FINAL REPORT

Title: Managing Fuels While Enhancing Prairie-Chicken Habitat

JFSP PROJECT ID: 13-1-06-8

July 2017

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List of Abbreviations/Acronyms

ANWR – Aransas National Wildlife Refuge

APCNWR – Attwater’s Prairie-Chicken National Wildlife Refuge

PSWMA – Packsaddle Wildlife Management Area

TGPP – Tallgrass Prairie Preserve

LEPC – Lesser prairie-chicken

GRPC – Greater prairie-chicken

ATPC – Attwater’s prairie-chicken

MSF – months since fire

Acknowledgements

We would like to thank the management personnel at each study site for providing logistical support with lodging and scheduling. Specifically, we would also like to thank J. Adams, M. Morrow, R. Chester, R. Hamilton, T. Brown, and S. Parry for providing GIS map layers of burn and grazing histories, local knowledge of site characteristics, and for their willingness to cooperate on this research project. A number of technicians made data collection possible: C. Thyer, T. Hart, T. Ragan, D. Mendez, and B. Confer. We would also like to thank Sherry Leis, Carol Blocksome, and Blayr Gourley with the Great Plains Fire Science Exchange for assistance with webinars, field days, science briefs, and other outreach activities.

Abstract

More than a century of fire suppression in the Great Plains has altered fire regimes and led to a conversion of grasslands to woodlands, thereby resulting in loss of habitat for grassland-obligate fauna, particularly prairie-chickens (*Tympanuchus* spp). An additional consequence of fire regime changes has been an increase in the occurrence of large, catastrophic wildfires in the southern Great Plains over the past 30 years. While prescribed fire has been proposed as a fuels reduction treatment, fire alone may have limited utility in the region and would likely require annual treatment, resulting in further loss of biodiversity. Pyric herbivory, which allows for an interaction between fire and grazing, has been implemented in some parts of the region and resulted in increased biodiversity and livestock production. We sought to evaluate the potential for pyric herbivory to simultaneously benefit fuels reduction and prairie-chicken habitat conservation objectives. We established a large-scale experiment to compare prescribed fire treatments without grazing to those where grazing is allowed to interact through pyric herbivory across four sites throughout the southern Great Plains. We used fuels data collected in the field to customize fuel models in BehavePlus 5.0 and simulated fire behavior characteristics. We also collected vegetation community data for comparison to known prairie-chicken habitat requirements. We found that time since fire is the main driver of biomass accumulation, and the fire-grazing interaction can mediate the rate of accumulation. We also found differences between treatments in vegetation community characteristics key to prairie-chicken habitat. Our data indicate that pyric herbivory offers extended fuels reduction benefits compared to fire-only treatments. Pyric herbivory also maintains vegetative community structure and composition suitable to the various life stages of prairie-chickens. We suggest the implementation of pyric herbivory as a fuels management practice in the southern Great Plains, especially in areas where conservation of biodiversity is also a concern.

The project addresses **Task Statement 6: Compatibility of fire, fuels and rehabilitation treatments with T&E gallinaceous birds** of JFSP Project Announcement FA-FON0013-0001.

Objectives

The primary objective of this research was to evaluate the potential for pyric herbivory to simultaneously benefit both fuels management and prairie-chicken conservation goals. To assess this, we developed the following hypotheses:

> <u>*Hypothesis 1*</u>*: Pyric herbivory (patch-burning) would increase the amount of time in which fire suppression tactics could be used to successfully extinguish wildfires compared to burning alone (no grazing).*
>
> <u>*Hypothesis 2*</u>*: Pyric herbivory (patch-burning) would provide at all times the known structural and dietary habitat requirements needed for lesser, greater, and Attwater's prairie chickens by creating a spatially shifting mosaic of vegetation structure and forage abundance, and extend the amount of time patches differ in structure and composition.*

Background

Long-term alterations of fire regimes at broad scales have led to significant loss of grasslands and declines in associated gallinaceous birds. In the Great Plains, decades of successful fire suppression have facilitated the conversion of grasslands to woodlands (Briggs et al. 2005). In addition to the resulting habitat loss and concomitant decline of prairie-chickens (*Tympanuchus* spp.) (Fuhlendorf et al. 2002, USFWS 2010), these ecosystem transitions have also been responsible for a 300% increase in wildfire activity and a 400% increase in area burned across the Great Plains (Donovan et al. 2017). Since 2000, wildfires in the southern Great Plains region have burned millions of hectares, causing unprecedented losses to property, livestock and human life, and accounting for as much as 51% of total area burned nationally (NIFC 2017). Additionally, some of the largest fires in the continental United States have occurred in this region, including the East Amarillo Complex fires of the 2005-2006 fire season, which burned nearly 400,000 ha (Mutch and Keller 2010, NIFC 2017).

The wildfire problem in the Great Plains has illustrated the need for development and implementation of effective fuels management strategies. To this end, agencies have stated prescribed fire will likely be the dominant long-term fuels management option in this region (USDI-BLM 2014). After burning, however, it is often customary in this region for managers to remove grazing animals from the landscape (Fuhlendorf et al. 2012), which allows rapid recovery of herbaceous biomass and limits the window of time in which fuels treatments are effective. Moreover, recent evidence suggests this practice may be unwarranted (Gates et al. 2017). Thus, we contend that the dominant approach to fuels management in this region, prescribed burning followed by grazing removal, has limited utility as a fuels reduction treatment unless expansive areas are treated on an annual basis. Annual burning in Great Plains grasslands would also represent a departure from the historic fire regime, which had an estimated mean fire return interval of 0-6 years (Guyette et al. 2012, Stambaugh et al. 2014). Additionally, these types of treatments often lead to homogeneous landscapes which lack the structural and compositional complexity characteristic of rangelands in the southern Great Plains (Fuhlendorf et al. 2002).

Prairie-chickens have been identified as umbrella species for grassland conservation (Winder et al. 2015). Considering that prairie-chickens require heterogeneous landscapes (Hagen et al. 2004, USFWS 2010), fuels management strategies which reduce heterogeneity may be detrimental to efforts to conserve remaining populations. Based on the guidelines of Hagen et al. (Hagen et al.), lesser prairie-chickens require areas with low-growing vegetation for lekking, moderate height vegetation for brooding, and taller, dense vegetation for nesting. Greater and Attwater's prairie-chickens also require similarly heterogeneous landscapes in order to fulfill (Lehmann 1941, USFWS 2010). Because these vegetation types do not coincide temporally with the needs of prairie-chickens, landscapes must include all three types simultaneously within the home range of prairie-chickens in order to sustain viable populations. Additionally, invertebrates serve as a critical food source for prairie-chickens, especially during the first two weeks of a chick's life (Hagen et al. 2005). Invertebrates are known to increase in richness and abundance in response to fire (Engle et al. 2008), and also correlate with abundance of forbs (Hagen et al. 2005).

In order to meet both conservation and fuels management goals, fuels treatments should promote heterogeneity while reducing fire behavior characteristics (e.g. flame length and rate of spread), which also enhances effectiveness of wildland firefighting techniques. Current suppression techniques used by wildland firefighters cease to be effective when flames reach lengths greater than 3.4 meters, with additional thresholds recognized at 1.2 and 2.4 meters (1.2 m – hand tools become ineffective; 2.4 m – reduced effectiveness of mechanical methods) (NWCG 2014).

Pyric herbivory, a rangeland management strategy which has been reported to increase biodiversity and livestock production, allows for the interaction of fire and grazing to occur in a manner similar to pre-European settlement. Pyric herbivory may present the best opportunity to promote heterogeneity while also meeting fuels management objectives. The practice focuses on increasing spatio-temporal heterogeneity across the landscape, and has been demonstrated to improve the diversity of other grassland obligate birds (Fuhlendorf et al. 2006, Hovick et al. 2014, Hovick et al. 2015).

Materials and Methods

We established a landscape-level sampling protocol replicated across 4 sites in the southern Great Plains: Aransas National Wildlife Refuge (NWR), Attwater's Prairie-chicken NWR, the Tallgrass Prairie Preserve, and Packsaddle Wildlife Management Area (Table 1). These sites span a climatic gradient from temperate to humid subtropical, and an east-west precipitation gradient from 113 cm to 66 cm. Pyric herbivory was part of the management strategy at each site except the Aransas NWR, which was not grazed by domestic herbivores. At each site, we attempted to also sample fire-only treatment patches of various time since fire, and fire/grazing patches with various time since fire as available.. In each patch, we randomly established 8 transects, each 25-m long to quantify vegetation structure, community composition, and fuel properties. Sampling was performed from June 2014 through August 2016. Vegetation structure and composition variables included mean and maximum height of herbaceous and woody plants and percent cover of plant functional groups. Fuels measurements included percent cover of 1-hour, 10-hour, and 100-hour fuels, litter, bare ground, and aboveground biomass. Along the same transects, we assessed percent cover of vegetation functional groups using the Daubenmire method (Daubenmire 1959). We also measured maximum and mean height of herbaceous vegetation and shrubs.

