RESEARCH ARTICLE

FIRE EFFECTS ON BASAL AREA, TILLER PRODUCTION, AND MORTALITY OF THE C_4 BUNCHGRASS, PURPLE THREEAWN

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ABSTRACT

Fire behavior associated with wild and prescribed fires is variable, but plays a vital role in how a plant responds to fire. Understanding the relationship between fire behavior and rangeland plant community response will help to improve the use of prescribed fire to achieve management objectives. Fire is an important ecological process in many rangeland ecosystems and can be used as a tool to maintain grassland plant communities and shift community composition. Purple threeawn (*Aristida purpurea* Nutt.) is a grass native to North America that has poor forage quality and the ability to form near monocultures. