

Susceptibility of Exotic Annual Grass Seeds to Fire

Sara B. Sweet, Guy B. Kyser, and Joseph M. DiTomaso*

Prescribed burning can control invasive annual grasses that threaten the biological and economic value of California grasslands. Susceptibility of grass seed to burning can depend on burn timing, exposure time, and type of exposure (direct flame heat or convective heat); thus, these factors can influence the success of a prescribed burning program. To further investigate these factors, laboratory simulations were conducted on barb goatgrass, medusahead, and ripgut brome at several stages of seed maturity, as determined by percent moisture of the inflorescences. Seeds were exposed either to direct flame using a Bunsen burner or to heated air in a muffle furnace. Flame treatments were conducted at one temperature (~400 C) and several exposure times (0 to 14 s), depending on the species. Furnace treatments included four temperatures (150, 200, 250, and 300 C) and seven exposure times (0, 10, 20, 30, 40, 60, or 80 s). Seed germination was analyzed for each temperature series to determine the LD₅₀ and LD₉₀ in seconds of exposure time. Susceptibility to furnace treatments, which simulated heat exposure of seeds on the soil surface, was not statistically different within a range of seed moisture levels for all three species. The LD₅₀ values at 250 C (typical soil temperature with grassland fire) ranged from 28 to 49 s, which far exceeds the time of exposure during a typical grassland fire. Susceptibility to flame showed a similar lack of change over maturation of medusahead and barb goatgrass seeds, with LD₉₀ values ranging between 4.8 and 7.4 s for all seed moisture levels. In contrast, ripgut brome seeds exposed to flame showed increasing susceptibility with reduced seed moisture content. The LD₉₀ values for exposure were less than one second for seed moisture levels at or below 10%, compared to 3.7 s for seeds at 55 to 60%. Although flame susceptibility increased for ripgut brome, seeds at all maturation stages were more sensitive than medusahead and barb goatgrass. Additionally, the LD₉₀ values for all three species are attainable under field conditions. Thus, burn prescriptions for these three species are not constrained by maturation stage, but should occur prior to seed drop and when fuel loading is high. This will maximize exposure time of seeds to direct flame.

Nomenclature: Medusahead, *Taeniatherum caput-medusae* (L.) Nevski ELYCA; barb goatgrass, *Aegilops triuncialis* L. AEGTR; ripgut brome, *Bromus diandrus* Roth BRODI.

Key words: Grassland, prescribed burning, rangeland, seed moisture, timing.

In most rangeland systems in California, nonnative winter annual grasses such as Italian ryegrass (*Lolium multiflorum* Lam.), wild oat (*Avena barbata* Pott ex Link), and soft brome (*Bromus hordeaceus* L.) can be desirable components of the production system. However, invasive winter annual grasses can severely threaten the biological integrity of California grasslands (Sawyer and Keeler-Wolf 1995; Tibor 2001), and many exotic annual grasses reduce livestock grazing capacity and nutritional quality of rangelands (Bovey et al. 1960; DiTomaso 2000; George

1992; Jacobsen 1929; Kennedy 1928; Young 1992). The most problematic of these exotic Mediterranean winter annual grasses, including barb goatgrass (*Aegilops triuncialis* L.), ripgut brome (*Bromus diandrus* Roth), downy brome (*Bromus tectorum* L.), red brome [*B. madritensis* L. subsp. *rubens* (L.) Husnot], and medusahead [*Taeniatherum caput-medusae* (L.) Nevski], have long-awned seeds (caryopses) that can injure animals foraging later in the season when the inflorescences are present (Young 1992). Few options exist for the selective control of noxious annual grasses in rangelands composed of other, desirable annual grasses. For example, herbicides that control undesirable annual grasses often injure desirable grasses, and grazing has limited effectiveness (George 1992; Shinn and Thill 2004).

Fortunately, several of these noxious grasses share a mid- to late-season phenological schedule that can make them

DOI: 10.1614/IPSM-07-040.1

*Graduate student, Staff Research Associate, and Cooperative Extension Specialist, Department of Plant Sciences, Mail Stop 4, University of California at Davis, Davis, CA 95616. Current address of first author: Restoration Resources, 3868 Cincinnati Ave., Rocklin, CA 95765. Corresponding author's E-mail: jmditomaso@ucdavis.edu

Interpretive Summary

Prescribed burning has been used to control exotic winter annual grasses, including barb goatgrass, medusahead, and ripgut brome. However, many factors can influence the success of fire, including burn timing, fuel load and fuel moisture, stage of seed maturity, flame temperature, and heat exposure time. The objective of this study was to better inform burn prescriptions for control of these three noxious annual grasses. Laboratory burn simulations were conducted at a range of seed maturity stages, temperatures, and exposure times. Convective heat from a furnace was used to simulate exposure of seeds on the soil surface to a grassland fire, whereas flaming with a burner simulated seed exposure to flames while still attached to the inflorescence. Burn effectiveness was determined by measuring seed survival in germination tests. Results indicate that seeds on the soil surface do not experience high enough temperatures or exposure times to give effective seed mortality. In the direct flame exposure study, barb goatgrass and medusahead were equally susceptible at all stages of maturity (green/red to brown) and required between 4.8 and 7.4 s of exposure to give 90% seed kill. Ripgut brome seeds were much more susceptible to direct flame heat, particularly at later stages of maturation (< 10% seed moisture) when seeds were brown. At this stage, < 1 s exposure to direct flames gave over 90% seed mortality. Based on these results, the most appropriate timing for barb goatgrass and medusahead control using prescribed fire is when the available fuel load provides sufficiently long flame exposure time to kill the exposed seeds. Because the seeds of ripgut brome shatter earlier than the other two species and effective flame exposure time was shorter, the most appropriate burn timing for this species would be early in the season, typically in late spring.

vulnerable to control by burning after desirable early-season annual grasses have set seed. The late maturation of seeds could be due to their dispersal strategy, in that animal-dispersed species can retain seeds longer in the canopy, or to the resource capture strategy, in that late-season species develop deep roots to enable growth and reproduction after the highly competitive early-season annuals have senesced. For example, medusahead matures at least a month later than most annual species, including grasses (Dahl and Tisdale 1975; Young et al. 1970). This provides a burn window when the seeds of undesirable annual grasses are still held in the canopy and are exposed to high flame temperatures, while the mature seeds of other desirable annual grasses are exposed to lower temperatures on the soil surface. In previous work, multiple years of prescribed burning nearly eliminated ripgut brome (Kyser and DiTomaso 2002) and barb goatgrass (DiTomaso et al. 2001) in two northern California sites. Moreover, several studies have reported over 90% medusahead reduction with a single prescribed burn (George 1992; McKell et al. 1962; Pollak and Kan 1996).

