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Short-Term Vegetation Response to Bulldozed Fire Lines in Northern Great Plains Grasslands

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Abstract: A bulldozed fire line is a fire-suppression technique that limits fire movement by altering fuel continuity through vegetation removal and mineral soil exposure. The ecological impacts of a bulldozed fire line may exceed the effects of the fire itself through lasting changes in the soil and vegetation properties; however, little research has been performed to quantify these impacts in grassland systems. In this study, we compared vegetation properties among burned, unburned, and bulldozed fire line conditions on two August 2012 grassland wildfires in Montana. Standing biomass, by growth form, was quantified in 2013 and 2014, and compared using a generalized linear model. Perennial grass production was significantly reduced, while annual grass and annual forb biomass increased in response to the fire line treatment. Shrub and total vegetation standing crop were reduced in response to the fire line in 2013; however, the treatment effects were diminished by 2014. The burned and unburned treatments were generally similar within two years post-fire. The loss of perennial grasses and invasion of competitive annual grasses such as cheatgrass (*Bromus tectorum* L.) may limit the vegetation recovery of the fire line and promote further invasion of annual grasses into these systems. The marginal impact of the fires on these plant communities suggests the need to limit the use of ad hoc bulldozed fire lines as a suppression activity. If a bulldozed fire line is constructed, we suggest limiting soil disturbance by restricting blade depth to remove only surface vegetation and restricting bulldozer use to flat slopes, even if working with the contour, and incorporating re-seeding as part of or immediately after fire line construction.

Keywords: fire line; wildfire; grassland; rangeland; fire suppression; invasive plants; *Bromus tectorum*; cheatgrass

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1. Introduction

Wildfires are threatening and jeopardize ecological, economic, and social systems. Fire-suppression activities in response to wildfire are designed to limit negative impacts to infrastructure, habitat, water and air quality, and aesthetic values along with vegetation and soil resources [1]. Paradoxically, however, the effects of fire-suppression activities can also have negative ecological consequences that may be substantial and persistent, and, in some instances, may exceed the impacts associated with the fires themselves [1,2]. For example, the ecological impacts of a bulldozed fire line can persist and may promote weed invasion [3–5], truncating plant succession on these disturbed sites and potentially serving as a corridor for the movement of invasive species into surrounding areas, particularly following a subsequent disturbance event [3,4,6,7]. A bulldozed fire line refers to strips of exposed soil where the surface vegetation has been removed by a bulldozer or road grader to break fuel continuity and limit fire spread [8].

Although bulldozed fire lines can be observed for decades after construction, little effort has been put into quantifying the ecological changes and accounting for the ecological costs associated with this fire management strategy, particularly in grassland systems. Thus, we initiated a research project to investigate the ecological impacts of bulldozed fire lines using two separate grassland wildfires, one in north-central Montana and the other in southwest Montana. Specifically, this study focused on determining the response in vegetation biomass to a bulldozed fire line in comparison to burned and unburned areas. We hypothesized that construction of the fire line would generate a reduction of perennial species biomass and an increase in weedy species relative to the burned and unburned portions of the areas.

2. Materials and Methods

2.1. Study Area

Two separate grassland wildfires occurred in August 2012 on two Montana State University properties. Both fires incorporated bulldozed fire lines (fuel breaks) as a suppression strategy, and represented a natural experiment to study the effects of the fire and suppression technique. One fire occurred at the Red Bluff Ranch, 4 km east of Norris, MT (45°35′14″ N, 111°37′11″ W), while the other occurred at the Thackeray Ranch, 27 km south of Havre, MT (48°22′7″ N, 109°35′39″ W) (Figure 1). The Red Bluff fire was part of a large human-caused wildfire spanning approximately 6000 ha, while the Thackeray Ranch fire was smaller at about 80 ha and lightning-caused. Both study areas exist within foothills grasslands that are primarily managed for livestock production.

