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Effectiveness and Cost of Downy Brome (*Bromus tectorum*) Control at High Elevation

Amy L. Concilio*

Downy brome (*Bromus tectorum*) is an invasive, annual grass that has spread through much of the Great Basin desert but remains patchy at high elevation. This study evaluates control options for outlier infestations in the eastern Sierra Nevada, CA, based on their ecological effectiveness and their economic and practical feasibility. I tested the efficacy of hand-pulling, sheet-mulching, and soil solarization followed by broadcast and seedball seeding of native forbs and grasses. Downy brome cover, density, and dominance in the seed bank decreased with all removal treatments. Soil solarization and sheet mulching were most successful at eliminating downy brome (decreasing density by 99% after just 1 yr of treatment in both cases), but they had negative nontarget impacts on other herbaceous species. Germination of native seeds was low with both broadcast and seedball seeding, probably because of dry conditions. Each of the methods tested has potential for decreasing or eliminating small-scale, outlier infestations of downy brome along roadsides and in disturbed sites and thereby helping to contain the invasion.

Nomenclature: Downy brome, *Bromus tectorum* L.

Key words: Cheatgrass, Great Basin desert, mulching, nontarget impacts, rangeland seeding, seed bank, Sierra Nevada, soil solarization.

Downy brome (*Bromus tectorum* L.) is an invasive, annual grass from Eurasia, with severe ecological and economic impacts on shrub–steppe ecosystems of the Intermountain West of the United States (Knapp 1996). At high density, downy brome can initiate an invasive grass–fire cycle, creating a positive feedback loop that promotes its own persistence and spread (Brooks et al. 2004; D'Antonio and Vitousek 1992). At elevations in the eastern Sierra Nevada, CA, above approximately 2200 m (7,218 ft), downy brome populations remain patchy and impacts appear minimal, probably because of physiological limitations associated with cold winter temperatures and deep snowpack (Chambers et al. 2007; Griffith and Loik 2010). However, global climate change may provide opportunities for downy brome range expansion in the region (Concilio et al. 2013). Outlier patches at the leading edge of the invasion should be targeted for eradication to reduce the likelihood of increased impacts on the region and to conserve relatively intact native sagebrush steppe habitat. Although much effort has been placed on controlling downy brome in highly invaded areas (e.g., Borman 2000; McIver et al. 2010), less experimental work has been done testing methods that target small patches, particularly at range margins where invasions may expand. This study tests the effectiveness of four control methods aimed at eliminating downy brome infestations at its high-elevation range margin.

A combination of invasive species removal followed by planting native species is recommended for restoring invaded rangeland ecosystems (DiTomaso 2000). Techniques that show promise for downy brome removal on a small scale include hand-pulling, mulching, and soil solarization (Tu et al. 2001), each of which have long histories of use in agricultural systems (Bond and Grundy 2001; Elmore et al. 1997) and have increasingly been used in wildland settings, but with mixed success (e.g., Banerjee et al. 2006; Hutchinson and Viers 2011). Although herbicides are often used to control small infestations of downy brome (Carpenter and Murray 2005), this approach can be impeded by regulatory obstacles and land managers' dependence on volunteer support for weed-removal work (Concilio 2012). I chose to test three nonchemical removal treatments, which can each be used with volunteer groups: hand-pulling, mulching, and soil solarization. I followed

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Management Implications

Downy brome is an invasive, annual grass that has spread through much of the Great Basin desert, with significant effects on native species. Control of downy brome is particularly challenging because of its impacts to the fire cycle. At the high-elevation extent of its range, however, it remains patchy, and native plant communities are still relatively intact. Removal of these outlier infestations could reduce downy brome spread, prevent future impacts on the fire cycle, and help conserve native sagebrush–steppe habitat. I tested the ecological effectiveness and the economic and practical feasibility of several control options for downy brome infestations at the western edge of the Great Basin desert, including hand-pulling, sheet-mulching, and soil solarization, followed by broadcast and seedball seeding of native forbs and grasses. Hand-pulling led to significant reductions in downy brome cover, reduced its dominance in the seed bank, and increased forb cover. Downy brome was virtually eliminated after both soil solarization and sheet mulching, but these treatments had negative impacts on other herbaceous plants. Reseeding efforts were unsuccessful, likely because of low soil moisture availability. Based on my results, I would recommend hand-pulling for controlling downy brome in areas where the native seed bank remains relatively intact, such as along hiking trails adjacent to undisturbed plant communities. Soil solarization and sheet mulching would be better options for use along roadsides, pack stations, and in other disturbed areas. Each of these control methods is relatively low technology, safe, and, thus, appropriate for volunteer groups, which could decrease costs of implementation. Proactive investment in containment of downy brome invasion at range margins could have significant economic and ecological benefits into the future.

removal treatments with two seeding treatments (broadcast and seedball) because revegetation with native species after invasive species removal can reduce the likelihood of colonization by disturbance-adapted exotic species (Carpenter and Murray 2005; Masters and Sheley 2001).