Not all prescribed burns for control of medusahead have yielded positive results. For example, three annual burnings near Alturas, CA, did not decrease medusahead (Young et al. 1972). Inconsistent results with burning for medusahead

control have been suggested to be due to differences in burn timing, fuel loads, or seed moisture content (McKell et al. 1962; Young et al. 1972).

The objective of this study was to determine the best timing to maximize the efficacy of prescription burning for control of three noxious annual grasses (barb goatgrass, medusahead, and ripgut brome). It is hypothesized that the efficiency of prescribed burning will be maximized when the seedheads of invasive annual grasses are exposed to higher flame temperatures for longer periods. Such conditions can be manipulated depending on fuels loads and burn timing. To test this, experiments were designed to evaluate the interaction between seed moisture content and susceptibility to heat. Both direct and indirect (soil surface) exposure to fire were simulated by exposing seeds at a range of moisture content to direct flames or to oven heat for various periods of time. This simulation would mimic a range of field conditions from mid-spring to late summer. The effectiveness of these treatments was determined subsequently by measuring seed survival in germination experiments.

Materials and Methods

Barb goatgrass, medusahead, and ripgut brome were planted in the fall of 2002 and 2003 in monoculture plots (4 by 4 m [13 by 13 ft]) at the University of California Davis Plant Sciences Field Station, Yolo County, CA, characterized as a Mediterranean climate with an average precipitation of 45 cm (17.7 in) per year. Inflorescences were collected throughout the time of flowering in both 2003 and 2004. Inflorescence collections were nonrandom and based on similarity of color to ensure uniform seed maturation. At collection, inflorescences were classified as green/red, red, red/brown, or brown. Collected plant materials were stored in resealable plastic bags and were weighed and used in experimental treatments within approximately 24 h. Subsamples of both inflorescences and seeds were weighed before and after drying for 1 wk in a 60 C (140 F) oven to calculate percent moisture. Preliminary comparisons of seed vs. inflorescence percent moisture at the same collection date showed little difference in the two values (Sweet 2005). Consequently, inflorescence percent moisture was considered a good estimate of seed percent moisture and was used in all subsequent experiments (Table 1).

To determine the change in inflorescence (2003 and 2004) and vegetation (2004 only) moisture content over time, samples were collected at several times from the end of April to the beginning of August. Vegetation moisture content is critical, because it provides the primary fuel to carry a prescribed fire. For each assessment, 10 inflorescences were collected based on uniform color of the majority of inflorescences in the field at that time. In 2004,

Table 1. Species, date, simulation type, percent moisture, and inflorescence color for all collections in 2003 and 2004. In 2004, furnace and flame simulations were conducted over a 2-d period. Mean percent moisture data based on n = 10.

Species	Date	Simulation Type	Mean % moisture \pm SD	Inflorescence color
Barb goatgrass	June 9, 2003	Flame & Furnace	43 \pm 3	Green/red
	June 19, 2003	Flame & Furnace	14 \pm 4	Red/brown
	July 9, 2003	Flame & Furnace	10 \pm 2	Brown
	May 28–29, 2004	Furnace/flame	48 \pm 3/40 \pm 7	Green/red
	June 4–5, 2004	Furnace/flame	27 \pm 8/34 \pm 4	Red
	June 11–12, 2004	Furnace/flame	10 \pm 1/8 \pm 1	Brown
Medusahead	June 9, 2003	Flame & Furnace	44 \pm 2	Green/red
	June 19, 2003	Flame & Furnace	35 \pm 2	Red
	July 9, 2003	Flame & Furnace	7 \pm 1	Brown
	May 28–29, 2004	Furnace/flame	45 \pm 4/42 \pm 2	Green/red
	June 4–5, 2004	Furnace/flame	30 \pm 4/28 \pm 7	Red
	June 11–12, 2004	Furnace/flame	10 \pm 2/9 \pm 2	Brown
Ripgut brome	July 16–17, 2004	Furnace/flame	11 \pm 1/8 \pm 1	Brown
	June 19, 2003	Flame & Furnace	10 \pm 2	Brown
	April 23, 2004	Flame & Furnace	60 \pm 2	Green/red
	May 2–3, 2004	Flame/furnace	55 \pm 3/54 \pm 4	Red
	May 9–10, 2004	Flame/furnace	17 \pm 11/10 \pm 8	Brown
	June 22–23, 2004	Flame/furnace	8 \pm 1/6 \pm 1	Brown

leaves and culms were also collected from the same plants. Both inflorescences and vegetation were weighed on the same day, dried for 1 wk in a 60 C oven, and reweighed to calculate percent moisture content.

The effects of fire were determined for both direct exposure to flame and for indirect exposure via convective heat. Inflorescence exposure to flame was simulated using a Bunsen burner. Experiments simulating exposure to convective heat were conducted with a brick-lined muffle furnace.¹ Furnace treatments simulated heat conditions on the soil surface or otherwise out of the direct path of a fire.

Each treatment included ten replications, and the experimental unit was the inflorescence. Inflorescences were collected on several dates in 2003 and 2004 from April to July, depending on the species (Table 1).

