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A systematic review of management efforts on goatgrass (*Aegilops* spp) dominance

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Abstract Goatgrass (*Aegilops*) species are some of the most aggressive invasive plants in the Western U.S. Despite intense management efforts, goatgrass continues to reduce the ecological and economic integrity of natural and agroecological systems. The mismatch between current research outcomes and practical needs of land managers is likely a result of limitations associated with generalizing from single location, treatment, or season studies. We conducted a systematic review of experiments testing control of two dominant goatgrass invaders (*A. cylindrica* and *A. triuncialis*) to identify general patterns in treatment efficiency. Using data from 391 separate experiments, we found that experimental treatments were more successful at controlling the dominance of *A. cylindrica* compared to *A. triuncialis*. For *A. cylindrica*, no treatment demonstrated particular utility for control. Treatment of *A. cylindrica* in the vegetative stage was more effective for control than treatment at other stages. For *A. triuncialis*, burning and grazing demonstrated effective overall control among all treatments, although grazing produced variable results. Treatment in the fruiting stage of *A. triuncialis* was more effective for control than treatment at other stages. For both species, multiple applications of a management treatment within a year resulted in no better control than a single application within a year. Additionally, treatments deployed in two consecutive years resulted in better control of both species, than a treatment deployed in a single year. This work highlights promising avenues for more intensive research on goatgrass weed control and suggests that management funding is most effectively utilized when employed across years rather than focused on a single year.

Keywords *Aegilops cylindrica* · *Aegilops triuncialis* · Grazing · Herbicide · Fire · IPM · Invasive species · Prescribed burning

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Introduction

The spread of nonnative plant species across diverse habitats is increasing. This worldwide invasion proceeds in tandem with increasing global connectivity (Ehrenfeld 2003; Simberloff 2011), and changing climatic conditions (Thomas 2010; Bradley et al. 2012), which can enhance the detrimental effects of invasives. Biological invasions influence biodiversity and ecosystem functioning and are an important driver of overall global environmental change (Ehrenfeld 2010; Vila et al. 2011). The effects of invasive plant species are broadly seen across both natural landscapes (Mack et al. 2000; Byers 2002) where they can threaten conservation goals (Powell et al. 2011; Vila et al. 2011), and in agroecological systems where they threaten production (Duncan et al. 2004).

In response to these increasingly broad impacts, invasion ecology research has been directed to understand species invasiveness and habitat vulnerability (e.g., Richardson and Pyšek 2006), the effects of novel invaders on community assembly (e.g., Richardson and Pyšek 2006), and to predict and reduce the arrival of novel pests (Levine and D'Antonio 2003; Westbrooks et al. 2014). For invasive plants alone, thousands of field and greenhouse studies have been conducted to evaluate effects on diversity of native communities, their productivity, and nutrient cycling (Vila et al. 2011). An even greater, peer-reviewed literature and body of commercial research exists on agricultural weed control (e.g., Parish 1990; Blackshaw et al. 2006).

Research on invasive plant management has largely focused on comparing treatment methods, such as chemical and mechanical approaches, and the reduction of local population growth rates (Shea et al. 2010). These studies have been helpful for elucidating successful habitat-specific management strategies for controlling invasive species. For example, studies documenting burning, biological control, herbicide, grazing, mowing, hand-pulling, and seeding of more desirable species have all been attempted with varying degrees of success for many invasive annual grasses in the western U.S. (e.g., James et al. 2015), each with distinct tradeoffs between economic and ecologic efficacy. However, the persistence and continued range expansion of many historically noxious weeds, even in areas where control is implemented (e.g., Westra et al. 1992), suggests that there remains an important need to bring the gap between current research directives and the practical needs of land managers and agricultural practitioners. It is likely that this mismatch is the result of limitations associated with generalizing from single location, single treatment, or single season studies.

Typically, studies of invasive plant management compare effectiveness across different treatment types (e.g., herbicides type). However, studies that investigate different treatment timing and treatment combinations may provide more insight into effective control strategies than single treatment comparisons (Smith et al. 2006; James et al. 2015). Understanding the complexity of how management characteristics might ultimately affect control outcomes is especially important for developing and deploying effective weed-control strategies for noxious species that invade different types of systems.

One particularly aggressive invasive plant across systems that has confounded most current management efforts for control is goatgrass (*Aegilops* spp). Both Jointed goatgrass (*Aegilops cylindrica* Host.) and barb goatgrass (*A. triuncialis* L.) are invasive annual grasses of Eurasian origin that are rapidly expanding in the central and western United States. *Aegilops* species are typical colonizers that rapidly invade new territories and develop large stands (Ostrowski et al. 2016), and can significantly modify both natural and agricultural plant communities (Donald and Ogg 1991). While jointed goatgrass is primarily a pest of wheat fields and adjacent areas (Westbrooks 1998), barb goatgrass typically impacts resources of rangelands and noncrop areas (Davy et al. 2008). Much less prevalent is the related congener ovate goatgrass (*A. geniculata* Roth) which can hybridize with wheat. Though a significant amount a research has been conducted on the control of these species, the increasing invasion of goatgrass highlights the need for a more comprehensive approach to investigating management approaches of this species in both natural and managed ecosystems.

We used a systematic review and analysis to synthesize data from the available published and well-quantified, unpublished studies documenting goatgrass control efforts to (1) identify if, on average, different types of management approaches are effective in reducing the incidence of *Aegilops* spp.; (2) identify if treatment characteristics (i.e., treatment duration, treatment deployment timing, and phenology at the time of treatment) differentially affected the dominance of *Aegilops* spp.; and (3) identify if soil type differentially affected the dominance of *Aegilops* spp. Our goals were to identify general patterns in treatment efficiency that could ultimately be used to improve management strategies, as well as identify key knowledge gaps of likely management outcomes that will help prioritize and justify future research efforts and ensure their utility to stakeholder groups.