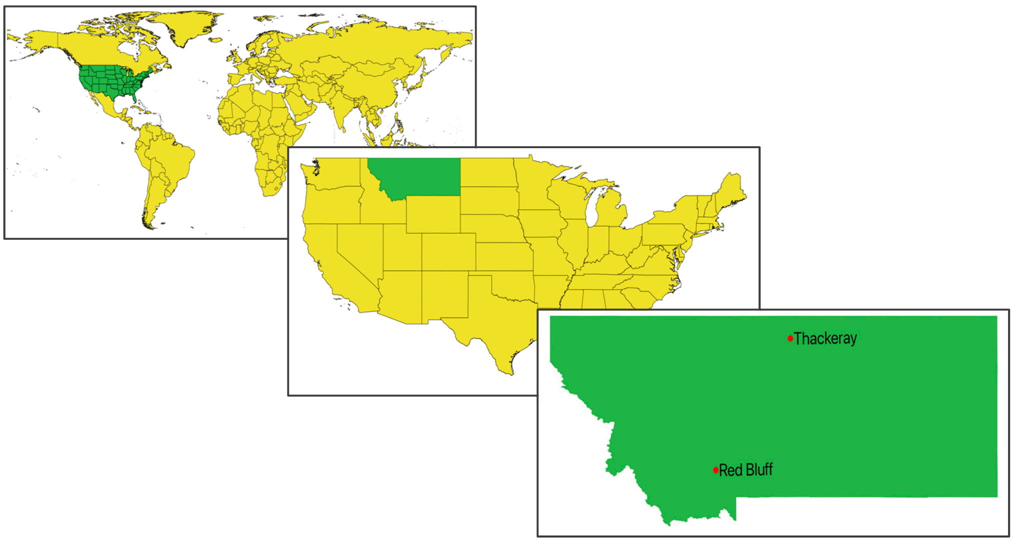

Figure 1. Study area locations shown within North America (**left**), the United States (**center**), and the state of Montana (**right**). Maps generated in QGIS [9].

The elevation at Red Bluff ranges from 1400 m to 1900 m and is in the foothills of the Madison and Gallatin Mountain ranges. The soils are characterized as sandy-skeletal to fine-loamy soils with gravelly to coarse-sandy loam surface horizons derived from gneiss, schist, and granite; some soils are very shallow, and there are occasional rocky outcrops [10]. The mean annual precipitation at Red Bluff is 41.5 cm, coming mostly as rain in the spring and early summer, and the mean annual temperature is 6.8 °C, ranging from −10.7 °C in January to 28.1 °C in July [11]. The vegetation at Red Bluff is dominated by native perennial grasses Idaho fescue (*Festuca idahoensis* Elmer) and bluebunch wheatgrass (*Pseudoroegneria spicata* (Pursh) A. Love), along with the native shrub fringed sagebrush (*Artemisia frigida* Willd.).

The elevation at the Thackeray Ranch ranges from 940 m to 1850 m, while the soils are characterized as fine- to coarse-loamy soils developed from igneous alluvial materials and/or glacial till in the foothills of the Bear's Paw Mountains [10]. The mean annual precipitation at Thackeray Ranch is 43.5 cm, with most rainfall occurring in early summer, and the average annual temperature is 5.1 °C, ranging from −11.2 °C in January to 26 °C in July [11]. The vegetation at Thackeray Ranch is dominated by perennial grasses including natives rough fescue (*Festuca campestris* Rydb.) and bluebunch wheatgrass, and the introduced species Kentucky bluegrass (*Poa pratensis* L.). Common native perennial forbs include western yarrow (*Achillea millefolium* L.) and golden pea (*Thermopsis rhombifolia* (Nutt. ex Pursh) Nutt. ex Richardson), along with localized arrowleaf balsamroot (*Balsamorhiza sagittate* (Pursh) Nutt.) presence.

2.2. Sampling Layout

We established 27 plots at each study area in three treatment conditions, representing burned, unburned and fire line conditions. Plots at Thackeray ranch were 16 m × 4 m and plots in Red Bluff were 17 m × 3 m, the width matching the width of the fire line built. Plots in the unburned and burned treatments were placed parallel to and within 10 m of the fire line. To capture the variability associated with differing ecological conditions at each location, three replicates of the plots were established within three different sites, giving us 27 plots at each study area (3 treatments × 3 sites × 3 replications = 27 plots). Sites were differentiated by aspect with sites on north, south, and west aspects at the Thackeray Ranch (labelled HN, HS, and HW, respectively) and north, south, and east aspects at Red Bluff (labelled RBN, RBS, and RBE, respectively). Plots in each replicate were established based on uniformity in landscape position and soil properties (i.e., surface texture and depth) to minimize the potential for differing pre-fire conditions to confound any observed treatment effects. Replicates were placed between 50 m and 200 m of each other and were treated as independent in our analyses.

