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Evaluation of Herbicide and Disking to Control Invasive Bluestems in a South Texas Coastal Prairie

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Abstract

Conservation and restoration efforts of native grasslands are being hindered by invasive, exotic plants. Exotic bluestem grasses (*Bothriochloa* and *Dichanthium* spp.) have become increasingly invasive throughout the rangelands of the central and southern Great Plains, United States. Accordingly, the aim of this study was to evaluate the efficacy of glyphosate, imazapyr, and imazapyr + glyphosate treatments with or without disking to remove exotic bluestems from a south Texas coastal prairie. We evaluated three different control regimens: 1) herbicide treatments only, 2) herbicide treatments followed by two diskings (H + D), and 3) disking followed by herbicide treatments (D + H). Percent exotic bluestem, native grass, and forb cover were visually estimated at 0 (pre-treatment: May 2006), 20, 52, and 104 wk after treatment (WAT). The herbicide-only and H + D regimens were ineffective at controlling exotic bluestems. However, exotic bluestem cover in herbicide-treated plots of the D + H regimen was significantly lower ($P \leq 0.05$) compared to control plots and most treatment plots of the herbicide-only and H + D regimens up to 52 WAT. Control regimens did not notably facilitate an increase in native grass cover from pre-treatment levels, but native grass cover remained the highest, and increased the most, in some imazapyr-treated plots of the herbicide-only and D + H regimens, respectively. In the H + D and D + H regimens, disking resulted in a flush of forb cover (up to 50%) at 52 WAT; yet forb cover was $\leq 5\%$ in these plots by 104 WAT. Exotic bluestem cover recovered back to, or was greater than, pre-treatment levels among most treatment plots across all three control regimens at 104 WAT. This study suggests that follow-up control measures are needed to suppress the re-invasion of exotic bluestems after initial control efforts. Additional studies are needed to evaluate other strategies to control exotic bluestems in rangelands of the central and southern United States.

Resumen

Los esfuerzos de conservación y reforestación de pastizales nativos han sido obstaculizados por plantas invasivas y tóxicas. El pasto exótico bluestem grasses (*Bothriochloa* and *Dichanthium* spp.) se ha vuelto cada vez mas invasivo en los pastizales del centro y el sur de las Grandes Planicies de Estados Unidos, por consiguiente, el objetivo de este estudio fue evaluar la eficiencia de tratamientos a base de glyphosate, imazapyr, y imazapyr + glyphosate con o sin arado de disco para remover los plantas exóticas de bluestem de un pastizal de las planicies de las costas de Texas. Evaluamos tres diferentes regímenes de control: 1) aplicación únicamente de herbicida; 2) aplicación de herbicida seguidos por las rastra de discos dos veces (H + D); y 3) rastra de discos seguido de la aplicación de herbicida (D + H). El porcentaje del pasto exótico bluestem, gramíneas nativas y cobertura herbácea fue estimado visualmente como 0 (pre-tratamiento: Mayo 2006), 20, 52, and 104 semanas después de la aplicación de los tratamientos (WAT). Los tratamientos solo herbicida y H + D no fueron efectivos para control del pasto exótico bluestems. Sin embargo, la cubierta de este pasto exótico en las parcelas bajo la aplicación de herbicida del régimen D + H fue significativamente menor ($P \leq 0.05$) comparado con las parcelas control y la mayoría de las parcelas tratadas solo con herbicida y H + D regímenes hasta 52 WAT. Los regímenes de control no facilitaron notablemente un incremento en la cobertura de pastos de niveles a comparación de los niveles antes de los tratamientos, pero la cobertura de los pastizales nativos permaneció como la más alta, y la que mas aumentó, en algunos parcelas tratadas con imazapyr o con solo herbicida y D + H regímenes, respectivamente. En los tratamientos H + D y D + H, y la rastra de discos resultaron en un aumento de la cobertura herbácea (de hasta 50%) en 52 WAT; sin embargo la cobertura fue $\leq 5\%$ en estas parcelas por 104 WAT. La cobertura del pasto exótico bluestem se recuperó, o fue más grande que, los niveles presentados antes de los tratamientos entre la mayoría de las parcelas tratadas a través de todos los tres regímenes de control a 104 WAT. Este estudio sugiere que el seguimiento de las medidas de control es necesario para suprimir una nueva invasión del pasto exótico bluestem después de esfuerzos iniciales para controlarlo. Estudios adicionales son necesarios para evaluar otras estrategias para controlar el pasto exótico bluestem en pastizales de centro y sur de los Estados Unidos.

Key Words: glyphosate, imazapyr, invasive grasses, native grasses, Old World bluestem, restoration

INTRODUCTION

For centuries, grass-dominated ecosystems across the globe have been continually under pressure from human-based activities. Today the world's natural grasslands and rangelands are some of the most threatened and/or endangered ecosystems worldwide (Samson and Knopf 1994; Noss et al. 1995; Hoekstra et al. 2005). Hoekstra and others (2005) reported that temperate grasslands, savannas, and shrublands had the

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highest risk of "biome-wide biodiversity loss," and they had the highest ratio of percent area converted to percent area protected of all 13 world biomes. Unfortunately exotic plant invasions into native grassland ecosystems are directly or indirectly the result of human-based activities, and these invasions are a hindrance and often significant threat to the conservation and restoration efforts of grass-dominated ecosystems worldwide (D'Antonio and Vitousek 1992; Stohlgren et al. 1999; Wilson and Pärtel 2003; Corbin and D'Antonio 2004; Reed et al. 2005; Rossiter-Rachor et al. 2009).

