2014

Native Plant Establishment Success Influenced by Spotted Knapweed (*Centaurea stoebe*) Control Method

Laurelin M. Martin
Grand Valley State University

Neil W. MacDonald
Grand Valley State University, macdonan@gvsu.edu

Tami E. Brown
Grand Valley State University

RESEARCH ARTICLE

Native Plant Establishment Success Influenced by Spotted Knapweed (*Centaurea stoebe*) Control Method

Laurelin M. Martin, Neil W. MacDonald and Tami E. Brown

ABSTRACT

Invasive species frequently need to be controlled as part of efforts to reestablish native species on degraded sites. While the effectiveness of differing control methods are often reported, the impacts these methods have on the establishment of a native plant community are often unknown. To determine methods that effectively reduce spotted knapweed (*Centaurea stoebe*) while enhancing native species establishment, we tested 12 treatment combinations consisting of an initial site preparation (mowing, mowing + clopyralid, or mowing + glyphosate), in factorial combination with annual adult knapweed hand pulling and/or burning. We established 48 plots and applied site preparation treatments during summer 2008, seeded 23 native forbs and grasses during spring 2009, pulled adult knapweed annually from 2009–2012, and burned in the early spring 2012. During July of 2011 and 2012, percent cover of all species was visually estimated. By 2011, seeded species had established in all treatment plots, including plots that retained greater than 50% knapweed cover, indicating that native species successfully established despite knapweed dominance. Mowing alone had no longterm impacts on community development. Clopyralid favored non-native grass establishment, while glyphosate encouraged non-native forbs. Clopyralid had minimal impacts on native forb establishment, but did effectively control knapweed. Pulling reduced knapweed cover, increased non-native grass cover and enhanced native species establishment. Burning had little impact, possibly due to low intensity and unseasonable weather. On the heavily invaded site we studied, combining the use of clopyralid with hand pulling effectively controlled knapweed and favored the establishment of seeded native grasses and forbs.

Keywords: community development, ecological restoration, invasive plants, Michigan prairie, native diversity

Successful restoration often requires the concomitant control of invasive species, which otherwise will hinder the restoration effort, especially on degraded land. Following invasive plant establishment, restoration of a native plant community becomes very challenging (DiTomaso 2000). Invasive plants are capable of altering ecosystem function (Weidenhamer and Callaway 2010), nutrient cycles (Ehrenfeld et al. 2001, Allison and Vitousek 2004), and disturbance regimes (D'Antonio and Vitousek 1992, Brooks et al. 2004), resulting in a continuing need for longterm control efforts (D'Antonio and Meyerson 2002).

Control efforts targeting invasive species can also inhibit the development of a native community (Erskine Ogden and Rejmánek 2005, Rinella et al. 2009, Ortega and Pearson 2011). Successful control of one invasive plant may open the community to further invasion or surges in dominance of other non-natives already present (Zavaleta et al. 2001, Ortega and Pearson 2011). Unfortunately, it is infrequent for studies targeting invasive species control to report on the effects of these treatments on the restored plant community (Reid et al. 2009, Kettenring and Reinhardt Adams 2011). Thus, it is highly desirable to determine which methods can be used to control invasive plants while also allowing for either uninhibited or accelerated restoration of a native community.

Spotted knapweed (*Centaurea stoebe*; hereafter knapweed) has invaded over 2.9 million hectares in North America (DiTomaso 2000) and can successfully invade plant communities on both remnant and disturbed sites. Following invasion, knapweed forms peripherally enlarging monocultures that seed profusely, have allelopathic effects on susceptible species, and negatively impact ecosystem richness and diversity (Watson and Renney 1974, Schirman 1981, Tyser 1992, Sheley et al. 1998, Kedzie-Webb et al. 2001, Thorpe et al. 2009). While it is known that knapweed can be controlled using a variety of methods including herbicide application (Rice

Ecological Restoration Vol. 32, No. 3, 2014
ISSN 1522-4740 E-ISSN 1543-4079

et al. 1997), biological controls (Story et al. 2006, but see Ortega et al. 2012), and controlled burning (MacDonald et al. 2007), resurgence of knapweed is very likely without the formation of a competitive, native community (Sheley et al. 1996), especially on sites in which seeds from previous infestations are present in the seed bank (Sheley et al. 1996, Carpinelli et al. 2004). As diverse native plant communities are more capable of resisting knapweed invasion (Kennedy et al. 2002, Bakker and Wilson 2004, Maron and Marler 2007), it is important during any restoration project to ensure that such diverse native systems are reestablished.

Targeting native plant establishment in combination with knapweed control requires knowledge on how community development will be affected. For instance, the controlled burning of native, fire-adapted species stimulates flower stalk production, facilitates seedling establishment, enhances productivity, and increases warm-season grasses (Old 1969, Abrams et al. 1986, Howe 1994, Maret and Wilson 2005). In addition, carefully timed burns can reduce knapweed cover and seed viability (Emery and Gross 2005, MacDonald et al. 2007, Vermeire and Rinella 2009). Applying effective control methods, but relying on a remnant native seed bank or colonization from nearby sites for native species establishment may result in communities with lower species richness (Heslinga and Grese 2010), especially in isolated areas. Therefore, seeding with a diverse mix of native species immediately following control treatment may facilitate native species establishment and competition with knapweed (Tyser et al. 1998).

The objective of this study was to determine the most effective treatment for increasing native plant diversity while also reducing knapweed on an invaded site in western Michigan, US. To achieve this aim, 12 different treatment combinations were tested to determine which would result in reduced knapweed cover and increased native species diversity, cover, and floristic quality. These treatments included factorial combinations of mowing alone or mowing in combination with a single application of either a broadleaf-specific herbicide (clopyralid), or broad-spectrum herbicide (glyphosate), hand pulling of adult knapweed, and burning. Based on our review of published literature and previous study in adjacent areas (MacDonald et al. 2003, 2007), we hypothesized: (1) a single mowing would have little longterm impacts, (2) use of clopyralid would reduce knapweed cover and lead to increases in grass cover, (3) application of glyphosate would reduce competition during native species seedling establishment, but allow for rapid knapweed resurgence, (4) pulling of adult knapweed would reduce knapweed cover, allowing for increased native species establishment due to decreased competition, (5) controlled burns performed in mid-Spring would both reduce knapweed and increase native warm-season grasses, (6) the broadleaf-specific herbicide treatment (clopyralid) would result in higher grass cover, while the broad-spectrum herbicide (glyphosate) + pulling + burning treatment and the mowing + pulling + burning treatment would lead to the highest native diversity. Within the context of these hypotheses, the goal of the restoration was to establish a diverse native plant community that would effectively resist reinfestation by knapweed while providing opportunities for active management to reinforce the trajectory toward the maintenance of native species and processes.

Methods

Study Area

Our study site was within the Bass River Recreation Area, Ottawa County, Michigan, US (43°00′49″N, 86°01′47″W). Typical precipitation for the area, based on the 30-year average, is 369 mm (NCDC 2009). During the study, total precipitation from April through August was 386 mm during 2009, 381 mm during 2010, 510 mm during 2011 and 302 mm during 2012, as determined from the Muskegon, Michigan National Weather Service station (NCDC 2014). Normal temperatures for the area are 18.3 °C in June, 21.1 °C in July, and 20.3 °C in August (NCDC 2014). Temperature averages during the study for June, July and August respectively were 18.9 °C, 18.8 °C, and 19.9 °C for 2009, 19.8 °C , 23.9 °C, and 23.9 °C for 2010, 19.7 °C, 24.1 °C, and 21.8 °C for 2011, and 20.8 °C, 25.4 °C, and 21.2 °C for 2012 (NCDC 2014). Thus, while 2009 and 2010 experienced relatively normal weather, in 2011 there was above average precipitation, and in 2012, low precipitation and high temperatures led to a severe drought conditions lasting from mid-June through mid-October (NDMC 2013).

Prior to establishment of the Bass River Recreation Area, the site was highly disturbed by extensive gravel mining in the mid-1900s (MacDonald et al. 2003), leaving a persistent ruderal plant community infested by spotted knapweed (MacDonald et al. 2003, 2007, 2013). Knapweed was the dominant invasive plant at our study site prior to the initiation of our study with 60% to 70% cover based upon the total pre-treatment knapweed density (236 ± 16 m^{-2} SE, , MacDonald et al. 2013). Previous studies at this site demonstrated that native grass establishment and fire reintroduction could successfully control knapweed (MacDonald et al. 2003, 2007), but these approaches resulted in a community with very low native diversity. The current study design expands on these works through the use of larger plots, incorporation of a more diverse seed mix, application of different combinations of knapweed control treatments, and an extensive evaluation of the developing community.