Table 1. Summary descriptions of plant communities, climate, ownership, Tympanuchus species studied, and grazing regimes for each study site, sampled from June 2014 through August 2017. ANWR – Aransas National Wildlife Refuge; APCNWR – Attwater's Prairie-Chicken National Wildlife Refuge; PSWMA – Packsaddle Wildlife Management Area; TGPP – Tallgrass Prairie Preserve; USFWS = US Fish & Wildlife Service; TNC = The Nature Conservancy; ODWC = Oklahoma Department of Wildlife Conservation; MAP – Mean Annual Precipitation, based on 30-yr average 1986-2015, obtained from USDA-NRCS Agricultural Applied Climate Information System (Ag-ACIS). Growing Season Length (days above 0°C) also obtained from USDA-NRCS Ag-ACIS, stations nearest study site with available data. ATPC = Attwater's prairie-chicken; LEPC = Lesser prairie-chicken; GRPC = Greater prairie-chicken.

Plant community	**Gulf coastal prairie**		**Sand shinnery**	**Sand sagebrush**	**Tallgrass prairie**
Study site	ANWR	APCNWR	PSWMA		TGPP
Size (ha)	46,000	4,200	7,900		16,000
State	TX	TX	OK		OK
Entity	USFWS	USFWS	ODWC		TNC
Herbivore type	none	*Bos taurus*	*Bos taurus*		*Bos taurus, Bison bison*
MAP (cm)	105	111	66		113
Growing Season	338	251	198		203
Dominant herbaceous vegetation	*Schizachyrium scoparium, Sorghastrum nutans, Spartina spartinae*	*Schizachyrium scoparium, Sorghastrum nutans, Panicum virgatum*	*Schyzachyrium scoparium, Andropogon gerardii, Bouteloua curtipendula*		*Andropogon gerardii, Schizachyrium scoparium, Sorghastrum nutans*
Dominant woody vegetation	*Prosopis glandulosa, Quercus virginiana*	NA	*Quercus havardii*	*Artemisia filifolia*	*Quercus marilandica, Q. stellata,*
Reference	USFWS 2010a	USFWS 2010b	Carroll et al. 2017		Hamilton 2007
Ag-ACIS station #	48057	48089	40045		40113
***Tympanuchus* spp.**	ATPC	ATPC	LEPC		GRPC

In addition to measures of vegetation and fuels characteristics, we sampled invertebrates within each patch using the sweep net method (Hagen et al. 2004, Engle et al. 2008) by conducting 25 sweeps along each transect during the summer sampling period. We transferred invertebrates from the net into plastic freezer bags, immediately stored in coolers, then frozen until processing, at which time they were dried, weighed, and sorted to order. We pooled samples from transects within patches, and recorded biomass and number of orders per patch.

Using fuels characteristics from field data, we created customized dynamic fuel models within the BehavePlus 5.0 fire modeling software (Heinsch and Andrews 2010). We initialized models using the most appropriate model for each site, then customized them using fuels parameters collected from our field observations. Fuels characteristics not measured directly were maintained as the default for the fuel type. We note that our results related to fire behavior likely include some “noise” as a result of the patchy nature of the fires at all sites. Because the sites are managed to increase diversity, fires are often allowed to burn in a heterogeneous manner even within a specified burn unit. This practice allows for fuel continuity, or lack thereof, to influence fire spread and fire intensity throughout the burn unit. As a result, some transects may have fallen within “unburned” portions of a larger burned patch, or portions which burned under different intensity. Such instances would result in differential effects of fire on the vegetation. Additionally, the inherent heterogeneity of some of our study sites may include vegetation which burns poorly (or not at all) under prescribed conditions due to its structural or compositional characteristics. However, our dynamic fuel models were unable to incorporate such heterogeneity directly.

To evaluate the implications to suppression capabilities from long-term alteration of fire regimes, we assessed thresholds in flammability characteristics of eastern redcedar (*Juniperus* *virginiana*), a highly volatile woody species that commonly encroaches long-unburned grasslands. We determined thresholds in redcedar flammability in a laboratory at the University of Nebraska-Lincoln, NE, USA. All foliage sampling was conducted at the Twin Lakes Wildlife Management Area (WMA) in Seward, County, NE (lat 40˚82N; long -96˚94W). We harvested foliage from a randomly selected lush, female redcedar tree approximately 3m in height. To limit the amount of variation in foliar fuel moisture content (FMC) among foliage samples, we harvested all samples (6 cm in length) from the lower third of the crown and from the tips of branches only (Jolly and Hadlow 2012, Pausas et al. 2012). Immediately following harvest, we placed all foliage samples (100 total) into plastic bags to prevent moisture loss during transport to the laboratory. We immediately weighed all samples in the laboratory to obtain a fresh (wet) weight.

We conducted a pilot study to establish the relationship between the amount of time spent in a 60°C convection oven and the FMC of redcedar foliage. The pilot study determined how long to leave each sample in the oven to obtain a desired FMC. We immediately weighed foliage samples (10 total) following harvest to obtain a fresh (wet) weight. We placed samples in the 60°C convection oven and weighed every 10 minutes. We repeated this process until all foliage samples were completely dry and maintained a constant weight. We calculated the FMC of each foliage sample on a dry weight basis for each time interval.

We established foliar fuel moisture content classes (10 total) ranging from live (wet) to 0% FMC. We first calculated the FMC of fresh (wet) foliage samples to establish the upper bound of FMC classes. We then established foliar fuel moisture content classes ranging from 180% (live foliage) to 0% (oven dry) in 20% increments. Each FMC class consisted of 10 foliage samples that were individually subjected to flammability measurements.

To conduct flammability measurements, we used a laboratory vent hood with no forced airflow (Pausas et al. 2012). A wide mouth Bunsen burner provided the pilot flame for ignition (Scarff and Westoby 2006). To represent a moderate flame temperature, we placed the pilot flame (718°C ± 3°C) approximately 3.3 cm below the foliage samples and was held at a constant height of approximately 1.5 cm (Dimitrakopoulos and Papaioannou 2001, Weir and Scasta 2014). We securely positioned samples on top of a wire mesh above the flame for the duration of ignition or 120 s if ignition did not occur. To maintain consistency between samples and to avoid extraneous heat transfer between the wire mesh and juniper foliage, the wire mesh was cooled between ignitions.

For each FMC class and sample, we measured three common components of plant flammability (Table 1). To measure the ignitibility of redcedar across FMC classes, we used a stopwatch to record the amount of time it took for each sample to ignite once placed above the pilot flame (Anderson 1970, Dimitrakopoulos and Papaioannou 2001). To measure the combustibility of redcedar across FMC classes, we measured the maximum height of the visual flame to the nearest mm (Anderson 1970, White and Zipperer 2010). To measure the sustainability of redcedar across FMC classes, we calculated the amount of time each sample maintained flaming combustion once placed above the pilot flame to the nearest half second (Anderson 1970, White and Zipperer 2010). Consumability was not measured in this study because every foliage sample was completely consumed during combustion. To determine flame height and time-spent combusting, we used a LumaSense MC320LHT thermal imaging camera in collaboration with LumaSpec RT software. We measured infrared radiation (energy released) and recorded every half second for a 320 x 220 cell array, where each cell was 0.49 mm x 0.49 mm. We used the online calculator provided by LumaSense Technologies (see https://www.lumasenseinc.com/EN/home/home-lumasense-technologies.html) to calculate cell size given the distance from our camera to the sample (406 mm). Using LumaSpec RT software, we recorded an infrared video of each sample for *post hoc* analysis of combustibility and sustainability. By replaying each video in LumaSpec RT software, we were able to calculate the height of each flame to the nearest mm, as well as measure the duration of flaming combustion for each sample to the nearest half second.

Because our data were unbalanced and hierarchical in nature, with four levels of hierarchy in vegetation structural measurements (sample within transect within burn unit within study site), we created linear and generalized linear mixed effects models using the lme4 package in R (Bates et al. 2013, R Core Team 2016). These models are more robust to such data structure than traditional ANOVA or MANOVA, which only allow for inclusion of one error term. To correct for spatial autocorrelation (e.g. transects in the same burn unit are presumed to be similar, as are burn units in the same study site), we specified site as a random variable, using the model structure (1|Site/Unit/Transect). To account for a limited amount (~25%) of temporal pseudoreplication as well as repeated measurements across years, we treated collection year as a crossed random variable (1|Collect.Year). We used the same model structure for analysis of differences in fire characteristics.

Results and Discussion

Fuel Accumulation

Our data suggest that fuels (biomass) and the rate of fuels accumulation are influenced directly by time since fire ($\beta = 2.185$, $\sigma = 0.088$, $p < 0.001$) in the southern Great Plains. Fuel loads increased rapidly with increasing time since fire (Figure 1), but the rate of accumulation was mediated by the fire-grazing interaction (*β* = - 0.514, *σ* = 0.106, *p* < 0.001). Peak fuel loads in fire-only treatments exceeded 6,000 kg per hectare at approximately 24 months post-fire, whereas fuel loads in pyric herbivory treatments peaked slightly higher than 4,000 kg per hectare. Fuel loads in pyric herbivory treatment also lagged behind those in fire-only treatments by several months, peaking at approximately 32 months post-fire.

