE, SAP slightly increased annual forb cover across years ($F = 7.61$, $P = 0.051$) and overall, cover decreased from 2014 to 2015 ($F = 12.79$, $P = 0.023$; see Fig. 4f). At WRR, there was a borderline interaction of SAP with year ($F = 5.8$, $P = 0.074$; see Fig. 4f), but no contrasts of means were significantly different. At SGE, 81% of 2015 annual forb cover was desert alyssum (*Alyssum detertorum* Stapf). At WRR, plots without SAP were codominated by tall tumble mustard (*Sisymbrium altissimum* L.) and small tumbleweed mustard (*S. loeselii* L.), while plots with SAP contained a diversity of non-native and native annual forbs at low cover values, including yellow sweetclover (*Melilotus officinalis* L.), prickly lettuce (*Lactuca serriola* L.), small tumbleweed mustard, hoary tansyaster (*Macaeranthera canescens* [Pursh] A. Gray), and western salsify (*Tragopogon dubius* Scop.).

Downy brome density in 2013 was not significantly affected by SAP at SGE, but at WRR, downy brome density was about twofold lower with SAP ($F = 28.29$, $P = 0.006$; see Fig. 4g). At SGE, SAP increased downy brome cover ($F = 10.59$, $P = 0.031$) and the effect was particularly evident in 2015 (see Fig. 4h). At WRR, there was no

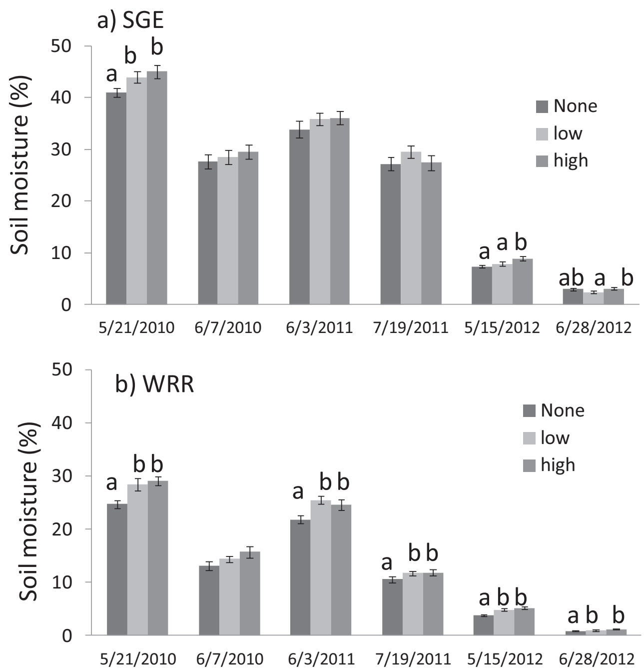

Figure 3. Experiment 1 percent volumetric soil moisture in response to DirtGlue soil binding agent (three levels: None, Low, or High) at two sites: Sagebrush (SGE; **a**) and Wagon Road Ridge (WRR; **b**) on six measurement dates, averaged over superabsorbent polymer and rolling treatments. Error bars = standard of error. Bars not sharing letters are significantly different at $\alpha = 0.05$ within a measurement date. Bars with no letters are not significantly different within a measurement date.

significant effect of SAP on downy brome cover. Cover increased from 2014 to 2015 ($F = 9.22$, $P = 0.039$; see Fig. 4h). Across years and treatments, downy brome cover was much higher at WRR than at SGE ($F = 61.72$, $P < 0.0001$) and in 2015 the difference (averaged across treatments) was 53.6% ± 6.4% at WRR versus 9.8% ± 3.2% at SGE (see Fig. 4h).

At SGE, SAP increased soil moisture on 16 May 2014 ($t = 3.30$, $P = 0.003$), the date with the highest soil moisture of any measured (Fig. 5a). At WRR, SAP significantly increased soil moisture on two dates: 19 June 2013 ($t = 3.30$, $P = 0.013$) and 16 May 2014 ($t = 3.30$, $P = 0.003$; Fig. 5b). Soil moisture was higher at SGE, which averaged 11.9% ± 10.1% across dates and treatment, than at WRR, which averaged only 8.3% ± 7.6% ($F = 65.90$; $P < 0.0001$).

Discussion

Both SAP and binding agent treatments influenced water availability, downy brome, and native perennial species. However, for both treatments, whether or not effects were beneficial or detrimental to native species establishment depended on site, treatment, and year. Rolling had few significant effects on perennial grasses and did not affect downy brome.

SAP had mostly beneficial effects at WRR in both Experiment 1 (310 $kg \cdot ha^{-2}$ application rate) and Experiment 2 (450 $kg \cdot ha^{-2}$ application rate). With SAP, perennial grass density was higher (Expt. 1), perennial grass cover was higher (Expt. 2), downy brome density was lower (Expt. 2), and downy brome cover was lower (Expt. 1) than without SAP. At SGE, SAP effects were nonsignificant in Experiment 1 (67 $kg \cdot ha^{-2}$ application rate), but in Experiment 2 2015 downy brome cover increased fourfold with SAP (450 $kg \cdot ha^{-2}$ application rate) and SAP had no effect on perennial grass cover. Across years and treatments in both experiments, downy brome was more prevalent at WRR than at SGE. A strong negative effect of SAP on perennial forb density in Experiment 2 was observed at both sites.

The negative effect of SAP on forbs was due primarily to the seeded species Lewis flax, which was responsible for 50–70% of the response, but the direction of response was the same for the seeded species Utah sweetvetch (*Hedysarum boreale* Nutt.), as well as the unseeded species lobeleaf groundsel (*Packera multilobata* [Torr. & A. Gray ex. A. Gray] W.A. Weber & Á Löve), hollyleaf clover (*Trifolium gymnocarpon* Nutt.), and lesser rushy milkvetch (*Astragalus convallarius* Greene). All of these are taproot-developing species, and SAP was applied only in the top 5–10 cm of soil. The morphology of the root systems of these forbs may preclude benefits from shallowly incorporated SAP. SAP applied to a shallow depth in a restoration project may preferentially benefit annual or perennial grasses, as grasses have been shown to outcompete forbs in prairie restorations (Pywell et al. 2003). By 2 yr post treatment, there was no effect of SAP on forb cover, indicating that in this study, sufficient forbs nonetheless established to prevent a long-term negative effect of SAP.

Downy brome responses differed by site. At WRR, SAP-mediated competitive dynamics are a logical explanation for downy brome response; the positive effect of SAP on perennial grasses may have allowed perennial grasses to suppress downy brome. At SGE, different dynamics predominated; there was no significant effect of SAP on perennial grasses, and SAP benefitted downy brome in Experiment 2. The sites are separated by only 8 km and share many characteristics: Both had predominately native vegetation before the disturbances imposed in this study, and both are flat, with sandy loam soils in the Piceance soil series. Nonetheless, there are differences that may explain differential downy brome responses.

There were some differences in precipitation and seasonality of precipitation at the two sites. WRR, the mountain big sagebrush site, had slightly higher annual precipitation than SGE both during the course of this study (see Table 1) and in the PRISM 30-yr normals for 1981–2010 (WRR: 469 mm; SGE 408 mm (PRISM Climate Group 2019). Downy brome tends to be less dominant at more mesic, higher-elevation sites both rangewide (Chambers et al. 2016) and within the study region (Cottrell and Bonham 1992). However, since downy brome was consistently more prevalent at WRR than at SGE, these general patterns were reversed in our study. Variations in seasonality of precipitation can influence competitive balance between exotic winter-active grasses and native species, with higher exotic grass cover (Prevey and Seastedt 2014) and population growth (Prevey and Seastedt 2015) when more precipitation occurs in fall through early spring. While we observed some difference in winter/spring precipitation between sites in 2011–2012, there was virtually no difference during the years of Experiment 2, when the differential response of downy brome between sites was most evident (see Table 1). Also, the proportion of precipitation for fall through spring was virtually identical between the sites over the course of both Experiments: 65.3% ± 14.1% of total annual precipitation at SGE and 65.5% ± 13.7% at WRR (see Table 1). Thus, while some differences in precipitation were evident between sites, how these may have interacted with SAP application to influence downy brome response is not clear.