Exotic bluestem grasses (*Bothriochloa* Kuntze and *Dichanthium* Willem. spp.) are a group of C_4 perennial grasses introduced from Asia and Europe in the early 1900s to the central and southern Great Plains, United States (Celarier and Harlan 1955; McCoy et al. 1992). It has been estimated that greater than 1 million ha of rangeland in Oklahoma and Texas has been seeded with exotic bluestems since the mid-1980s for soil conservation and enhancement of rangeland forage and livestock production (Dewald et al. 1985; White and Dewald 1996). Exotic bluestems were valued for their high productivity, forage quality, and tolerance of intensive grazing, and accordingly, exotic bluestem pastures were established to complement the less productive native range (Celarier and Harlan 1955; Eck and Sims 1984; Coyne and Bradford 1985). Moreover, agronomists noted early on that exotic bluestems exhibited superior traits such as high seedling vigor, which aided their ease of establishment and enhanced their competitiveness, compared to their native congeners (*Andropogon* spp.; Coyne and Bradford 1985).

Despite their past and present notoriety as desirable rangeland forage grasses (McCoy et al. 1992), various exotic bluestem species are spreading rapidly across the Great Plains landscape becoming unwelcome invaders of natural ecosystems (Gabbard and Fowler 2007; Smith 2010). In central and south Texas, the two most problematic exotic bluestems are King Ranch (*Bothriochloa ischaemum* var. *songarica* [Rupr. ex Fisch. & C.A. Mey.] Celarier & Harlan) and Kleberg bluestems (*Dichanthium annulatum* [Forssk.] Stapf) (Hatch et al. 1999; Gabbard and Fowler 2007; Smith 2010). In Kansas a recent study reported that Caucasian bluestem (*Bothriochloa bladhii* [Retz.] S. T. Blake) was a superior competitor to some native grasses (Schmidt et al. 2008). In addition, native plant diversity (Reed et al. 2005; Gabbard and Fowler 2007) and small mammal (Sammon and Wilkins 2005) and avian species richness (Hickman et al. 2006) were often lower in areas dominated by exotic bluestems relative to native vegetation. Taken together, these findings suggest exotic bluestems have the potential, like other well-known invasive grasses of the United States (e.g., cheatgrass [*Bromus tectorum* L.]: Christian and Wilson 1999; cogongrass [*Imperata cylindrical* (L.) P. Beauv.]: Dozier et al. 1998) to significantly alter the ecology of natural grass-dominated ecosystems.

Selective control of exotic plants which invade communities dominated by plant species possessing similar traits and physiology (e.g., exotic C_4 grasses in native C_4 grass–dominated grasslands; Reed et al. 2005; Simmons et al. 2007; Ruckman et al. 2011) remains a challenge that has yet to be resolved (Corbin and D'Antonio 2010). Exotic bluestem invasions into native C_4 grasslands and savannas of the central and southern United States exemplify this challenge for land managers. Nonetheless, prescribed fire may be one restoration tool that may help control exotic bluestems in C_4-dominated grasslands (Simmons et al. 2007; Ruckman et al. 2011). In addition, recent studies have demonstrated the abundance of exotic bluestems can be substantially reduced over the short term with herbicides, particularly imazapyr and glyphosate (Harmoney et al. 2004, 2007, 2010; Simmons et al. 2007). Despite recent success at managing exotic bluestem populations, controlling these invasive grasses remains a challenge, and all control options for these species have yet to be explored. Recently re-vegetating native grasses in a Blackland prairie in central Texas using disking, glyphosate, and imazapic (Plateau) was marginally successful due to the rapid reinvasion of exotic bluestems during the same year (Mittlehauser et al. 2011). However, combining herbicides (dalapon, imazapyr, or glyphosate) and disking has successfully controlled cogongrass for more than 1 yr in the southeastern United States (Willard et al. 1996; Terry et al. 1997).

Here we report the findings of a study conducted to evaluate the efficacy of glyphosate, imazapyr, and imazapyr + glyphosate treatments with or without disking to control exotic bluestems in a south Texas coastal prairie. In this study we evaluated three different exotic bluestem control regimens: 1) herbicide treatments only, 2) herbicide treatments followed by two diskings (H + D), and 3) disking followed by herbicide treatments (D + H). We hypothesized imazapyr and imazapyr + glyphosate treatments would be more effective at controlling exotic bluestems than glyphosate (regardless of active ingredient or application rate) because imazapyr has both foliar and soil activity, whereas glyphosate has only foliar activity (Tu et al. 2001). We further hypothesized the combination of herbicide and disking treatments, regardless of sequence, would provide more persistent control of exotic bluestems compared to herbicide treatments alone.

METHODS

Site Description

This study was conducted at the Rob and Bessie Welder Wildlife Foundation Refuge (hereafter Welder Refuge; lat 28°07′N, long 97°24′W) in San Patricio County, Texas, approximately 19 km north of Corpus Christi, Texas. The Welder Refuge encompasses 3 120 ha and is located in a transitional area between the Gulf Coast Prairies and Marshes and the South Texas Plains Ecoregions (Gould 1975). The relative humidity of south Texas along the Gulf of Mexico is high, and the region is characterized as subtropical, but it often experiences extensive droughts and semiarid conditions (Drawe et al. 1978). Soils of the Welder Refuge range from sandy loams near riparian areas to calcareous clay and clay loams on the uplands (Drawe et al. 1978). The long-term (1971–2000) mean annual temperature and daily maximum/minimum temperatures at the Welder Refuge are 21.3°C and 26.8/15.8°C, respectively (NOAA 2010). The long-term mean annual precipitation from 1956 to 2008 at the Welder Refuge was 923 mm. Frost-free days at the Welder Refuge range from 275 to 330 $d \cdot yr^{-1}$, and elevations are generally flat (Soil Survey Staff, USDA-NRCS 2010).