My objectives were to (1) test the effectiveness of each treatment at decreasing downy brome cover, density, and dominance over other herbaceous species in the seed bank; (2) test and compare the effectiveness of seeding methods at increasing native species cover after brome removal; and (3) quantify and compare labor and materials costs associated with each treatment.

Materials and Methods

Study Sites. This research was conducted in the eastern Sierra Nevada, Mono County, CA, at the western edge of the Great Basin Desert. Research plots were set up at two sites within 17 km (10.6 mi) of one another: on the campus of Cerro Coso Community College (Cerro Coso) in the town of Mammoth Lakes, CA (37.64°N, 118.97°W; elevation approximately 2400 m; and in the Inyo National Forest around the Sierra Nevada Aquatic Research Laboratory (SNARL; Valentine Eastern Sierra University of California Natural Reserve) about 16 km south of Mammoth Lakes (37.61°N, 118.82°W; elevation approximately 2150 m). The region experiences cold, wet winters and warm, dry summers, with approximately 75% of the annual precipitation falling as snow between November and March. Cerro Coso receives more precipitation, averaging (mean ± SD) 651 ± 218 mm yr^{-1} (25.6 ± 8.6 in yr^{-1}) (20-yr average; Western Regional Climate Center 2012). SNARL receives an average of 313 ± 132 mm yr^{-1} (24-yr average measured with an onsite weather station). At both sites, mean daily air temperature reaches a minimum in January of −5 to −10 C (23 to 50 F) and a maximum in July of 20 to 25 C.

At Cerro Coso, experimental plots were located within parking lot planters that were installed in 2003 (Figure 1). The soils were scraped and leveled and then covered with two inches of compacted Redwood Nitrolized Forest Humus (Kellogg Supply Company, Carson, CA). Ornamental shrubs and grasses were planted from nursery transplants, and herbaceous weeds later invaded the site. A mix of native and nonnative ornamental plants and weeds now cover the planters; dominant species include mountain big sagebrush [*Artemisia tridentata* Nutt. ssp. *vaseyana* (Rydb.) Beetle], bush cinquefoil [*Dasiphora floribunda* (Pursh) Kartesz, comb. nov. ined.], greenleaf manzanita (*Arctostaphylos patula* Greene), quackgrass [*Elymus repens* (L.) Gould], beardless wildrye [*Leymus triticoides* (Buckley) Pilg.], annual bluegrass (*Poa annua* L.), panicle willowherb (*Epilobium brachycarpum* K. Presl), white sweetclover (*Melilotus albus* Medik.), and hoary tansyaster [*Machaeranthera canescens* (Pursh) A. Gray].

SNARL is located within a natural sagebrush–steppe ecosystem. Soils are composed of sandy loam and gravelly sandy loam (Orr and Howald 2000). The site is dominated by two widespread shrub species: basin big sagebrush (*Artemisia tridentata* Nutt. ssp. *tridentata*) and antelope bitterbrush [*Purshia tridentata* (Pursh) DC.], which make up about 20% each of the total land cover. The remaining area is primarily open space with < 10% herbaceous cover and native perennial grasses, most of which are native species (see Orr and Howald [2000] for a complete species list).

Field Methods. At Cerro Coso, four restoration treatments were applied in 2009, including control (C); mechanical removal by hand-pulling with no seeding (PN); mechanical removal by hand-pulling, followed by seeding (PS); and sheet mulching (M). Within the PS plots, we tested two different seeding methods: broadcast and seedball. The plots were located throughout a parking lot in 12 irregularly shaped island planters, ranging in size from 25 to 66 m^2 (269.1 to 710.4 ft^2), each of which was invaded by downy brome at the start of the experiment (Figure 1A). Downy brome density ranged from 500 to 6,800 individuals m^{-2} (46.5 to 631.7 individuals m^{-2}) (median

