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Long-Term Efficacy of Glyphosate for Smooth Brome Control in Native Prairie

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Effective control measures are required for the invasive forage grass smooth brome in native prairie to maintain native prairie diversity and function. The objective of this study was to assess the long-term effectiveness of glyphosate as a control method for smooth brome and to evaluate the subsequent recovery of native prairie species at Kernen Prairie near Saskatoon, SK, Canada. In 1999 and 2000, a total of forty 6- to 8-m-diameter patches of smooth brome were spot sprayed with glyphosate; community composition in each patch was monitored for 17 yr. Following glyphosate application, the abundance of smooth brome decreased, and recovery of native species richness and the abundance of important native species, including plains rough fescue, was observed. In the long term however, the elimination of smooth brome created empty niche space ultimately occupied by other invasive species, particularly Kentucky bluegrass. The spot application of glyphosate is thus an effective control method for reducing smooth brome in native prairie; however, maintaining desirable native species composition in this system posttreatment depends on other factors, including the presence of additional invasive species that may move in after the elimination of smooth brome.

Nomenclature: Glyphosate; smooth brome, *Bromus inermis* Leyss. BROIN; plains rough fescue, *Festuca hallii* (Vasey) Piper.; Kentucky bluegrass, *Poa pratensis* L. POAPR.

Key words: Broad-spectrum herbicide, fescue grassland, invasive forage grass, native species recovery.

Smooth brome (*Bromus inermis* Leyss.), is a nonnative forage grass and an aggressive invader of native prairie dominated by plains rough fescue [*Festuca hallii* (Vasey) Piper] (Grilz and Romo 1995; Otfinowski et al. 2007; Stotz et al. 2017). Smooth brome can colonize quickly, displacing native species through rapid spread via densely branching rhizomes, excessive litter accumulation, and altered nitrogen cycling (Carrigy et al. 2016; Dibbern 1947; Otfinowski and Kenkel 2008; Piper et al. 2015a). Invasions of smooth brome pose a significant threat to the composition and function of northern fescue prairies (Mamet et al. 2017; Otfinowski et al. 2007; Piper et al. 2015b), and effective control measures are therefore required.

Management techniques including mowing, grazing, and fire can limit smooth brome spread but are rarely effective at fully controlling smooth brome infestations (Grilz and Romo 1995; Otfinowski et al. 2007; Stotz et al. 2017). Herbicides, including glyphosate, can provide effective short-term control of smooth brome (Bahm et al. 2011b; Grilz and Romo 1995; Link et al. 2017; Wagner et al. 2017). Spot application of glyphosate has been recommended for controlling smooth brome in native prairie; however, the long-term efficacy of this treatment is not well understood (Grilz and Romo 1995). Because glyphosate is a nonselective herbicide, non-target effects to native plants are likely to occur and may impact posttreatment native community recovery (Wagner et al. 2017). The objectives of this study were to (1) assess the long-term effectiveness of spot-spraying a 10% glyphosate solution in a single-pulse application as a control method for smooth brome control in native prairie and (2) evaluate the subsequent recovery of native prairie plant species. These objectives were examined using a 17-yr study at Kernen Prairie, a native fescue prairie near Saskatoon, SK, Canada.

Materials and Methods

Study Site. Research was conducted at Kernen Prairie, a 130-ha fescue grassland located near Saskatoon, SK, Canada (52.16°N, 106.53°W). The site is relatively flat, with fine-textured Vertisolic soils and areas of sandy loam Vertic

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Management Implications

Prairie habitats dominated by plains rough fescue need to be monitored regularly to detect smooth brome invasions; small dispersed patches of smooth brome may facilitate subsequent invasion and should be eliminated promptly. Hand-sprayed glyphosate applications on small (2- to 3-m diameter) isolated smooth brome patches provide effective long-term brome control. Successful natural re-establishment of native species will occur should sufficient native propagules be available. Monitoring is required to ensure complete smooth brome control and to detect the establishment of other invasive species.

