Invasive Plant Science and Management 2015 8:317–322

Burning Controls Barb Goatgrass (*Aegilops triuncialis*) in California Grasslands for at Least 7 Years

Jaymee T. Marty, Sara B. Sweet, and Jennifer J. Buck-Diaz*

Barb goatgrass is an invasive annual grass from the Mediterranean region that negatively affects both native plant biodiversity and the forage quality of grasslands. Prescribed burning may be the best landscape-level tool available to manage invasive species like barb goatgrass while also enhancing biodiversity, but few studies have quantified the long-term effects of fire on goatgrass and the rest of the plant community. We assessed the effects of fire on an invading front of barb goatgrass on a private ranch in Sacramento County, CA. We established burned and unburned treatment plots within the goatgrass-infested area and used prescribed fire to burn the treatment plots in June 2005. We monitored plant-community composition before burning and for 7 consecutive yr following the burn. Additionally, we tested the viability of goatgrass seeds in both burned and unburned plots. One year after the burn, goatgrass cover in burned plots was 3% compared with 21% in unburned plots. This reduction in goatgrass cover was still strong 2 yr after the burn (burned, 6%; unburned, 27%) and weaker but still statistically significant for 4 of the next 5 yr. The burn also reduced germination of goatgrass seed by 99% as indicated by seed-viability tests conducted in the laboratory. The native plant community responded positively to the burn treatment in the first year following the burn with an increase in native diversity in burned plots vs. unburned plots, but the effect was not detectable in subsequent years. Nonnative annual forb species cover also increased in the first year following the burn. Our study shows that a single springtime burn can result in a short-term boost in native species diversity, reduced seed germination of barb goatgrass to near zero, and reduced cover of barb goatgrass for at least 7 yr after the burn.

Nomenclature: Barb goatgrass, *Aegilops triuncialis* L.

Key words: Biodiversity, fire, grassland management, invasive species, rangeland.

Grasslands in California provide a wealth of biological, social, and economic values. Many rare and endangered species and sensitive communities are found in California grasslands (Sawyer et al. 2009). Much of this land is also used for grazing livestock and supports California's cattle industry, worth $3 billion in 2013 (NASS 2013). However, invasive, nonnative annual grasses threaten the biological and economic values of these grasslands. Biological value is decreased because these weeds form dense, expansive stands that drastically reduce the abundance of native species (Crampton 1974; DiTomaso et al. 2007). Some nonnative species like barb goatgrass (*Aegilops triuncialis* L.) reduce the economic value of the land by reducing the carrying capacity for livestock (Davy et al. 2008; George et al. 1992). Goatgrass in particular reduces palatable forage production by 50 to 75% (Peters et al. 1996), provides poor nutrition (Bovey et al. 1960), and can injure animals with its long, stiff awns (DiTomaso 1994).

Barb goatgrass is a winter annual grass from the Mediterranean region. The inflorescence is spike-like, with woody, inflexible glumes encasing mature spikelets (Davy et al. 2008). The inflorescence is usually dispersed as a single unit, but spikelets remain intact even if separated from the spike. Most spikelets contain two seeds, with one about 2.5 times larger than the other (Dyer 2004). Both the large seed and the glumes can inhibit germination of the small seed, which may serve to ensure that a fraction of seeds remain in the soil seed bank (Dyer 2004).

Landscape-scale weed-control methods in California grasslands, such as grazing, fire, herbicide treatment, and biological control, are more limited than those available for control

DOI: 10.1614/IPSM-D-14-00043.1

* Ecologist and Ecologist, The Nature Conservancy, Galt, CA 95632; Vegetation Ecologist, California Native Plant Society, Sacramento, CA 95816. Current address of first author: Marty Ecological Consulting, Sacramento, CA 95826. Corresponding author's E-mail: martyjt@me.com

https://doi.org/10.1614/IPSM-D-14-00043.1 Published online by Cambridge University Press