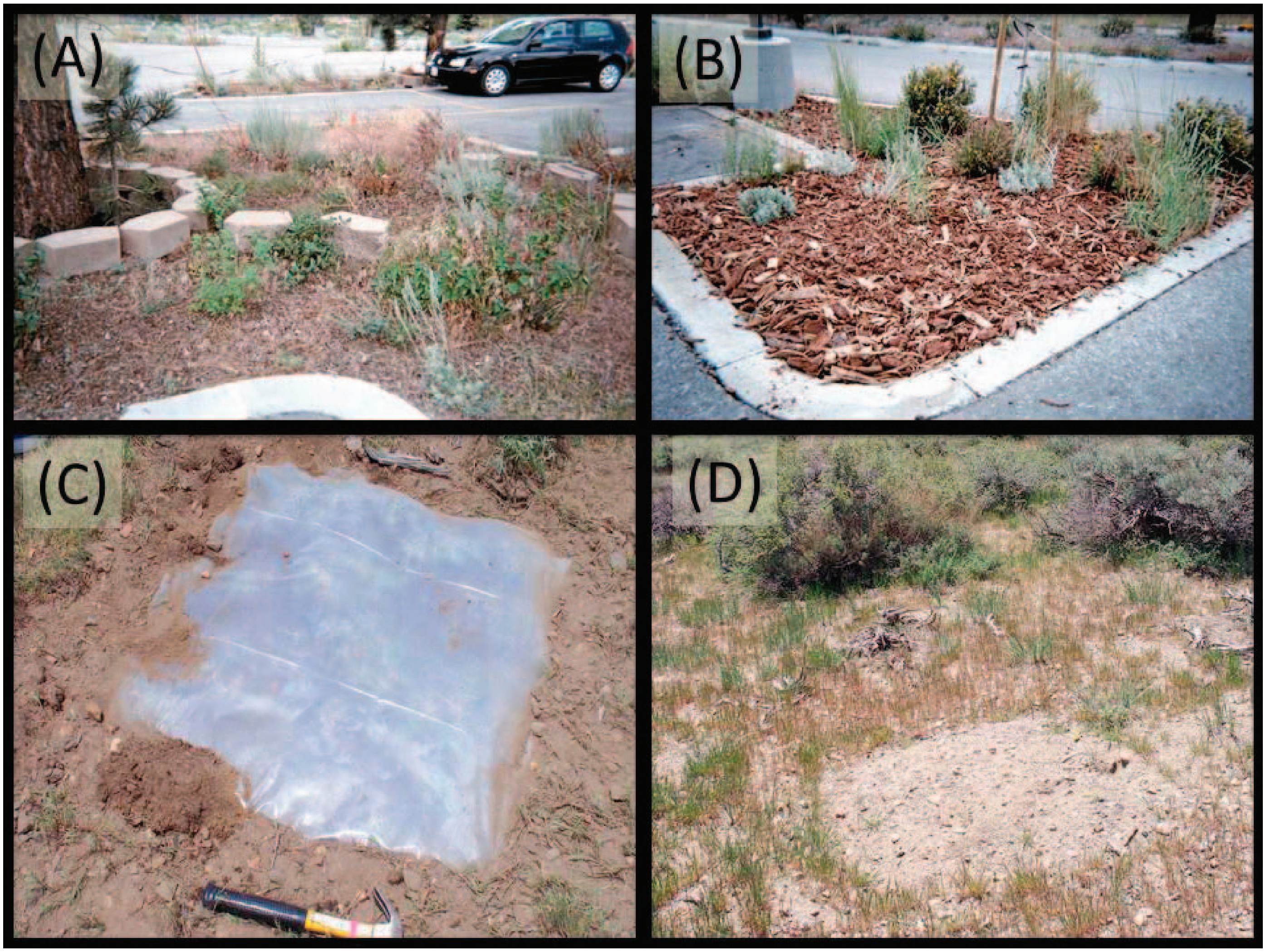

Figure 1. Treatments and study sites, including (A) control, and (B) mulched plots at the Cerro Coso Community College (Mammoth Lakes, CA) site and soil solarization plots at the Inyo National Forest around the Sierra Nevada Aquatic Research Laboratory (near Mammoth Lakes, CA) (C) during, and (D) after treatment. (Color for this figure is available in the online version of this paper.)

= 796; 25% quartile = 348; 75% quartile = 2,448), and there was no significant difference between control and treated plots before treatments were applied ($U = 420$; df = 1; P = 0.2414). Each treatment was replicated three times on full island planters (the PS plots were split: half of each planter received seedballs and half received broadcast seeding).