In the furnace treatments, both temperature and time of exposure were manipulated. In 2003, temperatures of 100, 150, 200, 250, and 300 C were used based on results of fusion pyrometers placed on the soil surface in prescribed burns of California grasslands infested with yellow starthistle (*Centaurea solstitialis* L.), where soil surface temperatures ranged from 149 to 302 C (DiTomaso et al. 1999). Exposure times of 10, 20, 30, 40, and 60 s were similar to those used by Willis et al. (1988) and McKell et al. (1962), and represented the range of potential exposure times under slower burn conditions (e.g., morning burns, back burns). In 2004, the 100 C treatment and the 10 s exposure were omitted because they did not result in appreciable seed death during the 2003 experiment. An 80 s treatment was added because barb goatgrass seeds were

not completely killed in 2003 by 60 s exposures, even at 300 C.

All 10 inflorescences (barb goatgrass and medusahead) or spikelets (ripgut brome) were placed either directly in the furnace's steel tray (2003) or on a layer of soil level with the brim of the tray (2004) and treated simultaneously. In the field, senesced mature seeds typically disarticulate from the inflorescence. However, these studies evaluated timings before seed disarticulation. Therefore, intact inflorescences or spikelets were used, rather than individual seeds. After treatment, the 10 replication units were placed in a common paper bag (2003) or in individual coin envelopes (2004) and stored indoors under ambient conditions until germination testing.

Flame treatments were conducted with a single exposure temperature. A spike inflorescence (barb goatgrass and medusahead) or spikelets from a panicle inflorescence (ripgut brome) were exposed to the flame for several exposure times ranging from 0 to 14 s depending on the species and year. These structures represented the reproductive units that would be directly exposed to flames in a field burn condition. Field observations indicate that midday summer grassland fires result in inflorescence flame exposure times of about 3 to 5 s (DiTomaso, personal observation). Thus, the range of exposure times used in this experiment represent conditions that can occur with fast downwind burns and slower back burns or burns conducted under higher humidity. Each inflorescence or spikelet was considered one replicate. To ensure a constant flame temperature, the base of each replication unit was

positioned at the same height above the top of the burner. However, flame temperature varied even at this single height, likely due to fluctuating air currents in the laboratory. In 2003, flame temperature typically ranged from 300 to 400 C, whereas in 2004, the range was 350 to 450 C. This represents the upper range of soil surface temperatures demonstrated for grassland fires in California (DiTomaso et al. 1999).

Replication units in the flame simulation were treated by grasping the awns with metal tongs and holding the inflorescence right-side-up over the flame for the appropriate number of seconds. After exposure to flame, each replication unit was laid on a metal tray (2003) or a layer of soil (2004). In order to more completely simulate the conditions of a prescribed burn in the field, no effort was made to extinguish smoldering or burning plant material after removal from the flame. After all replications of a given treatment were completed, inflorescences or spikelets were placed in a common paper bag (2003) or individual coin envelopes (2004) and stored indoors under ambient conditions.

Germination tests were conducted to determine the effect of each heat treatment on seed mortality. Germination tests were conducted 7 to 8 mo after collecting inflorescences to allow for after-ripening and maximum germination (Gill and Blacklow 1985; Young et al. 1968). Additionally, awns were removed from the seeds of medusahead and ripgut brome, because a diffusible chemical in the awn has been shown to inhibit germination of medusahead (Nelson and Wilson 1969). For barb goatgrass, all tissues surrounding seeds (glumes, paleas, and lemmas) were removed, and large seeds were spaced well away from small ones to avoid inhibition of small seed germination (Dyer 2004).

In 2003, a random subsample of four seeds was taken from each of the 10 inflorescences in each treatment. Seeds from the furnace treatment came from any spikelet of the inflorescence. However, due to the rapid decrease in temperature with height above the Bunsen burner, only seeds from the lower six (medusahead) or three (barb goatgrass) spikelets were used in the flame treatment. The 40 seeds from each species and treatment were placed in one (barb goatgrass) or two (medusahead and ripgut brome) 10-cm Petri dishes containing 40 g (11.3 oz) of sterilized Yolo County fine sandy loam and 6 ml deionized (DI) water.

In 2004, to increase statistical robustness of the germination analysis, more seeds were used per replicate. In addition, a separate Petri dish was used for each inflorescence. Due to differences in seed size among species, 6-cm dishes were used for barb goatgrass and 10-cm dishes for medusahead and ripgut brome. Each dish contained one piece of blue blotter paper² moistened with 2 ml (barb goatgrass) or 5 ml (medusahead and ripgut) DI water. For furnace treatments, all seeds were used from barb goatgrass

inflorescences (8 to 12 per inflorescence) and the 20 uppermost seeds were taken from each medusahead inflorescence. For ripgut brome, the lowest three to four seeds (total of 20) were separated from every spikelet of the panicle. For flame treatments, every seed was used in the lowest three spikelets for barb goatgrass and in the lowest 2 cm of the inflorescence for medusahead. Seed selection for ripgut brome was similar to the 2003 protocol.

Germination tests were conducted in a growth chamber³ set to 10/14 h light/dark at 17/5 C, respectively. These light and temperature cycles represent average November conditions in Davis, California (www.worldclimate.com), when winter annual grasses typically germinate. Germination was monitored in the growth chamber for 14 d. The number of germinated seeds was recorded three times per week. Each germinated seed was removed after it was recorded, and DI water was added to the dish as necessary. A seed was considered to have germinated if any part of the radicle had emerged.