Table 1. The twelve treatment combinations tested during study at Bass River Recreation Area, Ottawa County, MI, US. The treatment combinations represent a factorial arrangement of treatments in a randomized complete block design, including three levels of initial site preparation, two levels of pulling, and two levels of burning.

Levels of Treatment			
Initial Site Preparation	**Pulling Treatment**	**Burn Treatment**	**n**
Mowed, 2008	None	None	4
Mowed, 2008	None	Burned, 2012	4
Mowed, 2008	Knapweed pulling, Annually	None	4
Mowed, 2008	Knapweed pulling, Annually	Burned, 2012	4
Mowed + clopyralid, 2008	None	None	4
Mowed + clopyralid, 2008	None	Burned, 2012	4
Mowed + clopyralid, 2008	Knapweed pulling, Annually	None	4
Mowed + clopyralid, 2008	Knapweed pulling, Annually	Burned, 2012	4
Mowed + glyphosate, 2008	None	None	4
Mowed + glyphosate, 2008	None	Burned, 2012	4
Mowed + glyphosate, 2008	Knapweed pulling, Annually	None	4
Mowed + glyphosate, 2008	Knapweed pulling, Annually	Burned, 2012	4

Experimental Design

In July, 2008, we established the field experiment using a randomized complete block design with a fully crossed factorial arrangement of 12 treatment combinations and four replicate blocks for a total of 48 5 m by 5 m plots. The 12 treatment combinations consisted of three initial site preparation treatments of mowing, mowing plus clopyralid, or mowing plus glyphosate; each combined with or without hand pulling and with or without burning (Table 1). Buffers were mowed yearly in late June, with plots separated by 2.5 m buffers, and blocks surrounded by 5 m buffers. While there was no true "control" treatment combination in the sense of including plots with no treatments whatsoever, in the context of this experiment the plots that were only mowed once and did not receive either pulling or burning can be considered a control as a single mowing was not expected to have any longterm impacts on community trajectory.

Prior to implementation of treatments, all plots were dominated by spotted knapweed and other non-native grasses and forbs, including Kentucky bluegrass (*Poa pratensis*), quackgrass (*Elymus repens*), rabbitfoot clover (*Trifolium arvense*), sweetclover (*Melilotus officinalis*), and Canada bluegrass (*Poa compressa*). None of the species included in the native seed mix were present on the plots before the initiation of the experiment, with the exception of a few scattered occurrences of little bluestem (*Schizachyrium scoparium*) and big bluestem (*Andropogon gerardii*). In the summer of 2008, the entire site was mowed to facilitate plot layout, reduce knapweed seedfall prior to other treatments and ease herbicide application (Packard and Mutel 1997). Randomly selected plots were subsequently treated with a single application of the broad-spectrum herbicide glyphosate (Roundup Concentrate Plus®, Monsanto, Marysville, OH), at a rate of 9.9 kg ae ha^{-1} (n = 16), or the broadleaf-specific herbicide clopyralid (Transline®, Dow AgroSciences, Indianapolis, IN), at a rate of 0.6 kg ae ha^{-1} (n = 16). The remaining 16 plots did not receive any additional site preparation. These mowed-only plots allowed us to determine if native plants could be established simply by interseeding following minimal site preparation.

In the spring of 2009, we seeded all plots at a rate of 22 kg ha^{-1} with a mixture of native species representative of Michigan dry-mesic prairie, dry sand prairie and oak barrens (Kost et al. 2007). The seed mix included five native warm-season grasses, which comprised a total of 60% of the mix, and 18 native forbs, which made up the remaining 40% of the mix (Table 2). Pulling of adult, bolted knapweed on designated plots (n = 24) began in July of 2009 and continued annually thereafter. Pulling entailed removing adult knapweed, including the taproot, in advance of flowering to prevent seed production and dispersal within the plot with the aid of a handheld weed puller (Ergonomic Hand Weeder, Item #2306, Shanghai Worth Garden Products Co., Ltd., Shanghai, 156 China).

Controlled burning of the designated plots (n = 24) took place on April 2, 2012 (MacDonald et al. 2013). Unseasonably warm weather during March of 2012 resulted in advanced plant phenology causing us to burn earlier than is optimal for knapweed control (Emery and Gross 2005, MacDonald et al. 2007). Fire temperature at ground level was measured with pyrometers constructed using Tempilaq G® indicator solutions (Tempil, South Plainfield, NJ). These solutions were painted on ceramic tiles and melt at specified temperatures. The 14 indicators used ranged from 79 °C to 204 °C, at 14 °C intervals, and 232 °C to 316 °C, at 28 °C intervals, as this has been shown to include the ranges of temperature in controlled burns (Kennard et al. 2005). Four pyrometers were installed per plot on the morning of the burns. Immediately following the burns, the pyrometers were collected and inspected to determine the highest temperature indicator that showed signs of changing during the fire.

Plant Surveys

In 2009 and 2010, we recorded the presence/absence of each grass and forb species in the seed mix on five 0.25 m^2 frames randomly located on each plot. In 2011 and 2012, we visually estimated percent cover of each grass and forb species in each plot, determining a plot estimate by averaging one cover estimate from each of the four quarters of the plot. This

Table 2. Seeded species presence as a percent of the 48 total treatment plots at Bass River Recreation Area, Ottawa County, MI, US. Species are ordered in terms of presence during 2011. Column C corresponds to the coefficient of conservatism for each species specific to Michigan (MDNR 2001).

Family	Species	Common Name	C	2011	2012
Poaceae	*Andropogon gerardii*	Big Bluestem	5	100.0%	97.9%
Poaceae	*Schizachyrium scoparium*	Little Bluestem	5	100.0%	100.0%
Poaceae	*Sorghastrum nutans*	Indiangrass	6	100.0%	100.0%
Lamiaceae	*Monarda fistulosa*	Wild Bergamot	2	97.9%	95.8%
Asteraceae	*Coreopsis lanceolata*	Lanceleaf Tickseed	8	93.8%	93.8%
Lamiaceae	*Monarda punctata*	Spotted Beebalm	4	87.5%	66.7%
Asteraceae	*Rudbeckia hirta*	Blackeyed Susan	1	83.3%	85.4%
Apocynaceae	*Asclepias tuberosa*	Butterfly Milkweed	5	77.1%	62.5%
Poaceae	*Elymus canadensis*	Canada Wildrye	4	43.8%	16.7%
Asteraceae	*Ratibida pinnata*	Pinnate Prairie Coneflower	4	39.6%	29.2%
Asteraceae	*Pseudognaphalium helleri*	Heller's Cudweed	2	12.5%	18.8%
Fabaceae	*Lupinus perennis*	Sundial Lupine	7	12.5%	0.0%
Poaceae	*Panicum virgatum*	Switchgrass	4	12.5%	8.3%
Asteraceae	*Solidago nemoralis*	Gray Goldenrod	2	10.4%	8.3%
Asteraceae	*Coreopsis tripteris*	Tall Tickseed	7	8.3%	2.1%
Fabaceae	*Lespedeza capitata*	Roundhead Lespedeza	5	6.3%	8.3%
Verbenaceae	*Verbena stricta*	Hoary Verbena	4	2.1%	4.2%
Asteraceae	*Coreopsis palmata*	Stiff Tickseed	10	2.1%	2.1%
Asteraceae	*Helianthus occidentalis*	Fewleaf Sunflower	8	2.1%	2.1%
Asteraceae	*Solidago speciosa*	Showy Goldenrod	5	2.1%	0.0%
Asteraceae	*Solidago juncea*	Early Goldenrod	3	0.0%	0.0%
Fabaceae	*Tephrosia virginiana*	Virginia Tephrosia	10	0.0%	0.0%
Commelinaceae	*Tradescantia ohiensis*	Bluejacket	5	0.0%	0.0%

entailed dividing each 5 m by 5 m plot into quarters, with two researchers each estimating the cover of two quarters. During both years, each researcher consistently examined the same two quarters within each plot. To standardize visual estimates among researchers, we referred to published area charts (Anderson 1986), and used 0.1 m² PVC frames as a standard area reference. Following data collection, we calculated the relative percent cover (p_i) of each species on each plot by dividing the summed total cover of each species by the summed total cover of the plot.

