Impacts of seeding and seeding plus mulching treatments on exotic plant invasion and native plant recovery following the 2010 Fourmile Canyon Fire, Colorado

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Abstract

Following the 2010 Fourmile Canyon Fire, 170 ha (422 ac) of moderately and severely burned areas were seeded with a mixture of quick growing grass species to provide exotic plants with competition during the first few postfire years. Additionally, some seeded areas were also mulched for runoff and erosion control. We established a network of unburned (UNBURN), burned only (BURN), burned and seeded (SEED), and burned, seeded, and mulched (SEEDMULCH) plots to (1) quantify seeded grass germination and establishment, (2) assess the impacts of seed and seed plus mulch treatments on exotic plants, and (3) examine if native plant recovery is impacted by seed and seed plus mulch treatments. We found that the seeding treatments, both alone and in combination with mulching, had no impact on exotic plants during the first postfire year, probably because seeded grass and mulch cover were generally low. The native plant community also appears to be largely unaffected by the treatments at this point in time. Our results provide Boulder County Parks and Open Space with scientific data on the effectiveness of postfire seeding and seeding plus mulching treatments at meeting treatment objectives in the first postfire year. In view of the considerable cost of postfire rehabilitation activities, we recommend that additional work be conducted over the next few critical postfire years so that longer-term trends can be identified.

Introduction

By consuming vegetation and litter, altering soil structure, and increasing light and nutrient availability, severe wildfires greatly increase the risk of soil erosion, water runoff, and exotic plant establishment (D'Antonio 2000; Zouhar *et al.* 2008; Fornwalt *et al.* 2010). Post-fire damage due to erosion, runoff, and exotic plants can be extensive and costly, especially when both ecosystem properties (*e.g.*, nutrient cycling, plant succession, hydrologic processes) and human values (*e.g.*, water supplies, infrastructure) are affected (Beyers 2004). Because damage due to these threats can be extensive and costly, managers commonly prescribe postfire stabilization and rehabilitation treatments such as seeding and mulching (Robichaud *et al.* 2000, 2010; Peppin *et al.* 2011).

Postfire seeding and mulching treatments may have both intended and unintended impacts on understory plant communities. Seeding treatments typically utilize seeds of exotic cereal or pasture grasses because they are inexpensive, readily available, and quick growing, although native species increasingly are being incorporated into seed mixes (Robichaud *et al.* 2000; Peppin *et al.* 2011). While seeding may be prescribed in an attempt to combat a variety of postfire risks, including exotic species establishment and spread, the treatments are nonetheless predicated on the assumption that seeded species will enhance total plant cover. However, seeding is often ineffective due to poor seeded species establishment (Robichaud *et al.* 2000; Beyers 2004). Conversely, high rates of establishment may unintentionally suppress the regeneration of natives (Beyers 2004). Early-successional natives, which commonly establish following fire from the soil seedbank, appear to be particularly impacted (Schoennagel and Waller 1999; Keeley 2004).

Mulching treatments, in contrast, typically have erosion control as their primary objective (Robichaud *et al.* 2010); however, mulching may also impact understory plants. Agricultural straw is the most widely used material, but wood excelsior, wood strands, and wood chips have also been utilized (Robichaud *et al.* 2010). When combined with seeding, mulching has the potential to encourage seeded species establishment by minimizing seed movement, conserving soil moisture, and moderating soil temperatures (Binkley *et al.* 2003; Massman *et al.* 2006; Miller and Seastedt 2009). Similarly, mulching may encourage plant development from soil-stored seeds and from surviving belowground organs. Mulching may also reduce plant-available soil nitrogen (N), at least temporarily (Binkley *et al.* 2003); this may discourage the establishment of exotic species with high N demand (Zink and Allen 1998; Perry *et al.* 2010). However, thickly-applied mulch may actually impede understory plant development by reducing water penetration into the soil and physically obstructing seedling emergence (Massman *et al.* 2006; Robichaud *et al.* 2010). Both seeding and mulching may also unintentionally introduce exotics if materials are contaminated with seeds of exotic species.

Pinus ponderosa (ponderosa pine) – dominated forests in the Colorado Front Range have experienced a series of large and severe wildfires since the mid-1990s. To date, Colorado's most destructive wildfire in terms of damage to personal property is the 2010 Fourmile Canyon Fire, encompassing 2,502 ha (6,181 ac) and causing more than $217 million in damage (Fourmile Emergency Stabilization Team 2010). Approximately 1,492 ha (3,685 ac) burned with moderate to high severity.

Because the area burned by the Fourmile Canyon Fire is known to contain numerous exotic plant species, many of which are classified as noxious weeds in Colorado, managers prescribed that approximately 170 ha (422 ac) of the Fourmile Canyon Fire be seeded with a mixture of quick growing grass species (Fourmile Emergency Stabilization Team 2010; C. DeLeo personal communication). Seeding treatments were specifically designed to provide exotic species with competition for light and water during the first few postfire years. Additionally, many of the seeding locations fell within areas to be mulched for runoff and erosion control (Fourmile Emergency Stabilization Team 2010). In this research project, we examined the effectiveness of seeding and seeding plus mulching treatments at minimizing the introduction and spread of exotic plants while promoting native plant establishment. Our specific objectives were as follows:

- *Quantify seeded grass establishment and growth, both alone and in combination with mulch.*
- *Examine the impacts of seeding and seeding plus mulching on noxious weeds and other exotic plant species.*
- *Assess the effects of seeding and seeding plus mulching treatments on native plant recovery.*

Methods

Study area

Our study was conducted in and around the Fourmile Canyon Fire, approximately 10 km (6 mi) west of Boulder, Colorado. The topography in this area is rugged and complex, ranging in elevation from approximately 2,000 to 2,700 m (6,560 to 8,856 ft). Generally, soils are derived from metamorphic and igneous parent materials, and are coarse-textured and poorly developed (USDA NRCS 2008). Annual precipitation averages 48 cm (19 in), much of which falls during the winter and spring (Station 050848, 1893-2010, Western Regional Climate Center, http://www.wrcc.dri.edu). The mean annual temperature is 11° C (51° F), with a mean summer temperature of 21° C (70° F).

The Fourmile Canyon Fire was ignited on September 6, 2010. Gusting winds and low relative humidity on that day allowed the fire to reach approximately 2,321 ha (5,733 ac) by day's end. Fire growth was minimal over the following week, due in part to cooler, moister weather conditions and to aggressive fire suppression efforts. On September 13, 2010, the Fourmile Canyon Fire was declared contained. The final fire size was estimated at 2,502 ha (6,181 ac), 40% of which was unburned or lightly burned (Figure 1); 49% of the fire area burned with moderate severity and 11% with high severity. A more thorough description of the Fourmile's fire behavior and fire suppression efforts, as well as of the fire's physical setting, can be found in Graham *et al.* (2011).

Seeding and mulching treatments were conducted within the Fourmile Canyon Fire in spring 2011 (Fourmile Emergency Stabilization Team 2010; C. DeLeo personal communication; Figures 1 and 2). Seeding treatments were implemented by manually broadcasting and raking in seed on approximately 170 ha (422 ac) of moderately and severely burned areas with 0 to 60% slopes. Seeds were applied within a 30 m buffer on each side of roads and driveways at a rate of 587 seeds m^{-2} (55 seeds ft^{-2}). Species included in the seeding mix were the native perennial species *Elymus elymoides* (bottlebrush squirreltail), *E. trachycaulus* 'First Strike' ('First Strike' slender wheatgrass), and *Poa secunda* 'UP Colorado Plateau' ('UP Colorado Plateau' Sandberg's bluegrass), and the exotic annual *Avena sativa* (oats; Table 1).

Aerial mulching treatments were applied to approximately 790 ha (1950 ac) of moderately and severely burned forest where slopes were between 20 and 60%. Mulch was applied to achieve 50-75% ground cover. Roughly 82% of the mulched area was treated with certified weed-free *Triticum aestivum* or *Hordeum vulgare* (wheat or barley) straw, and 18% of the area was treated with WoodStraw®, an engineered wood strand product.