Chernozems (Soil Classification Working Group 1998). Kernen Prairie is in a transition zone between aspen parkland and moist mixed grassland ecoregions (Padbury et al. 1998). Plains rough fescue is the dominant species, with shortbristle needle and thread grass (western porcupine grass) [*Hesperostipa curtiseta* (Hitchc.) Barkworth], and slender wheatgrass [*Elymus trachycaulus* spp. *trachycaulus* (Link.) Gould ex Shinners] (Pylypec 1986). Scattered stands of quaking aspen (trembling aspen) (*Populus tremuloides* Michx.) are present in four low-lying areas, along with shrubs such as western snowberry (*Symphoricarpos occidentalis* Hook.) and silverberry (wolf-willow) (*Elaeagnus commutata* Bernh. ex Rydb.) (Pylypec 1986). Kernen Prairie has a mean annual temperature of 1.6 C (–24.3 C in January; 25.4 C in July) and 360 mm of precipitation (Grilz and Romo 1995). Current management strategies at Kernen Prairie include light conservation grazing by cattle from May through September (begun in 2006 and continuing to the present) and occasional spring and fall patch burning (Mori 2009).

Experimental Design. Patches of smooth brome can be found scattered throughout Kernen Prairie. In 1999, 20 representative patches of smooth brome were haphazardly chosen, with 20 more selected in 2000. Patches were each roughly circular and approximately 6 to 8 m in diameter with cover of smooth brome in the patch visually estimated to be between 85% and 95%. All patches were surrounded by intact native plant communities. On July 13, 1999, 20 of the patches were treated with herbicide, with the remaining 20 treated on July 10, 2000. No unsprayed control plots were used in this study. One application of 10% glyphosate solution was made with a handheld sprayer when the smooth brome was in the early inflorescence emergence stage of development. The treatment area included the entire smooth brome patch and the periphery (roughly 1 m beyond the edge of the smooth brome patch).

Data Collection. All 40 patches were monitored annually between late July and early August for 10 yr starting the year after the application of glyphosate (i.e., 2000–2010 and 2001–2011). Patches were surveyed again in July 2016 (16 and 17 yr after treatment). In each survey year, the percent cover of all vascular plants in each patch was measured using three permanent parallel transects 5 m in length and spaced 1-m apart across each smooth brome patch. A 20 by 50 cm quadrat was placed at 1-m intervals along each of the 5-m transects for a total of 5 quadrats transect^{-1} and 15 patch^{-1}. Percent cover values were assigned to plant, bare soil, and litter cover. Foliar percent cover values were estimated for all vascular plant species, bare soil, and litter cover in each quadrat. Quadrat values were averaged to a patch-level value.

Data Analysis. Changes in the abundance of species and measures of community structure with time post–glyphosate treatment were analyzed using generalized additive mixed models (GAMs). In each model, species percent cover was the response variable, time since glyphosate treatment was the predictor variable, and patch was a random factor to account for repeat sampling within patches. GAM models were selected because they are a powerful method to describe complex nonlinear relationships without the need to a priori determine an underlying model equation (Wood 2006). Species analyzed included smooth brome, the important native species rough bentgrass (*Agrostis scabra* Willd.), slender wheatgrass, plains rough fescue, and fringed sage (pasture sage) (*Artemisia frigida* Willd.), and the invasive species Canada thistle [*Cirsium arvense* (L.) Scop.], Kentucky bluegrass (*Poa pratensis* L.), and perennial sowthistle (*Sonchus arvensis* L.). Similar models examining the changes in plant community structure were run with response variables including native species richness, total abundance of invasive species, and the proportion of total community cover made up by invasive species. The total abundance of invasive species was the sum of the cover of both the major ones analyzed individually (smooth brome, Canada thistle, Kentucky bluegrass, and perennial sowthistle) and several less common species, including absinth (*Artemisia absinthium* L.), musk thistle (nodding thistle) (*Carduus nutans* L.), flixweed [*Descurainia sophia* (L.) Webb ex Prantl], alfalfa (*Medicago sativa* L.), common dandelion (*Taraxacum officinale* G.H. Weber ex Wiggers), and yellow salsify (goat's beard) (*Tragopogon dubius* Scop.). All GAM models were fit using the generalized additive mixed model (*gamm*) function in the mgvc library of R statistical software (v. 3.2.2; R Development Core Team 2016; Wood 2006, 2011).