Management Implications

We studied the long-term effects of a single, prescribed burn on barb goatgrass control and on native and nonnative species diversity in a grassland community in California. A single, late-spring burn reduced the cover of goatgrass for at least 7 yr following the burn. The burn had short-lived, positive effects on the native plant community with an increase in native plant cover and richness for a single year following the burn. The long-lasting effect of a single burn on the goatgrass was unexpected, given other research, which suggests that 2 consecutive yr of fire treatment are required for significant control. We suspect that this burn was particularly effective because it was conducted during a year with high fuel loads, which allowed ground temperatures to reach levels necessary to effectively kill the goatgrass seeds as they fell to the ground in the inflorescence. Our germination study confirmed that the fire effectively reduced the germination rate of seeds contained within intact, but burned, spikelets to near zero. It is rare for a study to track a management treatment for more than 2 to 3 yr, but our results demonstrate that there is great value in doing so. Prescribed burning is a very costly and risky treatment to implement, so understanding how well it works and how often a site should be burned to control the target species is very useful for decision makers. We were also able to document a distinct trend in goatgrass and native species cover over that period and to evaluate how that trend aligned with climatic data like rainfall. In fact, we believe total rainfall amounts may have affected the goatgrass in two ways: high rainfall in the year of the burn produced above-average biomass, which fed a hotter and more-complete burn, and low rainfall starting 3 yr after the burn may have reduced the cover of goatgrass in both burned and unburned plots, potentially prolonging the fire's effect.

of spot infestations, and tradeoffs between economics and efficacy are often required. Livestock grazing generally provides limited barb goatgrass control, although it may yield satisfactory control if the infested areas are heavily grazed (Peters et al. 1996), and grazing is timed for seed head emergence (Davy et al. 2008). Mowing, sometimes used as a surrogate for grazing, if carefully timed, may increase control (Davy et al. 2008); however, mowing is not selective and costs are high over large scales. Some herbicides may be effective as a method for controlling goatgrass on rangelands (Aigner and Woerly 2011); however, the treatment may damage other desirable forage grasses and forbs (DiTomaso et al. 2001). Work by Aigner and Woerly (2011) in serpentine grasslands showed some promise controlling goatgrass using grass-selective herbicides applied at the appropriate time with little collateral damage to the rest of the plant community. Biocontrol agents have not been developed and likely will not be pursued because of the close relationship between goatgrass and cultivated wheat (*Triticum aestivum* L.).

Prescribed fire may be the most effective of all of these methods for successfully controlling goatgrass. In Mendocino County, CA, DiTomaso et al. (2001) documented effective goatgrass control in rangelands by applying prescribed fire for 2 consecutive yr. The authors initially attributed lack of control after the first year to patchy burning, but since, have hypothesized that a single burn may be ineffective because small seeds from the preburn year will first be inhibited by the glumes and large seeds and are then insulated in the soil during the first burn (J. M. DiTomaso, personal communication). Hopkinson et al. (1999) also used fire to control barb goatgrass and found it reduced the cover of the grass, but a single burn was not effective at reducing spread of the species. Because of the expenses of planning, permitting, and implementing a burn, a better understanding of circumstances that lead to desired outcomes over many years is required.

To investigate the efficacy of fire for controlling barb goatgrass and promoting native plant biodiversity, we burned four, 15- by 20-m (49- by 66-ft) treatment plots in conjunction with a larger 120-ha (296.5 ac) prescribed burn in an area with an invading front of goatgrass in early June on a private ranch near Ione, CA. Barb goatgrass was patchily distributed on this site at the time of study implementation in areas with well-drained soils. Goatgrass patches ranged in size from 10 to 1,000 m^2 (108 to 10,764 ft^2) with cover values within these patches ranging from < 5 to $> 75\%$ cover. We measured the response of goatgrass as well as the rest of the plant community to the fire treatment compared with unburned controls before the burn and for 7 yr following the burn. We also monitored fire temperature in the burned treatments and tested seed germination of goatgrass seeds collected from burned and unburned plots. Our success criteria for our burn treatment were (1) a reduction of goatgrass cover by $> 50\%$ in burned plots when compared with unburned plots, (2) maintenance of a lower cover of goatgrass in burned plots more than 1 yr postburn, and (3) increased native plant diversity in burned plots compared with unburned plots 1 yr postburn.