Plot selection

Study plot locations were selected using a two-tiered approach. First, approximately thirty potential plot locations were identified using GIS for each of the following four treatments: unburned (UNBURN), burned (BURN), burned and seeded (SEED), and burned, seeded, and mulched with straw (SEEDMULCH). Due to the relatively small area treated with WoodStraw, this mulching treatment was not evaluated here. All potential plot locations were limited to public lands within ~30 m (100 ft) of public roads. Potential plot locations within the fire were further limited to areas classified as burning with moderate or high severity on the burn severity coverage developed by the Fourmile Emergency Stabilization Team, while potential unburned plots were further limited to areas within 2 km (1.2 mi) of the fire perimeter. Next, because on-the-ground conditions can differ from conditions depicted in GIS coverages, the suitability of each potential plot location was assessed during follow-up visits. Potential plot locations falling in or near riparian areas, on slopes exceeding 40%, or within 100 m (328 ft) of an already-established plot were disregarded. A total of 40 plot locations met all criteria, and plots were established at each.

Data collection

Plots were 100-m^2 (20 m by 5 m) (1076-ft^2; 66 ft by 16 ft) in size, and were oriented with the plot's long axis paralleling the road (Figure 3). The understory plant community in each plot was characterized by estimating vegetative cover for each grass, forb, and shrub species in five 1-m^2 (11-ft^2) quadrats. Quadrats were equally spaced along a transect bisecting the plot down the long axis. We also noted the presence of all additional species within the larger 100-m^2 plot.

Plots were sampled in mid to late summer to capture maximal plant diversity and cover. Nomenclature follows the USDA Plants Database (USDA NRCS 2011), although varieties and subspecies are not distinguished. In some instances, observations were made only to genus, either because hybridization is common (*e.g.*, *Rosa*), or because species are difficult to determine when sampled outside peak phenological development (*e.g.*, *Antennaria*). We determined the nativity of each species (native or exotic to the continental United States) using the Flora of North America and the Plants Database (Flora of North America Editorial Committee 1993+; USDA NRCS 2011). Voucher specimens were collected and subsequently verified at the Colorado State University herbarium (http://herbarium.biology.colostate.edu/); they are being stored at the Rocky Mountain Research Station in Fort Collins, Colorado.

Burn severity, overstory stand structure, and forest floor data were also collected within each plot. Plot burn severity was assessed as either low, moderate, or high following the methodologies outlined in Parsons *et al.* (2010). Overstory stand structure was determined by measuring diameter at breast height, species, live or dead status, percent crown scorch, and percent crown consumption for all trees over 1.4 m (4.5 ft) tall. Percent cover of abiotic forest floor components including litter, duff, wood, mulch, ash, and bare soil were ocularly estimated in the five 1-m^2 quadrats. Plot slope and aspect were also noted.

Data analysis

We tested for plot-level differences in site and understory response variables among treatments using multiresponse permutation procedures (MRPP), a nonparametric alternative to analysis of variance. MRPP is a useful tool for ecological data analysis because it is not limited by assumptions of normally-distributed data or of homogeneous variances (Zimmerman *et al.*

1985). Because MRPP is not available in most statistical packages, we conducted our analyses in Microsoft Excel 2007 using the procedure outlined in Mielke and Berry (2001). All statistical tests were evaluated with an alpha of 0.05. Significant variables were further examined for pairwise differences between treatments using the Peritz closure method (Petrondas and Gabriel 1983).

We used regression to examine relationships between quadrat-level straw mulch cover and seeded grass cover for SEEDMULCH plots, and between quadrat-level seeded grass cover and native and exotic plant cover for SEED and SEEDMULCH plots. These analyses were conducted using PROC GLIMMIX in SAS 9.2. All cover variables were beta transformed prior to analyses to improve the distribution and homoscedasticity of residuals (Smithson and Verkuilen 2006).

The seeded species *E. elymoides* and *E. trachycaulus* are common throughout Boulder County. Unfortunately, there was no way for us to reliably distinguish between plants arising as a result of the Fourmile seeding treatments versus plants regenerating naturally from seed or surviving belowground organs. For the sake of consistency, we attribute all occurrences of these species to the seeding treatments in the analyses that follow. While this will not impact the interpretation of MRPP tests that compare response variables across treatments (because *E. elymoides* cover in SEED and SEEDMULCH plots is compared to that found in UNBURN and BURN plots), it may result in an overestimate of the seeded grass values used in the regressions, because these analyses solely use data from SEED and SEEDMULCH plots.

Results and discussion

Similarity of site conditions

Because postfire seeding and mulching treatments were so pervasive along moderately and severely burned public roads, we were only able to locate and measure five plots within the fire perimeter that were not treated in any way (BURN plots; Table 2; Figure 1).   Additionally, we located and measured 11 SEED plots, 9 SEEDMULCH plots, and 14 UNBURN plots.

Plots within the four treatments appear to be similar in their environmental conditions (Table 3). Slopes of SEEDMULCH plots were on average 10° greater than those in UNBURN plots; otherwise, slope did not differ among treatments. Furthermore, the treatments did not differ in aspect (expressed as degrees from south), prefire overstory density, or prefire overstory basal area.

Seeded grass establishment and growth

Not surprisingly, total seeded grass abundance and cover were greater in areas that were seeded than in those that were not (Figure 4). However, these measures did not differ between SEED and SEEDMULCH plots, with seeded grasses present in 74% of 1-m^2 quadrats and totaling to 2.9% cover, on average.

The exotic annual cereal grass *A. sativa* was by far the most successful of the four grass species seeded in the Fourmile Canyon Fire. Cover for this species averaged 2.7% in SEED and SEEDMULCH plots and accounted for nearly 90% of total seeded grass cover (Figure 4). *A. sativa* occurred in 70% of SEED and SEEDMULCH quadrats. As with total seeded grass abundance and cover, *A. sativa* abundance and cover were not statistically different between SEED and SEEDMULCH plots (Figure 4).

Of the three native perennial species seeded in the Fourmile Canyon Fire, *E. elymoides* was also regularly encountered; however, this species is very common in Boulder County, and it is likely that many of its occurrences in our plots are from natural regeneration. This is exemplified by the fact that *E. elymoides* cover and abundance in UNBURN and BURN plots did not differ from values observed in SEED and SEEDMULCH plots. In contrast, *E. trachycaulus* was rarely encountered, and *P. secunda* was not encountered at all. It could be that *E. trachycaulus* and *P. secunda* were more common in our plots but were too immature to be identified. We anticipate that these three perennial grass species will continue to increase in cover in seeded areas in subsequent years.

Scanty seeded grass establishment in the first postfire year has been reported by others working in Colorado Front Range *P. ponderosa* forests. For example, Wagenbrenner *et al.* (2006) reported that seeded grass germination was poor one year following the 2000 Bobcat Gulch Fire, resulting in no difference in total plant cover between seeded and unseeded areas. Similarly, Rough (2007) also did not observe any first-year differences in total plant cover between seeded and unseeded portions of the 2002 Hayman Fire. Seed movement due to steep terrain and gravelly soils, as well as relatively low levels of precipitation even in average years, may all contribute to the apparent difficulty in establishing seeded grasses in burned Front Range forests.

Our finding that mulching treatments did not facilitate seeded grass establishment and/or growth in the first postfire year is also consistent with other studies (Badia and Marti 2000; Kruse et al 2004; Rough 2007). In the case of the Fourmile Canyon Fire, this is likely due to the low cover of mulch within the mulched areas. Though mulching treatments were intended to achieve 50-75% mulch cover, it rarely exceeded 25% in any quadrat, and averaged only 6.8% across all SEEDMULCH plots. However, the weak but positive relationship between total seeded grass cover and straw mulch cover in SEEDMULCH quadrats suggests that high levels of mulch may indeed facilitate seeded grass establishment and growth (Figure 5).

Impacts of seed and seed-and-mulch treatments on exotic plants

Fire benefits many exotic plant species by creating favorable habitats for germination, establishment and growth (D'Antonio 2000; Zouhar 2008; Fornwalt *et al.* 2010), particularly in areas like Boulder County, where a long history of human disturbance has resulted in a considerable exotic plant community. Including the seeded species *A. sativa*, we identified 29 species not native to North America, accounting for 16% of all species identified (Appendix 1). Eighteen of these are forbs and eleven are graminoids. Eight of the exotic species classified as noxious weeds by the state of Colorado: *Bromus tectorum* (cheatgrass), *Carduus nutans* (musk thistle), *Cirsium arvense* (Canada thistle), *Convolvulus arvensis* (field bindweed), *Euphorbia esula* (leafy spurge), *Euphorbia myrsinites* (myrtle spurge), *Linaria vulgaris* (butter and eggs), and *Verbascum thapsus* (common mullein). Excluding *A. sativa*, *B. tectorum* and *Poa compressa* (Canada bluegrass) were the most widespread exotic species. Neither the occurrence nor the cover of these species differed statistically among the four treatments. Across all treatments, *B. tectorum* occurred in 48% of plots and 18% of quadrats; cover averaged 1.3% and accounted for 25% of total exotic cover. *P. compressa* occurred in 68% of plots and 11% of quadrats; with an average cover of 0.9%, it accounted for 16% of total exotic cover.