Results and Discussion

Smooth Brome Response. Spot spraying of glyphosate is an effective long-term control method for smooth brome in native fescue prairie. In the year following treatment, smooth brome was reduced to less than 5% average cover (from pretreatment values of 85% to 95%); this effect persisted for

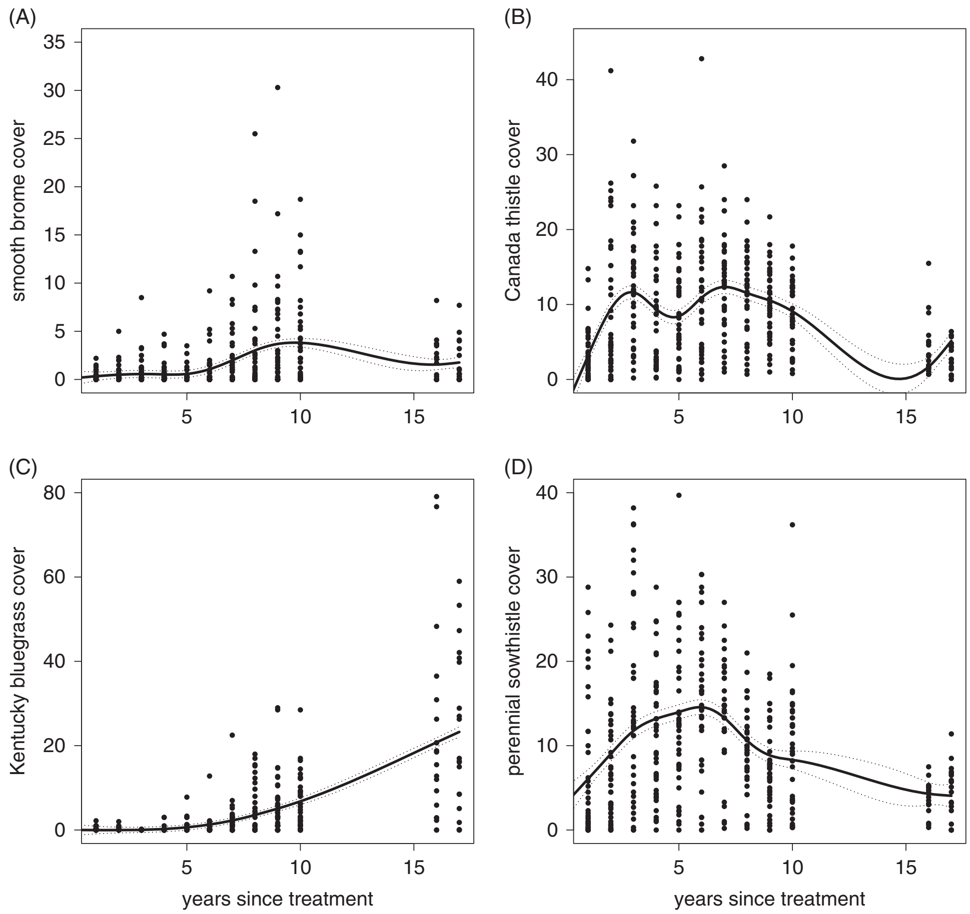

Figure 1. Change over time in the cover of the invasive species (A) smooth brome, (B) Canada thistle, (C) Kentucky bluegrass, and (D) perennial sowthistle. Dashed lines are 1 SE plus/minus the predicted values.