This study was conducted on Victoria clay soil with 0 to 3 percent slopes. Victoria clay is a Vertisol of the south Texas

Table 1. Treatments and application rates conducted for the herbicide-only, herbicide followed by disking (H + D), and disking followed by herbicide (D + H) control regimens ($n = 4$ blocks [replicates] per control regimen) at the Welder Wildlife Refuge in south Texas.

	Treatment[a]	Application rate	
		$L \cdot ha^{-1}$	$kg \cdot ai \cdot ha^{-1}$
1	Control[b]	—	—
2	Glyphosate	2.34	1.43
3	Glyphosate	6.92	4.28
4	Imazapyr	1.74	0.43
5	Imazapyr	3.48	0.86
6	Imazapyr	5.80	1.43
7	Imazapyr + glyphosate	1.74 + 2.34	0.43 + 1.43
8	Imazapyr + glyphosate	3.48 + 4.68	0.86 + 2.85

[a]See Methods section for treatment dates. All imazapyr treatments (4 through 8) included 0.25% $vol \cdot vol^{-1}$ of a nonionic surfactant.

[b]Control treatments consisted of no herbicide for the herbicide-only regimen, whereas control treatments for the H + D and D + H regimens consisted of disking only (also no herbicide).

coastal plain derived from Late Pleistocene marine sediments, and it is calcareous and well drained but very slow permeating (i.e., high water table) and shrinks and swells under dry and wet conditions, respectively (Soil Survey Staff, USDA-NRCS 2010). Native coastal prairie on Victoria clay is dominated by little bluestem (*Schizachyrium scoparium* [Michx.] Nash) (Drawe et al. 1978; Hatch et al. 1999). Other common native grasses include plains bristlegrass (*Setaria leucopila* [Scribn. & Merr.] K. Schum.), silver bluestem (*Bothriochloa laguroides* [DC.] Herter), buffalograss (*Bouteloua dactyloides* [Nutt.] J. T. Columbus), meadow dropseed (*Sporobolus asper* [P. Beauv.] Kunth), Texas wintergrass (*Nassella leucotricha* [Trin. & Rupr.] Pohl), Hall's panicum (*Panicum halli* Vasey), and vine mesquite grass (*Panicum obtusum* Kunth) (Hatch et al. 1999). Native forb (annual and perennial) abundance is generally low on Victoria clay soils (estimated 10% cover or less), and no exotic forb species were observed in the study area. Exotic bluestem invaded coastal prairie on clay and clay loam soils is generally dominated by Kleberg bluestem, yet mixed stands of Kleberg and Angleton bluestem (*Dichanthium aristatum* [Poir.] C. E. Hubbard) are common; monospecific stands of Angleton bluestem are common in moist depressions. King Ranch bluestem occurs infrequently on Victoria clay where it is most abundant on coarse textured (i.e., sandy loam) soils.

Experimental Design

This study was designed as a randomized complete block experiment. Experimental blocks were located in an area invaded by exotic bluestems ($\geq 50\%$ canopy cover), yet patchy remnants (~ 0.5–$2\ m^2$ in size) of native grasses and forbs also were not uncommon (≤ 10–25% canopy cover). We delineated a total of 12 experimental blocks (each 6.4 m $\times$ 26.8 m), and each block was partitioned into eight treatment plots (3.4 m $\times$ 6.4 m each; total $n = 96$ plots). We randomly assigned each of the 12 blocks to one of three control regimens (four blocks per control regimen): 1) herbicide only (no follow-up treatment), 2) herbicide followed by disking (hereafter H + D regimen), and 3) disking followed by herbicide (hereafter D + H regimen). Each of the eight plots within each block of the herbicide-only and H + D regimens received one of eight randomly assigned treatments, seven herbicide treatments and one no herbicide control, on 29 May 2006 (Table 1). All blocks of the H + D and D + H regimens were disked on 31 May 2006, and in addition, all blocks of the H + D regimen received a second disking on 18 Oct 2006 because the initial control regimen (herbicide [or no herbicide] plus one disking) had little effect at controlling exotic bluestems (Table 1). Last, plots within each block of the D + H regimen were randomly assigned one of the same eight treatments as the herbicide-only and H + D regimens on 23 July 2006. The intention of the three different control regimens was to evaluate the effectiveness of follow-up control techniques (herbicide or disking) relative to herbicides only to suppress the reinvasion of exotic bluestems in treatment areas that we hypothesize is facilitated from the germinable soil seedbank (including seed rain) or above-ground tiller regeneration via the crown bud bank (Harmoney et al. 2004, 2010). Further, we were interested in comparing the efficacy of the two sequences of herbicide and disking treatments (H + D vs. D + H regimens) to control exotic bluestems.

Herbicides were applied while walking at a steady rate (~ 3–5 kph) using a CO_2 pressurized backpack sprayer (R & D Sprayers, Opelousas, Louisiana) outfitted with a 3-m boom and six Tee-Jet 11003 flat-fan nozzles calibrated to deliver approximately 189 $L \cdot ha^{-1}$ at 0.25–28 $g \cdot cm^{-2}$ (Table 1). Herbicide treatments were conducted when wind speeds were 16 to 24 $km \cdot h^{-1}$, air temperatures ranged from 21° to $29^\circ C$, relative humidity ranged from 60% to 95%, and soil moisture was moderate (soils were not dry, nor exceptionally moist). Exotic bluestems were in the boot and/or flowering phenological stage when herbicide treatments were conducted for the herbicide-only and H + D regimens on 29 May 2006 (Table 1). Herbicide treatments were conducted for the D + H regimen on 23 July 2006 under similar climate conditions as described above (Table 1). For the D + H regimen, exotic bluestems present after the initial disking treatment (31 May 2006) were predominately in the vegetative growth stage at the time of herbicide applications, although a few individuals were in the boot and/or flowering stage.