Manual-pulling treatments were applied 2 yr consecutively (2009 and 2010) in the late spring (June) when most (> 75%) of the downy brome had flowered but not yet set seed. For PN and PS treatments, all downy brome was hand-pulled from plots, removed completely from the site, air dried, weighed, and then disposed. Plots that were pulled and seeded received a seeding treatment 1 time yr^{-1} during the following October and consisted of a mix of six native bunchgrasses and perennial forbs (collected from local stock by Comstock Seed, Inc., Gardnerville, NV) at a rate of 10 kg ha^{-1} (8.93 lb ac^{-1}). Before purchase, seeds of all six species were tested for germinability with tetrazolium (TZ) tests by the Wyoming Seed Analysis Laboratory (Powell, WY); seed viability ranged from 64 to 98% for grasses and 34 to 93% for forbs. Dormancy was only tested on three species and ranged from 39 to 85%. Seeds were either broadcast evenly across the plot or broadcast as seedballs prepared by mixing three parts dry compost (Enriched Planting Compost, Supersoil, Scotts Company, LLC, Marysville, OH) to five parts dry clay (Lincoln Fire Clay, Gladding McBean Division, Pabco Clay Products, LLC, Lincoln, CA), one part seeds, and one part water. The sheet-mulching treatment was done at Cerro Coso in the summer of 2009 (Figure 1B). Plots were covered completely (aside from space occupied by perennial plants) with two layers of cardboard under a 10- to 15-cm (3.9- to 5.9-in) layer of wood and bark chips from a local mill, mainly composed of shredded Jeffrey pine (*Pinus jeffreyi* Balf.; G.C. Forest & Firewood Products, Mammoth Lakes, CA). The cardboard was used to block light to understory plants and seeds and to inhibit their growth and germination.

At SNARL, I compared soil-solarization treatments with (SS) and without seeding (SN) to control (C) plots. In May 2010, three groups of plots were placed at least 1 km apart from one another at sites that were invaded by downy brome. Downy brome density ranged from 400 to 9,800 individuals m^{-2} (median = 2,350; 25% quartile = 1,725; 75% quartile = 38,925) and did not vary between solarized and control plots before treatments were applied ($U = 335.5$; df = 1; P = 0.9495). Plots were located in open spaces between shrubs and perennial grasses. Each group contained 12, 1-m^2 plots: 6 received the soil-solarization treatment, and 6 acted as controls. Soil solarization was accomplished by heating moist soil to high temperature over an extended period according to Elmore et al. (1997). To prepare the plots, I used shovels and hoes to break up the ground, dug a 5-cm-deep trench with 10 cm of buffer space around each plot (total area per plot and buffer = 1.44 m^2) and saturated the soil by adding 10 mm of water evenly across each plot. Clear, 4-mil (0.100 mm), polyethylene plastic was then laid over the entire plot and buffer area. The corners of the plastic were nailed into the ground, the edges were secured into the trenches, and soil was tucked around the edges so that the plastic was airtight (Figure 1C). I checked on the plastic weekly throughout the summer and repaired any rips or tears with clear tape. Plastic remained on the soil for 52 d (from June 1, 2010, to July 22, 2010). In October 2010, half the solarized plots (three plots per group of six; SS) were seeded with the broadcast-seeding method described above.

To determine effectiveness of restoration treatments, I measured downy brome density and percentage of cover before treatment (in 2009, at Cerro Coso; in 2010, at SNARL), and downy brome density, downy brome and herbaceous species percentage of cover (including all grasses and forbs aside from downy brome), and downy brome dominance in the seed bank after treatment (in 2010 and 2011, at Cerro Coso; in 2011 at SNARL). At Cerro Coso, I used a grid system to randomly identify sampling points within the plots, taking measurements at 1.5-m intervals throughout the entire plot with a 0.5-m buffer from the edge (for 6 to 15 samples $plot^{-1}$). At SNARL, 50- by 50-cm^2 (7.75- by 7.75-in^2) plots were sampled in the center of each 1-m^2 plot. In June of each year, I laid out a 50- by 50-cm^2 quadrat plot sectioned into 16 equal squares at each sampling point. Downy brome density was measured by counting every individual in a 12.5- by 12.5-cm^2 subplot in the southeast corner of each plot with one exception: in the posttreatment solarized plots, I counted individuals within the full plot rather than subplots because density was so low. In 2009 and 2011, at Cerro Coso, I collected aboveground downy brome biomass samples within the same subplots, dried them (48 h at 60 C), weighed them, and calculated biomass as mass per square meter. I visually estimated downy brome, forb, and other grass (excluding downy brome) cover in the same location, but within the full 50- by 50-cm^2 plot using modified Daubenmire (1959) cover classes: 0 to 1, 1 to 5, 5 to 10, 10 to 25, 25 to 50, 50 to 75, and 75 to 100%. The midpoint of the cover class was used as a response variable.

Samples for seed bank analysis were collected in 2010 and 2011 in October (before seeding treatments). At Cerro Coso, I sampled along a grid system at 1-m intervals in C, PN, and PS plots (not M), with sample sizes ranging from 16 to 34 samples $plot^{-1}$. At SNARL, I collected three samples $plot^{-1}$. Soil was collected inside of a 33-cm^2 cylinder (6.5 cm diameter) inserted to a depth of 10 cm. Seed bank analysis was not done on samples from the M plots because sampling under the thick mulch and cardboard layers would have disturbed the plots and potentially decreased the effectiveness of the treatment.