Methods

Study species

Jointed goatgrass was first discovered in winter wheat (*Triticum aestivum* L.) production in the United States in the late nineteenth or early twentieth century, but changing wheat production practices during recent decades have exacerbated its impacts (Donald and Ogg 1991). Jointed goatgrass and winter wheat have similar phenological and morphological characteristics, creating direct competition between the species that lowers winter wheat yield (Hill 1976). Jointed goatgrass seeds are difficult to separate from harvested grain of winter wheat and are considered a contaminant (Donald and Ogg 1991). Because of the close genetic relationship between jointed goatgrass and winter wheat, options for selective control are limited (Young et al. 2010).

Barb goatgrass has been present in the western United States since at least the 1920s (Jacobsen 1929; Kennedy 1928). In natural areas, barb goatgrass poses a considerable threat to native plant diversity (Drenovsky and Batten 2007). For example, unlike many other invasive annual grasses, barb goatgrass can successfully colonize and dominate serpentine grasslands (Lyons et al. 2010), which often contain high levels of native plant diversity and endemism. Barb goatgrass is also generally considered to be unpalatable to livestock unless grazed prior to the formation of reproductive structures (Peters et al. 1996; Davy et al. 2008).

Review and data extraction

We conducted a systematic review of research on goatgrass to evaluate the breadth and efficacy of control measures. We identified studies based on keyword searches ((‘goatgrass’ OR ‘Aegilops triuncialis’ OR ‘Aegilops cylindrica’ OR ‘Aegilops geniculata’) AND (‘control’ OR ‘management’ OR ‘herbicide’ OR ‘mow’ OR ‘graze’ OR ‘burn’ OR ‘competition’ OR ‘seeding’)) using ISI Web of Science, Google Scholar, Proquest, and WorldCat databases for studies published prior to June 2017. We also searched for candidate articles in the literature cited of studies found in our initial search.

We screened the resulting 149 studies and included their results in our analysis if they included (1) at least one goatgrass management treatment (herbicide, grazing, burning, mowing, seeding, or combinations thereof; hereafter, “treatments”); (2) a response to the treatment in terms of goatgrass percent cover or fitness correlates; and (3) experimental treatment units in an appropriate and sufficiently replicated experimental design. We used datathief III (datathief.org) to ascertain data points from published figures when necessary. We recorded means and standard deviations or standard errors as available in published text, tables, or figures and as received directly from study authors. The sources reviewed yielded 56 separate studies. For each of these, we collected data on target species (*A. cylindrica* or *A. geniculata* or *A. triuncialis*), response to treatment (cover or fitness), the maximum duration of treatment and observation (months), soil type (Serpentine soils or non-Serpentine soils), site type (agricultural system or natural area or greenhouse), and whether or not treatment costs were described.

We coalesced goatgrass cover, frequency, biomass, density, number of inflorescences, and number of spikelets into a single outcome metric. This was appropriate because biomass and percent cover are strongly correlated for grassland species (Robel et al. 1970) and because fitness measurements are correlated with biomass for goatgrass (Supplement, Table S1). Studies with other response variables (seed weight, germination rate, etc.) were excluded. This reduced the total number of experiments included in our analysis (for all goatgrass species) to 391 from 24 studies (Table S2).

Analysis

Disparate studies in systematic reviews that have data on means and errors are typically analyzed using meta-analysis. We took a different approach for several reasons. First, only 12 of the studies found included all the data needed to conduct a formal meta-analysis. We were reticent to significantly reduce our study sample size while also introducing both a temporal bias (older studies were much more likely to omit information such as standard errors than newer studies) and a bias against applied management research. Second, since our objective was to provide information for management, we were interested in the success or failure of a treatment, rather than an average effect size of a treatment (the primary outcome of a meta-analysis). In order to leverage all of the available data in a format that would most directly address management questions, we employed binomial tests to ascertain differences between combinations of invasive plant treatments across the studies that we collected.

We evaluated treatment success on a per-species relative scale since published literature does not report an absolute criterion. We calculated the percent control of each treatment replicate as (control plot—treated plot)/control plot × 100 and pooled the data within species. We did not combine species in the analysis because biological differences among species (Schneider et al. 2008) likely result in differential response to management approaches. We then split each species-specific dataset into quartiles. We defined "low control" as the lowest 25% of treatment responses including those where goatgrass increased after treatment. We defined "high control" as the highest 25% of control values. Because treatment efficacy varied by species, "low control" and "high control" represent different absolute percent control values for *A. cylindrica* and *A. triuncialis*. There were not enough studies with *A. geniculata* to investigate this species separately.

Each experimental treatment group was ranked as "low control", "high control," or "other" using the overall per-species quantile definitions. We summed the number of replicates in each control category for each treatment type (treatment type, herbicide type, phenology at application, soil type, number of treatments/year, and years of treatment). A replicate with more than one treatment category (i.e., early-season grazing) would be included in both categories. Different response types (i.e., % control, % fitness) were analyzed together.

We defined "ineffective" treatments as those with more "low control" replicates than would be expected by chance. Likewise, an "effective" treatment achieved a greater proportion of "high control" replicates than would be expected by chance. A treatment type could be simultaneously effective and ineffective if it resulted in a disproportionate numbers of both low and high control replicates (i.e., eliminated goatgrass if applied at the right time but otherwise increased goatgrass density).

Because the classifications of effective and ineffective were not mutually exclusive, we evaluated statistical efficacy and inefficacy independently. We performed separate, one-sided exact binomial tests to calculate the probability that the number of high (or low) would occur at the given sample size if the 25% null probability were true. This approach allowed us to include data without standard error measurements, and decreased the bias contributed by outlying treatment responses.