Experimental blocks which were randomly selected for disking (H + D and D + H regimens; $n = 8$) were mowed to a 6–8 cm height prior to the disking. Blocks treated with herbicides prior to disking (H + D regimen; $n = 4$) were mowed ~ 48 hr, after the herbicides were applied. Disking was conducted using a 4.8-m offset disk attached to a John Deere tractor. The H + D and D + H regimens were both disked on 31 May 2006, and the H + D blocks were disked for a second time on 18 October 2006 (~ 30 wk after initial herbicide treatments). All blocks were thoroughly disked (4–6 passes, ~ 20–25 cm deep) to uproot and incorporate all above-ground herbaceous vegetation into the soil. Table 1 lists all the treatment combinations for each control regimen, the respective herbicide application rates, and dates of performance.

Vegetation Monitoring

We visually estimated the percent cover of exotic bluestems, native grasses, and forbs (annual and perennial) in three 1-m^2 quadrats (i.e., $n = 3$ subsamples per plot) along one belt transect through the middle of treatment plot ($n = 96$ plots)

Table 2. Mixed model ANOVA results for the fixed main effects of treatment, control regime (regimen), weeks after treatment (WAT), and their interactions on percent exotic bluestem, native grass, and forb cover. Boldface indicates statistical significance.

		Exotic bluestem cover (%)		Native grass (%)		Forb cover (%)	
Effect	df	F	*P* value	F	*P* value	F	*P* value
Treatment (T)	7	**3.3**	**0.003**	1.9	0.08	0.6	0.78
Regimen (R)	2	**56.9**	**< 0.0001**	**6.8**	**0.002**	**27.0**	**< 0.0001**
WAT	3	**50.0**	**< 0.0001**	**42.4**	**< 0.0001**	**337.5**	**< 0.0001**
T × R	14	**3.5**	**0.0001**	1.2	0.30	**3.1**	**0.0004**
T × WAT	21	**3.1**	**< 0.0001**	0.8	0.70	1.1	0.38
R × WAT	6	**59.0**	**< 0.0001**	**6.9**	**< 0.0001**	**45.6**	**< 0.0001**
T × R × WAT	42	**2.6**	**< 0.0001**	0.9	0.71	**1.8**	**0.004**

at 0 (pre-treatment), 20, 52, and 104 wk after treatment (WAT) (Daubemire 1959; Bonham 1989). The three subsamples from each plot were averaged to obtain a replicate mean of percent exotic bluestem, native grass, and forb cover m^{-2} for each treatment plot ($n = 4$ replicates per treatment) within each control regimen. Plant nomenclature and authority follows Hatch et al. (1999) and USDA-NRCS PLANTS database (2011).

Statistical Analyses

A repeated measures mixed model analysis of variance (ANOVA; SAS v. 9.1, SAS Institute Inc., Cary, NC) was used to test for differences in percent exotic bluestem, native grass, and forb cover due to the fixed main effects of herbicide treatment, control regimen, and time (hereafter treatment, regimen, and WAT, respectively) and their interactions (Littell et al. 1996). Time (WAT) was the repeated measure, and block was the random effect. All main effects and interactions were included in all models. All response variables (exotic bluestem, native grass, and forb cover) were arcsine square-root transformed prior to analyses to meet the assumptions of normality and equality of variance for ANOVA (Zar 1999). Post hoc multiple mean comparison tests (LSMEANS) were performed when main and/or interaction effects were $P \leq 0.05$ (Zar 1999).

RESULTS

Herbicide Control of Exotic Bluestems

All main and interaction effects of the three-factor (herbicide, regimen, WAT) mixed model ANOVA were significant ($P < 0.003$ for all effects; Table 2). The herbicide × regimen × WAT interaction had a strong effect on exotic bluestem cover ($P < 0.0001$) indicating the effect of herbicide treatments on exotic bluestem cover varied by control regimen, and these patterns also varied temporally (Figs. 1A–1C).

At 20 WAT, exotic bluestem cover in all herbicide-treated plots within the herbicide-only and H + D regimens, regardless of active ingredient or application rate, was higher than pre-treatment levels (0 WAT; $P < 0.05$), and not different from control plots (no herbicide or disking only) ($P > 0.05$) (Figs. 1A and 1B). The second disking performed at ~30 WAT in all