Species composition in the seed bank was quantified with germination tests at the University of California, Santa Cruz, Plant Growth Facility. Tests for Cerro Coso plots took place in 2010 and 2011 between January and May, and tests for SNARL plots took place in 2011 only. Each sample was placed atop 5 cm of potting soil (Pro Mix HP, Premier Tech Horticulture, Québec, Canada) in a 288-cm^3 (17.6-in^3) pot with a surface area of 64 cm^2. Pots were watered daily for 1 min with a mister at 10:00 A.M. and 2:00 P.M. Ambient light was supplemented with overhead lights from 5:00 A.M. to 9:00 A.M. and from 5:00 P.M. to 7:00 P.M., for a consistent 15 h light d^{-1}. Mean daily air temperature for the duration of the experiment was 15.6 ± 3.9 C in 2010 and 20.0 ± 1.7 C in 2011. I surveyed pots weekly, counting and identifying each seedling until no new seedling growth had occurred for at least 3 wk (3.5 mo in 2010; 4 mo in 2011). Seedlings were identified to the species level when possible, and categorized as forb, shrub, grass (excluding downy brome), or downy brome.

Throughout the experiment, I kept a record of person–hours spent and cost of supplies for each treatment, and then calculated costs on a per-area basis. Costs for materials were minimal because I capitalized on local, free sources of cardboard and tree bark mulch. Assuming that land managers might not have the same opportunities, I calculated costs using average online prices for the top two retailers in California. Hourly costs of labor were calculated based on U.S. Department of Agriculture, Forest Service, base pay for a General Schedule (GS)-7 level employee, which, in 2012, was US$16.28 h^{-1} (OPM 2012).

Statistical Analyses. Differences in downy brome cover and density between treated plots were tested in pretreatment and posttreatment years within each site. Nonparametric analyses were used because the data could not be transformed to fit a normal distribution. I tested pretreatment differences in downy brome density and percentage of cover between C, P, and M at the Cerro Coso site in 2009 and posttreatment differences between the same groups in 2010 and 2011 using Kruskal-Wallis one-way ANOVA tests with post hoc Steel-Dwass comparisons (a nonparametric version of Tukey Honestly Significant Difference based on ranks; Neuhauser and Bretz 2001). Downy brome cover and density were compared between C and S at the SNARL site with Mann-Whitney *U* tests in 2010 (pretreatment) and 2011 (posttreatment). Native species percentage of cover was compared by treatment within each site in 2011 using the same analyses described above.

Downy brome dominance in the seed bank was calculated as the number of viable downy brome seeds divided by the total number of viable seeds and compared by site between C and P in 2010 and 2011 and between C and S in 2011 using Mann-Whitney *U* tests. I also compared PS to PN and SS to SN. However, neither the broadcast nor the seedball seeding method resulted in successful germination of seeded species, so I pooled PS and PN plots (P) and SN and SS plots (S) for most of the analyses.

All statistical analyses were run using JMP (Version 9; SAS Institute, Inc., Cary, NC). Means are reported with standard errors (mean $\pm$ 1 SEM) unless otherwise noted, and I considered differences to be significant when P values were < 0.05.

Results

I found that low-technology, nonchemical methods of control were effective at decreasing downy brome density, cover, and dominance in the seed bank at high elevation in the eastern Sierra Nevada, CA. All treatments resulted in a decrease in downy brome density compared with control plots and to pretreatment conditions (Tables 1 and 2). Density was reduced by 80% ($P < 0.0001$) and 99% ($P < 0.0001$) after 1 yr of treatments in pulled and mulched plots, respectively (Kruskall-Wallis comparison of density by treatment in 2010: $H = 44.70$; df = 2; $P < 0.0001$). After 2 yr, density was reduced even further in pulled plots (by 94% compared with pretreatment; $P < 0.0001$) and remained low in mulched plots ($P < 0.0001$; Table 1). Downy brome biomass per area decreased by 89% 2 yr after treatment in both pulled ($P < 0.0001$) and mulched ($P < 0.0001$) plots compared with controls (from 49 ± 15 g m^{-2} to 5.6 ± 1.5 g m^{-2} (1.45 ± 0.44 oz yd^{-1} to 0.17 ± 0.04 oz yd^{-1}) after pulling, and 5.5 ± 2.7 g m^{-2} after mulching treatments). Soil solarization led to a large decrease in downy brome density compared with the control plots: from an average of several thousand to 18 ± 3.6 individuals m^{-2} (Tables 1 and 2; Figure 1D).