Data Analysis

Using the relative percent cover calculated for each year, we determined plot diversity using the Shannon index of diversity:

1) $H' = -\Sigma\, p_i \log p_i$

and Simpson's index of diversity:

2) $D = 1-\Sigma\, p_i^2$

(McCune and Grace 2002). As recommended by Peet (1974), we used the exponential of H' for analysis, as this indicates the functional number of species in the sample. Interpretations of the results remain the same, with higher values indicating higher diversity. Simpson's index has a range from zero, with a single species present, to one, maximum diversity (Peet 1974). Estimates of percent cover have been used successfully in previous studies to calculate these diversity indices (Potvin and Vasseur 1997, Tilman et al. 1997), and avoid errors resulting from miscounting clonal species if density had been used.

To evaluate community quality, we calculated the mean coefficient of conservatism ($\bar{C}$), and a floristic quality index (FQI) for each plot to distinguish among treatment combinations containing ubiquitous native plants and those containing species more likely to occur in undisturbed native plant communities. These methods rely on coefficients of conservatism specific to Michigan (MDNR 2001), ranging from zero, representing ubiquitous native species, to ten, representing highly conserved native species (Taft et al. 1997). FQI was calculated for each plot by multiplying the $\bar{C}$ for the plot by the square root of the number of native species on the plot (Packard and Mutel 1997). Native tree and shrub species are not part of the target prairie community and were excluded from FQI and $\bar{C}$ analysis.

For analyses of community composition, we classified species into one of six groups: non-native forbs, knapweed, non-native grasses, native graminoids, native forbs, and tree/shrub species. The non-native forbs group does not include knapweed. As the dominant invasive species and a focus of our research, knapweed was classified independently. Following this classification, we calculated the relative percent cover for each grouping by summing the relative percent cover of all species within that group. As the tree/shrub group accounted for less than 0.4% relative cover in both years, we did not include it in subsequent analyses. We performed simple linear (Pearson) correlations among the remaining five groups, in addition to total grass cover (sum of non-native grasses and native graminoids cover) using JMP 9.0.0 (n = 48; JMP v. 9.0, SAS Institute, Cary, NC). In addition, the most prevalent native seeded species were analyzed to determine if the control treatments influenced their establishment.

We analyzed the 2009 and 2010 native grass and forb presence data and 2011 diversity indices, FQI, $\bar{C}$, and relative cover data using three levels of initial site preparation and two levels of pulling, as there were no burning effects prior to application of this treatment and these effects were pooled with error. The 2012 diversity indices, FQI, $\bar{C}$, and relative cover data were analyzed using the full factorial design, including the additional two levels of burning. As these data did not fully meet the assumptions of a parametric ANOVA, analyses were carried out using PERMANOVA, a nonparametric, permutational analysis of variance (Anderson 2001, McArdle and Anderson 2001, Anderson 2005), using Euclidean distances. Preliminary analyses suggested block effects were small and including block terms in the model would not greatly alter results, so we pooled block effects with error terms in the PERMANOVA. PERMANOVA is not designed to allow a repeated measures analysis of variance, so we ran separate analyses for each year. Post-hoc analyses were completed using nonparametric multiple comparison tests available in PERMANOVA (Anderson 2005). Significance was accepted at $p < 0.05$ for all tests.

In addition, based on soil testing performed at the onset of the study (MacDonald et al. 2013), we found that while soil properties did not differ significantly among the different treatment combinations, there was a trend toward lower gravel on plots assigned to the pulling treatments (PERMANOVA; F = 3.19, $p = 0.09$). Since variation in gravel content could affect soil moisture holding capacity and thus plant response, when a significant pulling effect was found, the data were re-analyzed using gravel as a covariate to ensure the apparent treatment effect was not related to underlying variation in soil properties.

Results

Seeding Effects

In 2009, 20.8 ± 3.3% (mean ± SE) of 0.25 m^2 frames sampled (averaged across all treatment combinations) had at least one seeded native grass species present, although no seeded forbs were identified. In 2010, 32.9 ± 3.8% of frames sampled had at least one seeded native grass species present and 17.5 ± 2.8% of frames had at least one seeded native forb species present. The percent occurrence of native grasses and forbs did not differ significantly among treatment combinations in either 2009 or 2010. We observed native forbs and grasses on all plots by three years after seeding, with 20 of the 23 seeded native species established on site (Table 2). By 2011, big bluestem, little bluestem, and Indiangrass (*Sorghastrum nutans*) had established in every plot (Table 2). Between 2011 and 2012, Indiangrass doubled in average relative cover from 1.8% to 3.6%. Coinciding with an increase in average native grass cover between 2011 and 2012 from 11.9% to 15.1%, there was a significant negative correlation between native and non-native grass cover in 2012 (Pearson correlation; r = - 0.47, $p < 0.001$).

Several forbs also had high frequency of establishment, including butterfly milkweed (*Asclepias tuberosa*), lanceleaf tickseed (*Coreopsis lanceolata*), wild bergamot (*Monarda fistulosa*), spotted beebalm (*Monarda punctata),* pinnate prairie coneflower (*Ratibida pinnata*), and blackeyed Susan (*Rudbeckia hirta*; Table 2). Between 2011 and 2012, lanceleaf tickseed quadrupled in average relative cover from 0.2% to 0.8%, irrespective of treatment.

Both the FQI and $\bar{C}$ of the entire site were increased by seeding. Volunteer native species found on site had a $\bar{C}$ of 2.72 and an FQI of 13.6, while including seeded native species resulted in a $\bar{C}$ of 3.79 and an FQI of 26.0.

Initial Site Preparation Effects

Initial site preparation influenced both the diversity and quality of the plant community, with lower diversity, but a higher $\bar{C}$ in clopyralid treatments (Table 3, Table S1). Non-native species, including non-native grasses, non-native forbs, and knapweed exhibited the greatest response to site preparation (Figure 1, Table S2). The clopyralid-only treatment maintained low knapweed cover through four years, while knapweed had resurged to near estimated pre-treatment levels on mowed-only and glyphosate-only treatments by 2011 (Figure 1, Table S2). Clopyralid also consistently resulted in greater non-native grass cover (Figure 1, Table S2). Glyphosate treatments contained the highest non-native forb cover in 2011 (29.4%), while non-native forb cover was lower and similar on the clopyralid and mowed treatments (7.7% and 7.4% respectively; Figure 1, Table S2).

The initial site preparation also impacted the establishment of native species (Table 4). In 2012, big bluestem had the highest relative percent cover in the glyphosate and clopyralid treatments (Table 4, Table S3). While pinnate prairie coneflower had low establishment success, both this species and blackeyed Susan occurred most prevalently on glyphosate treatments (Tables 2 and 4, Table S3).

Pulling Effects

Pulling resulted in lower Simpson's diversity during 2012, but tended to increase FQI. This effect, however, became non-significant when gravel was included as a covariate (Table 3, Table S1). In 2011, we observed

Table 3. Main effects means (SE) of site preparation and pulling treatments on Simpson's diversity, Shannon diversity, mean coefficient of conservatism ($\bar{C}$), and Floristic Quality Index (FQI), at Bass River Recreation Area, Ottawa County, Michigan, US. Means followed by different letters differ significantly. Letters a, b indicate differences among initial site preparation treatments within a single year; x, y indicate differences between pulling treatments within a single year ($p < 0.05$). See Table S1 for test-statistics.