Furthermore, we found that neither the Fourmile Canyon Fire, nor the seed and seed plus mulch treatments, have had an impact on total exotic richness or cover in the first postfire year (Figure 6). Excluding *A. sativa* from analyses reduces average exotic cover from 5.4% to 4.0%, but does not otherwise influence our findings. Additionally, regressing total seeded grass cover versus total exotic cover (excluding *A. sativa*) for SEED and SEEDMULCH plots revealed no relationship between the two variables (Figure 7).

Research is increasingly demonstrating that seeding treatments are ineffective at controlling exotics for all but the highest levels of seeded grass cover (Schoennagel and Waller 1999; Keeley 2004; Stella *et al*. 2010). In fact, Kruse *et al*. (2004) found that both mulching and seeding treatments actually increased exotics following the Megram Fire, California, likely due to contaminated materials; contaminated straw also was likely responsible for the spread of *B. tectorum* into previously uninvaded portions of the Hayman Fire, Colorado (Chong *et al*. 2003; Fornwalt *et al*. 2010). *B. tectorum* - contaminated straw and seed were used on the Fourmile Fire as well (C. DeLeo personal communication), and while our results did not show an increase in *B. tectorum* occurrence or cover due to treatments, it is possible that an increase may be seen in future years. The aggressive nature of this and other exotic species, and their potential to alter ecosystem processes and functions, necessitates continued monitoring within the burn.

Effects of seed and seed-and-mulch treatments on native plant recovery

We identified 154 native understory species across the 39 plots (Appendix 1). Of these, 29 were short-lived forbs, 82 were long-lived forbs, 24 were graminoids, and 19 were shrubs. Also present were the trees *Pinus ponderosa* (ponderosa pine), *Pseudotsuga menziesii* (Douglas-fir), *Populus tremuloides* (aspen), and *Juniperus scopulorum* (Rocky Mountain juniper).

While the Fourmile Canyon Fire appears to have had some impact on total native richness and cover and on native richness and cover within functional groups, the seed and seed plus mulch treatments have had little additional effect at this point in time (Figures 8, 9). These findings are irrespective of whether *E. elymoides* and *E. trachycaulus* are included in analyses.

However, the negative relationship between seeded grass cover and total native cover (excluding *E. elymoides* and *E. trachycaulus*) in SEED and SEEDMULCH was significant (Figure 10), suggesting that native species are potentially being suppressed at the highest levels of seeded grass establishment. Others have also found that low levels of seeded grass cover did not impact native species in fire-adapted ecosystems (Fornwalt 2009; Kruse *et al.* 2004), while high levels of seeded grass cover decreased native plant establishment and growth (Sexton 1998; Schoennagel and Waller 1999; Keeley 2004).

Conclusions

Our results provide Boulder County Parks and Open Space with scientific data on the effectiveness of postfire seeding and seeding plus mulching treatments at meeting treatment objectives in the first year following application. We found that the seeding treatments conducted within the Fourmile Canyon Fire, both alone and in combination with mulching, appear to have had no impact on exotic plants during the first postfire year, probably because seeded grass and mulch cover were generally low. Fortunately, the native plant community also appears to be largely unaffected by the treatments at this point in time. In view of the considerable cost of postfire rehabilitation activities, it is important that future work be conducted on the effectiveness and the ecological impacts of these treatments over the short and long-term.

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Table 1. Seed mix used in the Fourmile Canyon Fire.

Species	**% of mix**	**Seeds m^{-2} (Seeds ft^{-2})**
Avena sativa (oats)	10	48 (5)
Elymus elymoides (bottlebrush squirreltail)	14	75 (7)
Elymus trachycaulus ‘First Strike’ (‘First Strike’ slender wheatgrass)	68	366 (34)
Poa secunda ‘UP Colorado Plateau’ (‘UP Colorado Plateau’ Sandberg’s bluegrass)	18	97 (9)
Total	100	587 (55)

Table 2. Number of unburned (UNBURN), burned only (BURN), burned and seeded (SEED), and burned, seeded, and mulched (SEEDMULCH) plots established within and surrounding the Fourrmile Canyon Fire.

Fire severity	**UNBURN**	**BURN**	**SEED**	**SEEDMULCH**
Unburned	14	0	0	0
Moderate severity	0	3	5	4
High severity	0	2	7	5
Total	14	5	12	9

Table 3. Attributes of unburned (UNBURN), burned only (BURN), burned and seeded (SEED), and burned, seeded, and mulched (SEEDMULCH) plots established within and surrounding the Fourmile Canyon Fire. Values are means ± standard errors. Values followed by different letters for an attribute indicate significant differences among treatments.

	UNBURN	**BURN**	**SEED**	**SEEDMULCH**
Aspect (degrees from south)	63.4 ± 10.0	79.6 ± 27.9	61.0 ± 15.6	40.2 ± 12.8
Slope (degrees)	10.9 ± 2.4 a	10.9 ± 2.4 ab	13.3 ± 2.0 ab	20.5 ± 2.2 b
Prefire overstory density (trees ha^{-1})	842.9 ± 322.0	620.0 ± 139.3	408.0 ± 101.0	600.0 ± 150.0
Prefire overstory basal area (m^2 ha^{-1})	16.0 ± 2.9	14.4 ± 3.6	9.8 ± 3.4	10.6 ± 4.4

Figure 1. Locations of the 40 unburned, burned only, burned and seeded, and burned, seeded, and mulched plots established within and surrounding the Fourmile Fire.

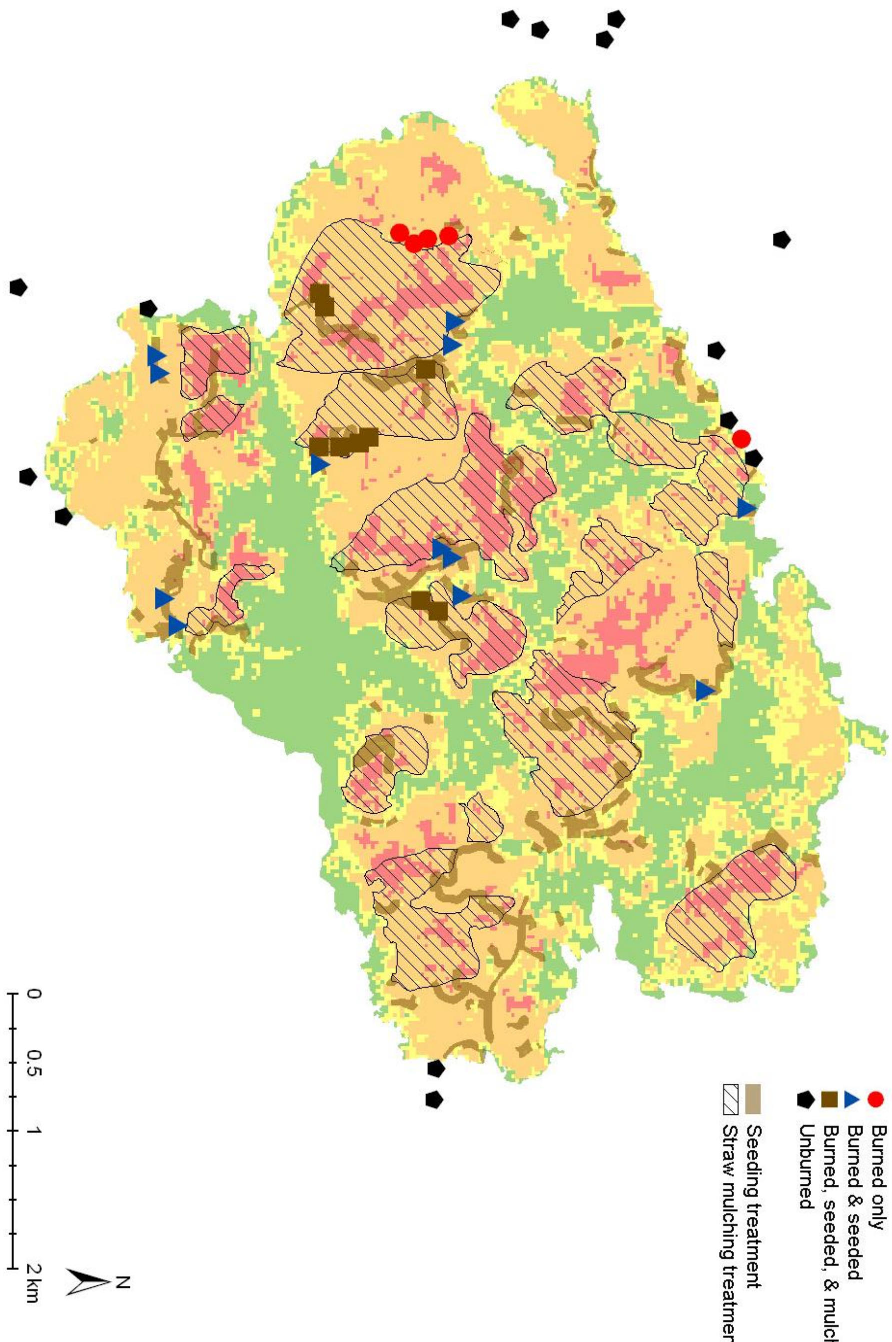


Figure 2. (a) Seeding and (b) mulching treatments were applied to moderately and severely burned portions of the Fourmile Canyon Fire in spring 2011. Photos courtesy of Wildlands Restoration Volunteers.