The difference between Experiment 1 and Experiment 2 in downy brome response at SGE may have been related to interannual differences in precipitation and/or SAP application rate. 2011, 2012, and 2013 had dry preceding autumns, averaging just 68 mm of precipitation. In contrast, 2014 and 2015 had wet preceding autumns, averaging 148 mm of precipitation (see Table 1). In Experiment 1, dry conditions and low SAP application rate may have prevented downy brome from benefitting from SAP. In Experiment 2, higher precipitation combined with a higher SAP application rate may have allowed SAP to benefit downy brome.

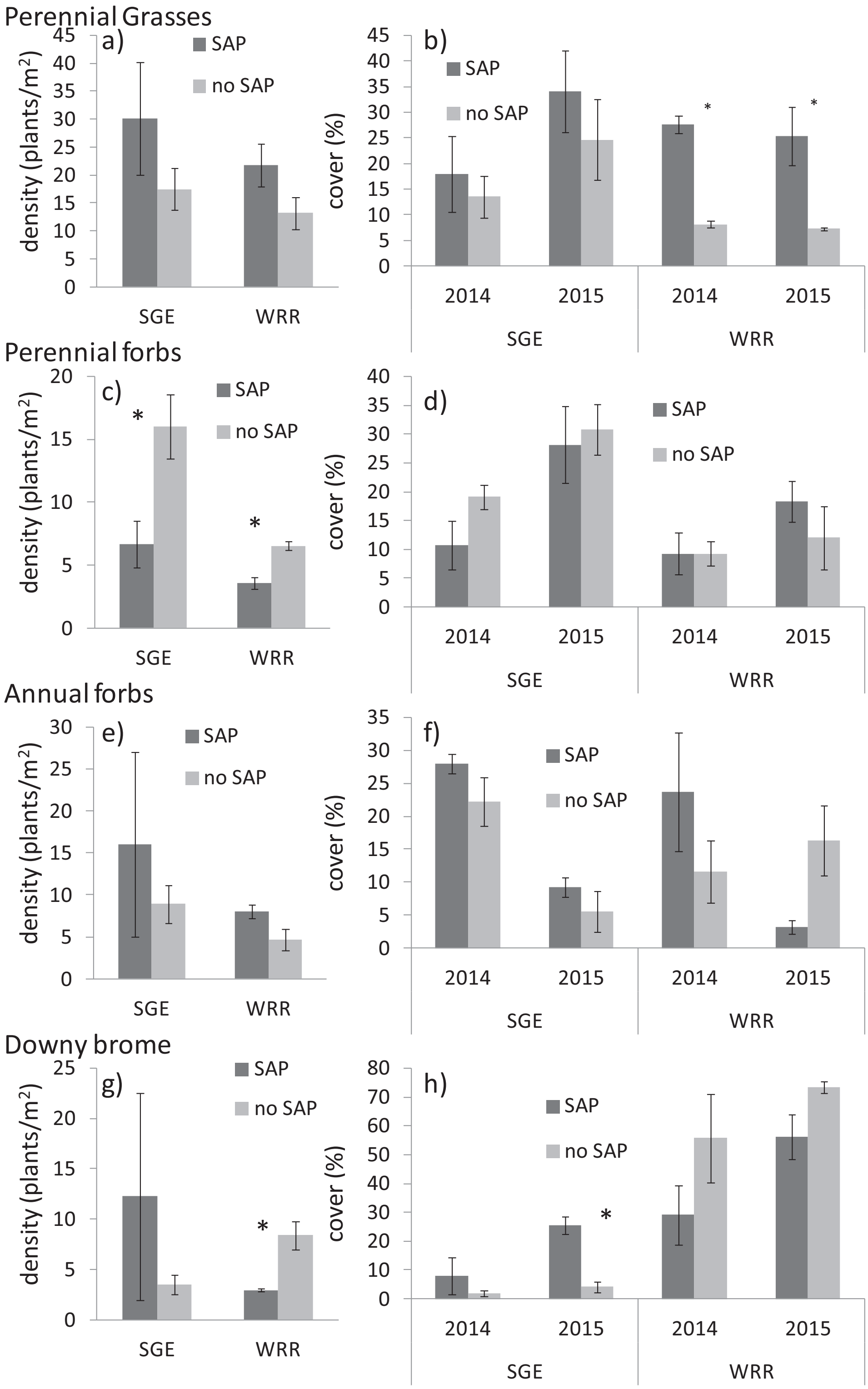

Figure 4. Experiment 2 responses (density: left panels, cover: right panels) of four functional groups, perennial grasses (**a** and **b**), perennial forbs (**c** and **d**), annual forbs (**e** and **f**), and downy brome (**g** and **h**) in 2013 **(a, c, e, g)** and 2014–2015 (**b, d, f, h**) to a superabsorbent polymer soil amendment (SAP) at two sites: SGE and WRR. Error bars = standard of error. *Stars* indicate significantly different means at $\alpha = 0.05$.

A difference in competitive dynamics due to the presence of dominant weedy species is also a possible explanation for site-specific responses to SAP. A species such as tall tumble mustard could potentially drive such a dynamic. Tall tumble mustard is a tall-statured annual or biennial with a deep taproot, is capable of retarding the development of seeded perennial grasses (Allen and Knight 1984), and is prevalent at WRR but absent at SGE. However, we found no significant main effects of SAP on tall tumble mustard density or cover in Experiment 1 or Experiment 2, and the direction of means were in opposite directions between

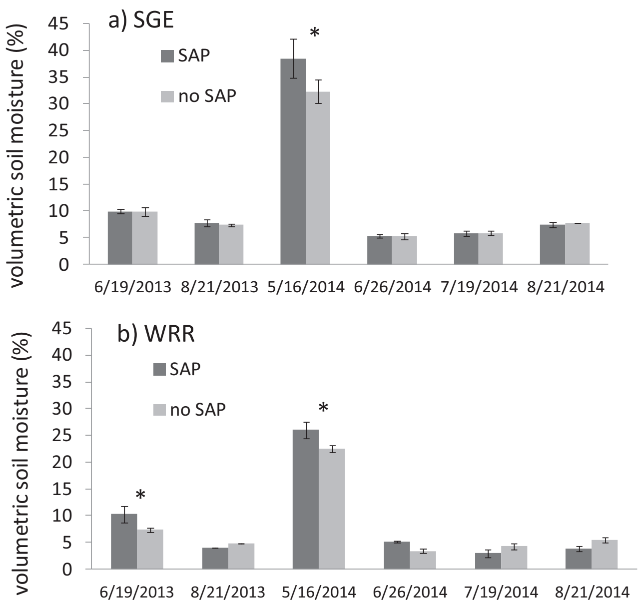