	Initial Site Preparation Treatment			Pulling Treatment	
	Mow	Clopyralid	Glyphosate	None	Pulled
Simpson's Diversity					
2011	0.61 (0.03)	0.54 (0.05)	0.63 (0.03)	0.58 (0.03)	0.60 (0.03)
2012	0.63 (0.03) ^{a}	0.44 (0.04) ^{b}	0.66 (0.03) ^{a}	0.63 (0.03) ^{x}	0.53 (0.03) ^{y}
Shannon Diversity					
2011	4.31 (0.26)	3.94 (0.39)	5.17 (0.44)	4.24 (0.29)	4.71 (0.33)
2012	4.37 (0.37) ^{a}	3.13 (0.26) ^{b}	5.33 (0.48) ^{a}	4.64 (0.37)	3.91 (0.33)
$\bar{C}$					
2011	3.53 (0.07) ^{ab}	3.73 (0.13) ^{a}	3.34 (0.07) ^{b}	3.52 (0.06)	3.56 (0.10)
2012	3.61 (0.77) ^{b}	4.02 (0.12) ^{a}	3.64 (0.08) ^{b}	3.66 (0.08)	3.85 (0.10)
FQI					
2011	13.51 (0.46)	13.31 (0.33)	13.88 (0.42)	13.05 (0.25)	14.09 (0.37)
2012	12.66 (0.60)	12.87 (0.38)	13.18 (0.35)	12.23 (0.32)	13.57 (0.37)

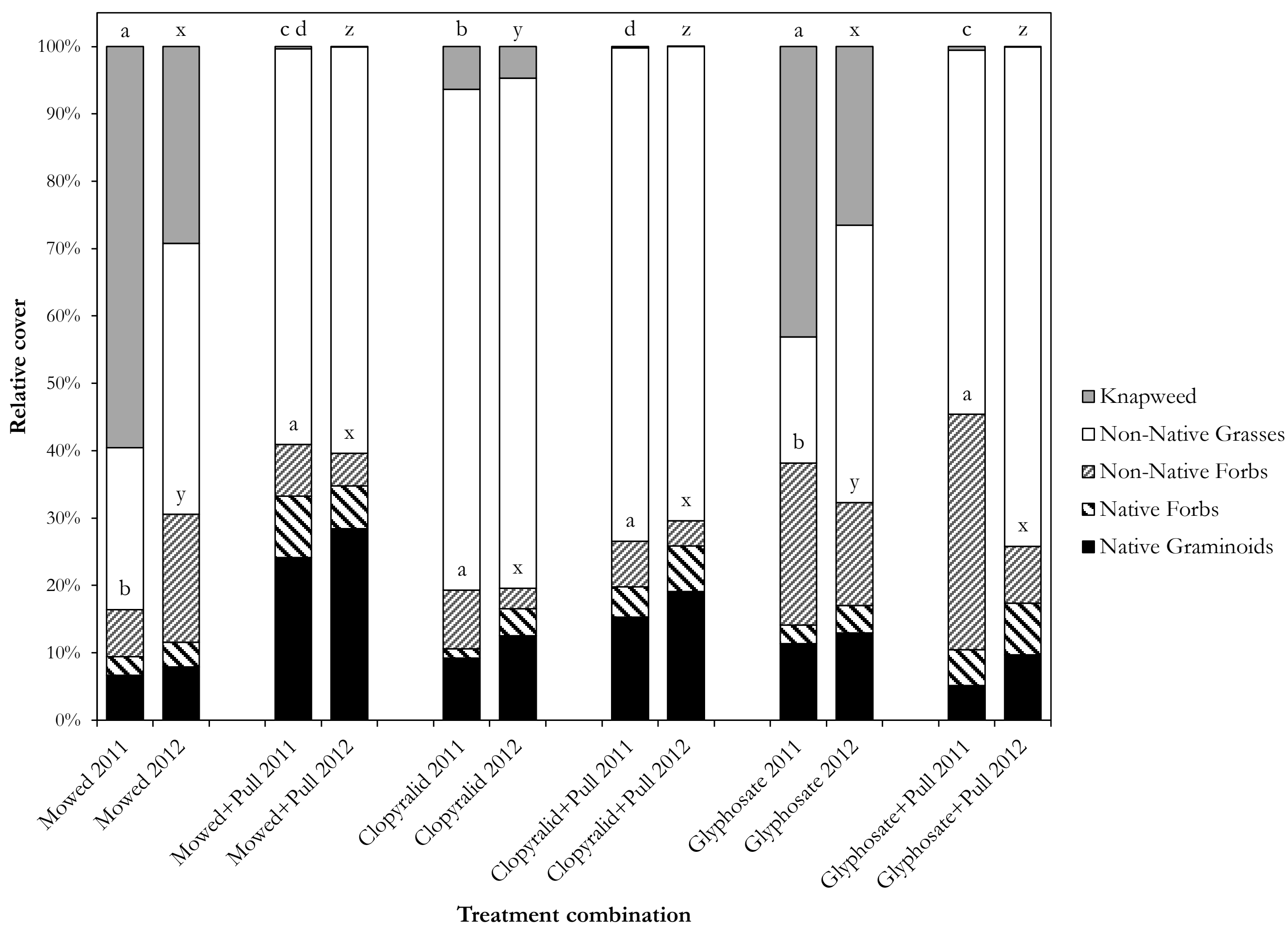

Figure 1. Plant community composition as affected by site preparation and pulling at Bass River Recreation Area. Treatments that differ significantly ($p < 0.05$) are indicated by different letters: a, b, c, and d compare means for 2011; x, y and z compare means for 2012. Letters within the non-native grasses bars indicate differences among these treatments, letters above the knapweed bars indicate differences among these treatments. See Table S2 for exact *p*-values.

Table 4. Main effects means (SE) of site preparation, pulling and burning treatments on native seeded species at Bass River Recreation Area, Ottawa County, Michigan, US. All values given represent relative percent cover. Means followed by different letters differ significantly. Letters a, b, c indicate differences among initial site preparation treatments within a single year; m, n indicate differences between pulling treatments within a single year; x, y indicate differences between burn treatments within a single year ($p < 0.05$). See Table S3 for test statistics.

	Initial Site Preparation Treatment			Pulling Treatment		Burning Treatment	
	Mow	Clopyralid	Glyphosate	None	Pulled	None	Burned
	%	%	%	%	%	%	%
Big Bluestem							
2011	0.77 (0.18)	1.06 (0.15)	1.05 (0.10)	0.81 (0.08)	1.11 (0.14)	0.99 (0.10)	0.93 (0.14)
2012	1.17 (0.19) ^{b}	1.83 (0.24) ^{a}	2.06 (0.31) ^{a}	1.37 (0.21)	2.00 (0.20)	1.74 (0.22)	1.63 (0.22)
Butterfly Milkweed							
2011	0.06 (0.02)	0.05 (0.01)	0.07 (0.02)	0.04 (0.01) ^{n}	0.08 (0.02) ^{m}	0.05 (0.01)	0.07 (0.01)
2012	0.04 (0.02)	0.10 (0.03)	0.11 (0.04)	0.04 (0.01) ^{n}	0.13 (0.03) ^{m}	0.06 (0.01)	0.10 (0.03)
Spotted Beebalm							
2011	0.60 (0.16)	0.32 (0.09)	0.42 (0.10)	0.24 (0.06) ^{n}	0.66 (0.11) ^{m}	0.49 (0.11)	0.41 (0.09)
2012	0.27 (0.11)	0.16 (0.05)	0.47 (0.14)	0.20 (0.06)	0.40 (0.10)	0.48 (0.09) ^{x}	0.12 (0.07) ^{y}
Pinnate Prairie Coneflower							
2011	0.02 (0.01) ^{b}	0.01 (0.01) ^{b}	0.08 (0.02) ^{a}	0.03 (0.01)	0.04 (0.01)	0.03 (0.01)	0.04 (0.01)
2012	0.01 (0.01) ^{b}	0.01 (0.01) ^{b}	0.10 (0.03) ^{a}	0.03 (0.01)	0.05 (0.02)	0.04 (0.01)	0.04 (0.02)
Blackeyed Susan							
2011	0.22 (0.04) ^{b}	0.11 (0.04) ^{b}	0.57 (0.15) ^{a}	0.19 (0.06)	0.41 (0.10)	0.27 (0.05)	0.33 (0.11)
2012	0.18 (0.04) ^{b}	0.07 (0.02) ^{c}	0.43 (0.11) ^{a}	0.15 (0.04)	0.30 (0.08)	0.25 (0.07)	0.21 (0.06)
Little Bluestem							
2011	0.86 (0.16)	0.57 (0.07)	0.58 (0.15)	0.50 (0.07) ^{n}	0.84 (0.22) ^{m}	0.72 (0.10)	0.62 (0.10)
2012	3.34 (0.82) ^{a}	1.37 (0.20) b	2.01 (0.40) ^{ab}	1.49 (0.24) ^{n}	2.99 (0.58) ^{m}	2.55 (0.56)	1.93 (0.33)

higher native forb cover within the pulling treatment as compared to treatments that did not include pulling (6.3% compared to 2.3%; Figure 1, Table S2), but this effect was less pronounced in 2012 (6.9% compared to 3.9%). Knapweed cover was reduced to less than 0.6% after three years and to 0.06% after four years in all pulling treatments (Figure 1, Table S2). As adult knapweed was removed, the remaining knapweed cover represented the presence of juveniles or seedlings. Pulling also resulted in greater non-native grass cover (Figure 1, Table S2). Increases in non-native grass cover corresponded to decreases in non-native forbs (Pearson correlation; 2011: $r = -0.41$, $p = 0.004$; 2012: $r = -0.50$, $p < 0.001$), and knapweed (Pearson correlation; 2011: $r = -0.67$, $p < 0.001$; 2012: $r = -0.58$, $p < 0.001$). Total grass cover had an increasing negative correlation with knapweed (Pearson correlation; 2011: $r = -0.77$, $p < 0.001$; 2012: $r = -0.83$, $p < 0.001$).