(a) Seeding treatments (photo by Linard Cimermanis)

(b) Mulching treatments (photographer unknown)

Figure 3. Schematic diagram illustrating the sampling design for all plots. Plots were 100-m^2 in size (~1076-ft^2), with the plot's long axis parallel to the road. The understory plant community in each plot was characterized by estimating cover for each vascular understory plant species in five 1-m^2 (~11-ft^2) quadrats.   The cover of abiotic forest floor components including litter, wood, mulch, ash, and bare soil was estimated in the quadrats as well. The presence of all additional species within the larger 100-m^2 plot was also noted.

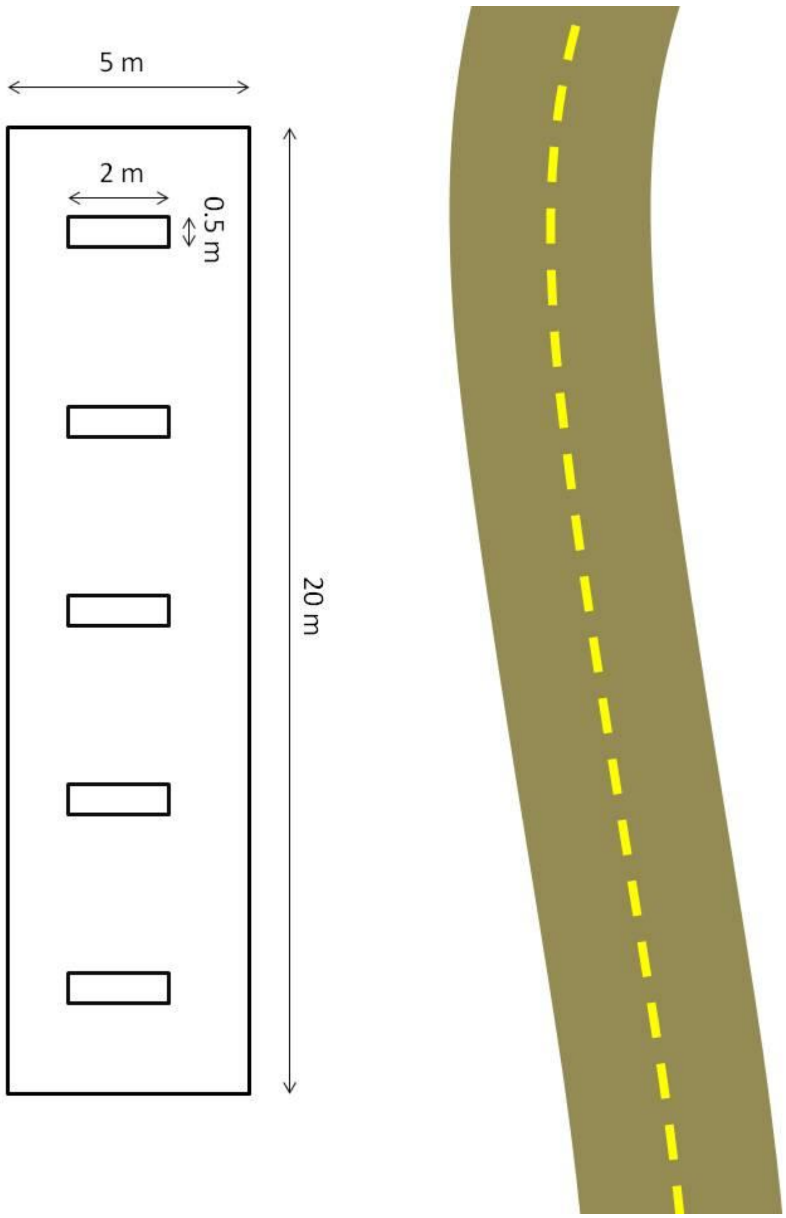


Figure 4. Mean frequency and cover (± standard error) of seeded grasses, by treatment. Values followed by different letters for an attribute indicate significant differences among treatments. *Poa secunda* is not shown because it was never encountered in our plots.

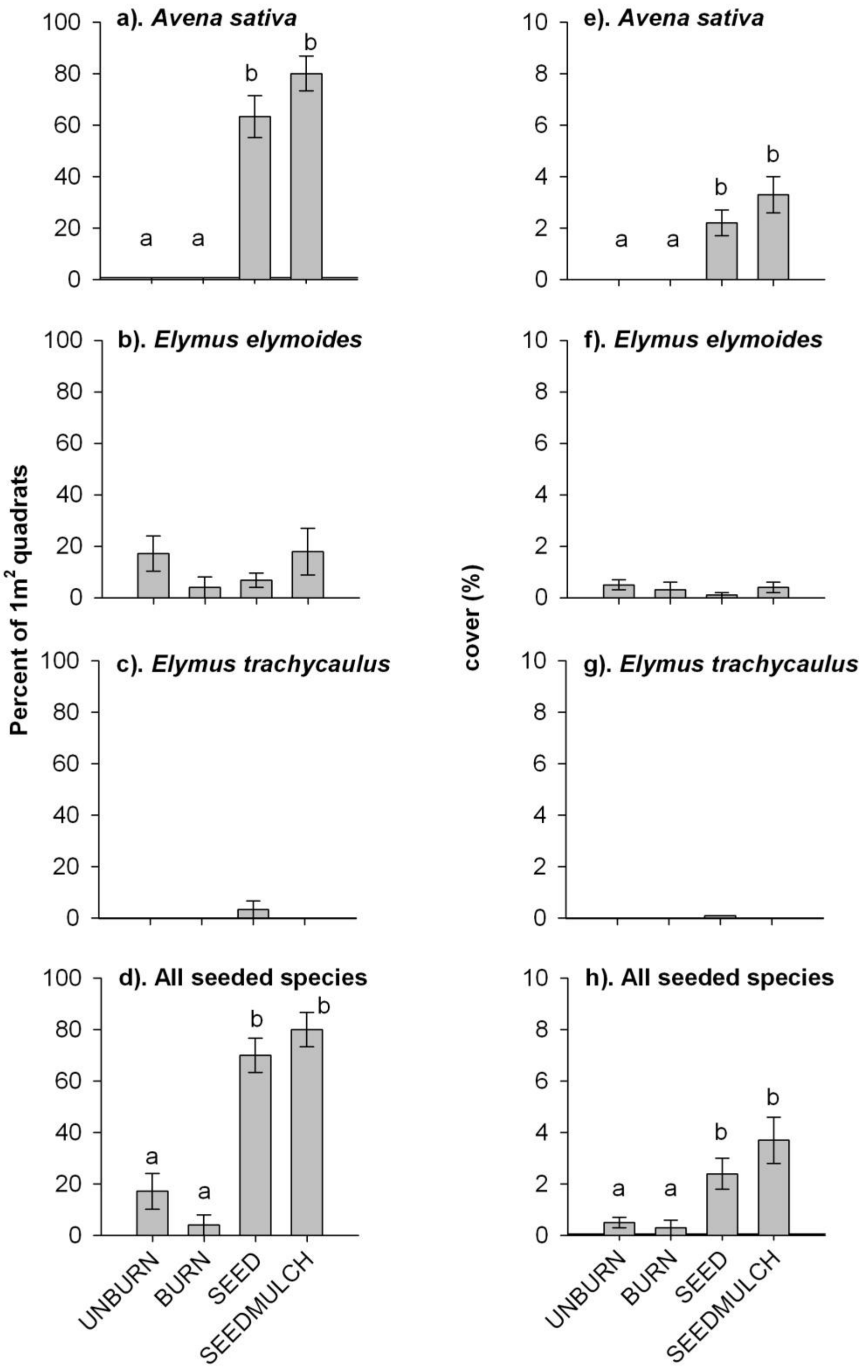


Figure 5. Cover of straw mulch versus total seeded grass cover in SEEDMULCH quadrats.