Materials and Methods

Setting. This study was conducted on a 5,000-ha property located in eastern Sacramento County, CA (38°38′N, 121°02′W; elevation, 75 m). The climate of this region is Mediterranean, with average annual rainfall of 56 cm (22 in) occurring between the months of October and May; < 2 cm of rain falls during the summer months.

The area is gently sloped with low-lying hills that rise in elevation from 50 to 160 m. The vegetation on the site is typical of California annual grasslands where overall plant cover is dominated by nonnative annual grass and forb species while native species, particularly forbs, contribute significantly to overall species richness despite their low abundance (Sawyer et al. 2009). Vernal pools occur in the lower, flatter areas within the grassland and are abundant on approximately one-third of the area. Cattle have grazed the site for the past 100 or more yr. Cattle graze the entire site each year from approximately October through June at

https://doi.org/10.1614/IPSM-D-14-00043.1 Published online by Cambridge University Press

a stocking rate of one animal unit (cow–calf pair) per 2.4 ha.

The study site is situated on a 2 to 3 million-yr-old alluvial terrace, known as the Laguna Formation, formed from alluvial deposition on the east side of the Sacramento Valley. The main soil map unit found within the site areas is the Corning complex, with 0 to 8% slopes. The Corning series taxonomic class is described as fine, mixed, active, thermic Typic Palexeralf (Tugel 1993). An underlying, cemented duripan supports the formation of shallow wetlands called vernal pools in areas where mound–intermound topographic relief exists. The study plots were all located in mound areas and assumed to be at least 2 to 3 m above the hardpan.

A prescribed fire program was instituted on this site in 2002 to manage the nonnative grass species medusahead (*Elymus caput-medusae* L.) and to promote native forb species diversity. Before this, small sections of the site burned approximately every 5 to 10 yr because of wildfire activity.

Research Methods. Before the prescribed burn, we established four macroplots containing paired burned and unburned treatment plots within large patches of goatgrass on the site. Macroplots were spaced sufficiently far apart (mean, 310 m) to ensure spatial independence. Each treatment plot was approximately 15 m by 20 m and permanently marked with washers and nails. The burn treatments were randomly assigned to the treatment plots within the established macroplots. We recorded the highest temperature reached within each burned plot on two, 50-cm-tall, copper pipes painted with temperature-sensitive paints (Tempilaq, Tempil Division, LA-CO Industries, Elk Grove Village, IL; temperature range 93 to 343 C [199 to 649 F]) at soil level and 50 cm above the soil surface.

Immediately after the fire, seed heads were collected from burned and unburned plots for use in germination trials. In July 2005, we conducted three separate germination trials in the laboratory on an equal number of both large (n = 10) and small seeds (n = 10). We ran three separate trials of three germination attempts of 20 seeds for all four burned and two of the unburned plots. Each replicate was placed in a petri dish on moist filter paper to prevent the seeds from drying out. Each dish received direct sunlight throughout the day. The number of germinated seeds was recorded daily until all seeds were germinated or 3 d of no new germination had elapsed.

We subsampled plant cover within each burned and unburned plot along three transects marked permanently with nails. We estimated goatgrass cover along three, 35-cm-wide by 10-m-long belt transects (n = 3 transects × 4 macroplots × 2 treatments = 24 transects total) further subdivided into 10 segments with dimensions of 1 m by 35 cm. We measured total vascular plant cover by species within two, 35-cm by 70-cm, permanent quadrats placed at randomly selected locations along each transect (n = 2 quadrats × 3 transects × 4 macroplots × 2 treatments = 48 quadrats total). We monitored the vegetation before conducting the burn in June of 2005 and at the same time of year for 7 consecutive yr after the burn. Plant cover was recorded using Daubenmire cover classes (Barbour et al. 1987). For analyses, all cover class values were converted to midpoint cover values to calculate percentage of cover. Plant species taxonomy follows Baldwin et al. (2012).