2.3. Data Collection and Analyses

Three parallel transects were placed lengthwise in each plot, and above ground biomass was sampled in three 50 × 50 cm quadrats on each transect in 2013 and two quadrats in each transect in 2014. Biomass quadrats were placed 20 cm away from and parallel to transects, and both transects and quadrats were positioned within the plot using a systematic random approach. In both years, biomass was sampled in June and July by clipping vegetation at ground level with hand-held shears and then sorted into growth forms, including perennial grass, perennial forb, annual grass, annual forb, and shrub. Biomass samples were dried at 65 °C for 48 h and then weighed. Unfortunately, in 2013 we were not able to collect vegetation data from the RBE site, as cattle grazed the site prior to our attempted data collection. Data were collected from all sites in 2014.

Biomass data were averaged at the plot level and then scaled up to a kg·ha^{-1} value. To evaluate the effects of the burned, unburned, and fire line treatments on the responses of perennial grass, perennial forb, annual grass, annual forb, shrub, and total biomass, we used generalized linear models with a negative binomial distribution. The explanatory variables included treatment, site, and treatment-by-site interaction. To avoid infinite confidence intervals for treatment groups where all response values were zeros, we added a small constant (i.e., 1) to a random subset of zeroes in the annual grass and annual forb responses. This transformation maintained the data structure and reflected the detection limits of our sampling design. Pairwise comparisons of treatment means within sites were performed using a Tukey adjustment to control for the familywise error rate. Analyses were performed separately for each year using R [12].

3. Results

3.1. Perennial Grass

In 2013, treatment, site, and treatment x site interactions were all significant with respect to perennial grass production (Table 1). There was a reduction in perennial grass production associated with the fire line treatment, although the strength of the effect was dependent on the site (Table 2 and Figure 2A). Interestingly, the reduction in perennial grass production associated with fire line construction was not statistically different from the burned treatment at site RBS. Neither the burned nor unburned treatments differed in perennial grass production in any site (Table 2). In 2014, the impact of the fire line remained clear, with significantly lower perennial grass production on the fire lines compared to the other treatments at all sites except RBS, where perennial grass production at the fire line was similar to the other treatments (Table 2 and Figure 2B). As observed in 2013, the burned and unburned treatments were similar with respect to perennial grass production at all sites.

Table 1. P-values from Type III tests of the effects of treatment, site, and treatment and site interaction from generalized linear models with biomass response variables of total vegetation, perennial grass, perennial forb, shrub, annual grass, and annual forb for the years 2013 and 2014. Treatment × Site represents the treatment and site interaction.

	Perennial Grass	Perennial Forb	Annual Grass	Annual Forb	Shrub	Total Vegetation
Treatment						
2013	<0.0001	0.1981	<0.0001	0.0209	0.0075	0.0062
2014	<0.0001	0.3292	<0.0001	<0.0001	0.1472	0.8053
Site						
2013	0.0047	0.0023	<0.0001	<0.0001	0.0099	<0.0001
2014	0.4152	0.0147	<0.0001	<0.0001	<0.0001	<0.0001
Treatment × Site						
2013	0.0002	0.2369	<0.0001	0.8000	0.0012	0.0248
2014	0.0009	0.0416	0.0001	0.0001	0.0264	0.8517