We did not perform post hoc adjustments for multiple comparison because we anticipated a probability of Type II errors. By nature, the determination of statistical significance across multiple studies is likely to include more confounding errors than a single site with many replicates. Furthermore, an experimental treatment represents a series of replicates, decreasing the overall probability of a Type 1 error. Finally, the lack of error information in many studies forced us to use binomial tests, which are less statistically powerful than tests which incorporate error information.

We were not able to test for significant interactions between treatment type and target phenology due to low sample size and bias in treatment timing. In order to perform log-linear models that account for sampling bias, the expected values would need to be 4 or greater (Crawley 2013). Application was inherently limited by physiological constraints (i.e., herbicide must be applied when the plant is still taking in nutrients) and management policies (i.e., burn restrictions), and skewed toward previously effective treatments. We present the sample sizes as observational data in the results section to highlight gaps in knowledge and constraints in treatment.

We argue that the proportion of high-control treatments represents a better metric for invasion control. That is, treatments that consistently produce high control are more likely to be successful than those that have a higher average effect size. Our approach represents the best compromise for the long-spanning, highly unbalanced data set yielded from literature searches. Traditional meta-analysis techniques were inappropriate as our many studies lacked error information, and the low sample size in some treatment categories precluded log-linear models. The use of overall distribution to provide relative categories of treatment success enabled us to incorporate relative effect size into our evaluation.

Results

Trends and bias

Treatment of *A. cylindrica* yielded greater control ($n = 174$, median = 63.4%, IQ range median 25.3–85.9%) than treatment of *A. triuncialis* ($n = 84$, median = 10.5%, IQ range 4.6–50.8%; $W = 10570$, $p < 0.001$). No cost information associated with experimental treatments were recorded in any of the studies used in our analysis.

Aegilops cylindrica

Treatment types

At the $p = 0.05$ level, all treatment types were statistically equivalent in controlling *A. cylindrica* (Fig. 1a, Table 1). At the $p = 0.10$ level, herbicide was more effective than other treatments (43 of 139 treatments, $p = 0.067$ Fig. 1, Table 1).

Herbicides varied greatly in ability to control *A. cylindrica*. Imazamox (high-control/total treatments = 27/71, $p = 0.01$), Pronamide (high-control/total treatments = 3/3, $p = 0.016$), and Propham (high-control/total treatments = 3/3, $p = 0.016$) were particularly effective at controlling *A. cylindrica* (Fig. 1b, Table 1) while Ethiozin (low-control/total treatments = 5/5, $p < 0.001$) and Ethiozin and Metribuzin (low-control/total treatments = 3/3, $p = 0.016$) were particularly ineffective (Fig. 1b, Table 1). Sulfosulfuron was marginally ineffective (low-control/total treatments = 7/15, $p = 0.057$ Fig. 1b, Table 1).

Treatment characteristics

Treatments applied to the vegetative stage were more effective (high-control/total treatments = 29/62, $p < 0.001$) than those applied at seed (high-control/total treatments = 9/38, $p = 0.063$), seedling (high control/total treatments = 5/42, $p = 0.99$) and fruiting stages (high-control/total treatments = 0/10, $p = 1.0$) while those applied to flowering stage were particularly ineffective (low-control/total treatments = 3/3, $p = 0.016$; Fig. 1c, Table 1). Within one generation, a single application (high-control/total treatments = 43/157, $p = 0.27$) performed as well as multiple applications (two applications: high-control/total treatments = 0/7, $p = 1.0$, and four applications: high-control/total treatments = 0/6, $p = 1.0$, Fig. 1d, Table 1). However, treatment in two consecutive years was more effective than treatment within 1 year (1 year: high-control/total treatments = 34/52, $p = 0.80$; 2 years: high-control/total treatments = 9/20, $p = 0.041$; Fig. 1e, Table 1).

Treatment type by timing interaction

Only herbicide was sufficiently replicated to perform treatment by contingency analysis ($n > 20$ for 5 phenologies). Moreover, a complete offset in timing between the two most common treatments (herbicide at seed, seedling, and vegetative stages and burn during reproductive stages) indicates that the influence of treatment timing cannot be separated from the effects of treatment type (Table 2).

Aegilops triuncialis

Treatment types

Burning (4 of 6 treatments high control, $p = 0.038$) and grazing (high-control/total treatments = 4/6, $p = 0.038$) produced more high control replicates than would be expected by chance (Fig. 2a, Table 3), but the results of grazing were mixed overall. While four of six grazing treatments achieved > 54% control, the remaining two actually increased the density of *A. triuncialis* (Fig. 2a, Table 3). Both treatments which benefitted *A. triuncialis* were applied multiple times per year (early and mid season, 20% increase; continuous grazing at 20 cm, 84% increase). Treatments with high control included early-season grazing ($n = 1$, 67% decrease), and grazing supplemented with hand clipping to remove thatch ($n = 3$, 83-88% control).