the first 5 yr (Figure 1a). Fifty percent of patches had no detected smooth brome, and of those with smooth brome present, none had cover greater than 5% (Table 1). Strong initial suppression of smooth brome in the first 5 yr posttreatment is consistent with other studies of the short-term effectiveness of spot spraying 0.5 to 1.2 kg glyphosate ha^{-1} in May when the grasses are ~ 15 cm tall (Grilz and Romo 1995; Sather 1987); the continued suppression of brome in many plots for more than 15 yr demonstrates that long-term smooth brome control can be achieved. In years 5 to 10 posttreatment, there was a significant increase in average smooth brome cover; this increase was primarily driven by two patches that rose ≥25% smooth brome cover (Figure 1a; Tables 1 and 2). In years 16 and 17 posttreatment, brome abundance again declined to below 5%, demonstrating that the overall risk of increase by this species is low. Conservation grazing was introduced at this site in 2006 (Mori 2009). Grazing cannot explain the initial brome declines but may have contributed to the continued suppression of smooth brome. As noted by Grilz and Romo (1995), it is important that monitoring and, if needed, subsequent control efforts such as additional herbicide applications or mechanical removal be done to ensure complete control. It is not clear whether the persistent smooth brome populations at this

Table 1. Percentage of the 40 patches with detected smooth brome and proportion of patches with smooth brome cover ≥5%.[a]

Years posttreatment	Percentage with smooth brome	Percentage with smooth brome ≥5%
1	45	0
2	47.5	2.5
3	52.5	2.5
4	50	0
5	42.5	0
6	47.5	5
7	70	12.5
8	72.5	22.5
9	77.5	30
10	77.5	27.5
16–17	60	5

[a] All patches had 85% to 95% brome cover before treatment.

Table 2. GAM model statistics (significance of the smoothed term and model variance explained) for the 10 response variables analyzed versus time.

Response variable	Smoothed term (years since treatment)	R^2
Smooth brome	$F(1, 5.1) = 21.31$; $P < 0.001$	0.147
Canada thistle	$F(1, 7.7) = 21.11$; $P < 0.001$	0.167
Kentucky bluegrass	$F(1, 3.1) = 117.30$; $P < 0.001$	0.428
Perennial sowthistle	$F(1, 5.4) = 18.81$; $P < 0.001$	0.161
Plains rough fescue	$F(1, 1) = 44.79$; $P < 0.001$	0.063
Slender wheatgrass	$F(1, 4.8) = 43.82$; $P < 0.001$	0.261
Rough bentgrass	$F(1, 5.7) = 37.82$; $P < 0.001$	0.287
Fringed sage	$F(1, 5.9) = 31.51$; $P < 0.001$	0.225
Native richness	$F(1, 6.9) = 53.35$; $P < 0.001$	0.295
Invasive proportion of community	$F(1, 4.1) = 3.53$; $P = 0.007$	0.017
Native cover	$F(1, 4.03) = 21.57$; $P < 0.001$	0.115
Invasive cover	$F(1, 2.5) = 23.52$; $P < 0.001$	0.092

site are suppressed individuals that survived the herbicide or new recruits from seed.

Native Species Response. Successful native species recovery post–smooth brome treatment is evident in the increases in abundance of the important native species rough bentgrass, slender wheatgrass, plains rough fescue, and fringed sage, and in the general increase in native species richness and cover (Figures 2 and 3a and c). Three of these species, rough bentgrass, slender wheatgrass, and fringed sage, eventually decreased in abundance 16 and 17 yr posttreatment, whereas plains rough fescue continued to increase in abundance over time. The long-term increase in plains rough fescue cover is particularly important, because that species is an indication of healthy late-successional grassland in this ecoregion (Coupland and Brayshaw 1953). Manual spraying of glyphosate can decrease native species richness, particularly grass species richness, in the first years posttreatment (Power et al. 2013); however, it appears that in this system native recovery was rapid. This is important, because alternative application