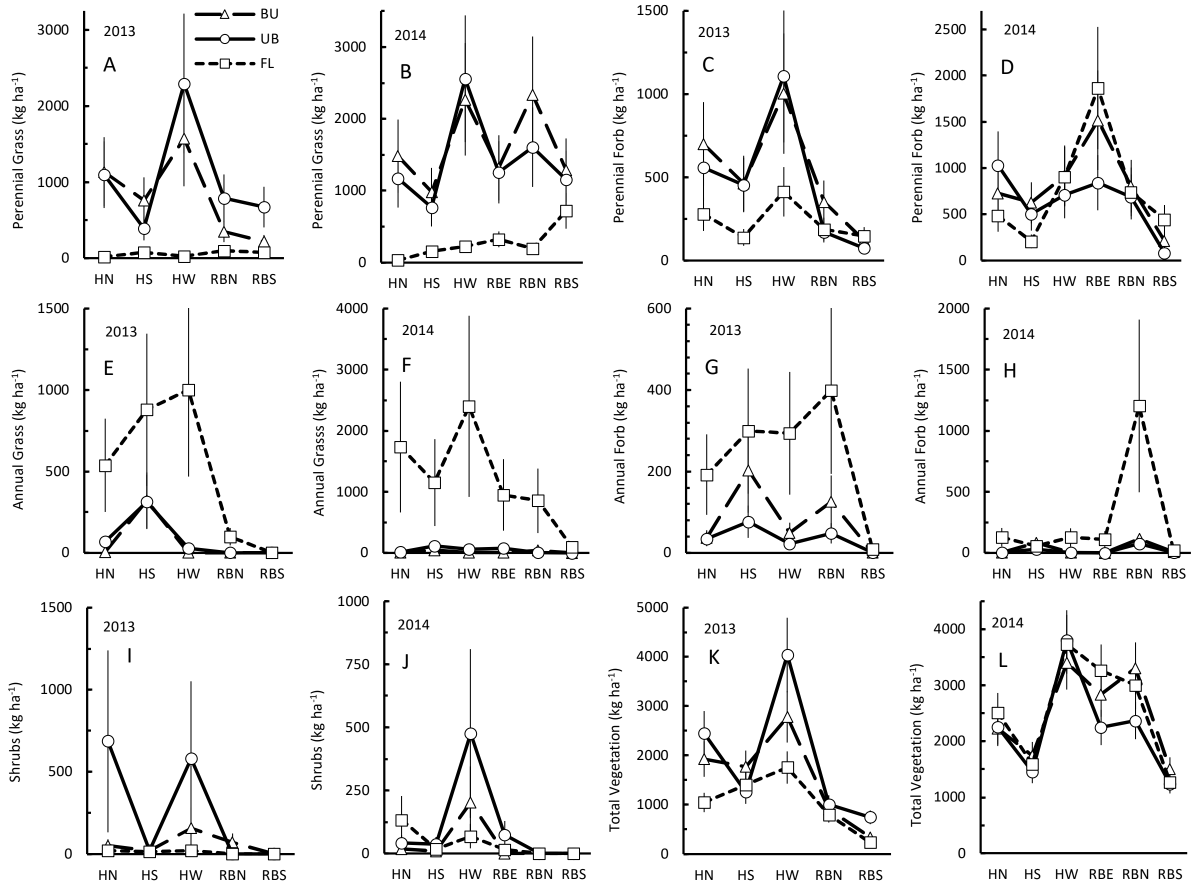

Figure 2. The effects of burned (BU), unburned (UB), and fire line (FL) treatments on the production (kg/ha) of perennial grass, perennial forb, annual grass, annual forb, shrub, and total vegetation in 2013 and 2014. Sites are represented on the *x*-axis and symbols and lines are treatment-estimated marginal means within sites. Error bars are ± se. Individual panels of response and year combinations are identified by letter (**A**–**L**). Although not continuous data, lines between points display the interaction between treatments and sites.

3.2. Perennial Forbs

In 2013, treatments did not appear to impact perennial forb production, with all three treatments exhibiting similar perennial forb biomass across all sites (Table 1 and Figure 2C). Site differences were apparent, with HN and HW sites exhibiting higher forb biomass (Table 1 and Figure 2C). Likewise, in 2014 all treatments were similar in perennial forb production except for RBS, where the unburned treatment was the lowest, fire line the highest, and burned similar to both (Table 2 and Figure 2D).

3.3. Annual Grasses

In 2013, treatment, site, and the treatment × site interaction were all significant in explaining the variability in annual grass production (Table 1). Generally, we observed an increase in annual grass biomass in response to fire line construction, however the significance of this effect was dependent on the site (Table 2 and Figure 2E). Neither RBS nor HS sites showed a significant difference in annual grass production, although an increasing trend was apparent in HS (Figure 2E). No common patterns were observed with respect to the burned treatment and annual grass production, with some sites showing reductions in annual grass in response to the fire (i.e., HN and HW) and others not exhibiting any differences. In 2014, all three factors (treatment, site, and site × treatment interaction) were again significant in explaining the patterns observed in annual grass production (Table 1). The impact of fire line construction was clearer than in 2013, showing elevated annual grass biomass in all sites in response to this treatment (Table 2 and Figure 2F). The burned treatment was similar to the unburned treatment in half of the sites, and the patterns (higher or lower) were inconsistent among the other sites.