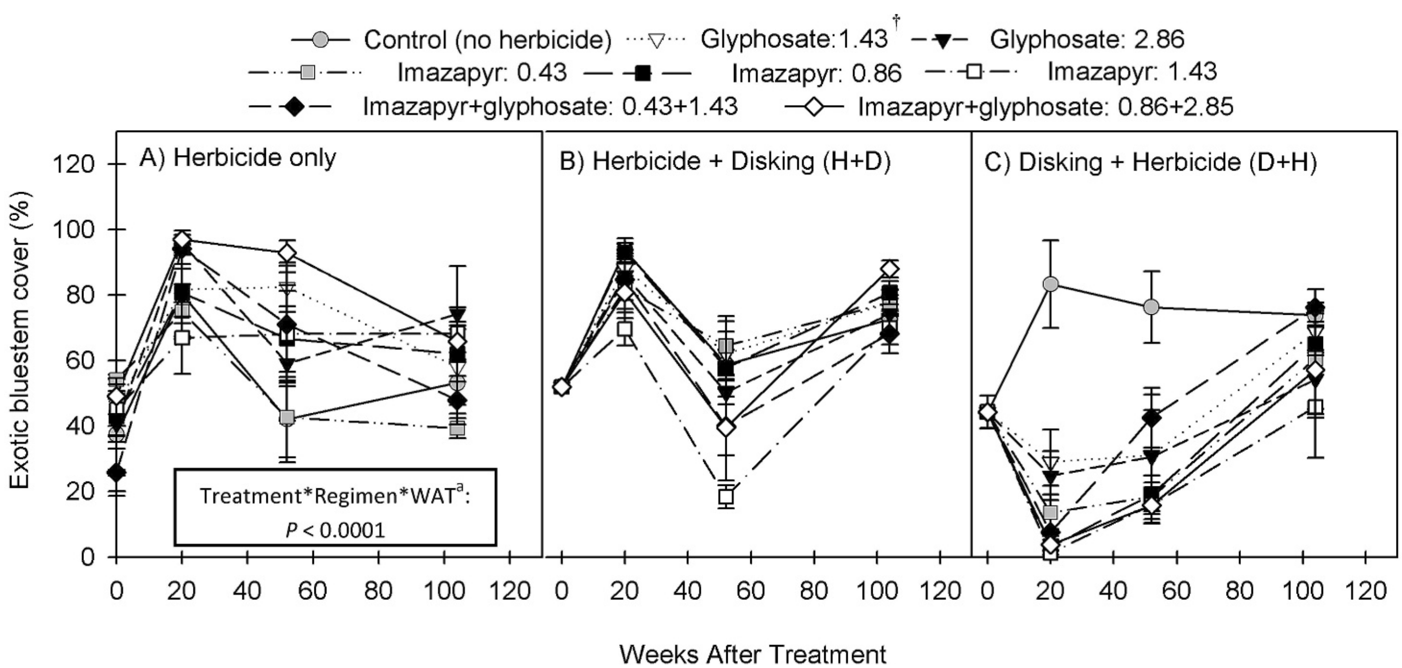

Figure 1. Exotic bluestem cover (%) among treatments within the **A**, herbicide-only, **B**, herbicide + disking (H + D), and **C**, disking + herbicide (D + H) regimens. †Numerical values after each treatment represent application rates in $kg \cdot ai \cdot ha^{-1}$ (see Table 1). [a]WAT = Weeks After Treatment.

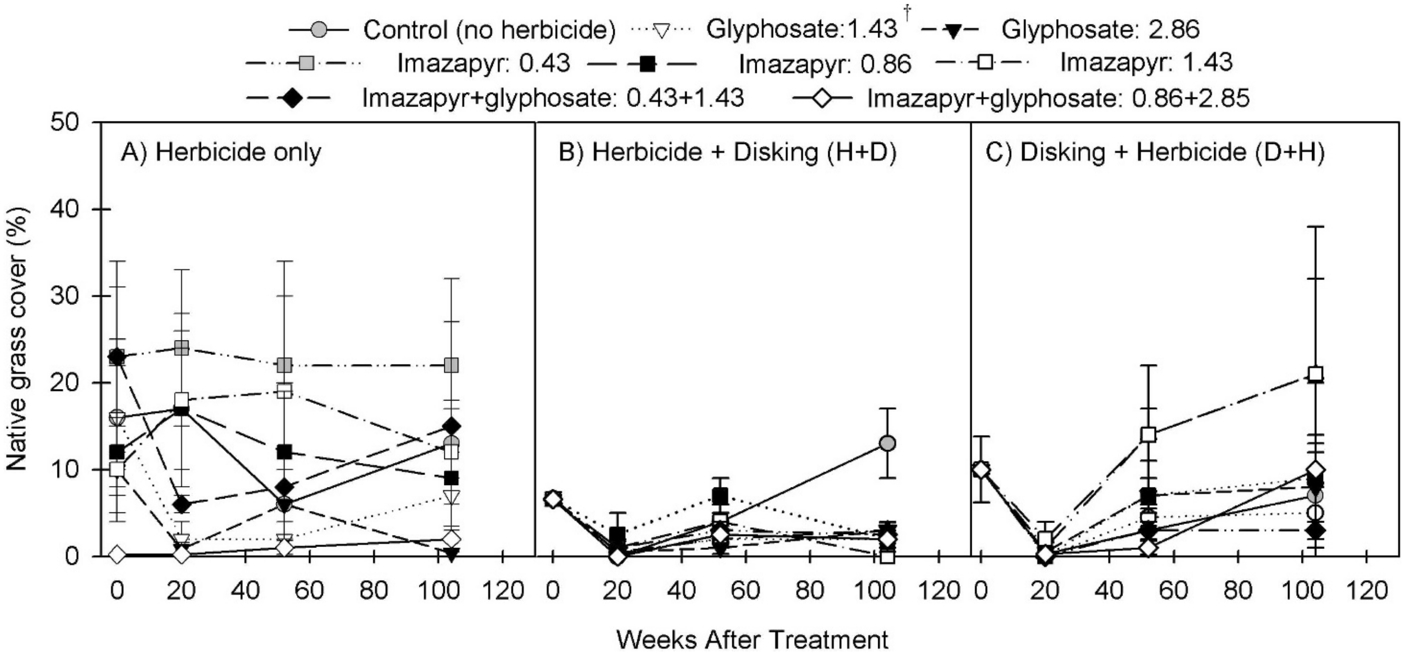

Figure 2. Native grass cover (%) among treatments within the **A**, herbicide-only, **B**, herbicide + disking (H + D), and **C**, disking + herbicide (D + H) regimens. †Numerical values after each treatment represent application rates in kg · ai · ha^{-1} (see Table 1).

blocks of the H+D regimen reduced exotic bluestem cover from 20 to 52 WAT ($P < 0.05$; Fig. 1B). Within the H+D regimen at 52 WAT, plots treated with imazapyr at 1.43 kg · ai · ha^{-1} (highest application rate of imazapyr; Table 1) averaged 18 ± 4% exotic bluestem cover, which was significantly lower than all other treatment plots, which averaged ≥ 40% exotic bluestem cover ($P \leq 0.002$; Fig. 1B). In contrast, herbicide-treated plots within the D + H regimen, regardless of active ingredient or application rate, had significantly lower exotic bluestem cover than control plots at 20 and 52 WAT ($P < 0.05$; Fig. 1C). By 104 WAT, exotic bluestems dominated nearly all treatment plots among all control regimens (50% to 80% exotic bluestem cover; Figs. 1A–1C). Nonetheless, plots treated with imazapyr at 1.43 kg · ai · ha^{-1} in the D + H regimen averaged 46% ± 16% exotic bluestem cover at 104 WAT, which was significantly lower than the disking only, no herbicide control plots (74% ± 4%; $P = 0.02$; Fig. 1C).