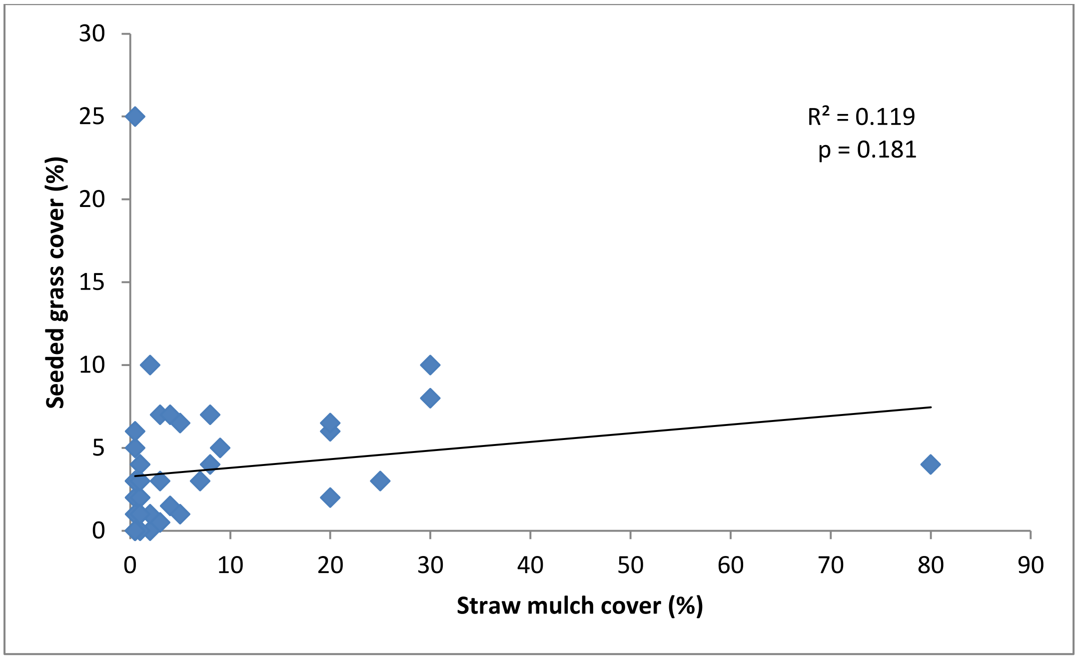


Figure 6. Total richness and cover (± standard error) for exotic species. There were no significant differences among treatments. *A. sativa* is included in exotic species values; removing this species from changes values somewhat but does not change significances.

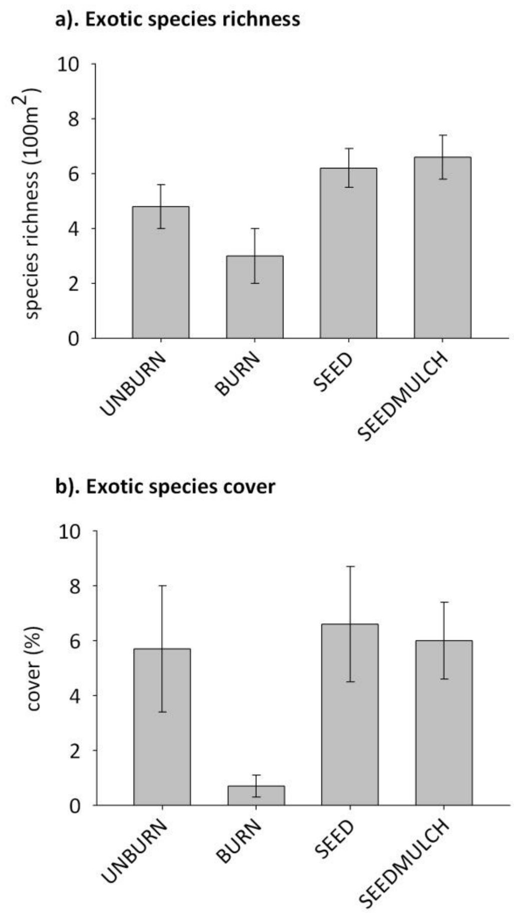


Figure 7. Total seeded grass cover versus total exotic cover in SEED and SEEDMULCH plots. Total exotic cover excludes *Avena sativa*, the seeded exotic grass. Both SEED and SEEDMULCH data are shown together since neither seeded grass cover nor total exotic cover differed between the two treatments.

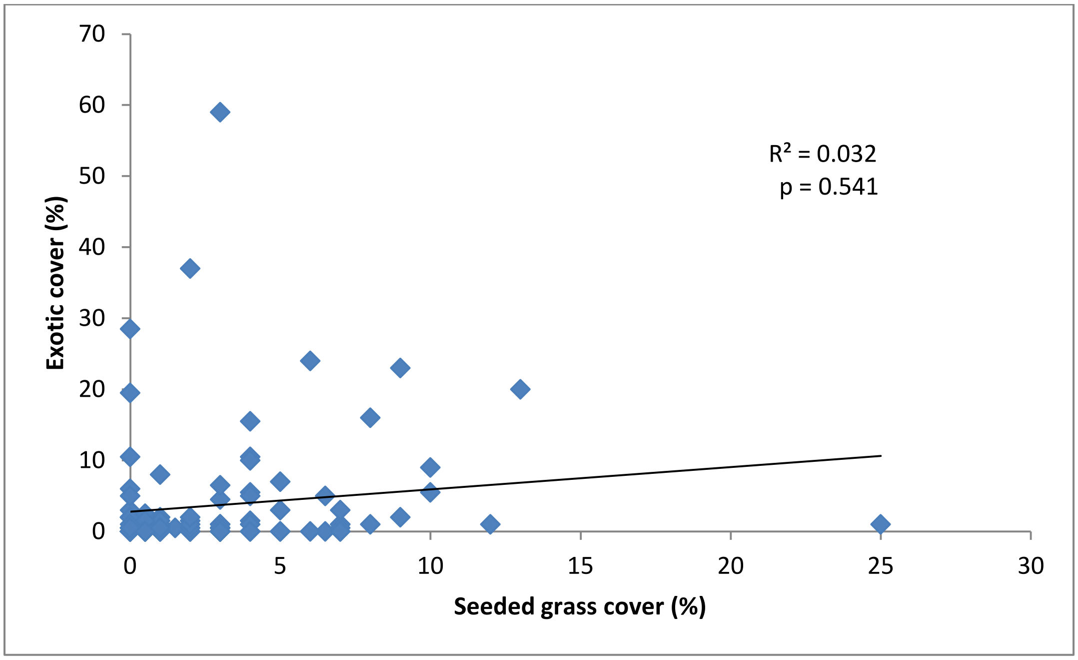


Figure 8. Total richness and cover (± standard error) for native species, by treatment. Values followed by different letters for an attribute indicate significant differences among treatments. *E. elymoides* and *E. trachycaulus* are included in native species values; removing these species from analyses changes values somewhat but does not change significances.

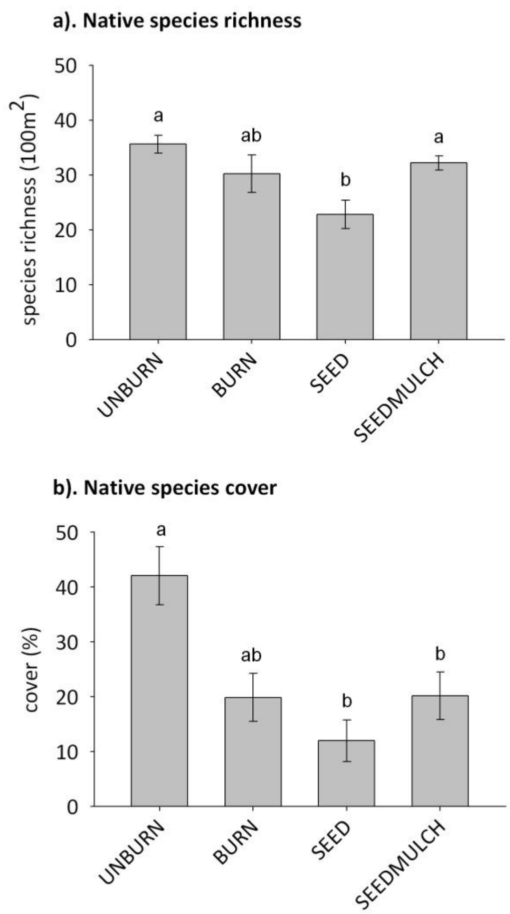


Figure 9. Total richness and cover (± standard error) for native species, by treatment and functional group. Values followed by different letters indicate significant differences among treatments. *E. elymoides* and *E. trachycaulus* are included in graminoid values; removing these species from analyses changes values somewhat but does not change significances.