3.4. Annual Forbs

In 2013, both treatment and site were significant with respect to annual forb production, however the interaction was not (Table 1). We observed greater biomass of annual forbs associated with the fire line treatment (Figure 2G). In 2014, treatment, site, and treatment × site interactions were all important in explaining patterns in annual forb production (Table 1). Apart from HS and RBS, annual forbs were more abundant in the fire line treatments, while no differences were apparent between the burned and unburned treatments (Table 2 and Figure 2H). RBN exhibited a substantial peak in annual forb production in contrast to the other sites.

3.5. Shrubs

In 2013, treatment, site, and treatment × site interactions were significant in explaining shrub biomass (Table 1). The fire line treatment generally exhibited low shrub production regardless of whether shrubs were present on the unburned treatments (Table 2 and Figure 2I). Burning also had the effect of lowering shrub biomass. Treatment impacts differed by site, with differences observed in shrub production in HN and HW associated with the burned and fire line treatments (Table 2 and Figure 2I). In 2014, treatment was not a significant variable, while site and treatment × site interaction remained important in explaining shrub biomass variability (Table 1). There were no significant treatment effects at any sites with the exception of RBE, where the fire line and unburned were similar, but shrub biomass in the burned treatment was lower (Table 2 and Figure 2J).

3.6. Total Vegetation

In 2013, treatment, site, and the treatment × site interactions were all significant factors in explaining the variation observed in total vegetation production (Table 1). Few consistent patterns in treatment effects were observed, however the fire line and burned treatments trended lower in total biomass in four of the five sites. The strength of the treatment effects varied across sites, with some sites exhibiting significant treatment effects while others did not (Table 2 and Figure 2K). In 2014, only site remained a significant factor in total vegetation production, and all treatment effects observed in 2013 had diminished (Table 2 and Figure 2L).

Table 2. P-values from pairwise comparisons among treatments within sites for the responses of perennial grass, perennial forb, annual grass, annual forb, shrub, and total vegetation. Sites are HN, HS, HW, RBE, RBN, and RBS, while treatments are burned (BU), unburned (UB), and fire line (FL).

		2013			2014		
		BU–FL	**BU–UB**	**FL–UB**	**BU–FL**	**BU–UB**	**FL–UB**
Perennial Grass	**HN**	<0.0001	0.9978	<0.0001	<0.0001	0.8780	<0.0001
	HS	0.0001	0.4666	0.0105	0.0005	0.8688	0.0033
	HW	<0.0001	0.7817	<0.0001	<0.0001	0.9679	<0.0001
	RBE	-	-	-	0.0108	0.9946	0.0145
	RBN	0.0659	0.3267	0.0007	<0.0001	0.7199	0.0001
	RBS	0.1603	0.1147	0.0004	0.4587	0.9750	0.5917
Perennial Forb	**HN**	0.1683	0.8982	0.3607	0.6957	0.7674	0.2885
	HS	0.0491	0.9994	0.0535	0.0727	0.9044	0.1817
	HW	0.1907	0.9786	0.1283	0.9996	0.8637	0.1817
	RBE	-	-	-	0.9110	0.4689	0.2522
	RBN	0.4369	0.3211	0.9757	0.9863	0.9484	0.9873
	RBS	0.9240	0.6125	0.3828	0.3061	0.1438	0.0024
Annual Grass	**HN**	<0.0001	0.0013	0.0177	<0.0001	0.2885	<0.0001
	HS	0.3764	0.9993	0.3568	0.0006	0.5273	0.0232
	HW	<0.0001	0.0007	<0.0001	<0.0001	0.0488	0.0001
	RBE	-	-	-	<0.0001	0.0001	0.0095
	RBN	<0.0001	0.8797	<0.0001	0.0017	0.0011	<0.0001
	RBS	1.0000	1.0000	1.0000	0.0001	0.8896	<0.0001
Annual Forb	**HN**	0.0611	0.9942	0.0474	<0.0001	0.9422	<0.0001
	HS	0.8552	0.3753	0.1481	0.8840	0.4785	0.7720
	HW	0.0378	0.5376	0.0013	<0.0001	0.8320	<0.0001
	RBE	-	-	-	<0.0001	1.0000	<0.0001
	RBN	0.2490	0.3884	0.0104	0.0133	0.8706	0.0026
	RBS	0.0383	0.9355	0.0652	0.4420	0.8208	0.1693
Shrub	**HN**	0.6817	0.0565	0.0051	0.1179	0.6791	0.4880
	HS	0.9582	1.0000	0.9582	0.8169	0.3463	0.7110
	HW	0.1775	0.4841	0.0098	0.5236	0.6680	0.1276
	RBE	-	-	-	0.0174	0.0004	0.2730
	RBN	0.0016	0.0013	0.9098	1.0000	0.7511	0.7511
	RBS	1.000	0.9098	0.9098	0.9515	0.7511	0.8991
Total Vegetation	**HN**	0.0547	0.6427	0.0039	0.8233	0.9980	0.8544
	HS	0.6654	0.3987	0.9016	0.8901	0.6390	0.8978
	HW	0.1910	0.3357	0.0047	0.8874	0.8404	0.9949
	RBE	-	-	-	0.7587	0.4706	0.1448
	RBN	0.8736	0.9067	0.6297	0.8785	0.2190	0.4654
	RBS	0.3408	0.0086	<0.0001	0.6828	0.6073	0.9922