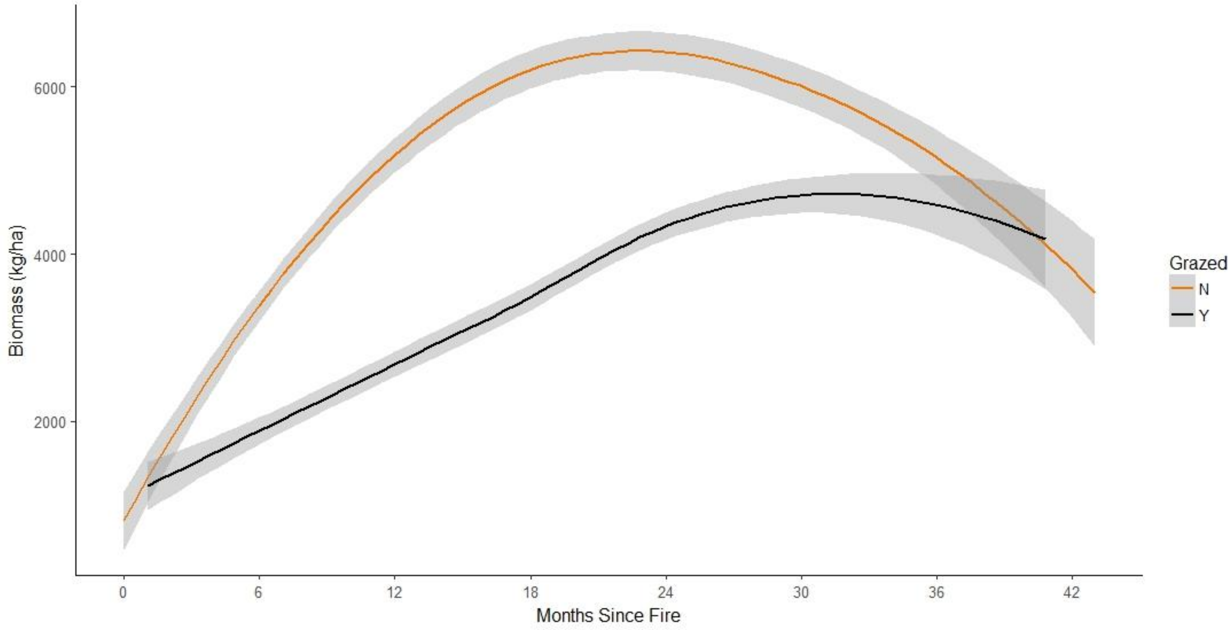

Figure 1. Mean biomass with increasing months since fire in pyric herbivory (black) and fire-only (orange) treatments. Shaded area indicates 95% confidence interval.

Percent cover of one-hour fine fuels (Figure 2) were similarly affected by time since fire (*β* = 0.110, *σ* = 0.013, *p* < 0.001) and the fire-grazing interaction (*β* = - 0.131, *σ* = 0.019, *p* < 0.001). One-hour fuels in both treatments increased similarly until about 6 months post-fire, at which time the rate of increase in pyric herbivory treatments declined. Approximately 27 months post-fire, cover of 1-hour fuels in pyric herbivory treatments increased in rate of accumulation, probably as a result of grazing patterns associated with pyric herbivory. These results suggest that pyric herbivory can be used as a fuels management technique to extend treatment effects beyond those of prescribed fire alone.

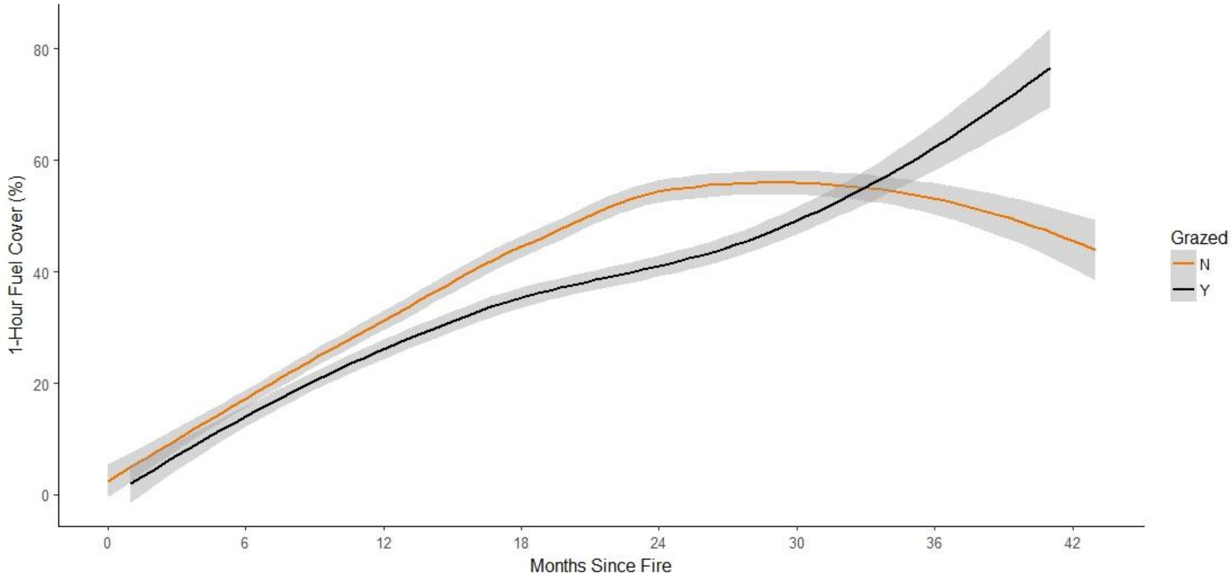

Figure 2. Percent cover of 1-hour fine fuels with increasing time since fire in pyric herbivory (black) and fire-only (orange) treatments. Shaded area indicates 95% confidence interval.

Fire Behavior

Flame lengths simulated from our dynamic fuel models in BehavePlus differed between treatments as a result of time since fire and the fire-grazing interaction (Table 2). Flame lengths under all simulated weather conditions were lower in pyric herbivory than in fire-only treatments.

Table 2. Beta coefficients, standard errors, and significance levels for fixed effects of the fire-grazing interaction and the main effects of time (months) since fire (MSF) and grazing. Simulations were performed using high and low wind scenarios and for fuel moisture content (FMC) ranging from 5 to 35%. Shaded cells indicate statistically non-significant results.

			Interaction effects (MSF*Grazing)			Main effects (MSF)			Main effects (Grazing)		
	Wind (km per h)	FMC (%)	*β*	*σ*	*p*	*β*	*σ*	*p*	*β*	*σ*	*p*
Flame Length	40	5	-0.097	0.035	<0.01	0.406	0.024	<0.001	-2.166	1.325	0.11
		10	-0.085	0.029	<0.01	0.333	0.021	<0.001	-1.723	1.090	0.12
		15	-0.080	0.026	<0.01	0.030	0.018	<0.001	-1.466	0.969	0.13
		20	-0.077	0.024	<0.01	0.276	0.017	<0.001	-1.344	0.903	0.15
		25	-0.072	0.023	<0.01	0.253	0.016	<0.001	-1.233	0.836	0.15
		30	-0.073	0.020	<0.001	0.219	0.014	<0.001	-0.825	0.725	0.26
		35	-0.064	0.013	<0.001	0.150	0.009	<0.001	-0.273	0.490	0.58
	16	5	-0.039	0.017	<0.05	0.196	0.013	<0.001	-1.064	0.657	<0.05
		10	-0.029	0.014	<0.05	0.160	0.011	<0.001	-0.914	0.543	0.1
		15	-0.026	0.013	<0.05	0.142	0.009	<0.001	-0.821	0.483	0.1
		20	-0.011	0.015	0.06	0.132	0.009	<0.001	-0.800	0.452	0.09
		25	-0.020	0.011	0.08	0.121	0.008	<0.001	-0.750	0.423	0.08
		30	-0.016	0.010	0.11	0.102	0.007	<0.001	-0.658	0.365	0.08
		35	-0.010	0.007	0.15	0.073	0.005	<0.001	-0.522	0.271	0.06
Rate of Spread	40	5	-0.006	0.020	0.78	0.147	0.016	<0.001	-1.868	0.641	<0.01
		10	-0.013	0.016	0.43	0.118	0.012	<0.001	-1.371	0.502	<0.05
		15	-0.014	0.013	0.29	0.099	0.010	<0.001	-1.098	0.414	<0.05
		20	-0.014	0.012	0.24	0.088	0.008	<0.001	-0.953	0.367	<0.05
		25	-0.011	0.010	0.28	0.073	0.007	<0.001	-0.802	0.309	<0.05
		30	-0.019	0.008	<0.05	0.062	0.006	<0.001	-0.489	0.244	0.052
		35	-0.018	0.004	<0.001	0.038	0.003	<0.001	-0.124	0.135	0.36
	16	5	0.002	0.006	0.76	0.023	0.004	<0.001	-0.301	0.148	<0.05
		10	0.005	0.004	0.21	0.019	0.003	<0.001	-0.337	0.110	<0.01
		15	0.004	0.003	0.2	0.016	0.002	<0.001	-0.286	0.090	<0.01
		20	0.004	0.003	0.19	0.014	0.002	<0.001	-0.258	0.079	<0.01
		25	0.004	0.003	0.11	0.012	0.002	<0.001	-0.240	0.073	<0.01
		30	0.003	0.002	0.23	0.011	0.002	<0.001	-0.189	0.060	<0.01
		35	0.002	0.001	0.13	0.008	0.001	<0.001	-0.151	0.043	<0.01