Pulling favored the establishment of seeded native species, with butterfly milkweed, spotted beebalm, and little bluestem exhibiting greater cover on the pulling treatments during at least one year of the study (Table 4, Table S3). Little bluestem had the greatest cover in the mowing-pulling treatment in 2012 (5.1%). While not significant with gravel included as a covariate, there was also a trend toward higher cover within pulling treatments for big bluestem during 2012, wild bergamot during 2011, and blackeyed Susan during both years (Table 4, Table S3).

Burning Effects

Average plot temperatures during the 2012 burn ranged from < 79 °C to 159 °C. Burning resulted in lower $\bar{C}$ compared to unburned treatments (3.57 to 3.94, 2012; Table 3, Table S1); however, $\bar{C}$ had increased from the 2011 mean values of 3.49 on burned plots and 3.59 on unburned plots. Burning also resulted in reduced spotted beebalm cover, while spotted beebalm cover remained largely unchanged on unburned plots (Table 4, Table S3).

Discussion

Seeding Effects

An unexpected finding in our study was the ease with which many seeded native species established on site. By seeding, we facilitated greater native forb diversity, which can assist in the prevention of knapweed reinvasion (Sheley and Half 2006), and avoided low recruitment that would have been expected if we had relied on the native seed bank or outside colonization (Heslinga and Grese 2010). We also experienced fairly normal amounts of precipitation in 2009, 2010, and 2011. If we had experienced an extreme drought earlier in the study similar to the one experienced in 2012 after native species had successfully established, seeding may have been less successful. While the FQI of the entire site remains lower than 35, which is the value considered indicative of a plant community exhibiting floristic importance within Michigan (MDNR 2001), it is higher than would have been achieved by relying on volunteer species establishment alone (site FQI = 26.0 with seeded species, 13.6 without seeded species).

As with previous studies at this knapweed-infested site (MacDonald et al. 2003, 2007), big bluestem, little bluestem, and Indiangrass established successfully (Table 2). Competition from these species should result in reduced knapweed cover over time. Indiangrass, in particular, achieved uniform cover regardless of knapweed control treatments, demonstrating its establishment and persistence even within knapweed-dominated communities. The increasing negative correlation between total grass cover and knapweed is consistent with grass-induced suppression of knapweed (Lindquist et al. 1996, MacDonald et al. 2003). At the same time, a negative correlation between non-native grasses and native graminoids and increasing native graminoid cover (Figure 1) illustrate competition that may lead towards a transition from non-native grass-dominated to native graminoid-dominated communities. Similar results have been found by Foster et al. (2007), in which sowing of native and naturalized prairie species decreased non-native grass, including the most common non-native grass species found during our study, Kentucky bluegrass. Endress et al. (2012) found that while seeding native grasses into an invasive forb-dominated community lowered non-native grass cover within six years, cover of the dominant invasive forb was unaffected. In contrast, the native grasses seeded in our study have been shown to reduce knapweed dominance to 2.1% of total biomass or less through time (MacDonald et al. 2007).

While native grass dominance is likely to assist in knapweed suppression (MacDonald et al. 2003, 2007, Baer et al. 2004, McCain et al. 2010), this is not ideal given the goal of establishing a diverse community. Although there is no evidence of native forb suppression within the establishment stage of our study, it may be some time before we are able to determine whether competition with native grasses will have any undesirable effects on native forbs. Sluis (2002) found that increases in big bluestem dominance within prairie restorations paralleled reductions in species richness within 15 years, while Camill et al. (2004) saw similar results three years into their restoration. After knapweed has been successful suppressed, however, utilization of methods such as burning during varying intervals and seasons can counteract decreases in native diversity caused by competition from native grasses (Howe 1994).

Although species that are sensitive to the allelopathic effects of knapweed can persist in knapweed-infested areas (Perry et al. 2005), very little research has been published detailing which native forbs are capable of establishing in the presence of knapweed. We observed native forb establishment in all treatments, including those that retained high knapweed cover (Table 2). In addition, over 80% of the forbs studied had established within three years of seeding (Table 2). In particular, butterfly milkweed, lanceleaf tickseed, wild bergamot, spotted beebalm, and blackeyed Susan exhibited relatively high cover, with lanceleaf tickseed having similar cover on all treatments indicating establishment success even in knapweed-dominated communities (Table 4). Several of these species share similar characteristics with knapweed, which may ensure greater competition with knapweed as they continue to increase in cover (Pokorny et al. 2005). Such was the case with common yarrow (*Achillea millefolium*), which shares similar phenology and rooting morphology with knapweed and is more able to resist knapweed invasion (Maron and Marler 2007). Within our study, butterfly milkweed, wild bergamot, spotted beebalm, and blackeyed Susan share a similar flowering season with knapweed (Gleason and Cronquist 1991), and all have proven to be successful at establishing in the presence of knapweed. Seeded native forbs still have relatively low cover, however, and will require more time to demonstrate their competitive abilities. Once the native community becomes well established, it is expected to be more resistant to the resurgence of invasive plants, including knapweed.

Initial Site Preparation Effects

Of the three initial site preparation treatments tested, clopyralid had the most positive effect on the development of the native plant community. Clopyralid increased big bluestem (Table 4) and non-native grass cover (Figure 1), thereby helping to prevent knapweed resurgence. Use of broadleaf herbicide to control non-native forbs often results in increases in non-native grass cover (Sheley et al. 2004, Ortega and Pearson 2011, Endress et al. 2012, Skurski et al. 2013). While we were initially concerned that the persistence of clopyralid in the soils would reduce forb establishment (DiTomaso 2000, Enloe et al. 2005), we now believe the longterm trajectory of this community will trend towards a diverse blend of warm-season grasses and native forbs, as opposed to the grass-dominated community we had originally predicted. Clopyralid is particularly effective against the families Fabaceae and Asteraceae (Enloe et al. 2005), which includes knapweed, and 13 of the 18 forb species seeded (Table 2). Of the species we seeded, only blackeyed Susan exhibited reduced establishment on clopyralid treatments (Table 4), consistent with this known sensitivity. The relatively minor impact of clopyralid on native forbs that we observed may have been related to the sand to loamy sand soil of our study site (MacDonald et al. 2013), as clopyralid is lost rapidly from sandy soils by leaching (Dow AgroSciences 2010, 2011).

A single application of clopyralid provided knapweed control for at least four years post-treatment, even in the absence of pulling (Figure 1). As knapweed cover has been found to be inversely related to diversity (Kedzie-Webb et al. 2001), we anticipated greater diversity in treatments that had reduced knapweed cover. Yet, we believe that the non-native species presence within the community remains too high for diversity indices to indicate either the longterm trajectory or the current condition of the restoration. Despite the effective knapweed control, clopyralid resulted in communities with lower diversity during 2012. The higher diversity within mowing and glyphosate treatments coincides with lower $\bar{C}$ and higher knapweed cover in the absence of pulling, and higher non-native forb cover (Figure 1).

In contrast to the effectiveness of clopyralid, in absence of pulling the glyphosate-only treatment allowed for rapid knapweed resurgence from the seedbank (Figure 1). Glyphosate in combination with seeding native grasses may provide limited short-term success in terms of grass establishment and knapweed control. Previous studies have shown that in as little as three years knapweed density may be greater than pre-herbicide treatment, ultimately resulting in low longterm grass establishment (Sheley et al. 2001). Glyphosate, in absence of pulling, also resulted in lower grassy fuel, leaving greater unburned areas within the plots (L.M. Martin, personal observation). Still, big bluestem, pinnate prairie coneflower, and blackeyed Susan demonstrated higher cover within the glyphosate treatment (Table 4), indicating a positive change in the development of this community. However, it remains too early to know if the seeded native species will gain dominance within this developing community due to the persistence of non-native species, especially knapweed.