4. Discussion

A bulldozed fire line is designed to rapidly remove fuel, and as expected construction of the fire line decreased perennial grass production at both locations; this was evident across both years of this study. Vegetation recovery from fire line construction could come from either propagules in the soil (e.g., seed, rhizome, buried root crown) or seed dispersed from adjacent undisturbed sites [13]. In our sites, most of the dominant perennial grass species were long-lived obligate seed reproducers (i.e., an absence of stoloniferous or rhizomatous growth forms) with short-lived seeds (2–3 year seed viability) [13]. Many perennial grasses display weak dispersal patterns [13,14], suggesting that the main pathway for recolonization would be from propagules in the soil or tillering from existing grass root crowns on fire lines where only the surface vegetation was removed and surface soil relatively undisturbed. Perennial grass seeds tend to concentrate in the near-surface-soil horizons and litter layer [15,16]; thus any perennial grass seedbank on the fire line treatment may have been depleted during fire line construction where surface soil was disturbed. The recovery in perennial grass production at RBS, which was unique in our results, appeared to be associated with tussocks that remained alive but were displaced to the edge of the fire line, and the negligible soil disturbance apparent on the fire line at this site may have allowed for recovery from meristematic tissues available in the root crown.

The fire line treatment appeared to trigger an exotic annual grass invasion. The first year post fire, the fire line at HN, HW, and HS sites showed an increase of exotic annual species, including cheatgrass (*Bromus tectorum* L.) and Japanese brome (*Bromus arvensis* L.), while the fire line at RBN showed an increase in cheatgrass only. By 2014, all three fire lines at the Red Bluff sites appeared to be invaded by cheatgrass. Both cheatgrass and Japanese brome are well-known for their invasive and competitive abilities [3,6], associated with their high reproductive capacity due to high seed production and extended period of germination from fall through winter and early spring, as well as a high germination rate [17–19]. In addition, they exhibit vigorous winter root growth that allows these winter annuals to use soil water early in the growing season, which may create water-stressed conditions for native plants during their active growth period in spring and early summer [20,21]. Both species reproduce solely from seeds, can exhibit seed viability for up to 11 years [17,18], and disperse efficiently either by animals or wind [5,22].

The variability we observed in post-fire production of annual grasses was likely associated with seed availability, and we speculate that high annual grass biomass in the unburned conditions increased the rate and magnitude of the response in annual grass to the fire line treatment. Both cheatgrass and Japanese brome existed in all three sites at the Thackeray Ranch, while cheatgrass was observed at the RBE site in the unburned conditions. Annual grasses were not registered on the unburned treatment at the RBS or RBN sites, thus we concluded that these sites experienced an invasion of annual grasses on the fire line treatment within two years of the fire. This corroborates other research findings from this area that suggested soil disturbance was an important factor in determining the abundance of annual grasses [23,24]. A soil seedbank assessment would aid in discriminating between seedbank- and invasion-induced responses in annual grasses.

Increases in annual forb biomass on burned and fire-line treatments were consistent with other study results where annual forbs comprised more of the vegetation on recently disturbed sites [4,7,25]. Although this trend was evident at all sites across both years, it was most evident in the RBN site, which had a high grazing impact as this site was located adjacent to a sheep camp and night paddock. Merriam et al. [4] also found comparable results in southern California, where a previously grazed and burned site had elevated non-native annual forb abundance. Annual forb production appeared to decrease in 2014, and we speculated that this was related to increased competition associated with elevated perennial grass abundance on the burned treatments and increased annual grass abundance on the fire line treatments.