Figure 5. Experiment 2 volumetric soil moisture in response to superabsorbent polymer soil amendment (SAP) at two sites: **a,** Sagebrush and **b,** Wagon Road Ridge. Error bars = standard of error. *Stars* denote significantly different means at $\alpha = 0.05$.

experiments (higher with SAP in Experiment 1, lower with SAP in Experiment 2; data not shown). Thus, although differences existed between sites in dominant weedy species, their impact on SAP responses is uncertain.

A difference in SAP-mediated nutrient availability is a third possible explanation for site specific responses. While climate, seed distribution, or disturbance determine landscape-scale patterns in downy brome prevalence, at small spatial scales downy brome often invades patchily, suggesting that a localized factor such as soils or microclimate is also important (Belnap et al. 2016). On the Colorado Plateau, differences in soil P, depth, and K/Mg ratio are predictive of downy brome invasion (Belnap et al. 2016). Thus, greater soil nutrient limitation is a possible explanation for why SGE was less favorable for downy brome than WRR. Furthermore, SAP may have altered any such limitation. Because plants can only uptake nutrients when soils are moist, nutrient availability in arid environments is constrained by water availability (Barber 1995). Soil moisture availability in shallow soil layers is especially important; in fact, plants in the Great Basin may preferentially deplete shallow soil moisture layers as a strategy to prevent nutrient uptake by competitors (Ryel et al. 2010). By holding water in shallow soil layers, SAPs can increase nutrient uptake (Islam et al. 2011b), which may explain why SAPs have the potential to benefit downy brome. Variation in nutrient availability would explain why that benefit is more evident at some sites than others. As our nutrient data were limited to a single aggregate sample from each study site (see Table S1), this explanation would require further research to explore.