Data Analysis. We used repeated-measures ANOVA to test for treatment effects for each response variable across years. We used Mauchly's test for sphericity and determined significance using an uncorrected F test, where the sphericity assumption was met, and a Greenhouse-Geisser correction for those tests where that assumption was not met. Using a protected ANOVA approach (Scheiner 1993) for all variables with a significant time by burn interaction repeated-measures ANOVA test, we tested for treatment effects using ANOVA with macroplot as a block effect and burn treatment as a main effect for each variable measured in each year. In cases in which the data did not meet the ANOVA assumptions of normality, equal variance, or both, we used a Wilcoxon test, with macroplot included as a blocking factor, to test for significant burn effects (Sokal and Rohlf 1995). We report diversity as species richness. We tested all variables for any significant differences in the preburn year. Because native species richness was significantly different between treatments before the burn, we analyzed the difference in species richness between the year of interest and the preburn year. Simple linear-regression analysis was used to test for significant correlations between plant cover and total annual rainfall. All analyses were conducted using JMP statistical software, version 9 (SAS Institute, Cary, NC).

Results and Discussion

Fire temperature was on average 147 C higher at the soil surface than it was 50 cm above the ground (mean ± SE ground, 257 ± 10 C; at 50 cm, 110 ± 8 C; $P < 0.01$). Exposure of the goatgrass inflorescences to flames approximately 50 cm above the soil surface was roughly 1 s; however, they fell to the ground immediately following exposure to the flaming front and continued to experience the higher temperatures at the soil level for a longer period (J.T.M., personal observation). Barb goatgrass seeds collected from the unburned treatment plots had a very high germination rate (mean ± SE, 76.2 ± 4.9%), whereas germination of the seeds collected in the burned plots was near zero (mean ± SE, 1.25 ± 2.8%; $P < 0.0001$).

Burning had a strong effect on barb goatgrass cover over the 7 yr of the study (Table 1). Goatgrass cover in burned

https://doi.org/10.1614/IPSM-D-14-00043.1 Published online by Cambridge University Press

Table 1. Results (*F* test statistic and P values) of repeated-measures analysis of variance for (a) barb goatgrass cover, (b) native species cover, (c) nonnative forb cover, and (d) changes in native species richness in prescribed burn treatments from 2005 through 2012 in Sacramento County, CA. A Greenhouse-Geisser correction (*F* test values in italics) was used to determine significance level for tests where the assumption of sphericity was not met. Significance levels are indicated with asterisks after each *F* test value: ** P < 0.01, *** P < 0.001.

Effect	Barb goatgrass cover	Native cover	Nonnative forb cover	Native species
Time	*27.47****	*36.20****	13.08***	4.70***
Burn	27.73***	2.16	0.247	3.25
Time × burn	*6.72****	*4.45***	3.16**	3.72**

plots was significantly less than it was in unburned plots for 6 of the 7 yr after treatment (YAT; Figure 1; Table 2). By the fifth YAT, burned plots still had half the goatgrass cover of unburned plots. This pattern continued in the sixth YAT, but the effect was not statistically different. However, the burn effect was significant again in the seventh YAT.

Although burning strongly affected native plant cover over time (Table 1), native cover in the burned plots was only significantly higher than in the unburned plots 1 YAT (burned, 32.7 ± 5.2%; unburned, 13.0 ± 3.1%; χ^2 = 12.73, P < 0.01). This effect was not significant in later years (Figure 2). Similarly, burning affected mean nonnative forb cover over time (Table 1) with 58% higher cover 1 YAT in the burned vs. unburned treatment plots (burned, 28.8 ± 3%; unburned, 18.2 ± 3%; χ^2 = 6.55, P = 0.01). This effect was no longer significant in subsequent years.