Data were analyzed using probit regression in SAS.⁴ The “trial” variable was the total number of seeds in each dish, and the “event” variable was the total number of germinated seeds in that dish. One false germinated seed was added to one replication of any treatment with zero percent germination, in order to avoid zero variance in the statistical tests (M. R. Watnik, personal communication). The resulting curves predicted the probability of germination as a function of exposure time for each set of treatments conducted at a single temperature. Therefore, for each collection, there was one curve for the flame treatments and potentially five (2003) or four (2004) curves for the furnace treatments. However, in most cases only one temperature of the furnace treatments yielded data consistent with the assumptions of probit regression. SAS output included calculated values for various points on each curve, and user-specified fiducial intervals (confidence intervals for regression curves) for each point. Two lethal dose (LD) values, in units of exposure time, were calculated by SAS for each flame exposure curve: the LD₅₀ (exposure time that kills 50% of seeds) and LD₉₀ (exposure time that kills 90% of seeds). Only LD₅₀ values were obtained for the furnace-treated seeds and these values are presented. The fiducial interval was chosen to be 97.5%, because nonoverlap of two intervals indicates a statistically significant difference at the P = 0.05 level (M. R. Watnik, personal communication). Finally, the LD₅₀ and LD₉₀ values were compared across seed moisture or maturity levels within each species to determine whether seed moisture was associated with susceptibility to flame exposure.

Results and Discussion

Inflorescence color correlated well with percent moisture in both 2003 and 2004 (Table 1). Flaming and furnace

experiments were conducted at seed moisture percentages ranging between 48 and 8% for barb goatgrass, 45 and 8% for medusahead, and 60 and 6% for ripgut brome.

Seed germination of all three species was high (generally > 80%) at all seed moisture levels in both 2003 and 2004. Average germination for barb goatgrass, medusahead, and ripgut brome over both years was $94\% \pm 5$ (range 85 to 100%), $79\% \pm 12$ (range 65 to 95%), and $93\% \pm 7$ (range 80 to 100%), respectively. All LD values were calculated relative to percent germination in untreated controls. It was initially speculated that earlier burns, when seed moisture was higher, might be more effective because seeds were not yet viable. However, these data indicate that seeds of these three invasive grasses were viable under laboratory conditions throughout the sampling time.

Convective Heat Exposure. In previous work, soil surface temperatures during a prescribed burn in a yellow starthistle-infested grassland averaged 219 C in a first-year burn and 231 C in a second-year burn, with a range of 149 to 302 C (DiTomaso et al. 1999). In this laboratory experiment, a similar range was used to simulate convective heat from a typical grassland fire.

LD₅₀ values for high, medium, and low seed moisture in barb goatgrass, medusahead, and ripgut brome were plotted for each temperature treatment (Figure 1a–c). The data indicate that seed mortality in all three species is temperature-dependent, with increasing exposure time and temperature resulting in greater seed death. In addition, seed moisture content does not have a significant effect on susceptibility to convective heat in any of the three species. Medusahead and ripgut brome had similar LD₅₀ responses at 250 C (28.0 ± 3.6 s and 31.7 ± 6.1 s, respectively) and 300 C (22.3 ± 1.5 s and 22.0 ± 5.0 s, respectively). Barb goatgrass required longer exposure times or increased heat, as the LD₅₀ values at 250 and 300 C were 49.3 ± 4.0 s and 31.3 ± 4.9 s, respectively.

Most importantly, the furnace experiments demonstrated that the heat of a typical grassland fire is not sufficient to kill seeds on the soil surface. Soil surface temperatures during a grassland fire rarely reach 300 C, and exposure time is unlikely to exceed 10 s in most conditions, since grassland fires pass quickly and the soil surface cools rapidly (DiTomaso and Kyser, personal observation). Because soil surface heat exposure in grassland fires is far lower than necessary to achieve biologically significant seed mortality, grassland fires are not an effective tool to manage the soil seedbanks of these three grass species. This is in agreement with previous observations by George (1992) and Murphy and Lusk (1961).

Direct Flame Exposure. The flaming experiments presented here simulate the direct effect of fire heat on inflorescences in a grassland fire. Flame temperature was slightly lower than canopy temperatures reported by

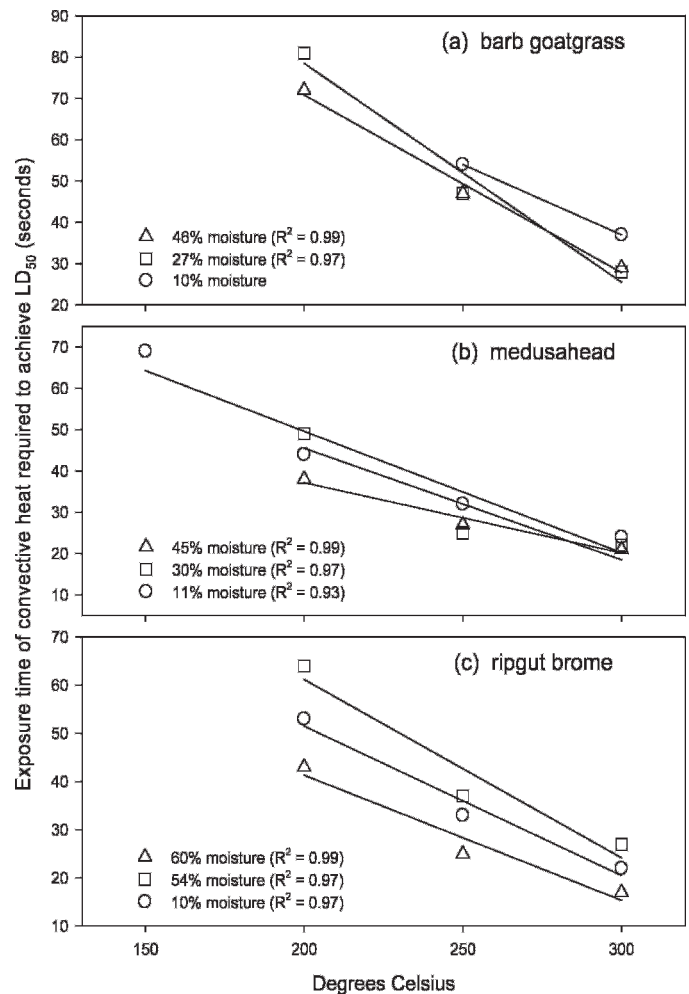


Figure 1. Plot of LD₅₀ values for (a) barb goatgrass, (b) medusahead, and (c) ripgut brome seeds exposed to 150, 200, 250, and 300 C furnace oven treatments at three moisture (maturation) levels. Data from 2003 and 2004 were combined. LD₅₀ values could not be determined for barb goatgrass at 10% seed moisture at 200 C and for most 150 C treatments. R² values for linear regression are presented for sets of three or more data points.