Native Grass and Forb Response

Native grasses. Native grass cover varied among treatments ($P = 0.08$) across control regimens (Table 2; Figs. 2A–2C), but control regimen had the strongest effect on native grass cover, and this effect varied with time after treatments (regimen × WAT, $P < 0.0001$; Table 2; Figs. 2A–2C). Considering that disking likely eliminated initial native grass cover in most plots of the H + D and D + H regimes, native grass cover tended to be higher in plots of the herbicide-only regimen compared to the H + D and D + H regimens (Figs. 2A–2C). All imazapyr-treated plots within the herbicide-only regimen contained some of the highest native grass cover, and not surprisingly, plots treated with glyphosate alone or in mixture experienced a decrease in native grass cover (Fig. 2A). Although disking initially eliminated native grass cover in the H + D and D + H regimens, native grass cover increased with time in plots treated with imazapyr at 0.43 and 1.43 kg · ai · ha^{-1} in the D + H regimen (Fig. 2C).

Forbs. Percent forb cover differed significantly by the three-way interaction, treatment × regimen × WAT ($P = 0.004$; Table 2), indicating herbicide treatments had varying effects on forb cover depending on control regimen and these patterns also varied temporally. Forb cover at 0 (pre-treatment) and 20 WAT did not differ ($P > 0.05$) between treatments within or between control regimens (Figs. 3A–3C). A flush of forb cover was evident at 52 WAT in treatment plots of the H + D and D + H regimens where forb cover averaged as high as 50% of the total plant canopy cover in some plots (Figs. 3B and 3C); yet at the same time, forb cover averaged less than 5% among most treatment plots within the herbicide-only regimen (Fig. 3A). By 104 WAT, forb cover averaged less than 5% in all treatment plots within the H + D and D + H regimens, while it averaged as much as 10–15% in some treatment plots in the herbicide-only regimen (Figs. 3A–3C).

DISCUSSION

Herbicides are frequently utilized to control rangeland weeds, but herbicide treatments alone often provide only short-term weed control (DiTomaso 2000), and we found this trend to hold true for controlling exotic bluestem grasses in a south Texas coastal prairie. Exotic bluestem control was most successful when exotic bluestem stands were first disked followed by herbicide treatments (Fig. 1C). Here exotic bluestem cover in herbicide-treated plots of the D + H regimen was significantly lower compared to control plots (no herbicide and/or disking only) and most treatment plots of the herbicide-only and H + D regimens up to 52 WAT (Fig. 1C). Although

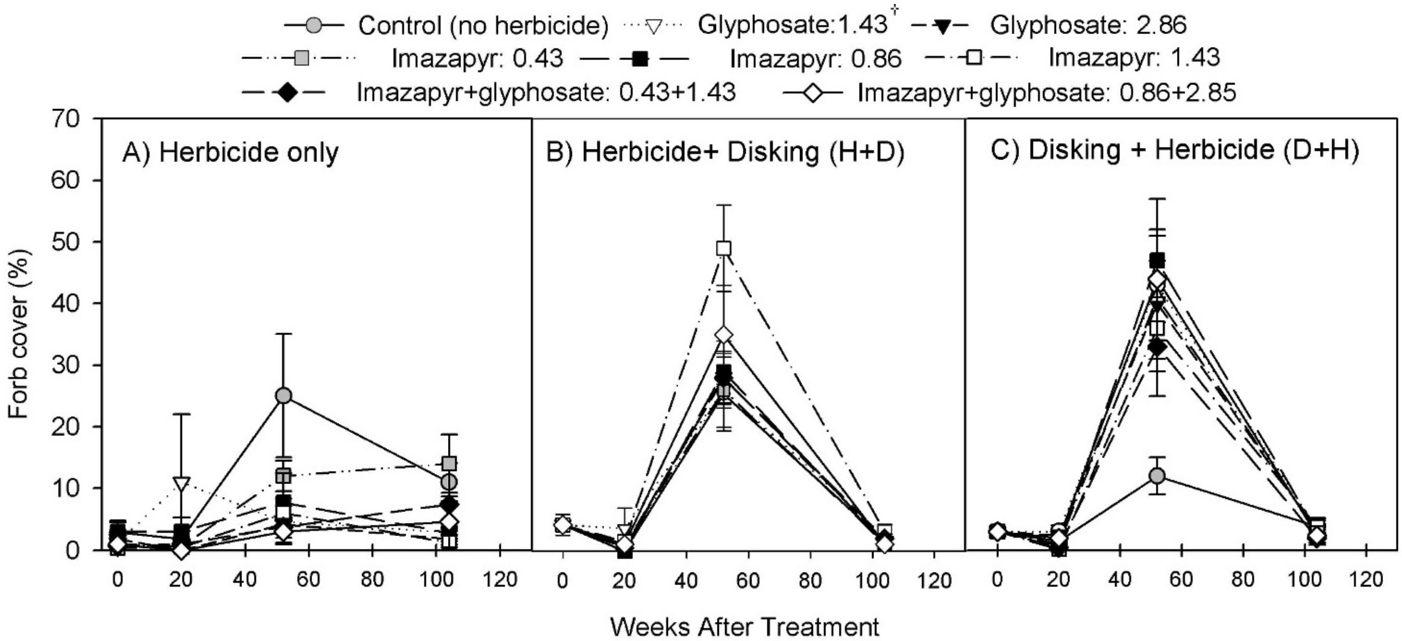

Figure 3. Forb cover (%) among treatments within the **A**, herbicide-only, **B**, herbicide + disking (H + D), and **C**, disking + herbicide (D + H) regimens. †Numerical values after each treatment represent application rates in kg · ai · ha^{-1} (see Table 1).

post-treatment exotic bluestem cover was often lower in some imazapyr-treated plots relative to other herbicide treatments across control regimens, contrary to what we expected imazapyr was generally no more effective than glyphosate at providing persistent control of exotic bluestems during this study (Figs. 1A–1C). Further, for the H + D control regimen a second follow-up disking was necessary to even reduce exotic bluestem for short period of time (Fig. 1B).