Fluazifop was particularly effective compared to other herbicides (high- control/total treatments = 4/5, $p = 0.015$, Fig. 2b, Table 3). Aminopyralid was

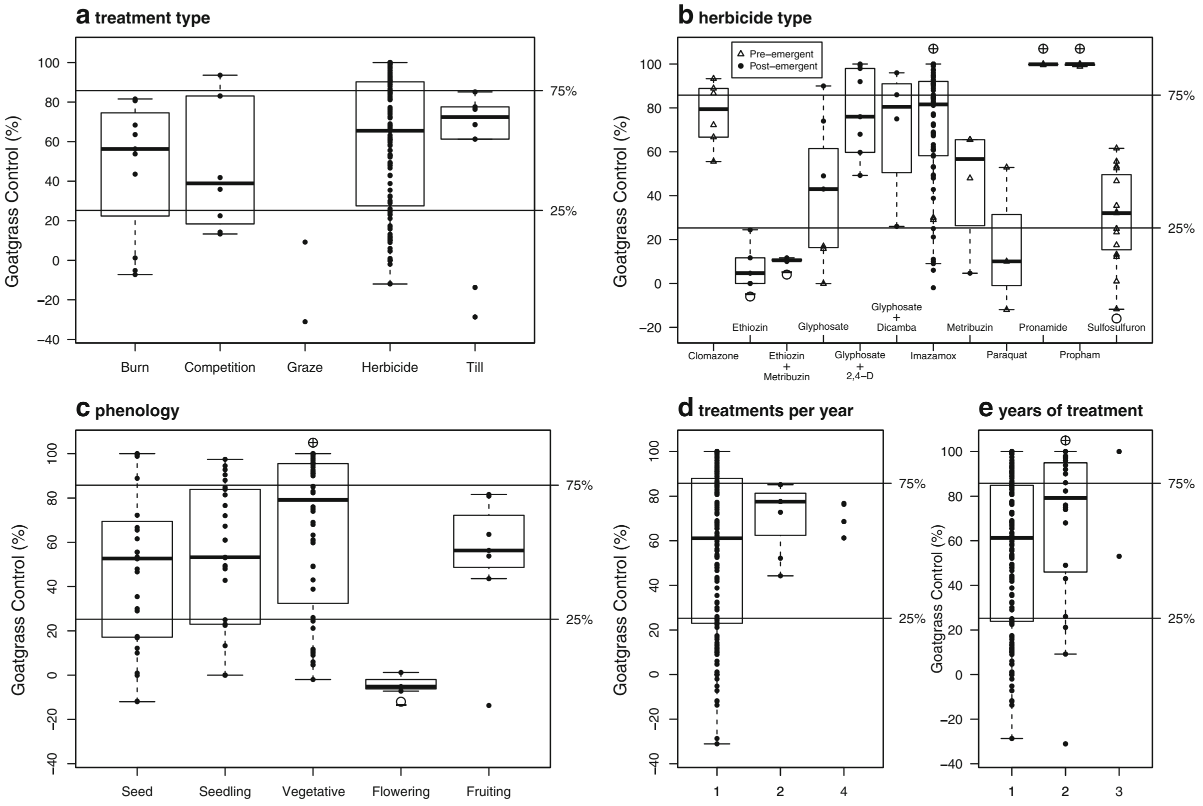

Fig. 1 Percent control and quartile breaks of *Aegilops cylindrica* within **a** treatment type, **b** herbicide type, **c** phenological stage, **d** treatments/year, and **e** years of treatment

marginally ineffective (low-control/total treatments = 7/13, $p = 0.08$, Fig. 2b, Table 3).

Treatment timing

Treatments applied in the fruiting phase were very effective overall (high-control/total treatments = 7/12, $p = 0.014$), whereas treatments applied in the vegetative phase were marginally ineffective (low-control/total treatments = 8/15 treatments low control, Fig. 2c, Table 3). Two treatment applications per generation (high-control/total treatments = 16/68, $p = 0.66$) performed no better than single treatment applications (high-control/total treatments = 4/14, $p = 0.48$, Fig. 2d, Table 3). However, application of treatments over two years (high-control/total treatments = 14/21, $p < 0.001$) was more effective than treatment within a single year (high-control/total treatments = 6/62, Fig. 2e, Table 3).

Treatment type by timing interaction

As in *Aegilops cylindrica,* only herbicide was sufficiently replicated to perform treatment by contingency analysis ($n > 20$ for 5 phenologies, Table 4). In fact, the remaining treatments were all performed at only one phase, preventing independent evaluation of treatment timing and method.

Discussion

In synthesizing all the available published studies on *Aegilops cylindrica* and *A. triuncialis* control experiments that were amenable to our analyses, we found that treatments tested to reduce *A. triuncialis* were less effective than those tested on its agricultural weed congener. Although ecological differences between the two species might suggest differential responses to management approaches (Daehler 1998), it is likely that this result is an artifact of experimental

Table 1 Statistical output overview for *Aegilops cylindrica*

	Total n	Low control $n < 25.3\%$	p	High control $n > 85.8\%$	p
Treatment type					
Burn	11	8	0.54	0	1.00
Competition	8	5	0.32	1	0.90
Herbicide	139	105	0.59	43	0.067
Till	12	10	0.84	0	1.000
Till and Burn	2	2	1.00	0	1.00
Herbicides					
Clomazone	6	0	1.00	3	0.17
Ethiozin	5	**5**	**< 0.001**	0	1.00
Ethiozin + Metribuzin	3	**3**	**0.016**	0	1.00
Glyphosate	7	3	0.24	1	0.87
Glyphosate + 2,4-D	9	0	1.00	4	0.17
Glyphosate + dicamba	4	0	1.00	2	0.26
Imazamox	71	7	0.99	**27**	**0.010**
Metribuzin	4	1	0.68	0	1.00
Paraquat	3	2	0.15	0	1.00
Pronamide	3	0	1.00	**3**	**0.016**
Propham	3	0	1.00	**3**	**0.016**
Sulfosulfuron	15	7	0.057	0	1.00
Phenology					
Flowering	3	**3**	**0.016**	0	1.00
Fruiting	8	2	0.63	0	1.00
Seed	40	12	0.28	9	0.63
Seedling	42	13	0.23	5	0.99
Vegetative	62	12	0.88	**29**	**< 0.001**
Treatment frequency					
Once/generation	157	44	0.21	43	0.27
Twice/generation	7	0	1.00	0	1.00
Four times/generation	6	0	1.00	0	1.00
Treatment duration					
One year	152	41	0.31	34	0.80
Two years	20	3	0.22	**9**	**0.041**
Site type					
Agricultural setting	92	24	0.44	29	0.09
Greenhouse	6	20	0.20	9	0.99
Natural area	4	0	1.00	1	0.68