After a single mowing, we saw no major longterm impacts on the community trajectory, as was expected. Mowing allowed for comparable levels of seeded species cover as both herbicide treatments, with the exception of lower big bluestem cover (Table 4), which should be temporary due to the dominant nature of this species (McCain et al. 2010). Yet, the ease with which native grasses and forbs established following such minimal site preparation indicates that seed limitations may be preventing natural recovery of some degraded sites (Foster et al. 2007), and shows promise for the development of communities with this treatment. As reported by MacDonald et al. (2013), the single mowing had few effects on knapweed densities on mowed-only plots, with a total knapweed density of 251 ± 47 m^{-2} (mean ± SE) in 2010, and remaining at a comparable level in 2011 (218 ± 38 m^{-2}). These values resemble total knapweed densities in untreated areas of the study site measured in 1999 (239 ± 16 m^{-2}). In addition, mature knapweed densities measured on the mowed-only plots in 2009 were 45.6 ± 4.7 m^{-2}. In comparison, mature knapweed densities measured in untreated areas in the vicinity of the study plots in summer, 2013, averaged 46.3 ± 7.7 m^{-2} and comprised 82.3 ± 3.1% (mean ± SE) of the total biomass (N.W. MacDonald, unpub. data). These comparisons demonstrate that mowed-only plots contained similar knapweed populations to untreated areas at the initiation of the study, and that adult knapweed densities in untreated areas did not spontaneously decline during the study period.

Pulling Effects

Pulling provided both effective knapweed control (MacDonald et al. 2013) and favored native grass and forb establishment, in addition to encouraging the development of grassy fuels that will facilitate future burns. Greatly reduced knapweed cover was maintained throughout the study, resulting in non-native grass-dominated communities (Figure 1). In turn, high non-native grass cover helps prevent knapweed resurgence (Lindquist et al. 1996) until the native grasses become dominant. Additionally, the decreases in non-native forb cover associated with increases in non-native grasses, indicate that these grasses may be competitively excluding non-native forbs, similar to results found by Bosy and Reader (1995).

Pulling increased the total cover of native forbs and several individual species, including butterfly milkweed, spotted beebalm, and little bluestem (Table 4), consistent with the trend towards a higher FQI on the pulled treatment (Table 3). We attribute the higher establishment of native forbs on pulled plots to reduced competition with knapweed, since pulling has been shown to substantially reduce knapweed density and biomass (MacDonald et al. 2013). Knapweed, which can have detrimental impacts on native forb establishment and persistence (Lesica and Sheley 1996, Maron and Marler 2008), was highly dominant prior to the initiation of our study. However, while we saw increases in the establishment of native forbs and one native grass when knapweed was manually removed, we also saw establishment and persistence of native species even in treatments with high knapweed cover. This indicates that the allelopathic effects of knapweed (Thorpe et al. 2009) had little impact on native species establishment and persistence on our study site.

It is possible that rather than elimination of the non-native species, disturbance caused by pulling encouraged seedling establishment; however, Skurski et al. (2013) found that a single manual removal of knapweed and replicated soil disturbance exhibited no difference in variables affected, with the exception of knapweed cover. This provides evidence that it was the removal of knapweed, rather than the disturbance, that facilitated native forb establishment within our study.

Burning Effects

We believe that due to the extended drought period experienced during June and July 2012, the effects of our burn on the native community may be delayed. Differences between burned and unburned sand prairies are less notable during drought years (Dhillion and Anderson 1994), and by reducing soil moisture (Anderson

1965), our burn may have exacerbated the effects of low soil moisture on productivity (Abrams et al. 1986, Briggs and Knapp 1995, Bowles and Jones 2013). In addition, burns conducted during the early spring result in lower soil moisture than mid- or late-Spring burns (Anderson 1965). We believe that reduced soil moisture may have accentuated lower spotted beebalm cover on the burning treatments (Table 4), which contributed to the lower $\overline{C}$ (Table 3). There also was little change from 2011 to 2012 in spotted beebalm cover on unburned treatments (Table 4), indicating that unlike many other seeded native species that increased in cover, spotted beebalm may be more susceptible to drought stress. Other studies have found that burning encourages germination and flower stalk production in native species (Kucera and Ehrenreich 1962, Old 1969, Maret and Wilson 2005), increases warm-season grass dominance (MacDonald et al. 2007), and that in combination with seeding of native species, fire can promote native species richness while decreasing non-native richness (Suding and Gross 2006).

While we had anticipated that burning would reduce knapweed cover, none of the plots reached an average fire temperature in excess of the 200 °C that has been shown to reduce knapweed germination rates in the laboratory (Abella and MacDonald 2000). Temperatures did exceed the 107 to 143 °C that has been shown to reduce knapweed germination under field conditions (Vermeire and Rinella 2009); however, weather conditions and timing were not optimal during our burn (MacDonald et al. 2013). Despite the low intensity of the initial burn, several of the treatment combinations should prove to be beneficial during future prescribed burns due to their high grass cover. The non-native grasses present within our study are mainly cool-season grasses that should be damaged by spring burns (Abrams et al. 1986), thereby reducing their cover. Additionally, spring burning has been shown to assist in the establishment of warm-season grasses in cool-season grass dominated communities (Doll et al. 2011), which would be beneficial in our pulling and clopyralid treatments that are non-native grass dominated (Figure 1). We believe that future burns performed during this long-term study will result in greater knapweed control and increased native species establishment.

Conclusions

Our results show that the method used for knapweed control played a large part in determining the development of a restored plant community. Hand pulling of knapweed assisted in native plant community establishment. Both clopyralid application and pulling encouraged the accumulation of grassy fuel loads, which will facilitate future burns that may help to further control knapweed, suppress other non-native species, and encourage establishment and dominance by native species. However, the labor required for pulling may limit this treatment to small knapweed infestations, areas pre-treated with a broadleaf-specific herbicide such as clopyralid, or areas where herbicide use would damage a sensitive remnant native community. Our use of a more diverse seed mix allowed for a greater number of potentially competitive species to establish, which may further prevent knapweed from returning to the site. Seeding with a mix of selected native species takes little time to implement, and produces a more desirable native plant community over time as evidenced by the increased FQI and $\overline{C}$ achieved through seeding. Through time, the interactive effects of site preparation methods, pulling, and burning may become more pronounced as the native plant community continues to develop.

Implications for Practice

- Seeding of selected native grasses and forbs following minimal site preparation was worthwhile on the knapweed-infested site we studied as certain species established without intensive treatment, including big bluestem, blackeyed Susan, butterfly milkweed, Indiangrass, lanceleaf tickseed, little bluestem, spotted beebalm, and wild bergamot. While native species cover may be initially low, increased native dominance will facilitate future management to gradually suppress knapweed.
- Although labor intensive, pulling of knapweed, in concert with seeding native species, was an effective treatment for reducing knapweed cover and increasing native grass and forb establishment.
- A single application of clopyralid provided long-lasting control of knapweed and had less than expected impact on seeded species establishment on this sandy site.
- A single treatment with glyphosate resulted in rapid resurgence of knapweed from the seedbank and increases in other non-native forbs. This approach would require intensive follow-up control measures to prevent continued knapweed dominance.
- Pulling of knapweed or a single application of clopyralid resulted in communities dominated by non-native grasses, which may prevent knapweed resurgence until seeded native grasses and forbs mature.
- To be effective, burning needs to be carefully timed to optimize knapweed control and encourage native species. In this study, a low-intensity early spring burn had minimal effects on either knapweed or native species cover.
- On sites that are heavily infested with spotted knapweed, initial treatment with a broadleaf-selective herbicide like clopyralid followed by annual hand pulling to control residual spotted knapweed would be most effective in controlling knapweed and favoring the establishment of seeded native grasses and forbs.

Acknowledgements

The authors thank C. Kapolka and T. Botting for assistance with field work; G. Palmgren, C. Ehrlich, and P. Whalen for approving use of the Bass River Recreation Area; P. Rodgers and L. Evans for conducting the burn; C. Martin for constructing pyrometers; Grand Valley State University for providing funding through a graduate assistantship, Presidential Research Grant, and the Student Summer Scholars Program; and T. Evans and T. Aschenbach and two anonymous reviewers for their thorough reviews and helpful comments.