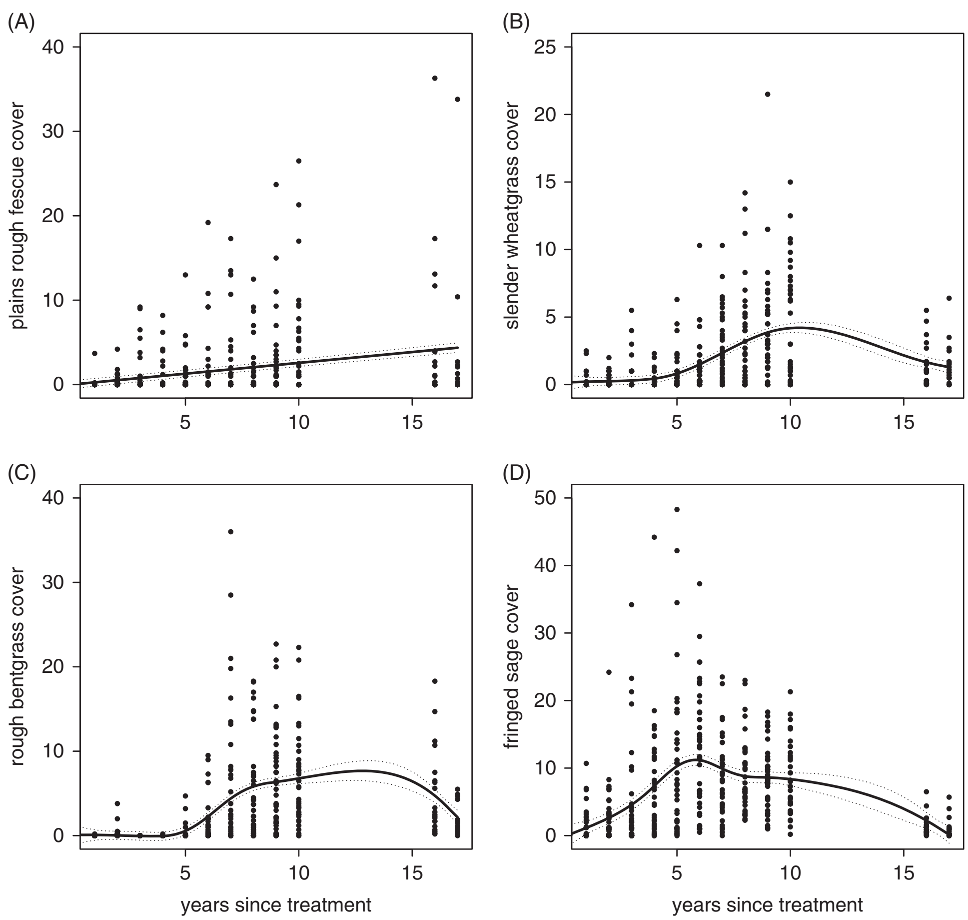

Figure 2. Change over time in the cover of the native species (A) plains rough fescue, (B) slender wheatgrass, (C) rough bentgrass, and (D) fringed sage. Dashed lines are 1 SE plus/minus the predicted values.