McKell et al. (1962), and roughly comparable to the mean of canopy temperatures reported by Keeley and McGinnis (2007) in the understory of a yellow pine forest. However, flame temperature can vary considerably within and across grassland fires, potentially due to fuel load, fuel composition, climatic conditions, and wind. Thus, the absolute values of lethal doses presented here can be considered valid for average conditions, but they potentially do not apply in all cases.

For barb goatgrass, there were no significant differences among seed moisture levels for both LD₅₀ and LD₉₀ (Figure 2a, b). Results from 2003 and 2004 were similar. Average LD₅₀ were 4.8 s (2003) and 4.1 s (2004), and average LD₉₀ were 7.4 s (2003) and 7.1 s (2004).

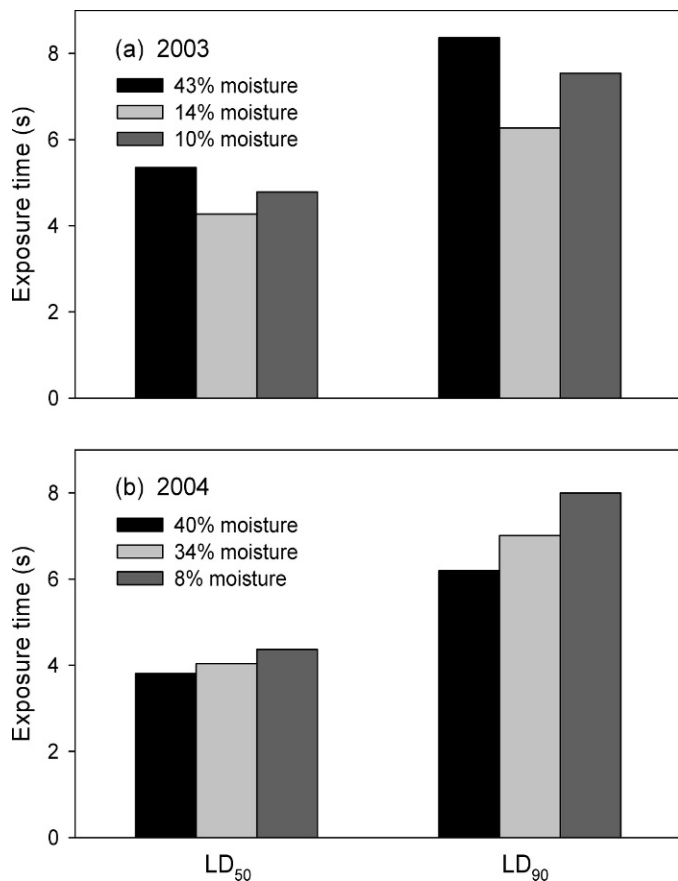


Figure 2. LD₅₀ and LD₉₀ values for barb goatgrass seeds exposed to flame treatments in (a) 2003 and (b) 2004 at three seed moisture (maturation) levels. Values were not significantly different ($P < 0.05$) among moisture levels within each year.

Results with medusahead were similar to barb goatgrass (Figure 3a, b). In 2003, there were no statistical differences in LD₅₀ and LD₉₀ among the three seed moisture levels. In 2004, four seed moisture levels were tested, again with no differences in LD₅₀. Among LD₉₀ values there was a statistical difference between 9 and 8% seed moisture, but this appears to be an artifact of little ecological significance. There was, however, some difference between the two years. Average LD₅₀ for 2003 and 2004 were 3.8 and 1.7 s, respectively, and average LD₉₀ for 2003 and 2004 were 6.5 and 4.8 s, respectively. The shorter LD values in 2004 may have been due to a slightly hotter flame in 2004 (350 to 450 C) compared to 2003 (300 to 400 C).

Overall, there was little evidence that maturity affected the susceptibility of barb goatgrass or medusahead seeds to direct flame. These results conflict with the conclusions of McKell et al. (1962), who found that medusahead seeds with moisture content below 30% were not as vulnerable to field burn conditions as seeds of higher moisture content. Additional support for the theory came from Young et al. (1972), who documented no decrease in