Supplementary Tables S1–S3 containing statistical details can be found online at: http://uwpress.wisc.edu/journals/journals/er-supplementary.html.

References

Abella, S.R. and N.W. MacDonald. 2000. Intense burns may reduce spotted knapweed germination. *Ecological Restoration* 18:203–205.

Abrams, M.D., A.K. Knapp and L.C. Hulbert. 1986. A ten-year record of aboveground biomass in a Kansas tallgrass prairie: Effects of fire and topographic position. *American Journal of Botany* 73:1509–1515.

Allison, S.D. and P.M. Vitousek. 2004. Rapid nutrient cycling in leaf litter from invasive plants in Hawai'i. *Oecologia* 141:612–619.

Anderson, K.L. 1965. Time of burning as it affects soil moisture in an ordinary upland bluestem prairie in the Flint Hills. *Journal of Range Management* 18:311–316.

Anderson, M.J. 2001. A new method for non-parametric multivariate analysis of variance. *Australian Ecology* 26:32–46.

Anderson, M.J. 2005. PERMANOVA: a FORTRAN computer program for permutational multivariate analysis of variance. Auckland, New Zealand: Department of Statistics, University of Auckland.

Anderson, W. 1986. A guide for estimating cover. *Rangelands* 8:236–238.

Baer, S.G., J.M. Blair, S.L. Collins, and A.K. Knapp. 2004. Plant community responses to resource availability and heterogeneity during restoration. *Oecologia* 139:617–629.

Bakker, J.D. and S.D. Wilson. 2004. Using ecological restoration to constrain biological invasion. *Journal of Applied Ecology* 41:1048–1064.

Bosy, J.L. and R.J. Reader. 1995. Mechanisms underlying the suppression of forb seedling emergence by grass (*Poa pratensis)* litter. *Functional Ecology* 9:635– 639.

Bowles, M.L. and M.D. Jones. 2013. Repeated burning of eastern tallgrass prairie increases richness and diversity, stabilizing late successional vegetation. *Ecological Applications* 23:464–478.

Briggs, J.M. and Knapp, A.K. 1995. Interannual variability in primary productivity in tallgrass prairie: Climate, soil moisture, topographic position, and fire as determinants of aboveground biomass. *American Journal of Botany* 82:1024– 1030.

Brooks, M.L., C.A. D'Antonio, D.M. Richardson, J.B. Grace. J.E. Keeley, J.M. DiTomaso, R.J. Hobbs, M. Pellant and D. Pyke. 2004. Effects of invasive alien plants on fire regimes. *BioScience* 54:677–688.

Camill, P., M.J. McKone, S.T. Sturges, W.J. Severud, E. Ellis, J. Limmer, C.B. Martin, R.T. Navratil, A.J. Purdie, B.S. Sandel, S. Talukder, and A. Trout. 2004. Community- and ecosystem-level changes in a species-rich tallgrass prairie restoration. *Ecological Applications* 14:1680–1694.

Carpinelli, M.F., R.L. Sheley and B.D. Maxwell. 2004. Revegetating weed-infested rangeland with niche-differentiated desirable species. *Journal of Rangeland Management* 57:97–105.

D'Antonio, C.M. and P.M. Vitousek. 1992. Biological invasions by exotic grasses, the grass/fire cycle, and global change. *Annual Review of Ecology and Systematics* 23:63–87.

D'Antonio, C. and L.A. Meyerson. 2002. Exotic plant species as problems and solutions in ecological restoration. *Restoration Ecology* 10:703–713.

Dhillion, S. and R.C Anderson. 1994. Production on burned and unburned sand prairies during drought and non-drought years. *Vegetatio* 115:51–59.

DiTomaso, J.M. 2000. Invasive weeds in rangelands: Species, impacts and management. *Weed Science* 48:255–265.

Doll, J.E., K.A. Haubensak, E.L. Bouressa and R.D. Jackson. 2011. Testing disturbance, seeding time, and soil amendments for establishing native warm-season grasses in non-native cool-season pasture. *Restoration Ecology* 19:1–8.

Dow AgroSciences. 2010. Transline® Herbicide Material Safety Data Sheet, Dow AgroSciences LLC, Indianapolis, IN.

Dow AgroSciences. 2011. Transline® Herbicide Specimen Label, Dow AgroSciences LLC, Indianapolis, IN.

Ehrenfeld, J.G., P. Kourtev and W. Huang. 2001. Changes in soil function following invasions of exotic understory plants in deciduous forests. *Ecological Applications* 11:1287–1300.

Emery, S.M. and K.L. Gross. 2005. Effects of timing of prescribed fire on demography of an invasive plant, spotted knapweed *Centaurea maculosa*. *Journal of Applied Ecology* 42:60–69.

Endress, B.A., C.G. Parks, B.J. Naylor, S.R. Radosevich and M. Porter. 2012. Grassland response to herbicides and seeding of native grasses 6 years post treatment. *Invasive Plant Science and Management.* 5:311–316.

Enloe, S.F., J.M. DiTomaso, B.S. Orloff and D.J. Drake. 2005. Perennial grass establishment integrated with clopyralid treatment for yellow starthistle management on annual range. *Weed Technology* 19:94–101.

Erskine Ogden, J.A. and M. Rejmánek. 2005. Recovery of native plant communities after the control of a dominant invasive plant species, *Foeniculum vulgare*: Implications for management. *Biological Conservation* 125:427–439.

Foster, B.L., C.A. Murphy, K.R. Keller, T.A. Aschenbach, E.J. Questad and K. Kindscher. 2007. Restoration of prairie community structure and ecosystem function in an abandoned hayfield: A sowing experiment. *Restoration Ecology* 15:652–661.

Gleason, H.A. and A. Cronquist. 1991. *Manual of vascular plants of northeastern United States and adjacent Canada,* 2nd Edition. The New York Botanical Press, Bronx, New York.

Heslinga, J.L. and R.E. Grese. 2010. Assessing plant community changes over sixteen years of restoration in a remnant Michigan tallgrass prairie. *American Midland Naturalist* 164:322–336.

Howe, H.F. 1994. Managing species diversity in tallgrass prairie: Assumptions and implications. *Conservation Biology* 8:691–704.

Kedzie-Webb, S.A., R.K. Sheley, J.J. Borkowski and J.S. Jacobs. 2001. Relationships between *Centaurea maculosa* and indigenous plant assemblages. *Western North American Naturalist* 61:43–49.

Kennard, D.K., K.W. Outcalt, D. Jones and J.J. O'Brien. 2005. Comparing techniques for estimating flame temperature of prescribed fires. *Fire Ecology* 1:75–83.

Kennedy, T.A., S. Naeem, K.M. Howe, J.M.H. Knops, D. Tilman and P. Reich. 2002. Biodiversity as a barrier to ecological invasion. *Nature* 417:636–638.

Kettenring, K.M. and C. Reinhardt Adams. 2011. Lessons learned from invasive plant control experiments: A systematic review and meta-analysis. *Journal of Applied Ecology* 48:970–979.

Kost, M.A., D.A. Albert, J.G. Cohen, B.S. Slaughter, R.K. Schillo, C.R. Weber, and K.A. Chapman. 2007. *Natural Communities of Michigan: Classification and Description.* Michigan Natural Features Inventory, Report No. 2007–21, Lansing, MI.

Kucera, C.L. and J.H. Ehrenreich. 1962. Some effects on annual burning on central Missouri prairie. *Ecology* 43:334–336.

Lesica, P. and J.S. Shelly. 1996. Competitive effects of *Centaurea maculosa* on the population dynamics of *Arbis fecunda*. *Bulletin of the Torrey Botanical Club* 123:111–121.

Lindquist, J.L., B.D. Maxwell, and T. Weaver. 1996. Potential for controlling the spread of *Centaurea maculosa* with grass competition. *Great Basin Naturalist* 56:267–271.

MacDonald, N.W., T. Koetje, and B.J. Perry. 2003. Native warm-season grass establishment on spotted knapweed-infested gravel mine spoils. *Journal of Soil and Water Conservation* 58:243–250.

MacDonald, N.W., B.T. Scull, and S.R. Abella. 2007. Mid-spring burning reduces Spotted Knapweed and increases native grasses during a Michigan experimental grassland establishment. *Restoration Ecology* 15:118–128.