Bolded values indicate significant (at alpha = 0.05) contributions of factors to differences in cover or fitness

limitations. For example, invasive plant management in agricultural systems benefit from a greater history and volume of research fueled by the financial cost of agricultural pests, compared to natural areas weeds (Radosevich et al. 2007). Moreover, natural systems might present lower accessibility to researchers where policy on natural lands might preclude testing of competitive species, the use of specialty equipment, and frequent monitoring in order to protect native populations. As a result, techniques for managing invasive plants in natural areas are likely much less refined, well tested, and effective than those typically

Table 2 Distribution of treatment types by treatment phenology for *Aegilops cylindrica*

	Seed	Seedling	Vegetative	Flowering	Fruit
Burn	3	8	0	0	0
Competition	0	4	0	0	0
Herbicide	38	38	63	2	0
Till	0	0	0	2	0

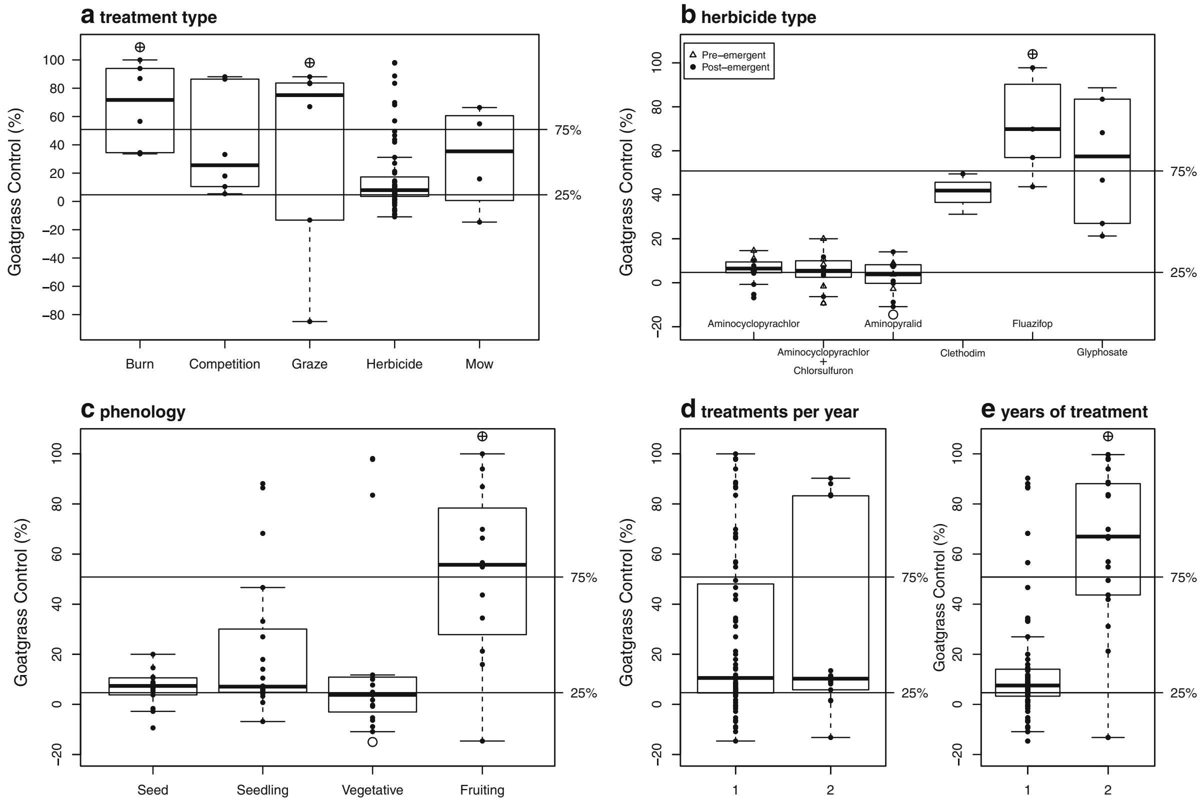

Fig. 2 Percent control and quartile breaks of *Aegilops triuncialis* within **a** treatment type, **b** herbicide type, **c** phenological stage, **d** treatments/year, and **e** years of treatment

deployed in agricultural systems. This work highlights a need for a more concerted effort by researchers to perform realistic and management-relevant experiments on invasive plant control in natural areas (e.g., Kettenring and Adams 2011).

Differences in herbicide identity used to treat *A. cylindrica* and *A. triuncialis* partially explain the discrepancy in herbicide effectiveness between species. For example, *A. triuncialis* trials were skewed toward ineffective herbicides, particularly aminocyclopyrachlor and aminopyralid (e.g., Beeler et al. 2012; Ferrell et al. 2012), while most herbicide research on *A. cylindrica* implemented the imidazolinone herbicide imazamox in conjunction with imazamox-resistant wheat. Although imazamox demonstrates highly effective control for a variety of grass and broadleaf crop weeds (Blackshaw 1998; Nelson et al. 1998), strict state-specific restrictions likely prevented the use of imazamox and other herbicides effective in agricultural settings in experiments involving *A. triuncialis.*

In our analysis, imazamox was likely highly effective against *A. cylindrica* for two reasons. First, both *A. cylindrica* and domestic wheat are cool-season C3 annual grasses, overlapping strongly in phenology. By negatively impacting *A. cylindrica*, but not wheat,