When simulating extreme weather conditions (wind speed=40 km per h, 5% fuel moisture), flame lengths in pyric herbivory treatments did not cross the 3.4 m threshold until approximately 8-9 months post-fire, compared to 3-4 months for fire-only (Figure 3A). When wind speed was reduced to 16 km per h and fuel moisture remained at 5%, patches managed with patch-burning maintained simulated flame lengths below 3.4 m for approximately 18 months compared to 6 months for fire-only treatments (Figure 3B).

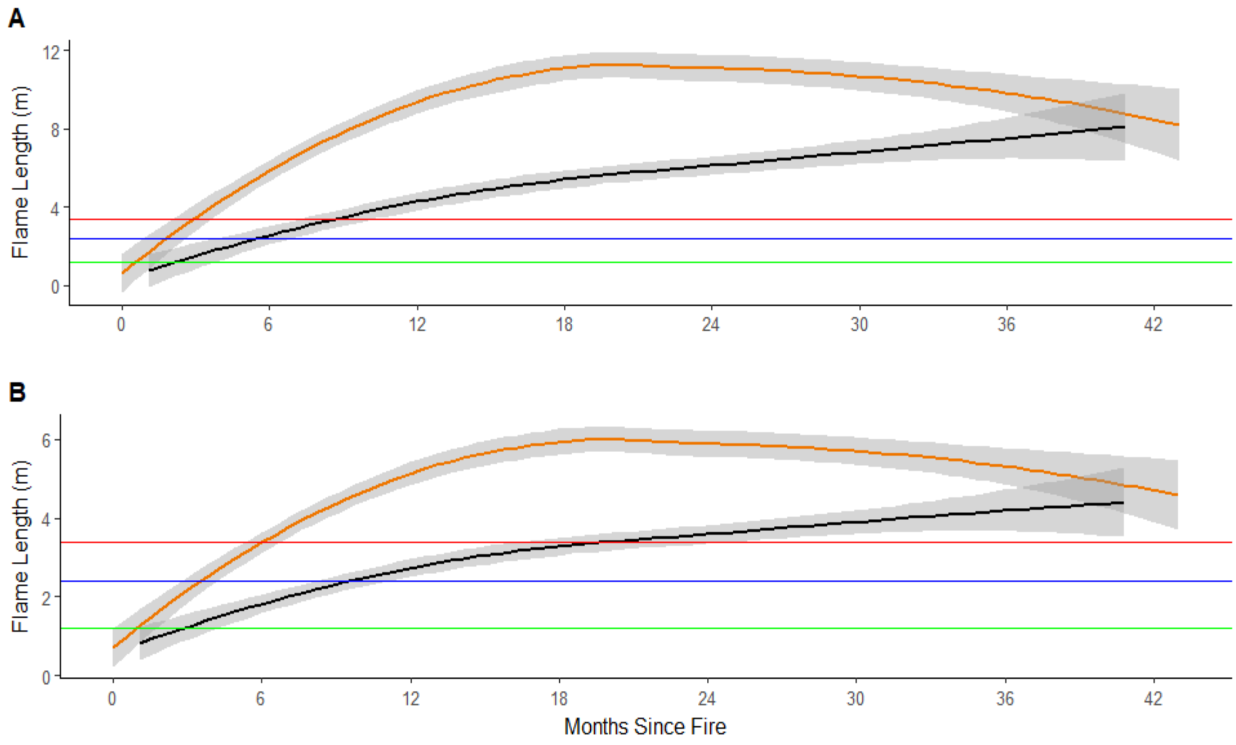

Figure 3. Mean simulated flame length (m) with increasing months since fire across sites for fire-only (orange) and patch-burned (black) treatments. Shaded areas indicate 95% confidence intervals. The green horizontal line indicates the maximum threshold (1.4 m) at which hand tools are effective for fighting wildland fires. The blue horizontal line indicates flame length at which aerial and heavy equipment effectiveness diminishes (2.4 m). The red horizontal line indicates the threshold at which standard wildland firefighting techniques become ineffective (3.4 m). Panel A simulated using high (40 km/h) wind speed and 5% fuel moisture. Panel B simulated using low (16 km/h) wind speed and 5% fuel moisture.

Our results also demonstrate that weather changes typical of diurnal patterns resulted in marked improvements in suppression capabilities in pyric herbivory treatments, but not in fire-only treatments. A decrease in wind speed (from 40 km per h to 16 km per h) paired with an increase in fuel moisture (from 5% to 10%) reduced flame lengths considerably, keeping flame lengths in pyric herbivory treatments below the 3.4 m threshold until 35 months post-fire. Moreover, this benefit was most prominent in the pyric herbivory treatments, as flame lengths in fire-only treatments rose above 3.4 m at 8 months post-fire (Figure 4).

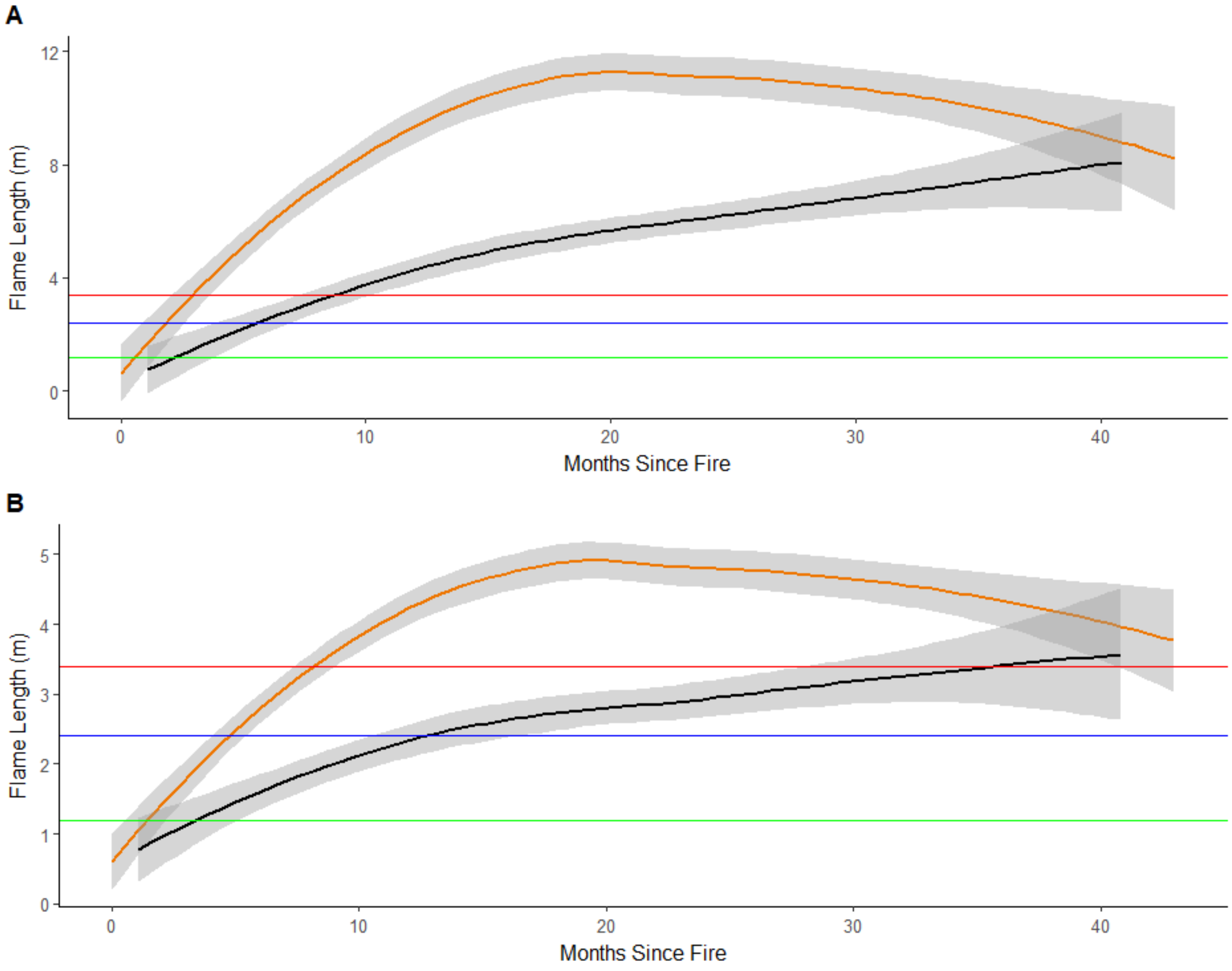

Figure 4. Mean simulated flame length (m) with increasing months since fire across sites for fire-only (orange) and patch-burned (black) treatments. Shaded areas indicate 95% confidence intervals. The green horizontal line indicates the maximum threshold (1.4 m) at which hand tools are effective for fighting wildland fires. The blue horizontal line indicates flame length at which aerial and heavy equipment effectiveness diminishes (2.4 m). The red horizontal line indicates

the threshold at which standard wildland firefighting techniques become ineffective (3.4 m). Panel A simulated using high (40 km/h) wind speed and 5% fuel moisture. Panel B simulated using low (16 km/h) wind speed and 10% fuel moisture. Changes in simulated weather conditions reflect typical changes associated with nightfall in the southern Great Plains