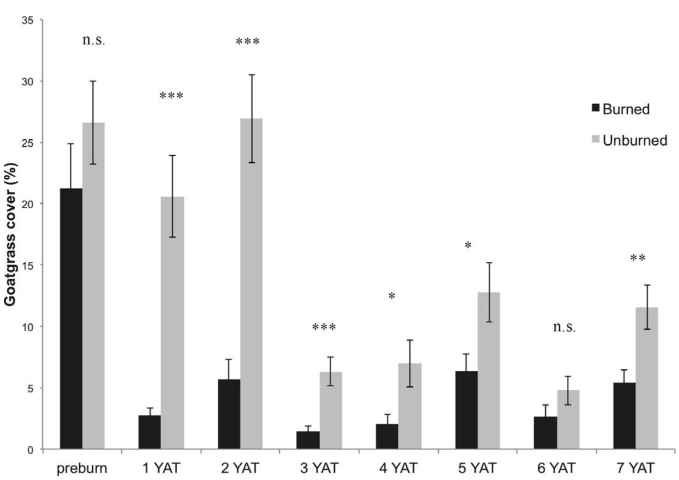

Figure 1. Absolute percentage of cover (mean ± SE) of goatgrass in burned and unburned plots prior to burning and 7 yr postburn. Values shown are means ± SE. Abbreviation: n.s., not significant. * P < 0.05; ** P < 0.01; *** P < 0.001.

A time-by-burning interaction in the repeated-measures ANOVA showed a significant effect of burning on the change in native species richness from the preburn year (2005) to the year following the burn (2006; Table 1); however, similar to native and nonnative plant species coverage, this effect was only present 1 YAT. In burned plots, native species richness increased from an average of 3.12 species (± 0.25) in 2005 to 4.0 species (± 0.33) 1 YAT (2006), whereas in unburned plots, native species richness decreased from 3.92 species (± 0.50) in 2005 to 3.41 species (± 0.40) (F = 9.60, P < 0.01). This effect was not detectable in subsequent years. Average annual native species cover was positively correlated with total annual precipitation measured each year between August and July (r^2 = 0.57; P = 0.02). Nonnative species cover was not significantly correlated with total precipitation.

Our results show that a single burn at the appropriate time of year can have lasting effects on goatgrass populations and can also increase native plant species cover and richness. A single burn significantly reduced goatgrass cover for at least 6 of the 7 yr following the burn. Although the benefits to the native plant community were significant, that effect did not last longer than a single year. The fire also increased nonnative forb species cover for a single year.

In contrast to our results, other fire studies in California focusing on goatgrass control found that a single burn was insufficient to control this species (DiTomaso et al. 2001; Hopkinson et al. 1999). DiTomaso et al. (2001) found that control of barb goatgrass was only achieved after 2 consecutive yr of fire treatment when applied to a coastal California grassland site. The authors attributed this to insufficient burn completeness in the first year compared with the second. Hopkinson et al. (1999) also found a single burn offered some control over barb goatgrass in another coastal California site, but the grass continued to spread on the site in the years following the fire.

Many factors have the potential to affect the efficacy of prescribed fire as a control tool for late-season invasive grasses, including burn timing, frequency, fuel moisture, site characteristics (e.g., topography, climate, land use patterns, soils) and weather conditions (Klinger et al. 2008). Others have found that heavy levels of residual biomass or thatch is correlated with increased burn efficacy, presumably because of slowing down of the flame front, increasing fire intensity, or both (Kyser et al. 2008). We speculate that this was a major reason we were successful in controlling goatgrass. Measurements of residual dry matter (RDM) taken in a separate study on the ranch in an unburned area confirm that 2005 was a particularly productive year, with RDM levels nearly double (mean,

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Table 2. Results (sum of squares, *F* test statistic, and P values) of ANOVA for barb goatgrass cover in prescribed burn treatments over 7 yr of the study conducted in Sacramento County, CA. Degrees of freedom (df) for each effect tested in the analysis are shown as numerator (num) and denominator (den). Significance levels are indicated with asterisks after each *F* test value: * $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$.[a]

Effect ($df_{num,den}$)		Preburn	1 YAT	2 YAT	3 YAT	4 YAT	5 YAT	6 YAT	7 YAT
Block ($df_{3,7}$)	SS	518.00	332.42	119.07	50.68	41.25	245.45	25.38	23.79
	F^P	1.19$^{n.s.}$	1.76	0.38$^{n.s.}$	2.07$^{n.s.}$	0.50$^{n.s.}$	1.95$^{n.s.}$	0.61$^{n.s.}$	0.84$^{n.s.}$
Burn ($df_{1,7}$)	SS	172.27	1913.52	2716.82	141.86	145.78	247.36	26.98	226.63
	F^P	1.19$^{n.s.}$	30.48***	26.41***	17.37***	5.31*	5.90*	1.95	8.01**

[a] Abbreviations: YAT, years after treatment; SS, sum of squares; F^P, F test statistic and p-value; n.s., not significant.