Whether driven by moisture regime, plant community dynamics, soil nutrient differences, or some other factor, downy brome has the potential to respond negatively or positivity to SAP addition depending on site specific factors that are not currently well understood. This may make it difficult to implement SAP application in a management context until further research is conducted to determine relevant site specific influences.

The binding agent treatment tested in Experiment 1 had variable effects, sometimes benefitting downy brome and sometimes benefitting perennial grasses, depending on site, SAP treatment, and rolling. At the SGE site, the low-BA treatment increased 2010 downy brome density over the no-BA treatment. At WRR, the opposite pattern was observed, but only in the absence of SAP: Downy brome density was lower with the high-BA treatment than with the no-BA treatment. Also at WRR, the high-BA treatment increased perennial grass density in the absence of SAP with rolling and slightly reduced it in the absence of SAP without rolling. This slight reduction in perennial grass density in a narrow set of circumstances was the only negative effect of binding agent we observed on perennial grasses. Binding agent increased soil moisture, especially at the highest application rate, supporting the manufacturer's claims that the product increases water infiltration. Unlike lignosulfonate binding agents, which have been shown to hinder plant establishment and increase runoff (Kuttner and Thomas 2017), the product we tested seems compatible with seeding efforts. Although it does not appear to be consistently helpful for downy brome control, it may be a useful tool for erosion control and dust abatement with concurrent reseeding. Application is likely to be limited to small areas such as oil and gas well pads because its application requires a significant volume of water to successfully incorporate the product into the soil. In order to apply the binding agent in the manner tested in this study, 3 200 gal/acre (30 000 L/ha) of water is needed, requiring a water truck.

There was little benefit of the rolling treatment for either downy brome control or perennial grass establishment, and rolling did not interact with binding agent to affect downy brome or native grass establishment. It can be concluded that the strategy of creating a thin layer of compacted soil in order to limit downy brome growth, either by rolling alone or applying a binding agent in conjunction with rolling, was not successful. These results concur with an earlier study that found static rolling had no significant impact on soil penetration resistance or downy brome density (Johnston 2015).

In summary, this study indicates that SAP may be beneficial for increasing perennial grass establishment but also may increase downy brome and hinder establishment of perennial forbs. Granulated SAP can easily be applied through a drill seeder, making SAP application a potentially practical tool for dryland restoration. However, the relative benefit of SAP to perennial versus downy brome appears to be site-specific. As positive effects of SAP on soil moisture were limited to the wettest days measured, SAP may be more effective at increasing soil moisture under relatively wetter conditions. A deeper understanding of site specific factors such as precipitation, soil nutrients, and species-specific responses to SAP is needed to inform management and use of SAP in arid-land restoration.

Management Implications

Granulated SAP can aid in the establishment of perennial grasses in dryland reseeding efforts. However, SAP also has the potential to benefit downy brome and hinder the establishment of perennial forbs. SAP may be helpful for promoting perennial grass establishment in areas where downy brome invasion is not a concern. SAP can be applied through a drill seeder, and when applied in this manner is effective at rates of 300 $kg \cdot ha^{-2}$ to 450 $kg \cdot ha^{-2}$.

The soil binding agent DirtGlue can increase soil moisture and may be useful as an erosion and dust control measurement that is compatible with reseeding. DirtGlue may benefit or hinder downy brome depending on site specific factors; therefore it may be most appropriate in areas where downy brome is not a concern.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.rama.2019.10.001.

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