Pyric herbivory was associated with a substantial decrease in percent of simulated flame lengths above the 3.4 m threshold at which wildland firefighting techniques cease to be effective. In high wind-low moisture scenarios, 79% of fire-only transects resulted in flame lengths greater than 3.4 m, compared to 58% of pyric herbivory transects (Figure 5).

Our simulations also revealed significant treatment effects on rates of spread (Table 2). In our most extreme simulated weather conditions, spread rates in fire-only treatments reached 3 m per s in approximately 6 months, compared to 33 months in pyric herbivory treatments (Figure 6A). We found that spread rates, like flame lengths, were also greatly affected by small changes in weather conditions. An increase in fuel moisture from 5% to 10%, with wind speed constant at 40 km per h, resulted in spread rates reaching 3 m per s at approximately 9 months in fire-only and remaining below 3 m per s in pyric herbivory treatments (Figure 6B).

In tests of Eastern redcedar flammability components, we found a threshold for ignitability (time to ignition) at 80% foliage moisture content (FMC). Below this threshold, time to ignition decreased rapidly. The rate of decrease was linear, with time to ignition of 9.0 s at 80% FMC, decreasing to 1.1 s at 0% FMC. Above 80% FMC, ignitability was constant.

Similar thresholds were observed for sustainability and combustibility, but at an FMC of less than 20%. At FMC between 20% and 80%, sustainability (amount of time combustion was sustained) ranged from 7.8 s to 10.1 s. Below 20% FMC, sustainability dropped by 22%. Combustibility (measured using flame height as a proxy) was also constant at FMC above 20%, but increased 45% when FMC fell below this threshold.

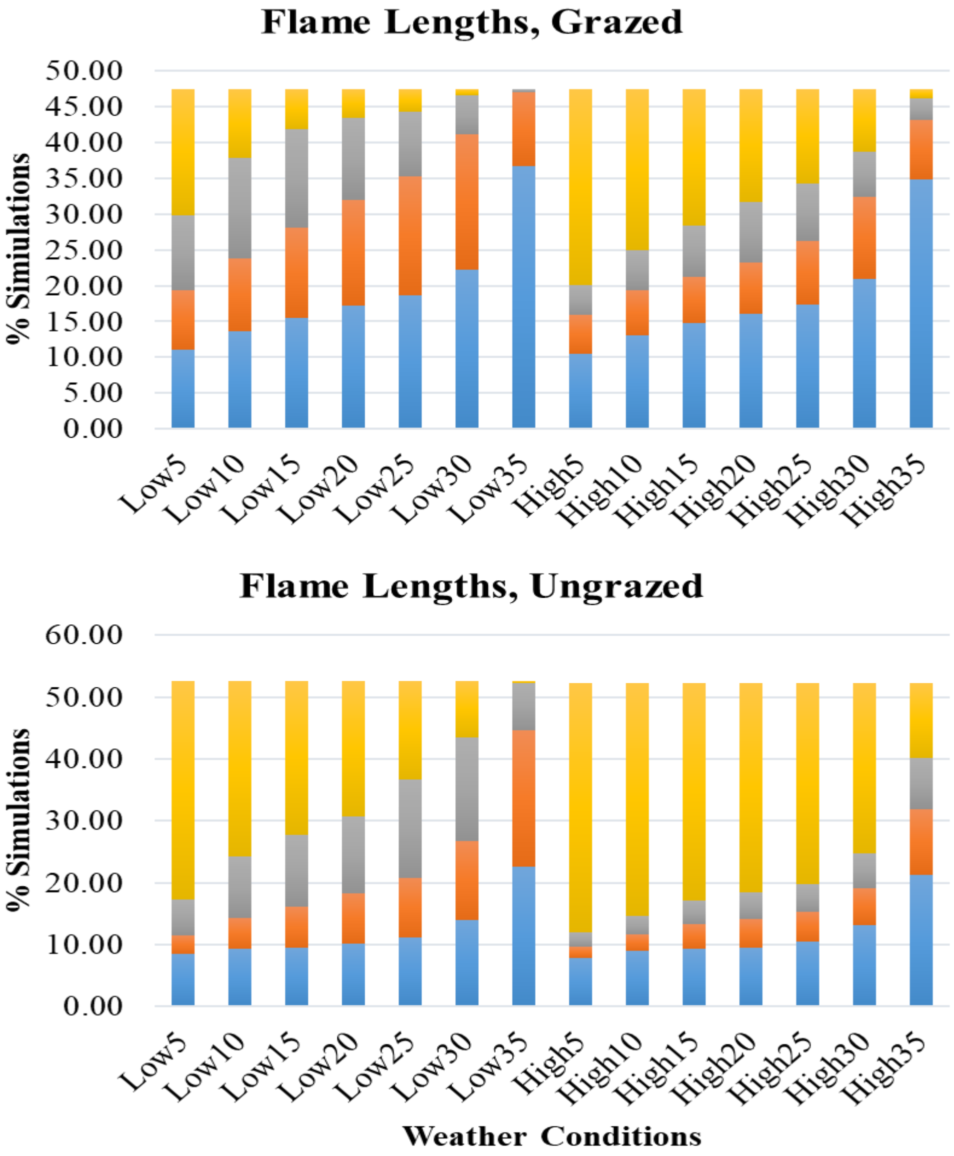

Figure 5. Percentages of fire simulations within each fire management threshold associated with effectiveness of wildland firefighting techniques for pyric herbivory (top)and fire-only (bottom) treatments. Weather conditions simulated were wind speeds 16 km per h (Low) and 40 km per h (High), and fuel moistures from 5 to 35 percent in increments of 5 percent. Note that 47% of sampled transects were in pyric herbivory treatments, while 53% of all sampled transects were fire-only. Blue = flame lengths ≤ 1.4 m, orange = flame lengths 1.41 – 2.4 m, gray = flame lengths 2.41 – 3.4 m, yellow = flame lengths ≥ 3.41 m.