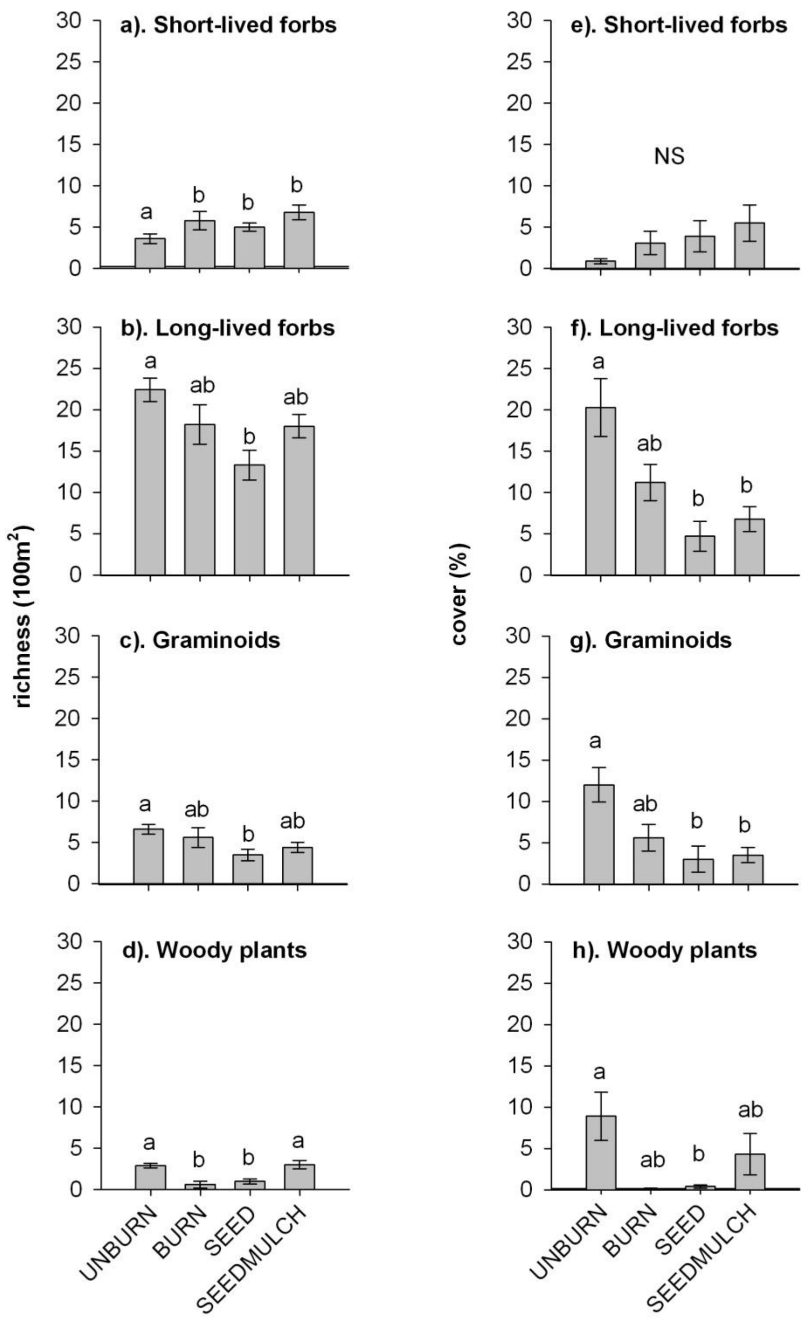
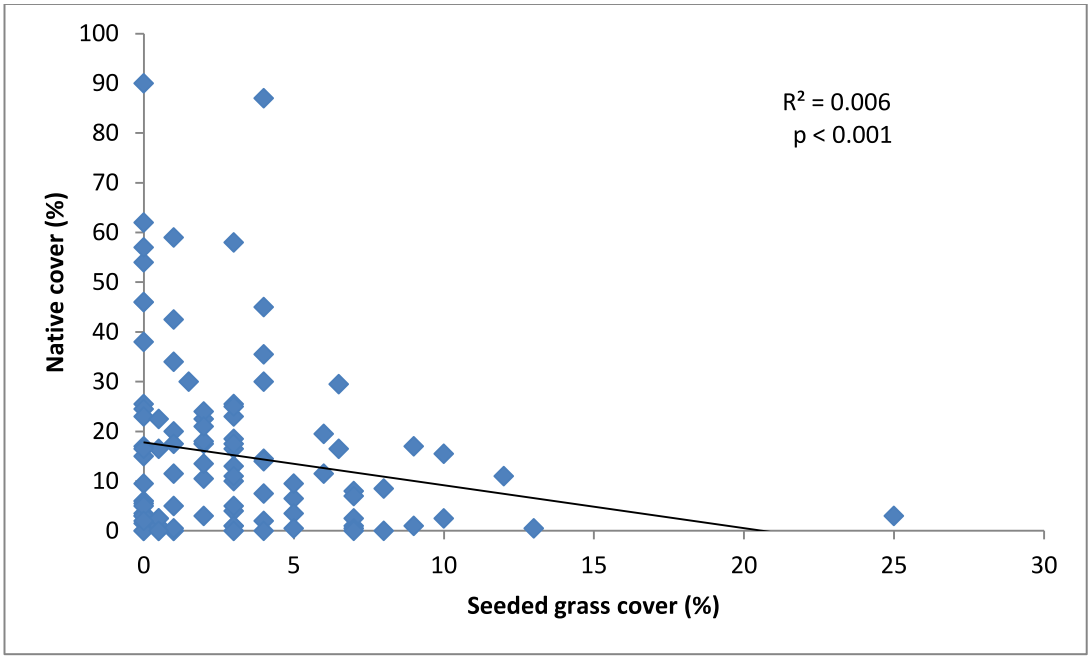


Figure 10. Total seeded grass cover versus total native cover in SEED and SEEDMULCH plots. Total native cover excludes *Elymus elymoides* and *E. trachycaulus*, the seeded native grasses that were encountered in this study. Both SEED and SEEDMULCH data are shown together since neither seeded grass cover nor total exotic cover differed between the two treatments.



Appendix 1. Short-lived forb, long-lived forb, graminoid, and shrub species encountered in the 40 plots.