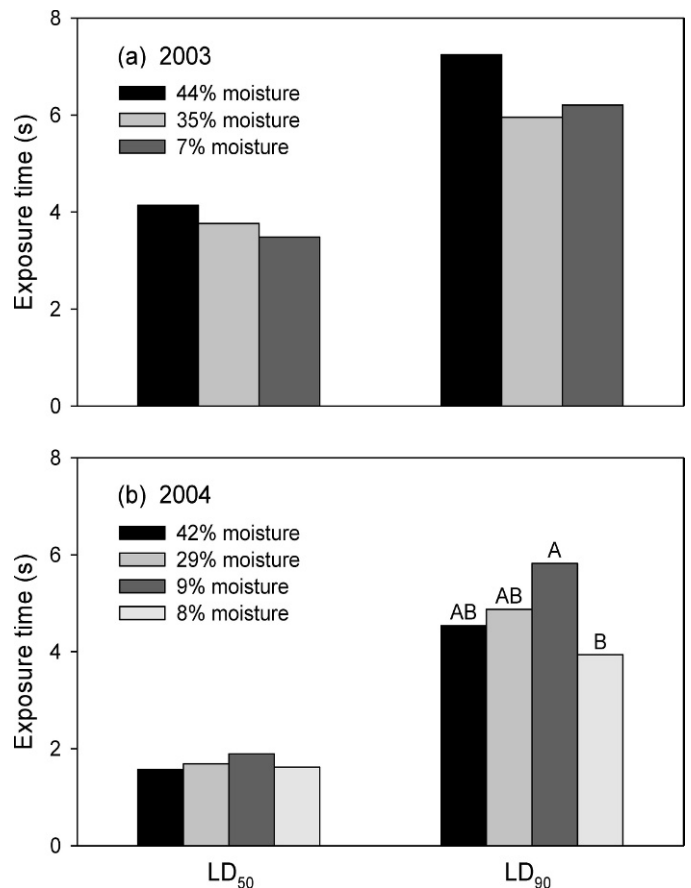


Figure 3. LD₅₀ and LD₉₀ values for medusahead seeds exposed to flame treatments in (a) 2003 and (b) 2004 at three or four seed moisture (maturation) levels. Different letters represent significant differences ($P < 0.05$) among moisture levels within LD₉₀ values in 2004. Values were not significantly different ($P < 0.05$) among moisture levels in 2003 and in LD₅₀ values in 2004.

percent cover of medusahead after prescribed burns conducted in late July or early August when seeds were mature. Based on these reports, recommendations were made to conduct prescribed burning when seed moisture levels were above 30%. However, in the experiments by McKell et al. (1962), researchers did not use seeds gathered at 30% moisture. Instead, mature seeds were remoistened to achieve the various treatment moisture levels. Contrary to their laboratory results, McKell et al. (1962) conducted prescribed burns in the field at several medusahead seed maturation stages, and found that all burns were equally effective. In the results presented here, burning at seed moisture levels either above or below 30% was very effective in killing seed of both barb goatgrass and medusahead.

In the case of ripgut brome, burning clearly was most effective at low seed moisture levels. Ripgut brome seeds consistently showed higher sensitivity to direct flame than the other two grasses, and drier seeds were statistically more

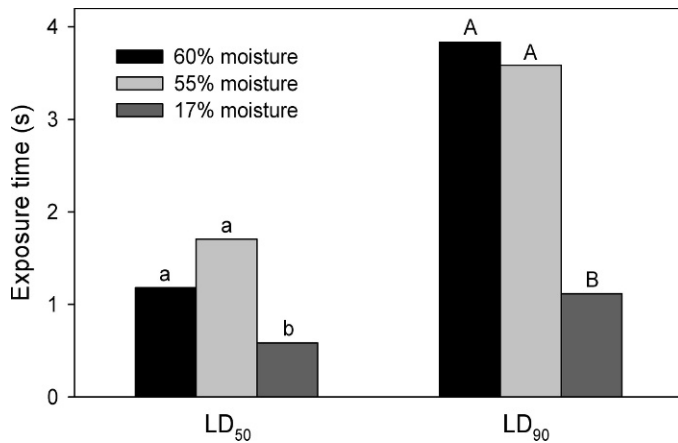


Figure 4. LD₅₀ and LD₉₀ values for ripgut brome seeds exposed to flame treatments in 2004 at three seed moisture (maturation) levels. Different letters represent significant differences ($P < 0.05$) among moisture levels within LD₅₀ or LD₉₀ values.

sensitive to flame heat than those with higher moisture levels (Figures 4 and 5). In 2003, only seeds with 10% moisture were evaluated, but in 2004, seeds at 60, 55, 17, and 6% moisture levels were tested. The average LD₅₀ and LD₉₀ for combined 60 and 55% seed moisture levels were 1.5 and 3.7 s, respectively, which are less than either barb goatgrass or medusahead at any seed moisture level (Figure 4). More importantly, the LD₅₀ and LD₉₀ at 17% seed moisture were 0.6 and 1.1 s, respectively. At seed moisture levels of 10% or less, nearly complete mortality occurred even at 1 s exposure to flame in both 2003 and 2004 (data combined in Figure 5). It was not possible to calculate precise LD₅₀ or LD₉₀ values from low seed moisture data, but these values would be < 1 s.

Results from the flame simulations can be used to generate predictions about burn timing for all three species. These results indicate that managers should time burns for ripgut brome control at later stages of seed maturation, when inflorescences are brown. In comparison, burns to control barb goatgrass and medusahead can be conducted at any point during seed maturation, when inflorescences are green/red to brown. With this broad range in burn timing, land managers can choose the most appropriate opportunity to burn depending upon suitable wind, humidity or temperature conditions, the impact of the fire on other desirable species, or permit restrictions.

Time Course of Moisture Loss and Implications for Management. Moisture loss from inflorescences (2003 and 2004) and vegetation (2004) of all three annual grasses was monitored at several time intervals from May to July in 2003 (data not shown) and from April to August in 2004 (Figures 6, 7, and 8). Data for inflorescence moisture loss from 2003 were very similar to 2004.

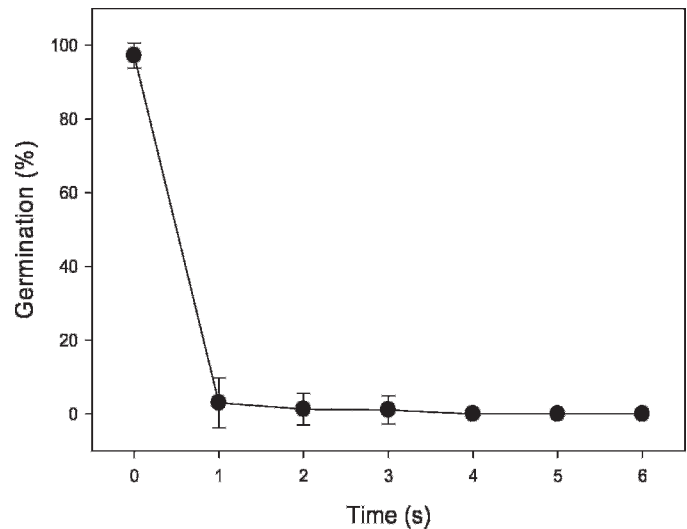


Figure 5. Percent (mean \pm SD) ripgut brome seed germination after exposure to flame treatments at seed moisture levels $\leq 10\%$. Data from 2003 and 2004 are combined.