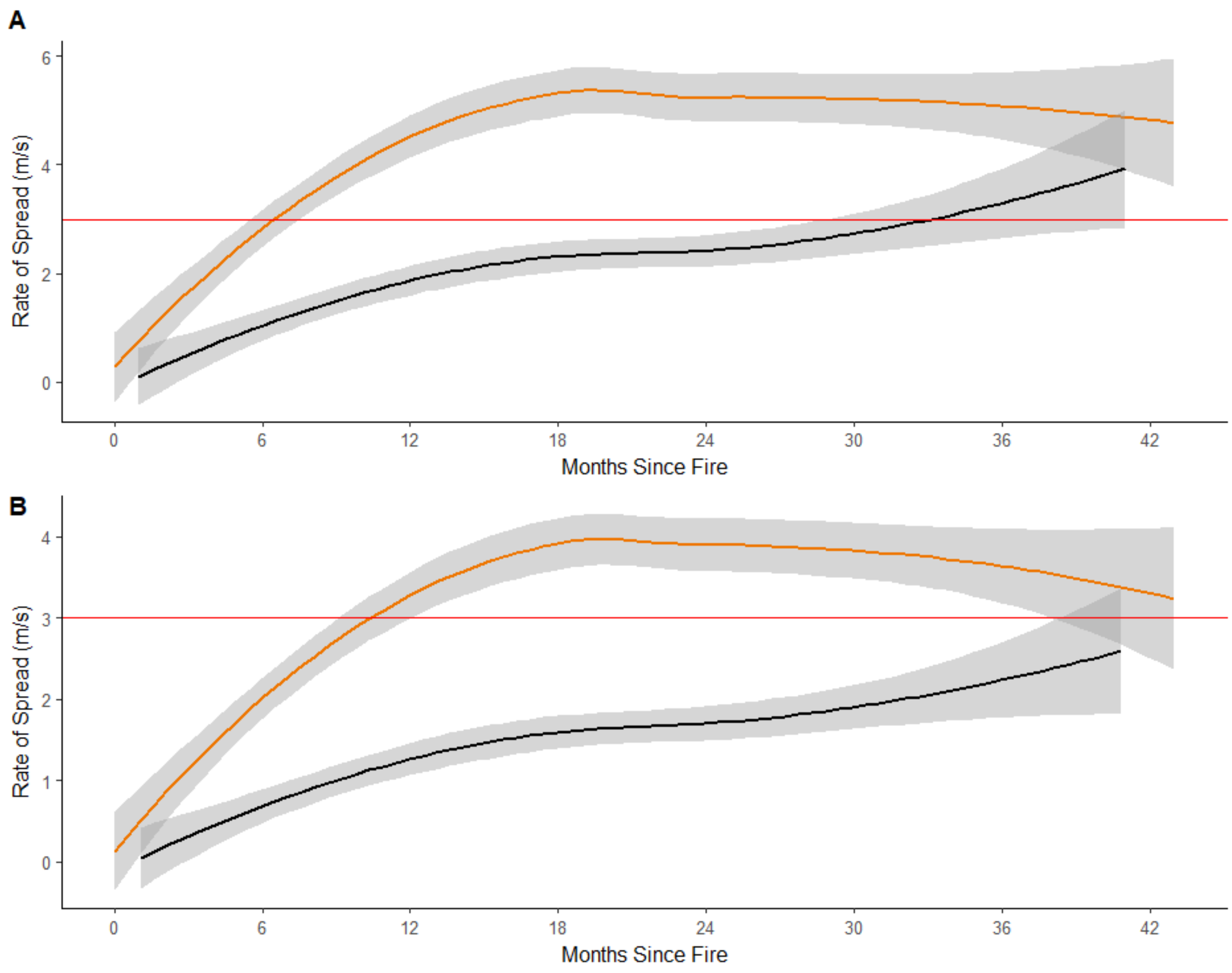

Figure 6. Mean simulated rate of spread (m/s) with increasing months since fire across sites for fire-only (orange) and patch-burned (black) treatments. Shaded areas indicate 95% confidence intervals. Panel A simulated using high (40 km/h) wind speed and 5% fuel moisture. Panel B simulated using high (40 km/h) wind speed and 10% fuel moisture. Horizontal red line at 3 m/s, equal to highest observed spread rate of the East Amarillo Complex fires of 2006.

Vegetation Community Characteristics

We identified differences in several key structural vegetation characteristics important to prairie-chicken habitat suitability. The interaction between time since fire and grazing had a significant effect on percent grass cover ($\beta = 0.03$, $\sigma = 0.016$, $p = 0.03$), which increased at a higher rate in fire-only patches. Grass cover was greater in fire-only treatments beginning approximately 6 months post-fire (Figure 7A). The fire-grazing interaction also had a significant effect on percent cover of forbs (β = -0.035, σ = 0.012, p = 0.003). Forbs, a critical component of prairie-chicken diets, had greater percent cover in pyric herbivory versus fire-only treatments for more than 24 months post-fire (Figure 7B), indicating that management via pyric herbivory has long-lasting potential to provide a greater forage resource than fire-only treatments. Moreover, forbs are positively correlated with abundance of insects, which provide an important forage base for prairie-chicken broods (Hagen et al. 2005, Morrow et al. 2015). Percent bare ground was higher in pyric herbivory than fire-only treatments, but only time since fire was a significant predictor (β = -0.14, σ = 0.012, p < 0.001). Differences in cover of bare ground were evident between 18 and 30 months post-fire (Figure 7C). The difference in bare ground suggest that pyric herbivory may improve the utility of patches with greater time since fire for prairie-chicken broods compared to fire-only treatments. Shrub cover was similar for both treatments, but this may have been a result of overall site differences in shrub presence. Prairie-chicken broods require areas with moderate canopy cover (~25-60%, 20-30 cm high) as well as sufficient bare ground to facilitate chick movement. Considering these recommendations, our results indicate that fire-only treatments exceeded 60% canopy cover within 12 months post-fire, while pyric herbivory maintains canopy cover below the maximum recommended.

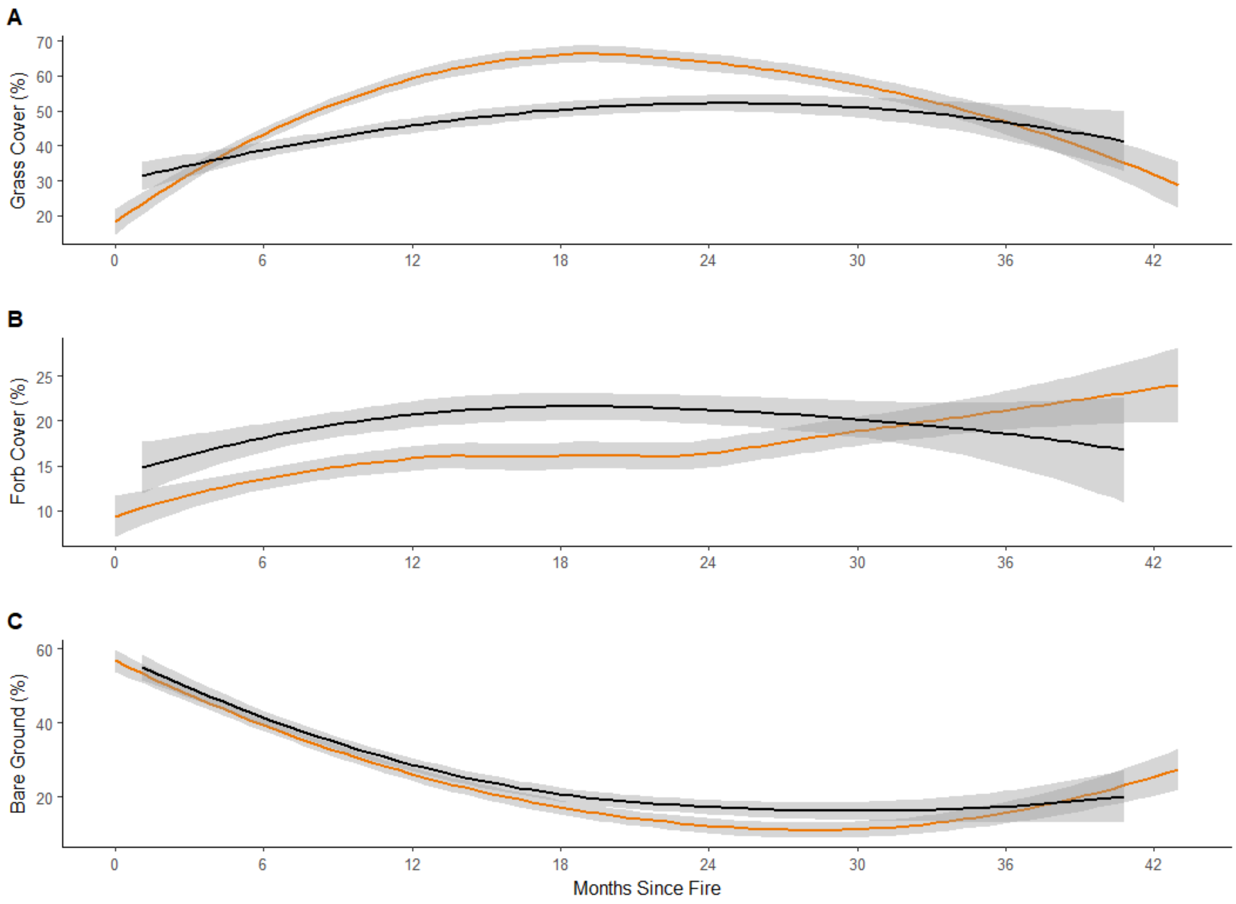

Figure 7. Percent cover of grasses (A), forbs (B), and bare ground (C) with increasing time since fire in pyric herbivory (black) and fire-only (orange) treatments. Shaded areas represent 95% confidence intervals.

We found no significant differences between treatments for invertebrate richness, with mean number of orders 8.63 and 7.79 for pyric herbivory and fire-only treatments, respectively (Table 3). The effect of the fire-grazing interaction on invertebrate biomass approached significance (p = 0.088), with mean biomass per patch of 4.05 g and 2.81g for pyric herbivory and fire-only treatments, respectively (Table 4). Lack of significance in richness may be due to not sorting to the species level. Lack of significance in biomass may be a result of our limited number of samples (n=58) or that we only had one sampling period per patch per year. Another possible explanation may be that patches within our study sites comprised a network of heterogeneous vegetation rather than large expanses of homogeneous vegetation, and that treatments within sites were in close proximity to one another.