Family	Species	Nativity	Habit
Agavaceae	*Yucca glauca* (soapweed yucca)	Native	Woody plant
Anacardiaceae	*Rhus trilobata* (skunkbush sumac)	Native	Woody plant
Apiaceae	*Aletes acaulis* (stemless Indian parsley)	Native	Long-lived forb
Apiaceae	*Cymopterus* (spring parsley)	Native	Long-lived forb
Apiaceae	*Harbouria trachypleura* (whiskbroom parsley)	Native	Long-lived forb
Apiaceae	*Pseudocymopterus montanus* (alpine false springparsley)	Native	Long-lived forb
Apocynaceae	*Apocynum androsaemifolium* (spreading dogbane)	Native	Long-lived forb
Asteraceae	*Achillea millefolium* (common yarrow)	Native	Long-lived forb
Asteraceae	*Agoseris glauca* (pale false dandelion)	Native	Long-lived forb
Asteraceae	*Ambrosia artemisiifolia* (annual ragweed)	Native	Short-lived forb
Asteraceae	*Antennaria* (pussytoes)	Native	Long-lived forb
Asteraceae	*Antennaria parvifolia* (small-leaf pussytoes)	Native	Long-lived forb
Asteraceae	*Antennaria rosea* (rosy pussytoes)	Native	Long-lived forb
Asteraceae	*Arnica cordifolia* (heartleaf arnica)	Native	Long-lived forb
Asteraceae	*Artemisia campestris* (field sagewort)	Native	Short-lived forb
Asteraceae	*Artemisia frigida* (fringed sage)	Native	Long-lived forb
Asteraceae	*Artemisia ludoviciana* (white sagebrush)	Native	Long-lived forb
Asteraceae	*Bahia dissecta* (ragleaf bahia)	Native	Short-lived forb
Asteraceae	*Carduus nutans* (musk thistle)	Exotic	Short-lived forb
Asteraceae	*Cirsium* (thistle)	Native or Exotic	Short- or Long-lived forb
Asteraceae	*Cirsium arvense* (Canada thistle)	Exotic	Long-lived forb
Asteraceae	*Erigeron compositus* (cutleaf daisy)	Native	Long-lived forb
Asteraceae	*Erigeron flagellaris* (trailing fleabane)	Native	Short-lived forb
Asteraceae	*Erigeron speciosus* (aspen fleabane)	Native	Long-lived forb
Asteraceae	*Erigeron subtrinervis* (threenerve fleabane)	Native	Long-lived forb
Asteraceae	*Gaillardia aristata* (blanketflower)	Native	Long-lived forb
Asteraceae	*Grindelia subalpina* (subalpine gumweed)	Native	Short-lived forb
Asteraceae	*Helianthus pumilus* (little sunflower)	Native	Long-lived forb
Asteraceae	*Heterotheca villosa* (hairy false goldenaster)	Native	Long-lived forb
Asteraceae	*Lactuca serriola* (prickly lettuce)	Exotic	Short-lived forb
Asteraceae	*Liatris punctata* (dotted blazing star)	Native	Long-lived forb
Asteraceae	*Packera fendleri* (Fendler's ragwort)	Native	Long-lived forb
Asteraceae	*Senecio crassulus* (thickleaf ragwort)	Native	Long-lived forb
Asteraceae	*Senecio integerrimus* (lambstongue ragwort)	Native	Short-lived forb
Asteraceae	*Solidago* (goldenrod)	Native	Long-lived forb
Asteraceae	*Solidago multiradiata* (Rocky Mountain goldenrod)	Native	Long-lived forb

Family	Species	Nativity	Habit
Asteraceae	*Taraxacum officinale* (common dandelion)	Exotic	Long-lived forb
Asteraceae	*Townsendia hookeri* (Hooker's Townsend daisy)	Native	Long-lived forb
Asteraceae	*Tragopogon dubius* (yellow salsify)	Exotic	Short-lived forb
Berberidaceae	*Mahonia repens* (creeping barberry)	Native	Woody plant
Boraginaceae	*Cryptantha virgata* (miner's candle)	Native	Short-lived forb
Boraginaceae	*Lappula occidentalis* (flatspine stickseed)	Native	Short-lived forb
Boraginaceae	*Lithospermum multiflorum* (many flowered stoneseed)	Native	Long-lived forb
Boraginaceae	*Mertensia lanceolata* (prairie bluebells)	Native	Long-lived forb
Brassicaceae	*Alyssum alyssoides* (pale madwort)	Exotic	Short-lived forb
Brassicaceae	*Alyssum simplex* (alyssum)	Exotic	Short-lived forb
Brassicaceae	*Arabis* (rockcress)	Native	Short- or Long-lived forb
Brassicaceae	*Arabis fendleri* (Fendler's rockcress)	Native	Long-lived forb
Brassicaceae	*Camelina microcarpa* (littlepod false flax)	Exotic	Short-lived forb
Brassicaceae	*Descurainia pinnata* (western tansymustard)	Native	Short-lived forb
Brassicaceae	*Descurainia sophia* (herb sophia)	Exotic	Short-lived forb
Brassicaceae	*Draba streptocarpa* (pretty draba)	Native	Long-lived forb
Brassicaceae	*Erysimum capitatum* (sanddune wallflower)	Native	Short-lived forb
Brassicaceae	*Lesquerella montana* (mountain bladderpod)	Native	Long-lived forb
Brassicaceae	*Noccaea montana* (alpine pennycress)	Native	Long-lived forb
Brassicaceae	*Sisymbrium altissimum* (tall tumblemustard)	Exotic	Short-lived forb
Brassicaceae	*Thlaspi arvense* (field pennycress)	Exotic	Short-lived forb
Cactaceae	*Opuntia polyacantha* (plains pricklypear)	Native	Woody plant
Cactaceae	*Pediocactus simpsonii* (mountain ball cactus)	Native	Woody plant
Campanulaceae	*Campanula rotundifolia* (bluebell bellflower)	Native	Long-lived forb
Caprifoliaceae	*Symphoricarpos albus* (common snowberry)	Native	Woody plant
Caryophyllaceae	*Cerastium arvense* (field chickweed)	Native	Long-lived forb
Caryophyllaceae	*Silene antirrhina* (sleepy catchfly)	Native	Short-lived forb
Caryophyllaceae	*Silene drummondii* (Drummond's campion)	Native	Long-lived forb
Caryophyllaceae	*Silene scouleri* (simple campion)	Native	Long-lived forb
Chenopodiaceae	*Chenopodium berlandieri* (pitseed goosefoot)	Native	Short-lived forb
Chenopodiaceae	*Chenopodium capitatum* (blite goosefoot)	Native	Short-lived forb
Chenopodiaceae	*Chenopodium fremontii* (Fremont's goosefoot)	Native	Short-lived forb
Chenopodiaceae	*Chenopodium leptophyllum* (narrowleaf goosefoot)	Native	Short-lived forb
Chenopodiaceae	*Salsola tragus* (prickly Russian thistle)	Exotic	Short-lived forb
Commelinaceae	*Tradescantia occidentalis* (prairie spiderwort)	Native	Long-lived forb
Convolvulaceae	*Convolvulus arvensis* (field bindweed)	Exotic	Long-lived forb
Crassulaceae	*Sedum lanceolatum* (spearleaf stonecrop)	Native	Long-lived forb
Cupressaceae	*Juniperus communis* (common juniper)	Native	Woody plant
Cyperaceae	*Carex* (sedge)	Native	Graminoid
Cyperaceae	*Carex inops* (long-stolon sedge)	Native	Graminoid
Cyperaceae	*Carex petasata* (Liddon sedge)	Native	Graminoid

Family	**Species**	**Nativity**	**Habit**
Cyperaceae	*Carex rossii* (Ross' sedge)	Native	Graminoid
Cyperaceae	*Carex siccata* (dryspike sedge)	Native	Graminoid
Dryopteridaceae	*Cystopteris fragilis* (brittle bladderfern)	Native	Long-lived forb
Elaeagnaceae	*Shepherdia canadensis* (russet buffaloberry)	Native	Woody plant
Ericaceae	*Arctostaphylos uva-ursi* (kinnikinnick)	Native	Woody plant
Euphorbiaceae	*Euphorbia brachycera* (horned spurge)	Native	Long-lived forb
Euphorbiaceae	*Euphorbia esula* (leafy spurge)	Exotic	Long-lived forb
Euphorbiaceae	*Euphorbia myrsinites* (myrtle spurge)	Exotic	Long-lived forb
Fabaceae	*Astragalus* (milkvetch)	Native	Long-lived forb
Fabaceae	*Astragalus laxmannii* (Laxmann's milkvetch)	Native	Long-lived forb
Fabaceae	*Astragalus parryi* (Parry's milkvetch)	Native	Long-lived forb
Fabaceae	*Astragalus shortianus* (Short's milkvetch)	Native	Long-lived forb
Fabaceae	*Astragalus tenellus* (looseflower milkvetch)	Native	Long-lived forb
Fabaceae	*Lupinus argenteus* (silvery lupine)	Native	Long-lived forb
Fabaceae	*Melilotus officinalis* (yellow sweetclover)	Exotic	Short-lived forb
Fabaceae	*Oxytropis deflexa* (nodding locoweed)	Native	Long-lived forb
Fabaceae	*Oxytropis lambertii* (purple locoweed)	Native	Long-lived forb
Fabaceae	*Oxytropis multiceps* (Nuttall's oxytrope)	Native	Long-lived forb
Fabaceae	*Thermopsis divaricarpa* (spreadfruit goldenbanner)	Native	Long-lived forb
Fumariaceae	*Corydalis aurea* (golden smoke)	Native	Short-lived forb
Gentianaceae	*Frasera speciosa* (monument plant)	Native	Long-lived forb
Geraniaceae	*Geranium caespitosum* (pineywoods geranium)	Native	Long-lived forb
Grossulariaceae	*Ribes* (currant)	Native	Woody plant
Grossulariaceae	*Ribes cereum* (wax currant)	Native	Woody plant
Hydrangeaceae	*Jamesia americana* (wax flower)	Native	Woody plant
Hydrophyllaceae	*Hydrophyllum fendleri* (Fendler's waterleaf)	Native	Long-lived forb
Hydrophyllaceae	*Phacelia alba* (white phacelia)	Native	Short-lived forb
Hydrophyllaceae	*Phacelia heterophylla* (varileaf phacelia)	Native	Short-lived forb
Lamiaceae	*Monarda fistulosa* (wild bergamot)	Native	Long-lived forb
Lamiaceae	*Scutellaria brittonii* (Britton's skullcap)	Native	Long-lived forb
Liliaceae	*Allium cernuum* (nodding onion)	Native	Long-lived forb
Liliaceae	*Allium textile* (textile onion)	Native	Long-lived forb
Liliaceae	*Calochortus gunnisonii* (Gunnison's mariposa lily)	Native	Long-lived forb
Liliaceae	*Maianthemum stellatum* (starry false lily of the valley)	Native	Long-lived forb
Linaceae	*Linum lewisii* (Lewis flax)	Native	Long-lived forb
Loasaceae	*Mentzelia dispersa* (bushy blazingstar)	Native	Short-lived forb
Loasaceae	*Mentzelia multiflora* (Adonis blazingstar)	Native	Short-lived forb
Onagraceae	*Gaura coccinea* (scarlet beeblossom)	Native	Long-lived forb
Onagraceae	*Gayophytum diffusum* (spreading groundsmoke)	Native	Short-lived forb
Onagraceae	*Oenothera* (evening primrose)	Native	