In general, vegetative moisture loss closely matched loss of moisture from the inflorescences. The time sequence for moisture loss in barb goatgrass (Figure 6) was similar to medusahead (Figure 7). Surprisingly, moisture in the vegetation of barb goatgrass and medusahead was greater than 40% and 30%, respectively, at the point when the color changed from green to brown. These results do not conform with the moisture categories of Murphy and Lusk (1961), who categorized medusahead based solely on appearance as green, purple-tinged, or dry. In the results presented here, the percent moisture of brown plant tissues varied widely and took 3 wk to reach a stable minimum value, which occurred in about mid-June in both 2003 (data not shown) and 2004 (Figures 6 and 7). This might have important implications regarding fuel loads and burn timing. For example, burns conducted in late spring when the vegetative tissues are brown, but moisture content is still high, might not burn as completely, or at the same rate or temperature compared to later burns when the vegetative moisture is low.

Seed drop began after inflorescence moisture reached a stable minimum level and continued for one to 2 mo (DiTomaso, personal observation). For barb goatgrass, initiation of seed drop was June 18 to 20 in both 2003 and 2004 (Figure 6). Medusahead began dropping seed June 18 in 2004 (Figure 7), but June 25 in the wetter 2003 season (data not shown).

As previously stated, the window for using prescribed fire to control barb goatgrass and medusahead is broad. For example, when a 2-yr burning program was used to control barb goatgrass in California pastures, the first-year burn was conducted in mid-May, with a second-year burn in early July (DiTomaso et al. 2001). In the pasture that

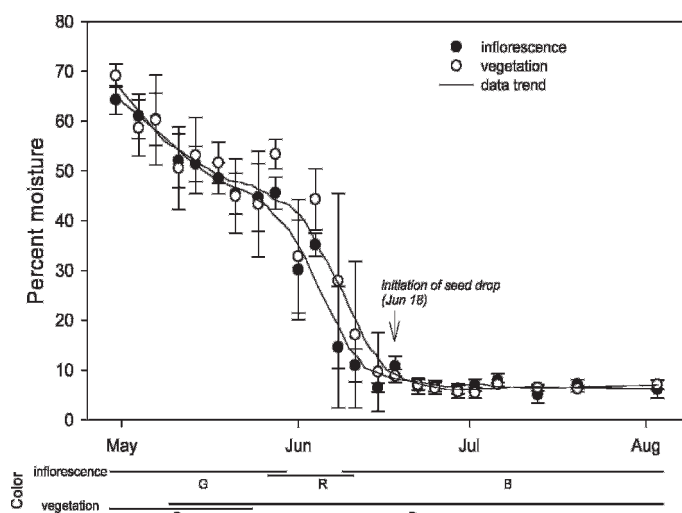


Figure 6. Percent moisture (mean \pm SD, $n = 10$) and dominant color in 2004 for barb goatgrass inflorescences (closed circles) and vegetation (open circles). G = green, R = red, B = brown. Date representing initiation of seed drop is indicated with arrow. Line for data trend was determined by a locally weighted regression (30%).

carried a fire in both years, barb goatgrass was completely controlled a year after the final burn. Similarly, successful prescribed burns for medusahead control have been conducted from late May to July (DiTomaso et al. 2005, 2006; Furbush 1953; Murphy and Lusk 1961; Pollak and Kan 1996). The laboratory studies presented here are supported by field studies and demonstrate that seed mortality can be achieved with prescribed burning conducted at a wide range of seed moisture levels between May and July (Table 1, Figures 6 and 7).

Not all studies show successful control of medusahead with burning. Young et al. (1972) reported that 3 consecutive yr of prescribed burning in late July or early August did not decrease medusahead cover in Lassen County, CA. Although this timing appears late, the study site was in the northeastern portion of the state and, at these timings, medusahead seeds were in the late soft dough stage, corresponding to relatively high inflorescence moisture content. Based on the results reported here, it is possible that the flame exposure time was not sufficient to kill the seed. McKell et al. (1962) showed that fast moving fires with short periods of maximum temperature were not effective in killing medusahead seeds. Thus, the main factor determining the success of prescribed burning for medusahead control could be the availability of an adequate fuel load, which would be expected to correlate with burn temperature and flame exposure time.

In addition to the fuel load, fuel moisture is a primary factor influencing burn speed and flame temperature. Moist fuels early in the season can reduce flame temperatures but increase flame exposure time by reducing

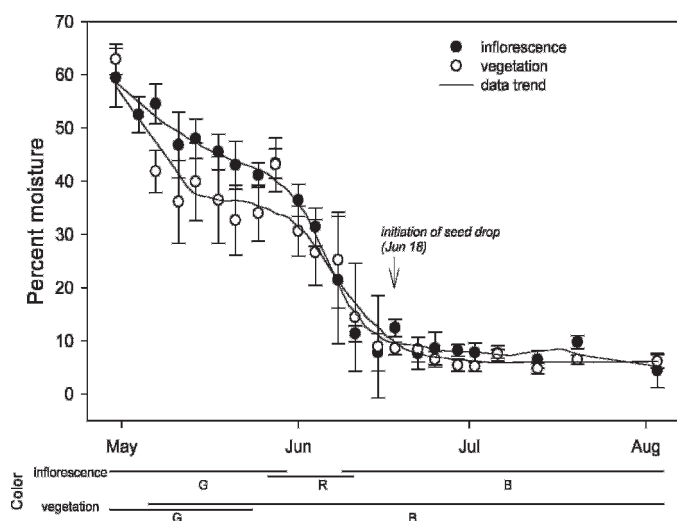


Figure 7. Percent moisture (mean \pm SD, $n = 10$) and dominant color in 2004 for medusahead inflorescences (closed circles) and vegetation (open circles). G = green, R = red, B = brown. Date representing initiation of seed drop is indicated with arrow. Line for data trend was determined by a locally weighted regression (30%).

the speed of the burn. Late-season burns with drier fuel loads are usually hotter but move faster, thus reducing the flame exposure time. McKell et al. (1962) measured maximum temperatures at 10 cm above the soil surface of about 515 C and 650 C for early (June) and late (August) burns, respectively. Flame temperatures used in this laboratory study were cooler (\sim 400 C) than those reported under field conditions, yet resulted in high seed mortality with a fairly short exposure time. Thus, it is speculated that exposure time—as influenced by fuel moisture—might play a more important role in killing barb goatgrass and medusahead seeds than flame temperature.