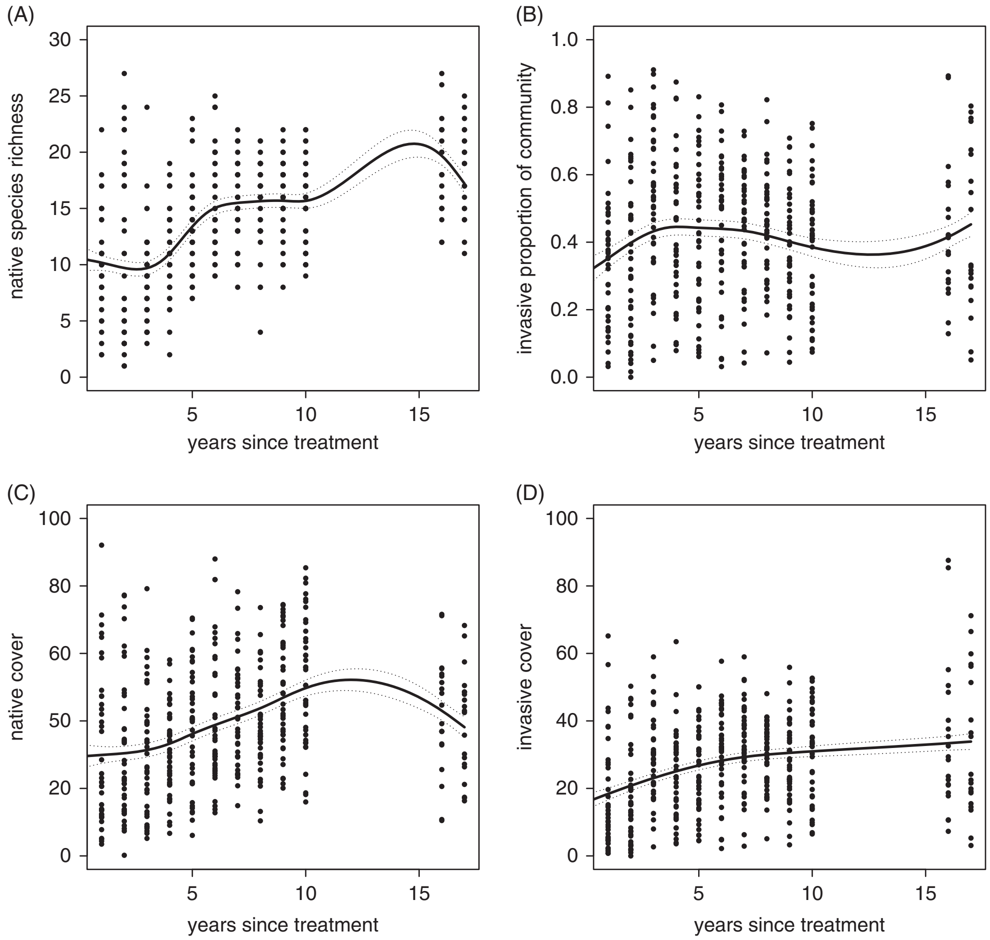

Figure 3. Change over time of (A) native species richness, (B) invasive proportion of community, (C) native species cover, and (D) invasive species cover. Dashed lines are 1 SE plus/minus the predicted values.

methods such as selective application of herbicide only to target plants are much more labor intensive and can have lower control efficacy (Nature Conservancy 2010). It should be noted that, compared with Power et al. (2013), the present study focused on smaller smooth brome patches with much higher invasive cover. The patches in the present study were surrounded by abundant native seed sources and established rhizomatous native perennials, while the plots studied by Power et al. (2013) were in intensively managed grasslands with relatively low species richness. In cases where native seed sources are not present, seeding native species postherbicide can also be effective at encouraging native community recovery (Link et al. 2017).

Other Invasive Species Response. Posttreatment, the cover of Canada thistle, perennial sowthistle, and Kentucky bluegrass increased over time (Figure 1b–d). The increases in Canada thistle and perennial sowthistle were short term, with peaks in abundance 6 to 7 yr posttreatment; however, Kentucky bluegrass steadily increased in abundance throughout the study. The total cover of invasive species rose through the first 10 yr of the study; given the similar rise in native cover, there were relatively few changes in the proportion of invasive species relative to native species during this time (Figure 3; Table 2). Declines in native cover and an increase in the proportion of invasive species 16 and 17 yr after treatment were largely driven by Kentucky bluegrass invasion (Figure 3; Table 2).

Overall, smooth brome removal opened space that was initially occupied by a mix of native and minor invasive species. The recovery of key native species combined with the general decline of many invasive species in the first 10 yr demonstrates that smooth brome removal initially put this community onto a successional trajectory to recovery. The declines in native species richness 16 and 17 yr posttreatment are symptomatic of the Kentucky bluegrass invasions that have been occurring on rangelands across the Northern Great Plains (Bahm et al. 2011a; DeKeyser et al. 2015; Sanderson et al. 2017; White et al. 2013). While large-scale climactic shifts are likely a major driver of Kentucky bluegrass invasion, local environmental changes driven by smooth brome may have also increased the susceptibility of these patches to Kentucky bluegrass invasion (Carrigy et al. 2016). For example, the changes in soil community structure and function caused by smooth brome (Mamet et al. 2017; Piper et al. 2015a, 2015b), may have made these microsites more attractive for Kentucky bluegrass.

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