Although all removal treatments effectively reduced downy brome cover (pulling: $P < 0.0001$; mulching: $P < 0.0001$; solarization: $P < 0.0001$) and density in the seed bank (pulling: $P < 0.0001$; solarization: $P < 0.0001$), they had varying effects on other herbaceous species (Table 1). Herb cover was not affected by hand-pulling ($P = 0.81$) or soil solarization ($P = 0.92$) but was reduced with mulching ($P = 0.034$), compared with the control plots. Downy brome dominance in the soil seed bank varied by treatment. At Cerro Coso, downy brome seeds made up $48 \pm 6\%$ of the diversity in soils from the control plots but was reduced to $5.1 \pm 1\%$ of the seed bank after 2 yr of pulling treatments in part because of an increase in seed density by the other herbaceous species ($P = 0.018$). At SNARL, downy brome seeds made up $78 \pm 5.2\%$ of the total seed bank in control plots. After soil solarization, downy brome seeds were completely eliminated from 15 of 18 plots (83%). However, there was also a complete elimination of other viable grass ($P = 0.043$) and forb seeds ($P = 0.0065$) in all solarized plots, making downy brome 100% dominant in the seed bank of the three plots where it was present.

Although downy brome removal treatments were successful, native plant seeding treatments were not. I saw no evidence of germination from any seeds from seedballs or from broadcast-seeded plots at Cerro Coso. At SNARL, I counted and identified all germinating seedlings in 2011 and found little difference between control and seeded plots.

Downy brome removal treatments varied in associated costs and labor (Table 3). Based on my estimates, labor costs were highest for soil solarization. Sheet mulching cost considerably less in person–hours than did other removal treatments, but materials costs were the highest. Comparing costs between removal treatments could be deceptive, however, because costs and labor could vary substantially within a treatment as well, based on site conditions. For example, the time required for hand pulling was reduced by 40% from 1 yr to the next because of the decreased downy brome density. I pulled five times more downy brome out of plots in 2009 compared with 2010 (35 kg dry mass in 2009, compared with 7 kg over an area of 116 m^2) in 32 person–hours compared with 20 hr, respectively.

Discussion

I found that low-technology, nonchemical methods of control were effective at substantially reducing downy brome infestations at high elevation in the eastern Sierra Nevada, CA. These approaches, however, have drawbacks in terms of high cost and potential nontarget impacts and

Table 1. Plant community response to hand-pulling and mulching treatments at Cerro Coso Community College (Mammoth Lakes, CA; Cerro Coso site) and solarization treatments at Inyo National Forest around the Sierra Nevada Aquatic Research Laboratory (near Mammoth Lakes, CA; SNARL site), including downy brome density before and after treatments, and downy brome cover, herbaceous cover (all herbaceous species aside from downy brome), downy brome seed density, and herbaceous seed density (excluding downy brome seeds) after treatments in control and treated plots at each site. Pretreatment data (means with SEM in parentheses) are from 2009 at Cerro Coso and 2010 at SNARL, and posttreatment data are from 2011 for both sites.

	Downy brome density		Cover		Downy brome seed density	
Site and treatment	Pretreatment	Posttreatment	Downy brome	Herbaceous	Downy brome	Herbaceous seed
	stems m^{-2}		%		seeds m^{-2}	
Cerro Coso site						
Control	1,637 (329)	1,683 (391)	28 (4.6)	19 (2.8)	1,354 (213)	1,343 (223)
Pulled	1,422 (525)	89 (20)	3.8 (1.2)	19 (3.2)	127 (32)	2,580 (525)
Mulched	1,458 (407)	41 (22)	4.4 (2.5)	11 (3.5)	NA	NA
SNARL site						
Control	3,105 (534)	2,327 (303)	52 (5.2)	1.9 (0.95)	1,131 (152)	132 (59)
Solarized	3,289 (571)	18 (3.6)	1.1 (0.43)	0.97 (0.22)	14.6 (8.3)	0 (0)

Abbreviations: NA, not available.

are, therefore, limited in application. The ecological, economic, and practical considerations that affect the feasibility of each method are discussed below.

Ecological Considerations. Downy brome removal treatments differed in their ecological effectiveness and nontarget impacts. Overall, the more effective downy brome control methods (solarization and mulching) were accompanied by negative impacts on other plants, whereas hand-pulling had a positive effect on other herbaceous species but was less successful at reducing downy brome infestations. Sheet mulching acts to physically suppress vegetative cover in the areas where it is applied and prevents germination of viable seeds by excluding light (Bond and Grundy 2001; Teasdale and Mohler 2000), so that method naturally had negative effects on any small-stature plants growing alongside the targeted brome plants. Likewise, soil solarization was highly effective at killing downy brome, but the treatment was indiscriminate and acted to kill all other seeds in the top soil layer. Although not measured here, mulching can affect soil chemistry (Bond and Grundy 2001; Zink and Allen 1998), and soil solarization can affect microbial communities (Scopa and Dumontet 2007) and nutrient cycling (Arora and Yaduraju 1998; Chen and Katan 1980). These potential nontarget impacts may be negative or positive for native plants and should be considered before treatment application.