2,640 vs. 1,528 kg ha^{-1} [2,358 vs. 1,365 lb ac^{-1}]) the levels measured in other years (J.T.M., unpublished data).

Although goatgrass seed heads in burned plots appeared relatively intact after the fire, the fire clearly damaged the seeds. Inferences from previous research suggest that temperatures documented in this burn at the height of 50 cm above the soil surface, approximately the height of undispersed seed heads, would be insufficient to provide an adequate kill, given the short time of exposure (Sweet et al. 2008). We speculate the main damage to the goatgrass seeds occurred after the seed head fell to the ground and experienced the higher temperatures we recorded at the soil surface. Once combustion was initiated, the seed head would continue to smolder after the flaming front passed, leading to seed mortality.

Our findings on the effects of prescribed burning on forb species cover and richness were consistent with other research on fire in California grasslands (Corbin et al. 2004; Marty 2002, 2007; Pollak and Kan 1998). These studies also showed an increase in native species cover and richness 1 yr after a single burn with a return to levels indistinguishable from the unburned plots by the next year. Numerous other studies have also recorded a positive response of nonnative forb species like broadleaf filaree [*Erodium botrys* (Cav.) Bertol.] to fire (Keeley et al. 2011). The reduction of nonnative grass competition in the year following the burn is believed to favor the germination and survival of native and nonnative forb species. Our findings also show that the cover of native species may be more tightly tied to seasonal rainfall patterns than that of nonnative species.

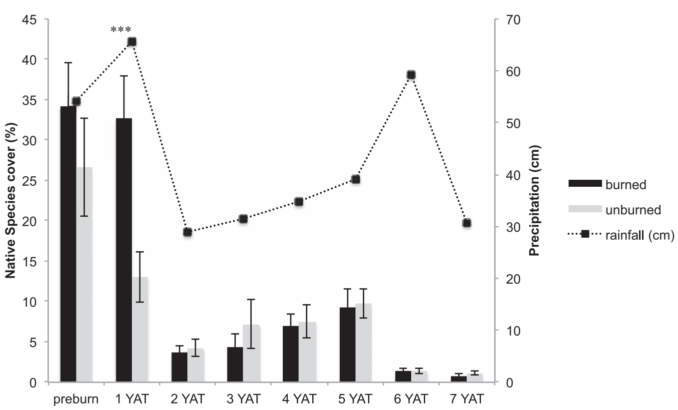

Figure 2. Absolute percentage of cover (mean ± SE) of native plants in burned and unburned plots before burning and 7 yr post burn. The dotted line portrays the total annual precipitation for the year of the burn and for 7 yr after treatment (YAT). Values shown are mean ± SE. All comparisons were not statistically significant, except 1 YAT where $P < 0.001$ (***). Precipitation data retrieved from http://www.sacflood.org (Ione Rd., sensor 280).

Our results show that a single prescribed fire can be an effective tool for long-term reduction in cover of problematic annual grasses, like barb goatgrass, while also promoting native diversity and improving overall forage quality in California grasslands. A single burn achieved our stated goal of reducing goatgrass cover by 50% compared with the unburned plots for 7 yr after the burn. However, a careful fire prescription should be followed, and proper site conditions appear to be necessary for maximum success. In particular, while prescribed burning is becoming increasingly challenging to implement in the wildland–urban interface as air quality and liability issues become even more prominent, it is important to maintain the ability to conduct burns when few other options for large-scale weed-reduction remain.

Acknowledgments

We are indebted to all of the TNC interns and technicians who worked on this project and to CALFIRE for planning and conducting the prescribed burn. We also want to thank Jim Chance for graciously allowing us to conduct this research, and our various funding sources, including the Anderson Grasslands Research Fund, Bernard Osher Foundation, and other private donors for their contributions.

https://doi.org/10.1614/IPSM-D-14-00043.1 Published online by Cambridge University Press

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Received June 6, 2014, and approved May 8, 2015.

Associate Editor for this paper: Kelly G. Lyons, Trinity University.

https://doi.org/10.1614/IPSM-D-14-00043.1 Published online by Cambridge University Press