Although shrubs were relatively rare across our sample plots, and this likely contributed to the high variability in our shrub production estimates, our results did suggest that the burn and fire line treatments can reduce shrub biomass. Although the treatment differences were negligible on most sites by 2014, we did not attribute this to recovery; rather, we feel that we under-sampled shrubs and inadequately represented the variability in this growth form, and we expect we simply did not find as many shrubs in 2014, generating the absence of a treatment effect.

Total vegetation biomass did not follow a pattern that would suggest a reduction in vegetation post fire and fire line treatments. Although in 2013, the fire line treatment generally reduced the vegetation production relative to the burned and unburned treatments, by the following year, these treatment differences were diminished. However, as our analyses of the various growth forms suggested, the bulk of the recovery in vegetation biomass associated with the fire line treatments was due to significant increases in annual grass and annual forb production rather than a general recovery of the vegetative community.

In these grassland ecosystems, changes in the vegetation associated with the construction of bulldozed fire lines were significant in comparison to the unburned and burned treatments. The loss of perennial grass species on the fire line treatment is a significant consequence, as recovery of these species is uncertain when soil and vegetation attributes are so dramatically altered. The abundance of exotic annual grasses exhibited an increasing trend on fire line treatments, and the long-term consequences of this invasion are uncertain. However, there is a large body of evidence suggesting that the competitive nature of these exotic annual grasses, especially cheatgrass, may prevent the recovery of desired perennial species [26–28]. Moreover, the establishment of these annual grasses in sites where they were not previously abundant may facilitate further invasion, particularly following the next disturbance.

Generally, the burned treatment exhibited a lesser impact on the vegetation compared to the fire line; in fact by the second year post fire, the burned and unburned treatments were similar. The fire was not detrimental to these grasslands; however the fire-suppression activities initiated a significant shift in vegetation, which may lead to long term ecosystem degradation. Although an argument for fire suppression is to preserve forage resources for livestock grazing, some research suggests that post-fire grazing may not degrade the plant community [29,30]; however, more research specific to the plant communities and fire conditions in question is required before incorporating this into a management approach.

5. Conclusions

The results of this study suggest that bulldozed fire lines may be more detrimental to the ecosystem than the fire itself. Therefore, our recommendation is that landowners and managers limit the ad hoc use of bulldozed fire lines as a fire-suppression strategy and instead create a planned fire line system incorporated within existing land management activities. Road systems through rangelands and along fence lines, ridge tops with scarce plant cover, cliffs, rivers, and hiking trails can serve as fire lines for any future fire and can be managed to limit weed spread and invasion. Moreover, road and trail systems that break up fuel continuity can be strategically placed around high-value infrastructure such as homesteads, barns, and hay crops to limit potential threats associated with future wildfires. In addition, other fire line approaches that limit soil disturbance, including mowing, grazing, prescribed fire, or greenstripping can be incorporated into fire management activities [31,32]. However, caution should be exercised as these may also have negative ecological consequences, including non-native plant invasion and wildlife habitat fragmentation [33].

If there is a need for bulldozed fire line construction, we suggest the following to reduce the ecological impacts: (1) To limit damage to existing vegetation and soil seedbank and promote rapid post-fire recovery, restrict bulldozer blade depth to minimize soil disturbance during fire line construction. In this study the site with the least impact associated with fire line construction had limited soil disturbance, yet broke fuel continuity by removing only the aboveground portion of the vegetation. (2) Minimize fire line construction on steep slopes. Even when constructing fire lines along the contour, steep slopes cause significant excavation on the upslope side and significant deposition on the downslope side, both of which can limit the recovery of pre-fire vegetation. (3) Re-seed fire lines as soon as practical after cessation of fire-suppression activities and when conditions will favor seed germination and seedling establishment. For many native perennial grasses, the natural availability of seed with which to recover from fire line disturbance is limited by the effects of the disturbance and the general paucity of propagules for these species. The dominance of exotic annual grasses may also limit the effectiveness of fire line re-seeding. However, if these exotic species are rare in the immediate vicinity, there appears to be a short window before they become dominant and seeding in this window may increase the establishment of seeded species. (4) Although not evaluated in this study, replacing displaced soil may be an option to limit loss of vegetative resources and promote recovery of native vegetation. However, soil disturbance associated with this activity may still promote the dominance of competitive annual grasses and limit recovery of desired species and the cost may be prohibitive, particularly on privately owned rangelands.

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