Downy brome seeds were not completely eliminated from the seed bank after any of the removal treatments, which is a cause for concern. Downy brome can respond to reduced intraspecific competition by increasing its seed production (Thill et al. 1984); that is, even if just a few individuals remain, they may each produce hundreds of viable seeds. Furthermore, a large number of viable caryopses can remain dormant and persist from 1 yr to the next (Mack and Pyke 1983; Young et al. 1969). Until downy brome is completely eliminated from the seed bank, treatments would need to be repeated. With soil

Table 2. Statistical comparisons between downy brome density (plants m^{-2}) and cover (%) and herbaceous cover (percentage of cover by all herbaceous species combined, except for downy brome), by treatment, at Inyo National Forest around the Sierra Nevada Aquatic Research Laboratory (near Mammoth Lakes, CA; SNARL site) (Mann-Whitney *U* tests) and Cerro Coso (Kruskall-Wallis tests) in 2011.

	Comparisons between solarized and control at SNARL				Comparisons between pulled, mulched, and control at Cerro Coso		
	df	*U*	*z*	P	df	*H*	P
Downy brome density	1	171	−5.1172	< 0.0001	2	39.7721	< 0.0001
Downy brome cover	1	171	−5.268	< 0.0001	2	35.6889	< 0.0001
Herbaceous cover	1	330	−0.097	0.9226	2	6.2158	0.0447

Table 3. Labor and materials costs associated with each downy brome control treatment for the 2 yr of hand-pulling treatment and the one-time mulching and soil solarization treatments. Labor was calculated at \$16.28 h^{-1}. Person–hours represent the actual time spent on the total area indicated. The final column represents the sum of both labor and materials costs per square meter for each treatment.

	Total person–hours	Total area	Person–hours	Labor cost	Materials cost (m^{-2})	Total cost (m^{-2})
	h	M^2	h m^{-3}	$ m^{-2}		
Hand-pulling						
2009	32	116	0.28	4.49	0.27	4.76
2010	20	116	0.17	2.81	0.27	3.08
Mulching						
2009	16	109	0.15	2.39	3.74	6.13
Soil solarization						
2010	16	18	0.89	14.47	0.55	15.02

solarization, both the aboveground biomass and the seeds were killed with just one treatment in most plots. However, brome was not totally eliminated from all solarized plots, so follow-up visits should be made to remove any seedlings that do emerge after treatment. Hand-pulling requires individuals to germinate to be effective (dormant viable seeds are not affected) and greater attention is required for a longer time to deplete the seed bank (Carpenter and Murray 2005).

It was not surprising that seeding treatments were unsuccessful; germination and establishment rates for seeded species are often low in arid rangeland ecosystems because of dry conditions (Ethridge et al. 1997; Monsen 2004; Owen et al. 2011). However, it is cause for concern. Reseeding is often recommended after removal of an invasive species to avoid reinfestation or invasion by another weedy species (DiTomaso 2000). Before removing downy brome from a site, managers should carefully consider which plants would be likely to colonize based on the vegetative community in the surrounding landscape (D'Antonio and Meyerson 2002). In cases in which managers are concerned about infestation of new weed populations, planting plugs or using alternative seeding methods designed to increase establishment (e.g., drought-adapted strains of seeds (Forbis 2011), matric priming (Hardegree 1994), or different seedbed preparation (Monsen and Stevens 2004)) could increase restoration success. Conversely, lack of investment in native species recruitment may seriously impede invasive species management over the long term.

Finally, other ecological impacts may exist that I did not capture because of the short-term and small-scale application of these treatments (Kettenring and Adams 2011). Interannual changes in climate or differences in vegetation or soils may result in unique treatment responses. Annual follow-up monitoring and flexibility to respond to unexpected outcomes would be important for any invasive species management program.

Economic and Practical Considerations. One of the main limitations to the downy brome removal methods studied here is the high treatment cost per area and the intensive associated labor. However, these methods require little training, have no significant safety hazards associated with them, and can, therefore, take advantage of help from volunteer teams. For solarization and hand-pulling, most of the calculated costs were from labor rather than materials; consequently, help from volunteers would substantially reduce per-area costs. Materials costs were high for sheet mulching, but these expenses could also be reduced. Free sources of mulching materials can often be located; indeed, a wide variety of mulching materials have been used with success in agricultural settings (Bond and Grundy 2001; Teasdale and Mohler 2000).