Family	Species	Nativity	Habit
Papaveraceae	*Argemone hispida* (rough pricklypoppy)	Native	Long-lived forb
Poaceae	*Achnatherum nelsonii* (Columbia needlegrass)	Native	Graminoid
Poaceae	*Agropyron/Elymus/Leymus/Pseudoregneria/ Thinopyrum* (wheatgrass)	Native or exotic	Graminoid
Poaceae	*Avena sativa* (common oat)	Exotic	Graminoid
Poaceae	*Bouteloua gracilis* (blue grama)	Native	Graminoid
Poaceae	*Bromus* (brome)	Native or Exotic	Graminoid
Poaceae	*Bromus arvensis* (field brome)	Exotic	Graminoid
Poaceae	*Bromus inermis* (smooth brome)	Exotic	Graminoid
Poaceae	*Bromus lanatipes* (woolly brome)	Native	Graminoid
Poaceae	*Bromus tectorum* (cheatgrass)	Exotic	Graminoid
Poaceae	*Calamagrostis purpurascens* (purple reedgrass)	Native	Graminoid
Poaceae	*Dactylis glomerata* (orchardgrass)	Exotic	Graminoid
Poaceae	*Danthonia parryi* (Parry's oatgrass)	Native	Graminoid
Poaceae	*Elymus albicans* (Montana wheatgrass)	Native	Graminoid
Poaceae	*Elymus elymoides* (bottlebrsh squirreltail)	Native	Graminoid
Poaceae	*Elymus trachycaulus* (slender wheatgrass)	Native	Graminoid
Poaceae	*Festuca saximontana* (Rocky Mountain fescue)	Native	Graminoid
Poaceae	*Hesperostipa comata* (needle-and-thread grass)	Native	Graminoid
Poaceae	*Koeleria macrantha* (prairie Junegrass)	Native	Graminoid
Poaceae	*Leucopoa kingii* (spike fescue)	Native	Graminoid
Poaceae	*Leymus ambiguus* (Colorado wildrye)	Native	Graminoid
Poaceae	*Muhlenbergia montana* (mountain muhly)	Native	Graminoid
Poaceae	*Pascopyrum smithii* (western wheatgrass)	Native	Graminoid
Poaceae	*Phleum pratense* (timothy)	Exotic	Graminoid
Poaceae	*Poa* (bluegrass)	Native or Exotic	Graminoid
Poaceae	*Poa compressa* (Canada bluegrass)	Exotic	Graminoid
Poaceae	*Poa fendleriana* (muttongrass)	Native	Graminoid
Poaceae	*Poa nemoralis* (wood bluegrass)	Native	Graminoid
Poaceae	*Poa pratensis* (Kentucky bluegrass)	Exotic	Graminoid
Poaceae	*Psathyrostachys juncea* (Russian wildrye)	Exotic	Graminoid
Poaceae	*Pseudoroegneria spicata* (bluebunch wheatgrass)	Native	Graminoid
Poaceae	*Schizachyrium scoparium* (little bluestem)	Native	Graminoid
Poaceae	*Secale cereale* (cereal rye)	Exotic	Graminoid
Poaceae	*Thinopyrum intermedium* (intermediate wheatgrass)	Exotic	Graminoid
Polemoniaceae	*Aliciella pinnatifida* (sticky gilia)	Native	Short-lived forb
Polemoniaceae	*Collomia linearis* (tiny trumpet)	Native	Short-lived forb
Polemoniaceae	*Ipomopsis aggregata* (scarlet gilia)	Native	Short-lived forb

Family	**Species**	**Nativity**	**Habit**
Polemoniaceae	*Microsteris gracilis* (slender phlox)	Native	Short-lived forb
Polemoniaceae	*Phlox multiflora* (flowery phlox)	Native	Long-lived forb
Polygonaceae	*Eriogonum alatum* (winged buckwheat)	Native	Long-lived forb
Polygonaceae	*Eriogonum flavum* (alpine golden buckwheat)	Native	Long-lived forb
Polygonaceae	*Eriogonum umbellatum* (sulphur-flower buckwheat)	Native	Long-lived forb
Polygonaceae	*Polygonum douglasii* (Douglas' knotweed)	Native	Short-lived forb
Portulacaceae	*Claytonia rosea* (western springbeauty)	Native	Long-lived forb
Primulaceae	*Androsace septentrionalis* (pygmyflower rockjasmine)	Native	Short-lived forb
Ranunculaceae	*Delphinium nuttallianum* (twolobe larkspur)	Native	Long-lived forb
Ranunculaceae	*Pulsatilla patens* (pasque flower)	Native	Long-lived forb
Rhamnaceae	*Ceanothus fendleri* (Fendler's ceanothus)	Native	Woody plant
Rosaceae	*Cercocarpus montanus* (alderleaf mountain mahogany)	Native	Woody plant
Rosaceae	*Physocarpus monogynus* (mountain ninebark)	Native	Woody plant
Rosaceae	*Potentilla fissa* (bigflower cinquefoil)	Native	Long-lived forb
Rosaceae	*Potentilla hippiana* (woolly cinquefoil)	Native	Long-lived forb
Rosaceae	*Potentilla pulcherrima x hippiana* (beautiful cinquefoil hybrid)	Native	Long-lived forb
Rosaceae	*Prunus pensylvanica* (pin cherry)	Native	Woody plant
Rosaceae	*Prunus virginiana* (chokecherry)	Native	Woody plant
Rosaceae	*Rosa* (rose)	Native	Woody plant
Rosaceae	*Rubus deliciosus* (delicious raspberry)	Native	Woody plant
Rubiaceae	*Galium boreale* (northern bedstraw)	Native	Long-lived forb
Santalaceae	*Comandra umbellata* (bastard toadflax)	Native	Long-lived forb
Saxifragaceae	*Heuchera parvifolia* (littleleaf alumroot)	Native	Long-lived forb
Scrophulariaceae	*Castilleja integra* (wholeleaf Indian paintbrush)	Native	Long-lived forb
Scrophulariaceae	*Castilleja linariifolia* (Wyoming Indian paintbrush)	Native	Long-lived forb
Scrophulariaceae	*Castilleja miniata* (giant red Indian paintbrush)	Native	Long-lived forb
Scrophulariaceae	*Collinsia parviflora* (maiden blue eyed Mary)	Native	Short-lived forb
Scrophulariaceae	*Linaria vulgaris* (butter and eggs)	Exotic	Long-lived forb
Scrophulariaceae	*Penstemon glaber* (sawsepal penstemon)	Native	Long-lived forb
Scrophulariaceae	*Penstemon virens* (Front Range beardtongue)	Native	Long-lived forb
Scrophulariaceae	*Scrophularia lanceolata* (lanceleaf figwort)	Native	Long-lived forb
Scrophulariaceae	*Verbascum thapsus* (common mullein)	Exotic	Short-lived forb
Solanaceae	*Physalis heterophylla* (clammy groundcherry)	Native	Long-lived forb
Solanaceae	*Solanum triflorum* (cutleaf nightshade)	Native	Short-lived forb
Violaceae	*Viola nuttallii* (Nuttall's violet)	Native	Long-lived forb