MacDonald, N.W., L.M. Martin, C.K. Kapolka, T.F. Botting, and T.E. Brown. 2013. Hand pulling following mowing and herbicide treatments increases control of spotted knapweed (*Centaurea stoebe*). *Invasive Plant Science and Management* 6(4):470–479.

Maron, J. and M. Marler. 2007. Native plant diversity resists invasion at both low and high resource levels. *Ecology* 88:2651–2661.

Maron, J.L. and M. Marler. 2008. Field-based competitive impacts between invaders and natives at varying resource supply. *Journal of Ecology* 96:1187–1197.

Maret, M.P. and M.V. Wilson. 2005. Fire and litter effects on seedling establishment in western Oregon upland prairies. *Restoration Ecology* 13:562–568.

McArdle, B.H. and M.J. Anderson. 2001. Fitting multivariate models to community data: A comment on distance based redundancy analysis. *Ecology* 82:290–297.

McCain, K.N.S., S.G. Baer, J.M. Blair and G.W.T. Wilson. 2010. Dominant grasses suppress local diversity in restored tallgrass prairie. *Restoration Ecology* 18:40–49.

McCune, B. and J.B. Grace. 2002. *Analysis of ecological communities.* Gleneden Beach, OR: MjM Software Design.

Michigan Department of Natural Resources (MDNR). 2001. Floristic quality assessment with wetland categories and examples of computer applications for the State of Michigan. www.dnr.state.mi.us/publications/pdfs/huntingwildlifehabitat/FQA.pdf

National Climatic Data Center (NCDC). 2009. Local climatological data, annual summary with comparative data for Muskegon, Michigan (KMKG). Monthly precipitation data for 1980–2009 obtained from the National Climatic Data Center, Asheville, NC. www.ncdc. noaa.gov/. Accessed: October 12, 2010.

National Climatic Data Center (NCDC). 2014. Annual climatological summary for Muskegon, Michigan 2009, 2010, 2011, 2012. www.ncdc.noaa.gov/. Accessed: March 27, 2014.

National Drought Mitigation Center (NDMC). 2013. U. S. Drought Monitor, Michigan, June 7, 2011 through October 18, 2011 and June 12, 2012 through October 16, 2012. National Drought Mitigation Center, University of Nebraska, Lincoln. droughtmonitor.unl.edu/. Accessed: February 23, 2013.

Old, S.M. 1969. Microclimate, fire, and plant production in an Illinois prairie. *Ecological Monographs* 39:355–385.

Ortega, Y.K. and D.E. Pearson. 2011. Long-term effects of weed control with picloram along a gradient of spotted knapweed invasion. *Rangeland Ecology & Management* 64:67–77.

Ortega, Y.K., D.E. Pearson, L.P. Waller, N.J. Sturdevant, and J.L. Maron. 2012. Population-level compensation impedes biological control of an invasive forb and indirect release of a native grass. *Ecology* 93:783–792.

Packard, S and C.F. Mutel, eds. 1997. *The Tallgrass Restoration Handbook: For Prairies, Savannas and Woodlands.* Island Press, Covelo, California.

Peet, R.K. 1974. The measurement of species diversity. *Annual Review of Ecology and Systematics* 5:285–307.

Perry, L.G., C. Johnson, É.R. Alford, J.M. Vivanco and M.W. Paschke. 2005. Screening of grassland plants for restoration after spotted knapweed invasion. *Restoration Ecology* 13:725–735.

Pokorny, M.L., R.L. Sheley, C.A. Zabinski, R.E. Engel, T.J. Svejcar, and J.J. Borkowski. 2005. Plant functional group diversity as a mechanism for invasion resistance. *Restoration Ecology* 13:448–459.

Potvin, C. and L. Vasseur. 1997. Long-term CO_2 enrichment of a pasture community: Species richness, dominance and succession. *Ecology* 78:666–677.

Reid, A.M., L. Morin, P.O. Downey, K. French and J.G. Virtue. 2009. Does invasive plant management aid the restoration of natural ecosystems? *Biological Conservation* 142:2342–2349.

Rice, P.M., J.C. Toney, D.J. Bedunah and C.E. Carlson. 1997. Plant community diversity and growth responses to herbicide applications for control of *Centaurea maculosa*. *Journal of Applied Ecology* 34:1397–1412.

Rinella, M.J., B.D. Maxwell, P.K. Fay, T. Weaver, and R.L. Sheley. 2009. Control effort exacerbates invasive species problem. *Ecological Applications* 19:155–162.

Schirman, R. 1981. Seed production and spring establishment of diffuse and spotted knapweed. *Journal of Range Management* 54:52–56.

Sheley, R.L., T.J. Svejcar, and B.D. Maxwell. 1996. A theoretical framework for developing successional weed management strategies on rangeland. *Weed Technology* 10:766–773.

Sheley, R.L., J.S. Jacobs and M.F. Carpinelli. 1998. Distribution, biology, and management of diffuse knapweed (*Centaurea diffuse)* and spotted knapweed *(Centaurea maculosa). Weed Technology* 12:353–362.

Sheley, R.L., J.S. Jacobs and D.E. Lucas. 2001. Revegetating spotted knapweed infested rangeland in a single entry. *Journal of Range Management* 54:144–151.

Sheley, R.L., J.S. Jacobs, and J.M. Martin. 2004. Integrating 2,4–D and sheep grazing to rehabilitate spotted knapweed infestations. *Journal of Range Management* 57:371–375.

Sheley, R.L. and M.L. Half. 2006. Enhancing native forb establishment and persistence using a rich seed mixture. *Restoration Ecology* 14:627–635.

Skurski, T.C., B.D. Maxwell, and L.J. Rew. 2013. Ecological tradeoffs in non-native plant management. *Biological Conservation* 159:292–302.

Sluis, W.J. 2002. Patterns of species richness and composition in re-created grassland. *Restoration Ecology* 10:677–684.

Story, J.M., N.W. Callan, J.G. Corn and L.J. White. 2006. Decline of spotted knapweed densities at two sites in western Montana with large populations of the introduced root weevil, *Cyphocleonus achates* (*Fahraeus*). *Biological Control* 38:227–232.

Suding, K.N. and K.L. Gross. 2006. Modifying native and exotic species richness correlations: The influence of fire and seed addition. *Ecological Applications* 16:1319–1326.

Taft, J.B., G.S. Wilhelm, D.M. Ladd, and L.A. Masters. 1997. Floristic quality assessment for vegetation in Illinois, a method for assessing vegetation integrity. *Erigenia* 15:3–95.

Thorpe, A.S., G.C. Thelen, A. Diaconu and R.M. Callaway. 2009. Root exudate is allelopathic in invaded community but not in native community: Field evidence for the novel weapons hypothesis. *Journal of Ecology* 97:641–645.

Tilman, D., J. Knops, D. Wedin, P. Reich, M. Ritchie and E. Siemann. 1997. The influence of functional diversity and composition on ecosystem processes. *Science* 277:1300–1302.

Tyser, R.W. 1992. Vegetation associated with two alien plant species in a fescue grassland in Glacier National Part, Montana. *Great Basin Naturalist* 52:189–193.

Tyser, R.W., J.M. Asebrook, R.W. Potter and L.L. Kurth. 1998. Roadside revegetation in Glacier National Park, USA: Effects of herbicide and seeding treatments. *Restoration Ecology* 6:197–206.

Vermeire, L.T. and M.J. Rinella. 2009. Fire alters emergence of invasive plant species from soil surface-deposited seeds. *Weed Science* 57:304–310.

Watson, A.K. and A.J. Renney. 1974. The biology of Canadian weeds. 6. *Centaurea diffusa and Centaurea maculosa. Canadian Journal of Plant Science* 54:687–701.

Weidenhamer, J.D. and R.M. Callaway. 2010. Direct and indirect effects of invasive plants on soil chemistry and ecosystem function. *Journal of Chemical Ecology* 36:59–69.

Zavaleta, E.S., R.J. Hobbs and H.A Mooney. 2001. Viewing invasive species removal in a whole-ecosystem context. *Trends in Ecology & Evolution* 16:454–459.

Laurelin M. Martin (corresponding author), Department of Biology, Grand Valley State University, Allendale, MI 49401-9403, lanninla@mail.gvsu.edu.

Neil W. MacDonald, Department of Biology, Grand Valley State University, Allendale, MI 49401-9403.

Tami E. Brown, Department of Biology, Grand Valley State University, Allendale, MI 49401-9403.