During this study, observations of treatment plots in the herbicide-only and H + D regimens between approximately 6 and 10 WAT indicated exotic bluestem cover was substantially reduced from pre-treatment levels (M. Ruffner, personal observation). These observations are consistent with the results of Harmoney et al. (2004), which reported imazapyr (1.4 kg · ha^{-1}) and glyphosate (3.36 kg · ha^{-1}) treatments provided 94% and 100% visual control of yellow bluestem at 9 WAT, respectively, for two consecutive years in Kansas, United States. Nevertheless, the first sampling time point at 20 WAT of this study revealed that nearly all herbicide-treated plots in the herbicide-only and H + D regimens had greater than 60% exotic bluestem cover, which was higher than pre-treatment levels (Figs. 1A and 1B). However, unpublished data from another herbicide control study also conducted in late May at the Welder Refuge shows that exotic bluestem cover at 8 WAT was significantly lower in glyphosate- and imazapyr-treated plots compared to control plots (M. Ruffner and T. Barnes, unpublished data). Unfortunately we did not capture these effects in this study; yet numerous field observations at the Welder Refuge suggest that exotic bluestems have consistent patterns of high propagule pressure, which we hypothesize facilitated the rapid reinvasion of exotic bluestems in the treatment plots of the herbicide-only and H + D regimens (M. Ruffner, personal observation). Accordingly, exotic bluestems likely reinvaded treatment areas in the herbicide-only and H + D regimens sometime after 10 wk post-treatment from the already present germinable soil seedbank and/or seed rain from established exotic bluestem stands located near our treatment plots. We also have additional unpublished data that show the germinable soil seedbank of exotic bluestems is dramatically higher (50–100 ×) than mid- and late-seral native C_4 grass species in the upper soil profile (upper 5 cm) (M. Ruffner and T.G. Barnes, unpublished data). Indeed, propagule pressure is often a key factor and predictor of biological invasions (Lockwood et al. 2005; Colauttie et al. 2006), and some exotic grass species have been found to have high germinable seed banks (Gibson et al. 2002; Setterfield et al. 2004; Cox and Allen 2008).

This study highlights the need of follow-up management to negate the reinvasion of exotic bluestems after initial control measures have been performed. Invasive, exotic grasses tend to be especially difficult to control with single herbicide applications. For instance, researchers have documented that yellow bluestem (Harmoney et al. 2004), reed canarygrass (Annen et al. 2005; Annen 2008), and bufflegrass (Tjelmand et al. 2008) are persistent re-invaders after single herbicide treatments. Recent work on Caucasian bluestem suggests that multiple control treatments are likely necessary to control exotic bluestem reinvasions via the germinable soil seedbank and above-ground tiller regeneration from surviving crown buds (Harmoney et al. 2007, 2010). For instance, split (Harmoney et al. 2007) and sequential herbicide treatments (Harmoney et al. 2010) were more effective than single treatments at controlling Caucasian bluestem in Kansas. The timing of treatments also plays a role in regard to the efficacy of treatments to control invasive, exotic plants (Harmoney et al. 2010, Ruckman et al. 2011). Moreover, multiple studies also have been reported to lessen the post-treatment regrowth of reed canarygrass (see Annen 2010). Harmoney et al. (2010) also noted that the recolonization of Caucasian bluestem from establishment of seedlings via the seedbank is influenced by amount of precipitation received the following growing season.

The sequence of control measures also appears to be important factor. For example, the most effective sequence of herbicide and disking to suppress the reinvasion of exotic bluestems was disking following by herbicide (D + H regimen). Here the initial disking killed the established exotic bluestem stand, and follow-up herbicide treatments likely suppressed the re-invasion of exotic bluestems via the soil seedbank or above-ground tiller regrowth from the crown bud bank. For the H + D regimen, in contrast, initial herbicide treatments likely killed most of the established exotic bluestems, and the follow-up disking helped control any individuals that were capable of regenerating above-ground tillers from the crown bud bank. Intuitively, however, the follow-up disking of the H + D regimen was a disturbance that further facilitated the release of exotic bluestems from the germinable soil seed bank. Thus, at 20 WAT it was apparent herbicide following disking is an ineffective sequence of control measures to reduce the abundance of exotic bluestems (Fig 1B). Thus, we conducted the second disking to the plots of the H + D regimen, and it helped reduce exotic bluestem cover temporarily, but it may also have brought additional germinable exotic bluestem seeds to the soil surface (Fig. 1B).