Table 3 Statistical output overview for *Aegilops triuncialis*

	Total n	$N < 4.68\%$ control	p	High control $n > 50\%$	p
Treatment type					
Burn	6	0	1	**4**	**0.038**
Competition	6	0	1	2	0.47
Graze	6	2	0.47	**4**	**0.038**
Herbicide	60	18	0.22	3	1
Mowing	4	1	0.68	2	0.26
Herbicides					
Aminocyclopyrachlor	16	4	0.6	0	1
Aminocyclopyrachlor + chlorsulfuron	16	6	0.2	0	1
Aminopyralid	13	**7**	**0.08**	0	1
Clethodim	3	0	1	0	1
Fluazifop	5	0	1	**4**	**0.015**
Glyphosate	6	0	1	3	0.17
Phenology					
Fruiting	12	1	0.97	**7**	**0.014**
Seed	14	4	0.59	0	1
Seedling	20	4	0.78	3	0.91
Vegetative	15	**8**	**0.017**	3	0.76
Treatment frequency					
Once/generation	68	17	0.54	16	0.66
Twice/generation	14	3	0.72	4	0.48
Treatment duration					
One year	62	19	0.19	6	1
Two years	21	2	0.99	**14**	**< 0.001**
Site type					
Agricultural setting	3	1	0.57	0	1
Greenhouse	6	0	1	2	0.47
Natural area	28	2	1	**18**	**< 0.0001**
Soils					
Serpentine	67	47	0.22	12	0.93
Nonserpentine	15	14	0.99	7	0.056

Bolded values indicate significant ($\alpha = 0.05$) contributions of factors to differences in cover or fitness

Table 4 Distribution of treatment types by treatment phenology for *Aegilops triuncialis*

	Seed	Seedling	Vegetative	Flowering	Fruiting
Burn	0	0	0	0	5
Competition	0	6	0	0	0
Herbicide	14	14	15	2	3
Mow	0	0	0	0	4

imazamox can provide a competitive advantage to the crop species (Davies et al. 2015), further limiting goatgrass dominance through enhanced competitive interactions. Second, imazamox is a post-emergent herbicide that must be taken up through actively growing tissue. This limits the application of imazamox to early in the life cycle of the target invasive. Early plant life stages, particularly the seedling stage, are noted for their vulnerability to disturbance and management treatments compared to later stages (Gornish et al. 2015). Our analysis of *A. cylindrica* supported this expectation as this species was most vulnerable to management treatments at the vegetative stage, compared to the fruiting stage.

Herbicide was not the only treatment that provided evidence for stage-specific effects in management outcomes. Although the grazing treatments differed slightly across experiments, we found that when *A. triuncialis* was grazed similarly to *A. cylindrica*, only early-season intense grazing reduced goatgrass density. Targeting young plants with early-season grazing has shown promise for the control of other invasive annual grasses, such as medusahead (Davy et al. 2015) and suggests that grazing that targets early life stages might hold utility for controlling goatgrass.

Targeting early life stages, however, might not be ideal for all treatment types. For example, employing fire earlier in the season when plants are still green can result in lower fire temperatures and less effective control (Willis et al. 1988). In fact, we found that the most effective burn treatments were applied in late summer after goatgrass vegetative and reproductive structures had dried, likely leading to fires that burn at higher temperatures. Because the large spikes of *Aegilops* can insulate seeds from external temperatures (Sweet et al. 2008), burn temperature may be especially critical for goatgrass control. The success of late season burns for controlling goatgrass is also reinforced by phenology. Typically, late season burns affect senesced goatgrass individuals, particularly goatgrass seeds that are vulnerable to mortality when exposed to fire (Willis et al. 1988; DiTomaso et al. 2001). Late in the season, goatgrass individuals are also unable to compensate for tissue loss through additional seed production or tillering.

Prescribed burning demonstrates promise for goatgrass control while potentially enhancing the cover of native forbs and grasses (DiTomaso et al. 2001) through litter and competition reduction (Menke 1992). However, the utility of fire for weed control is restricted by social concerns such as adjacent property ownership, public perceptions and federal regulations (Taylor and Daniel 1984). Environmental factors can also modify fire effects. For example, burning can be less effective for controlling grassland weeds in highly productive locations (Kyser et al. 2008). As an invader of low-productivity sites, *A. triuncialis* is likely to be the primary producer of thatch. Prescribed burning may therefore be particularly effective in heavily infested areas, where goatgrass thatch can carry fire, but ineffective in sparsely populated sites. Aigner and Woerly (2011) found burns were not possible after two years of *A. triuncialis* treatment because goatgrass density had been reduced to levels insufficient to carry a fire. Overall, fire may be a tool for goatgrass control that is best confined to dense populations in remote areas when possible.

For both species, we found that increasing the number of treatments used within a single year did not affect control outcomes. Treatments deployed earlier in the season to target early stages of goatgrass likely indirectly lead to elevated resource availability for late season neighboring plant species (Flory and Clay 2009), enhancing competitive dominance of the nontarget plant community. The nontarget plant community is subsequently able to better suppress any goatgrass individuals that might have escaped the initial treatment deployment, rendering a second treatment superfluous. Alternatively, a later season treatment deployment tends to occur after goatgrass loses its ability to compensate for tissue loss. In this case, a second treatment is unnecessary and would not result in added control.

In contrast to an absence of effects of repeated treatments within years, we found a strong multi-treatment effect across years. This is likely a result of compensatory effects that have been documented for other invasive annual plants (Gornish and James 2016). Multi-year treatments are able to control dominance of individuals that might have escaped a single year treatment, as well as address reinvasion from the seed bank. For example, sibling seeds of *A. triuncialis* germinate in alternate years (Dyer 2004), highlighting a need for treatments that address this invasion source. Burning might be a particularly effective approach in the second year of weed treatment because prescribed fire can produce higher temperatures at the soil surface than at plant height (Marty et al. 2015), resulting in higher seed mortality at the soil surface compared to the plant canopy.