Table 3. Summary table of invertebrate richness at each study site. TSF recorded as number of months since fire. PH = pyric herbivory treatment; Fire = fire-only treatment. ANWR – Aransas National Wildlife Refuge; APCNWR – Attwater's Prairie-Chicken National Wildlife Refuge; PSWMA – Packsaddle Wildlife Management Area; TGPP – Tallgrass Prairie Preserve. We sampled invertebrates only during the summer sampling period; NAs indicate no invertebrate sample for the corresponding TSF and treatment.

Site	Year	TSF < 12		TSF 12 - 24		TSF 24 - 36		TSF > 36	
		PH	Fire	PH	Fire	PH	Fire	PH	Fire
ANWR	2014	NA	9	NA	10	NA	7	NA	5
APCNWR	2014	5	NA	10	NA	NA	NA	5	NA
PSWMA	2014	NA	6	11	NA	9	NA	NA	NA
TGPP	2014	NA	NA	7	NA	8	NA	NA	NA
ANWR	2015	NA	9	NA	6	NA	5	NA	6
APCNWR	2015	12	13	13	NA	11	9	NA	NA
PSWMA	2015	11	9	12	NA	11	8	NA	NA
TGPP	2015	10	7	6	NA	9	NA	NA	NA
ANWR	2016	NA	8	NA	7	NA	7	NA	NA
APCNWR	2016	8	7	8	6	6	NA	NA	NA
PSWMA	2016	NA	NA	7	11	8	NA	NA	NA
TGPP	2016	5	10	8	8	8	NA	NA	NA

Table 4. Summary table of invertebrate biomass at each study site. TSF recorded as number of months since fire. PH = pyric herbivory treatment; Fire = fire-only treatment. ANWR – Aransas National Wildlife Refuge; APCNWR – Attwater's Prairie-Chicken National Wildlife Refuge; PSWMA – Packsaddle Wildlife Management Area; TGPP – Tallgrass Prairie Preserve. We sampled invertebrates only during the summer sampling period; NAs indicate no invertebrate sample for corresponding TSF and treatment.

Site	Year	TSF < 12		TSF 12 - 24		TSF 24 - 36		TSF > 36	
		PH	Fire	PH	Fire	PH	Fire	PH	Fire
ANWR	2014	NA	1.5	NA	1.9	NA	1	NA	0.6
APCNWR	2014	2.8	NA	14.3	NA	NA	NA	0.7	NA
PSWMA	2014	NA	2.3	4.2	NA	2.1	NA	NA	NA
TGPP	2014	NA	NA	2.4	NA	4.7	NA	NA	NA
ANWR	2015	NA	1.7	NA	0.9	NA	0.7	NA	0.8
APCNWR	2015	6.6	10.2	7.3	NA	22.1	14.4	NA	NA
PSWMA	2015	4.3	4.1	3.9	NA	1.8	1.8	NA	NA
TGPP	2015	0.8	3.9	2.1	NA	5.3	NA	NA	NA
ANWR	2016	NA	2.6	NA	1.1	NA	0.7	NA	NA
APCNWR	2016	0.4	3.3	0.5	1.1	1	NA	NA	NA
PSWMA	2016	NA	NA	1.6	2.2	2.8	NA	NA	NA
TGPP	2016	0.2	5.3	1.5	1.1	1.2	NA	NA	NA

Vegetation Structural Characteristics

Maximum height of herbaceous vegetation was higher in fire-only than in pyric herbivory treatments (Figure 8A). Six months post-fire, maximum herbaceous vegetation in fire-only treatments exceeded 67 cm, the height reported as preferred nesting habitat for Attwater's prairie-chickens, which avoided vegetation taller than 67 cm for nesting (Lockwood et al. 2005). Mean herbaceous vegetation was also higher in fire-only treatments (Figure 8B).

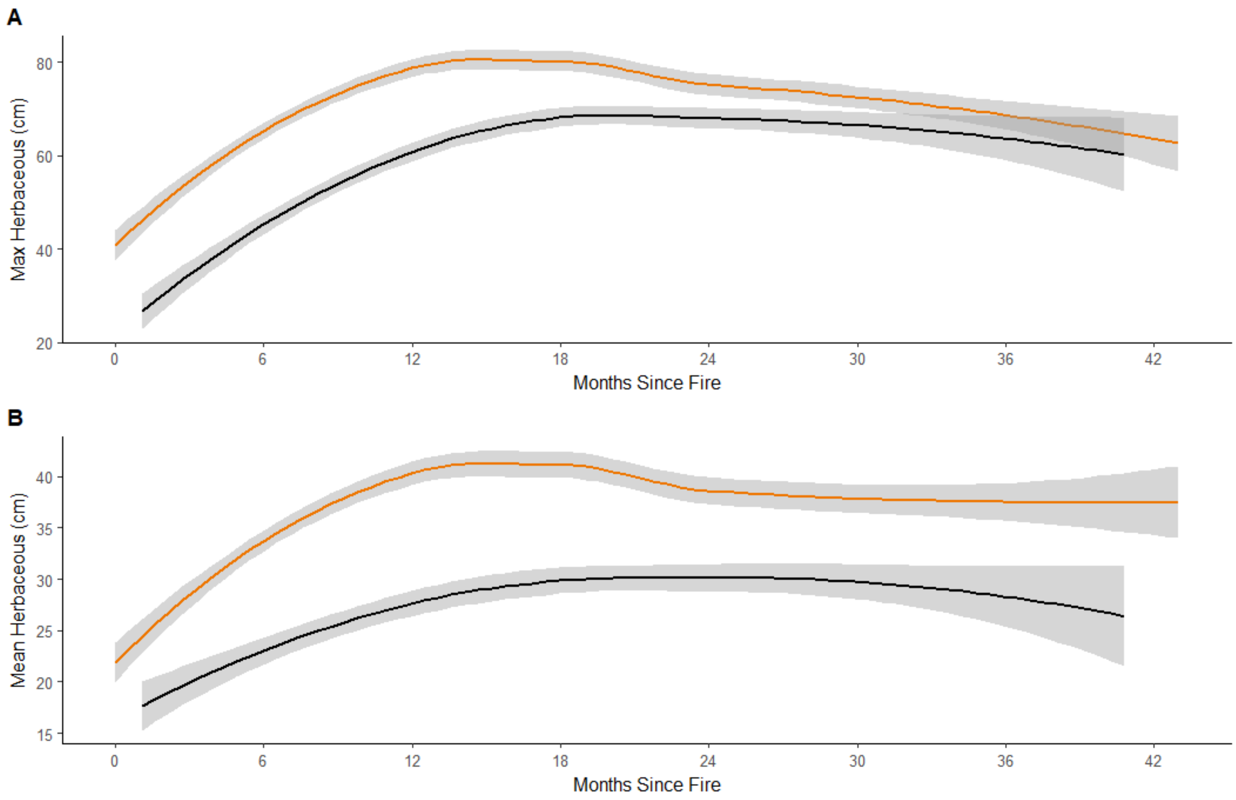

Figure 8. Trends of maximum (A) and mean (B) heights of herbaceous vegetation with increasing time since fire in pyric herbivory (black) and fire-only (orange) treatments. Shaded areas indicate 95% confidence intervals.

Conclusions and Implications for Management/Policy and Future Research

Fire Behavior

The results of our study indicate that the interaction of time since fire and herbivory is an important factor determining the amount and rate of accumulation of fuels in the southern Great Plains, and that the fire-grazing interaction can moderate the fuel response. The effect of pyric herbivory offers substantial benefits to fire suppression techniques when compared to fire-only treatments. Pyric herbivory reduced flame lengths and rates of fire spread for an extended period of time, which could provide for increased suppression capability. Perhaps most notably, subtle weather shifts typical of diurnal patterns (reduced wind speed, increased fuel moisture) resulted in more significant changes in percent of simulated flame lengths above 3.4 m, which were more pronounced in pyric herbivory treatments than in fire-only treatments (58%-20% and 79%-55%, respectively). Given the reductions in rates of fire spread, we suggest pyric herbivory could, if implemented at a landscape scale, result in lower area burned by wildfires in the southern Great Plains. Yet, in the event of fire weather conditions such as those observed during the East Amarillo Complex fires of 2006, with fuel moisture as low as 2-4%, sustained wind speeds of 35 km per hr, and gusts to 90 km per hr, it is not likely that any suppression measures will be adequate to prevent or extinguish fires.

We also quantified impacts on fire suppression capabilities resulting from ecosystem changes associated with long-term fire regime alteration, specifically the transition from grassland to woodlands dominated by eastern redcedar (*Juniperus virginiana*). Flammability thresholds relating to sustainability and combustibility of redcedar at 0-20% FMC can be more readily detected in the field than the threshold in ignitibility at 60-80% FMC. Foliage moisture content of woody plant species typically only drops below 20% during long periods of drought associated with large-scale woody die-offs. In the field, firefighters and managers will already be suspecting increased wildfire risk under such drought conditions. Visual cues (e.g. discoloration of foliage) are not apparent, however, when FMC of redcedar is 60-80%. For a firefighter or manager, a rapid change in the ignitability of redcedar means that the amount of time they have to react, or the ‘delay’ time, to ignition of redcedar foliage can suddenly shift once FMC changes by just 10% (Gill and Zylstra 2005). By monitoring FMC of redcedar at the onset of drought, firefighters and regional planners will have a better idea of when to expect rapid and sudden changes in the flammability and wildfire risk of redcedar than visual vegetation cues.