Based on the results presented here, burning for control of barb goatgrass and medusahead should be conducted at early to intermediate stages of seed development. Though seeds are equally susceptible to fire later in the season, later timing will result in a faster burn and reduced flame exposure time. Furthermore, delaying the burn allows a higher probability of seed drop. Seeds on the soil surface can survive the heat of grassland fires and this seedbank could be sufficient to reinfest the site in the following season.

In contrast to barb goatgrass and medusahead, ripgut brome lost moisture from vegetation and inflorescences much earlier in the season, and moisture loss was closely correlated with a change in color. By early May in 2003 (data not shown) and 2004 (Figure 8), moisture levels in both the inflorescences and vegetation had reached their stable low value concurrent with transition to a brown color.

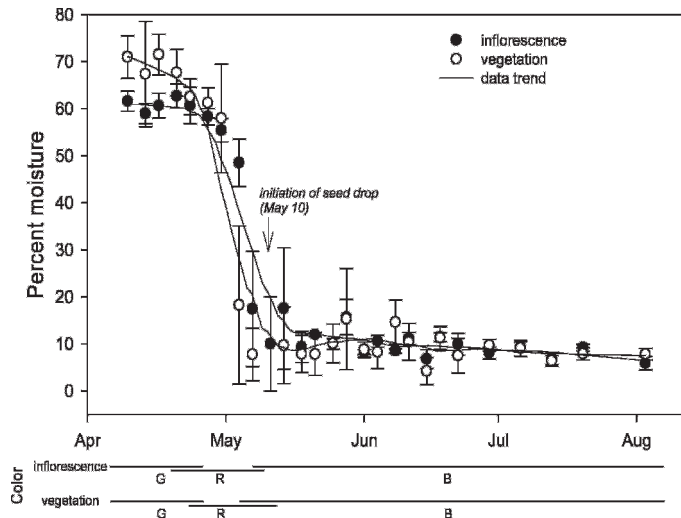


Figure 8. Percent moisture (mean \pm SD, $n = 10$) and dominant color in 2004 for ripgut brome inflorescences (closed circles) and vegetation (open circles). G = green, R = red, B = brown. Date representing initiation of seed drop is indicated with arrow. Line for data trend was determined by a locally weighted regression (30%).

Ripgut brome seed is less susceptible to flame exposure early in the season, at high seed moisture levels, but this is unlikely to be a factor in determining prescribed burn timing. Seed moisture reached its stable minimum about the first week of May in 2003 and 2004 (Figure 8), and prescribed fires are rarely conducted before mid-May. In addition, even ripgut brome seeds at the less susceptible moisture levels still had lower LD values than the other species tested. On the other hand, ripgut brome seed disarticulates about a month earlier (May 10) than either barb goatgrass or medusahead (June 18); consequently, burns conducted too late in the season, after ripgut brome seeds have dropped to the soil surface, might not give effective control. Land managers might need to time their burns for the control of ripgut brome more precisely than for the other two invasive grasses.

Interestingly, prescribed burns conducted in early July for the control of yellow starthistle also gave nearly complete control of ripgut brome (DiTomaso et al. 1999; 2006). This level of control was maintained for 4 yr after a 3-yr burn program (Kyser and DiTomaso 2002). By early July, many of the ripgut brome spikelets would already have shattered. It is possible, however, that the seeds remained on top of the thatch layer and were directly exposed to the fire. As a result, thatch might not only provide for a slower and hotter burn, but might also prevent seeds from contacting the soil surface, thus increasing their exposure to fire. Such a situation might not always be desirable, particular in areas where other nontarget species drop seeds on the thatch surface.

In conclusion, these three invasive rangeland grasses share a later phenology than many desirable annual grasses, and consequently their seeds are directly exposed to flame during mid- to late-season grassland fires. For barb goatgrass and medusahead, the effectiveness of control using prescribed fire does not appear to depend on seed moisture, but rather on the duration of direct exposure to the flame and the temperature of that flame. Slower, hotter burns would be more successful than cooler, faster burns. A successful burn would require sufficient fuel early in the season to ensure adequate heat or a long flame exposure time to kill the exposed seeds. In addition, the most appropriate timing window for a prescribed burn to control these two invasive annual grasses must occur prior to seed drop to ensure direct heating of seed.

Ripgut brome was considerably more sensitive to direct flame than barb goatgrass or medusahead and required a much shorter flame exposure time. However, ripgut brome matures and shatters its seed earlier than the other two species. Under many circumstances, the most appropriate burn timing for successful control of ripgut brome would be early in the season, typically in late spring. Thus, the burn timing window might be fairly narrow, but the probability of success within that window would be high, as even a cooler and faster burn would be expected to cause high levels of seed mortality.

Sources of Materials

- ¹ Muffle furnace, CPS 4022P, Thermolyne Corp., Dubuque, IA 52004.
- ² Blotter paper, Anchor Paper Co., St. Paul, MN 55101.
- ³ Growth chamber, model GR-36L, Percival Scientific, Perry, IA 50220.
- ⁴ Software, SAS Institute, Cary, NC 27513.

Acknowledgments

We thank Dr. David Spencer for his help in the statistical analysis of the results. We also thank Catherine Southard for her assistance with seed moisture measurements and the germination studies. This study was, in part, funded by the University of California IPM Exotic Pest and Disease Program.

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Received September 12, 2007, and approved December 18, 2007.