Weed control is typically accompanied by significant environmental, social, and economic costs. Research that attempts to identify successful invasive plant management with minimal nontarget effects is critical for healthy desired plant communities and productive systems. Since the length and complexity of research experiments can be limited, syntheses that identify patterns of treatment effectiveness across disparate experiments can provide insight into promising management approaches that might not be apparent from single studies. This work highlights several management recommendations for controlling goatgrass based on aggregated research data. These include the consideration of stage-specific treatment targets as well as the value of employing treatments across two consecutive years instead of multiple treatments within a single year.

This work also underscores important directions for future research. Variability in the effectiveness of grazing and herbicide illustrates differential effects of treatments based on type, duration, and timing. Research that includes these types of control approaches would provide better information to managers if treatments were employed at different levels (e.g., seasonal timing, amount/duration, type) to clarify irregularities associated with particular strategies. Research should also focus on investigating the utility of particular approaches across years, which has been shown to be more effective than single year control efforts. Finally, cost information associated with weer-control approaches is critical for managers, yet this information was essentially absent from the papers we reviewed. Researches should provide this information, when available, to enhance translation of research to practice. The work presented here is also a reminder of the need to link weed management research with end users through outreach and extension activities that attempt to provide science-based recommendations to managers. The utility of applied experimental outcomes is really enhanced when decision makers have a role in accessing, employing, and sometimes providing commentary on research information. Perhaps the more regular incorporation of end users in the design, deployment and assessment process of weer-control experiments would enhance the relevance of research as well as increase the rate at which experimental outcomes are employed in the field.

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References

Aigner PA, Woerly RJ (2011) Herbicides and mowing to control barb goatgrass (Aegilops triuncialis) and restore native plants in serpentine grasslands. Invasive Plant Sci Manag 4:448–457

Beeler JF, Armel GR, Brosnan JT, Vargas JJ, Klingeman WE, Koepke-Hill RM, Bates GE, Kopsell DA, Flanagan PC (2012) Trumpetcreeper control with various indole-3-acetic acid mimics and diflufenzopyr. HortTechnology 22:677–681

Blackshaw RE (1998) Postemergence weed control in pea (*Pisum sativum*) with imazamox. Weed Technol 12:64–68

Blackshaw RE, O'Donovan JT, Harker KN, Clayton GW, Stougaard RN (2006) Reduced herbicide doses in field crops: a review. Weed Biology 6:10–17

Bradley BA, Blumenthal DM, Early R, Groscholz ED, Lawler JJ, Miller LP, Sorte CJB, D'Antonio CM, Diez JM, Dukes JS, Ibanez I, Olden JD (2012) Global change, global trade, and the next wave of plant invasions. Front Ecol Environ 10:20–28

Byers JE (2002) Impact of non-indigenous species on natives enhanced by anthropogenic alteration of selection regimes. Oikos 97:449–458

Crawley M (2013) The R handbook. John Wiley & Sons Ltd., West Sussex

Daehler C (1998) The taxonomic distribution of invasive angiosperm plants: ecological insights and comparison to agricultural weeds. Biol Conserv 84:167–180

Davies KW, Boyd CS, Johnson DD, Nafus AM, Madsen MD (2015) Success of seeding native compared with introduced perennial vegetation for revegetating Medusahead-Invaded sagebrush rangeland. Rangel Ecol Manage 68:224–230

Davy JS, DiTomaso JM, Laca EA (2008) Barb Goatgrass. University of California Division of Agriculture and Natural Resources No. 8315, Davis, CA, p 5

Davy JS, Roche LM, Nay DE, Tate KW (2015) Plant community responses to cattle grazing in a noxious weed dominated rangeland. Calif Agric 69:4

DiTomaso J, Heise KL, Kyser GB, Merenlender AM, Keiffer RJ (2001) Carefully timed burning can control barb goatgrass. Calif Agric 55:47–53

Donald WW, Ogg AG Jr (1991) Biology and control of jointed goatgrass (*Aegilops cylindrica*), a review. Weed Technol 5:3–17

Drenovsky RE, Batten KM (2007) Invasion by *Aegilops triuncialis* (barb goatgrass) slows carbon and nutrient cycling in a serpentine grassland. Biol Invasions 9:107–116

Duncan CA, Jachetta JJ, Brown ML, Carrithers VF, Clark JK, DiTomaso JM, Lym RG, McDaniel KC, Renz MJ, Rice PM (2004) Assessing the economic, environmental, and societal losses from invasive plants on rangeland and wildlands. Weed Technol 18:1411–1416

Dyer AR (2004) Maternal and sibling factors induce dormancy in dimorphic seed pairs of *Aegilops triuncialis*. Plant Ecol 172:211–218

Ehrenfeld JG (2003) Effects of exotic plant invasions on soil nutrient cycling processes. Ecosystems 6:503–523

Ehrenfeld JG (2010) Ecosystem consequences of biological invasions. Annu Rev Ecol Evol Syst 41:59–80

Ferrell J, Sellers B, Jennings E (2012) Herbicidal control of Largeleaf Lantana (*Lantana camara*). Weed Technol 26:554–558

Flory SL, Clay K (2009) Invasive plant removal method determines native plant community responses. J Appl Ecol 46:434–442

Gornish ES, James JJ (2016) Interactions among habitat, management, and demography for an invasive annual grass. Plant Ecol 217:1247–1258

Gornish ES, Aanderud ZT, Sheley RL, Rinella MJ, Svejcar T, Englund SD, James JJ (2015) Altered snowfall and soil disturbance influence the early life stage transitions and recruitment of a native and invasive grass in a cold desert. Oecologia 177:595–606