Our study addresses a knowledge gap identified by Limb et al. (Limb et al. 2016), that few fire ecology studies consider the effects of time since fire. We also add to the evidence that deferment of grazing after fire is not warranted (Gates et al. 2017), at least in highly productive rangelands such as those found in the southern Great Plains. Additionally, we add to the discussion on the benefits of pyric herbivory to biodiversity, which have been stated by a number of researchers in recent years (Fuhlendorf and Engle 2004, Engle et al. 2008, Fuhlendorf et al. 2010, Hovick et al. 2014, Hovick et al. 2015).

Vegetation Community Characteristics

Although we did not find significant differences between treatments for all variables we measured, the differences we identified could provide considerable biological benefits to prairie-chickens during critical life stages. Given that forbs are known to be both a major food source of prairie-chickens and positively correlated to invertebrate abundance (Hagen et al.), even small changes in forb abundance across a landscape may impact survival of prairie-chickens. Matthews et al. (Matthews et al. 2011) reported that brood use of areas increased as forb cover increased. They also reported probability of brood use increased as bare ground increased (Matthews et al.). Our results indicate that pyric herbivory extends the amount of time patches meet the minimum threshold of bare ground. Therefore, in the shifting mosaic landscape offered by pyric herbivory, broods may be able to effectively use a higher proportion of the landscape than in a mosaic managed using fire alone.

Successful implementation of the pyric herbivory paradigm at a landscape scale will allow resource managers to better achieve fuels reduction objectives while still managing conservation objectives. Conservation benefits would not be limited to prairie-chickens, but extend to numerous other taxa (Engle et al. 2008, Powell 2008, Fuhlendorf et al. 2010). Pyric herbivory may also prove to be a cost-effective fuels management strategy for agencies and municipalities in the southern Great Plains, similar to targeted grazing practices in the western United States (Taylor Jr 2006). Furthermore, the livestock production benefits of pyric herbivory (Limb et al. 2016) may motivate private landowners in the region to implement the practice as well.

Future Research Needs

Future research should use geographic information systems or remote sensing to examine the optimal scale and pattern of pyric herbivory treatments within the southern Great Plains. Such research should consider areas near wildland urban interfaces, but must also account for the predominance of privately held lands in the region. Given the ability of pyric herbivory to improve effectiveness of prescribed fire treatments in the southern Great Plains, it may also offer potential benefits to fuels reduction treatments in other regions, particularly in wildland urban interface areas.

Appendix A: Contact Information for Key Project Personnel

Personnel	Role	Contact Information	Email Address
R. Dwayne Elmore	Principal Investigator	008C Agricultural Hall, Stillwater, OK 74078	dwayne.elmore@okstate.edu
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Heath Starns	Doctoral Student	008C Agricultural Hall, Stillwater, OK 74078	heath.d.starns@okstate.edu

Appendix B. Deliverables

Dates	Deliverable	Description
2014	Fire Science Synthesis	Thacker, E.T. and D.L. Twidwell. 2014. Synthesis on the effects of fire on lesser prairie-chickens. Fire Science Synthesis 2014-6. Great Plains Fire Science Exchange
2015	Conference Poster	Starns, H.D., S.D. Fuhlendorf, T.J. Hovick, E.T. Thacker, D. Twidwell, and R.D. Elmore. 2015. Patch-burning impacts on prairie-chicken habitat. 2015 Prairie Grouse Technical Council. Nevada, Missouri, USA.
2015	Conference Presentation	Starns, H.D., S.D. Fuhlendorf, T.J. Hovick, E.T. Thacker, D. Twidwell, and R.D. Elmore. 2015. Impacts on prairie-chicken habitat from management of rangeland fuels. 6th Association for Fire Ecology International Fire Congress. San Antonio, Texas, USA.

2015	Conference Presentation	Starns, H.D., S.D. Fuhlendorf, T.J. Hovick, E.T. Thacker, D. Twidwell, and R.D. Elmore. 2015. Impacts on prairie-chicken habitat from management of rangeland fuels. 2015 Patch-Burn-Grazing Conference. Pratt, Kansas, USA.
2015	Conference Presentation	Starns, H.D., S.D. Fuhlendorf, T.J. Hovick, E.T. Thacker, D. Twidwell, and R.D. Elmore. 2015. Impacts on prairie-chicken habitat from management of rangeland fuels. 2015 Annual Meeting of the Society for Range Management. Sacramento, California, USA.
2015	Conference Presentation	Bielski, C.H., Twidwell, D., Elmore, D.R., Engle, D.M., Fuhlendorf, S.D., Hovick, T.J., Thacker, E.T (2015). Flammability Thresholds of Eastern redcedar as a Potential Indicator of Heightened Wildfire Danger. Natural Areas Annual Conference in Little Rock, AR.
2015	Webinar	Elmore, R.D. 2015. Fire and Prairie-Chickens. Great Plains Fire Science Exchange.
2016	Conference Poster	Starns, H.D., S.D. Fuhlendorf, R.D. Elmore, M.E. Morrow, and R.E. Chester. 2016. Attwater's prairie-chicken us of burned areas. 2016 Annual Meeting of the Society for Range Management. Corpus Christi, Texas, USA.
2016	Conference Presentation	Starns, H.D., R.D. Elmore, S.D. Fuhlendorf, T.J. Hovick, E.T. Thacker, and D. Twidwell. 2016. Patch-burning implications to fire behavior and prairie-chicken habitat. 2016 Patch-Burn-Grazing Conference. Childress, Texas, USA.
2016	Conference Presentation	Starns, H.D., R.D. Elmore, S.D. Fuhlendorf, T.J. Hovick, E.T. Thacker, and D. Twidwell. 2016. The effects of patch-burning on wildland fuels management. 2016 Annual Meeting of the Society for Range Management. Corpus Christi, Texas, USA.
2016	Conference Presentation	Starns, H.D., R.D. Elmore, S.D. Fuhlendorf, T.J. Hovick, E.T. Thacker, and D. Twidwell. 2016. Patch-burning supports heterogeneity of prairie-chicken habitat. 2016 Annual Meeting of the Society for Range Management. Corpus Christi, Texas, USA.
2016	Conference Presentation	Bielski, C.H., D. Twidwell. 2016. Flammability thresholds of eastern redcedar as a potential indicator for heightened wildfire danger. Society for Range Management Annual Meeting. Corpus Christi, Texas, USA.
2016	Conference Presentation	Bielski, C.H., Twidwell, D., Fuhlendorf, S.D., Engle, D.M., Krueger, E.S., Carlson, J.D., Ochsner, T.E. (2016). Quantifying Dynamic Grassland Fuel Properties to Improve Fire Behavior Fuel Models. Southwest Fire Ecology Conference in Tucson, AZ.

2016	Conference Presentation	Bielski, C.H., Twidwell, D., Elmore, D.R., Engle, D.M., Fuhlendorf, S.D., Hovick, T.J., Thacker, E.T. (2016). Flammability Thresholds of Eastern redcedar as a Potential Indicator of Heightened Wildfire Danger. Society of Range Management 69th Annual Conference in Corpus Christi, TX.
2016	Field Tour for Managers	Field tour of Aransas NWR in cooperation with the Society for Range Management and the Great Plains Fire Science Exchange
2016	Outreach Posters for Research Sites	Starns H.D., S.D. Fuhlendorf, R.D. Elmore, D. Twidwell, E.T. Thacker, and T.J. Hovick. 2016. Conservation Orientated Fuels Management.
2016	Workshop	Workshop on range management for prairie-chickens for state, federal, and private managers.
2017	Conference Presentation	Starns, H.D., R.D. Elmore, S.D. Fuhlendorf, T.J. Hovick, E.T. Thacker, and D. Twidwell. 2017. Effects of fuels management techniques on fire suppression capability and prairie-chicken habitat. 2017 Annual Meeting of the Society for Range Management. St. George, Utah, USA.
2017	Fire Science Brief	Starns H.D., S.D. Fuhlendorf, R.D. Elmore, D. Twidwell, E.T. Thacker, and T.J. Hovick. 2017. Patch-Burning Reduces Fuels and Benefits Prairie-Chicken Conservation. Fire Science Brief 2017-1. Great Plains Fire Science Exchange.
2017	Thesis	Bielski CH. 2017. Complex vegetation dynamics at the fire, grazing, drought nexus. MS Thesis. University of Nebraska. Lincoln, Nebraska, USA. URL: http://digitalcommons.unl.edu/agronhortdiss/115.

Appendix C. Metadata

Data collected for this project includes vegetation and fuels data, fire simulation data, and invertebrate richness and biomass data. All data is stored as .csv and can be accessed from the US Forest Service Research Data Archive.

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