The potential for exotic grasses to rapidly reinvade treatments areas from the soil seedbank is exacerbated by the fact that southern Texas is located in a subtropical climate zone and its growing season can exceed 300 $d \cdot yr^{-1}$ (Soil Survey Staff, USDA-NRCS 2010). However, extended droughts are common in south Texas, and indeed, the establishment and survival of exotic bluestems from the germinable soil seedbank will largely be driven by soil water availability. Nevertheless, high seedling vigor is conferred by traits such as high water use efficiency and/or rapid developmental rates, which increase the chances of exotic bluestems reinvading treatment areas. Observations indicate that high phenotypic plasticity is evident in yellow bluestem populations in central Texas (Ruckman et al. 2011). For instance, established yellow bluestem plants were observed to transition from senescence to flowering in only 4 wk after a 25-mm rainfall event in central Texas (Ruckman et al. 2011). Hence, when soil water is not limiting the reinvasion of exotic grasses in treatment areas is likely when sufficient amounts of propagules are present. This was possibly the case when researchers attempted to reestablish native grasses in a Blackland prairie in central Texas that was formerly dominated by exotic bluestems (Mittlehauser et al. 2011). Tjelmand et al. (2008) reported that buffelgrass, another problematic invasive, exotic grass in south Texas, re-invaded treatment areas after the existing buffelgrass canopy was reduced by herbicide treatments, and they recommended additional management is needed to control buffelgrass reinvasions via seedling recruitment. Such consistent findings between Tjelmand et al. (2008) and those of this study strongly suggest that follow-up, perhaps repetitive, control treatments will be necessary to shift the balance from exotic bluestem dominance back to native plant communities.

None of the three control regimens facilitated a substantial increase in native grass cover from pre-treatment levels, but native grass cover remained the highest, and increased the most, in some imazapyr-treated plots of the herbicide-only and D + H regimens, respectively (Figs. 2A–2C). For the herbicide-only regimen, glyphosate and imazapyr + glyphosate treatments decreased native grass cover from pre-treatment levels likely due to the nonselective, broad spectrum effects of glyphosate (Fig 2A). Little and silver bluestem made up most of the native grass cover in our study plots and given that imazapyr treatments did not eliminate native grass cover, this suggests these little and silver bluestem ecotypes exhibit some tolerance to the effects of imazapyr. Previous work with the imidazolinone herbicide imazapic (Plateau) has shown that some native grasses (e.g., Indian grass [*Sorghastrum nutans* {L.} Nash], little bluestem, and big bluestem [*Andropogon geradii* Vitman] are tolerant to its phytotoxic effects (Barnes 2007; Ruffner and Barnes 2010; Bahm and Barnes 2011; Bahm et al. 2011). The recovery of native plants in areas heavily invaded by invasive exotic species is often severely impeded by seed and microsite limitation (Eriksson and Ehrlén 1992; Orrock et al. 2009). Again, the germinable native grass soil seed bank is likely depauperate in areas that have been dominated by exotic bluestems for an extensive period of time; therefore direct seeding of native grasses and forbs may be necessary to facilitate the recovery of native plant assemblages (Turnbull et al. 2000; Seabloom et al. 2003; Cox and Anderson 2004).

Forbs are important resources of rangeland ecosystems for many invertebrate and wildlife species (Arnold and Drawe 1979; Buckner and Landers 1979; Campbell-Kissock et al. 1985; Harper 2007), and the importance of forb communities are often overlooked in restoration efforts. Not surprisingly, soil disturbance mediated by disking facilitated a dramatic flush of forb cover in plots of both the H + D and D + H control regimens (Figs. 3B and 3C). Further, follow-up herbicide treatments of the D + H regimen mediated a greater increase in forb cover compared to the controls (disking only) (Fig. 3C). Most of the forb cover consisted of annual species being released from the soil seed bank although a few short-lived perennial forb species were observed. However, forb cover had drastically diminished by 104 WAT and, here, plots of H + D and D + H regimens were again dominated by exotic bluestems (Figs. 3B and 3C). Sands et al. (2009) found that areas with > 25% buffelgrass (*Pennisetum ciliare* L.) cover, another abundant exotic grass of the southern United States and northern Mexico, experienced a drastic decrease in native forb species richness and canopy cover. Such declines in forb species richness and/or diversity associated with the dominance of exotic grasses is likely to have negative consequences for many grasslands bird species (Flanders et al. 2006; Hickman et al. 2006; Sands et al. 2009). Restoring plant functional group diversity may help resist some exotic plant invasions (Sheley and Half 2006), and this factor certainly deserves further investigation in cases of buffelgrass and exotic bluestem invasions in the southern and central United States (see Tjelmand et al. 2008)

MANAGEMENT IMPLICATIONS

Herbicide treatments appear to be a temporary solution for controlling exotic bluestems in south Texas. However, exotic bluestem control could have been more effective with strategically timed herbicide applications (e.g., time points of low carbohydrate reserves) (Harmoney et al. 2010). Overall, imazapyr and glyphosate had similar effects on exotic bluestem cover, but in mixed stands of native and exotic bluestem grasses imazapyr treatments may have less nontarget effects on some native grass species. Nonetheless, follow-up management is likely necessary to suppress subsequent exotic bluestem reinvasions from the germinable soil seedbank (including seed rain) and/or above-ground tiller regeneration from the crown bud bank. Repeated or sequential herbicide treatments are certainly an option, but an integrative management approach that has yet to be fully explored may be the best strategy to control exotic bluestems (DiTomaso 2000). The sequence of combination treatments is also an important factor to consider, and in this study, disking followed by herbicide treatments (D+H regimen) provided the most persistent exotic bluestem control, whereby follow-up herbicide treatments suppressed the re-invasion of exotic bluestem via the soil seedbank or above-ground tiller growth from the bud bank. Nevertheless, in reality, exotic bluestems will be a persistent group of exotic grasses in rangelands throughout the central and southern United States for years to come. However, increased awareness needs to be disseminated to land managers, private landowners, and the public in regard to the potential negative impacts of exotic bluestems on native grass-dominated ecosystems. Additional studies are greatly needed to evaluate the effectiveness of other integrated management techniques that simultaneously control and prevent the propagation of exotic bluestems and promote the succession of native plant communities throughout the rangelands of the central and southern Great Plains, United States (Sheley et al. 1996; DiTomaso 2000; Masters and Sheley 2001).

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