Hill LV (1976) Development, competition and control of tansy mustard, jointed goatgrass and field bindweed in winter wheat, Ph.D. dissertation, Oklahoma State University

Jacobsen W (1929) Goatgrass—a weed pest of the range. Mon Bull Dept. Agric State Calif 18:37–41

James JJ, Gornish ES, DiTomaso JM, Davy J, Doran M, Becchetti T, Wilson R, Lile D, Laca E (2015) Managing medusahead (*Taeniatherum caput-medusae*) on rangeland: a meta analysis of control efforts and assessment of stakeholder needs. Rangel Ecol Manage 68:215–223

Kennedy P (1928) Goat grass or wild wheat (*Aegilops triuncialis*). Agron J 20:1292–1296

Kettenring KM, Adams CR (2011) Lessons learned from invasive plant control experiments: a systematic review and meta-analysis. J Appl Ecol 48:970–979

Kyser GB, Doran MP, McDougald NK, Orloff SB, Vargas RN, Wilson RG, DiTomaso JM (2008) Site characteristics determine the success of prescribed burning for medusahead (*Taeniatherum caput-medusae*) control. Invasive Plant Sci Manag 1:376–384

Levine JM, D'Antonio AM (2003) Forecasting biological invasions with increasing international trade. Conserv Biol 17(1):322–326

Lyons KG, Shapiro AM, Schwartz MW (2010) Distribution and ecotypic variation of the invasive annual barb goatgrass (*Aegilops triuncialis*) on serpentine soil. Invasive Plant Sci Manag 3:376–389

Mack RN, Simberloff D, Mark Lonsdale W, Evans H, Clout M, Bazzaz FA (2000) Biotic invasions: causes, epidemiology, global consequences, and control. Ecol Appl 10:689–710

Marty JT, Sweet SB, Buck-Diaz JJ (2015) Burning controls barb goatgrass (*Aegilops triuncialis*) in California grasslands for at least 7 years. Invasive Plant Sci Manag 8:317–322

Menke JW (1992) Grazing and fire management for native perennial grass restoration in California grasslands. Fremontia 20:22–25

Nelson KA, Renner KA, Penner D (1998) Weed control in soybean (*Glycine max*) with imazamox and imazethapyr. Weed Technol 46:587–594

Ostrowski MF, Prosperi JM, David J (2016) Potential implications of climate change on *Aegilops* species distribution: sympatry of these crop wild relatives with the major European crop *Triticum aestivum* and conservation issues. Plos One 11(4):15394

Parish S (1990) A review of non-chemical weed control techniques. Biol Agric Hortic 7:117–137

Peters A, Johnson D, George M (1996) Barb goatgrass: a threat to California rangelands. Rangelands 18:8–10

Powell KI, Chase JM, Knight TM (2011) A synthesis of plant invasion effects on biodiversity across spatial scales. Am J Bot 98:539–548

Radosevich SE, Holt JS, Ghersa CM (eds) (2007) Ecology of weeds and invasive plants: relationship to agriculture and natural resource management, 3rd edn. Wiley, New York, p 472

Richardson DM, Pyšek P (2006) Plant invasions: merging the concepts of species invasiveness and community invasibility. Prog Phys Geogr 30:409–431

Robel RJ, Briggs JN, Dayton AD, Hulbert LC (1970) Relationship between visual obstruction measurements and weight of grassland vegetation. J Range Manag 23:295–297

Schneider A, Molna I, Molnar-Lang M (2008) Utilisation of *Aegilops* (goatgrass) species to widen the genetic diversity of cultivated wheat. Euphytica 163:1–19

Shea K, Jongejans E, Skarpaas O, Kelly D, Sheppard AW (2010) Optimal management strategies to control local population growth or population spread may not be the same. Ecol Appl 20:1148–1161

Simberloff D (2011) How common are invasion-induced ecosystem impacts? Biol Invasions 13:1255–1268

Smith RG, Maxwell BD, Menalled FD, Rew LJ (2006) Lessons from agriculture may improve the management of invasive plants in wildland systems. Front Ecol Environ 4:428–434

Sweet SB, Kyser GB, DiTomaso JM (2008) Susceptibility of exotic annual grass seeds to fire. Invasive Plant Sci Manag 1:158–167

Taylor JG, Daniel TC (1984) Prescribed fire: public education and perception. J For 82:361–365

Thomas CD (2010) Climate, climate change and range boundaries. Divers Distrib 16:488–495

Vila M, Espinar JL, Hejda M, Hulme PE, Jarosik V, Maron JL, Pergl J, Schaffner U, Sun Y, Pysek P (2011) Ecological impacts of invasive alien plants: a meta-analysis of their effects on species, communities and ecosystems. Ecol Lett 14:702–708

Westbrooks RG (1998) Invasive plants: changing the landscape of America. US Government Documents (Utah Regional Depository): 490

Westbrooks RG, Manning ST, Waugh JD (2014) Early detection and rapid response: a cost-effective strategy for minimizing the establishment and spread of new and emerging invasive plants by global trade, travel and climate change. Invasive Species Glob Clim Change 4:305–325

Westra P, Chapman P, Stahlman PW, Miller SD, Fay PK (1992) Field Bindweed (*Convolvulus arvensis*) control with various herbicide combinations. Weed Technol 6:949–955

Willis B, Evans J, Dewey S (1988) Effects of temperature and flaming on germinability of jointed goatgrass (*Aegilops cylindrica* Host) seed. In: Proceedings-Western Society of Weed Science (USA)

Young FL, Ball DA, Thill DC, Alldredge JR, Ogg AG, Seefeldt SS (2010) Integrated weed management systems identified for jointed goatgrass (*Aegilops cylindrica*) in the Pacific Northwest. Weed Technol 24:430–439