Several practical considerations may also affect the feasibility of application of these methods. Because mulching and soil solarization can be effective with a single treatment, the bulk of labor costs are concentrated into 1 yr, whereas hand-pulling requires annual treatments for at least 3 yr. Hand-pulling may also pose scheduling challenges for managers because it is most successful if done at the specific phenological phase, just before seed set (Carpenter and Murray 2005). Timing for soil solarization and mulching is not as critical. Soil solarization does require repeated visitation to the site to repair broken plastic. However, most of my plots did not experience damage during the 2-mo treatment period, so fewer follow-up visits may be justified. Additionally, some researchers have found good results from just 1 mo of soil solarization (e.g., Arora and Yaduraju 1998); decreasing the time that plots are covered may also produce similar results.

Site location may affect cost and the practical feasibility of treatments as well. Distance from a water source is an important consideration for solarization treatments, and distance from a road would influence the feasibility of both solarization and mulching treatments. Transporting large volumes of mulch may be cost prohibitive, depending on

Table 4. Strengths and weaknesses of each downy brome control treatment tested and recommended uses.

Treatment	Strengths	Weaknesses	Recommended use
Hand-pulling	• Reduced downy brome cover • Increased herbaceous cover • Native seed bank maintained	• Tedious, time-consuming • Needs ongoing attention • Timing of treatments is critical • Large downy brome seed bank	• Wildland patches (e.g., along trails)
Mulching	• Reduced downy brome cover • Effective after a single season	• Eliminated all annual plants • Potential high cost for materials	• Disturbed areas (e.g., roadsides or pack stations)
Soil solarization	• Effective after a single season • Eliminated downy brome completely from 15 out of 18 plots	• Eliminated other plants • Tedious, time-consuming	• Disturbed areas far from weedy seed sources

both the distance to the site and the size of the infestation (Bond and Grundy 2001). For infestations located far from services, hand-pulling would be a better option.

Finally, it should be noted that my cost calculations do not follow these treatments to completion, so they may underestimate total costs. Additional labor costs would be necessary in the form of follow-up site visits for a minimum of several years after initial treatment application. Also, relative costs of solarization may not be comparable to hand-pulling or mulching because the sites at which treatments were applied differed (i.e., by initial downy brome density, infestation size, surrounding vegetation, soils). Variability in site conditions will likely affect both the total costs and the effectiveness of treatments at reducing downy brome.

Overall Site Suitability of Treatments. Even at reduced costs, none of the methods tested would be practical over large areas. However, these techniques can be targeted at small downy brome patches along roadsides and in other disturbed areas at the invasion front (such as those described by Banks and Baker [2011]). Eliminating outlier or satellite populations at the edge of an invasion could significantly reduce the associated long-term costs and impacts of nonnative species (Mack and Foster 2009; Moody and Mack 1988) because these infestations are likely to otherwise act as seed sources to uninvaded sites (With 2002). This strategy is being used to successfully contain the spread of yellow starthistle (*Centaurea solstitialis* L.) at the leading edge of its invaded range in the western Sierra Nevada, CA (CDFA 2012). This successful project should be used as a model for controlling other widespread invasive species, such as downy brome, when total eradication is not possible, but the potential costs of allowing the invasion to go unchecked could be severe.

Each of the downy brome removal methods tested here had different strengths and weaknesses that would make it appropriate for use on some infestations at the invasion front (Table 4). Because reseeding efforts were ineffective (and are difficult, in general, in arid rangelands), site selection for treatments that remove the native seed bank should be limited to locations where downy brome is dense (and the native seed bank is less likely to be intact) and where exotics are less likely to colonize. Sheet mulching would be practical for removing infestations in disturbed areas adjacent to wildlands, such as roadsides, pack stations, trailheads, or parking areas. Soil solarization would be best suited to dense downy brome patches surrounded by native species, far from nonnative seed sources, such as old sheep bedding areas. Hand-pulling could be used in locations where the native seed bank is likely to be intact.

To maximize downy brome containment and control, other methods should be used on larger-scale infestations at the invasion front in conjunction with those described here. Fire suppression and fuels management (e.g., through managed grazing, greenstripping, or planting fire-resistant native species that reduce the effects of downy brome on the fuelbed) would be appropriate complimentary approaches to reduce the chance of conversion to a grass–fire cycle and subsequent increased spread of downy brome (Brooks et al. 2004; Pellant et al. 2004). Investing preemptively in control of downy brome at the invasion front could reduce long-term costs and effects on the ecosystem and provide an opportunity for conservation of relatively undisturbed sagebrush-steppe habitat.

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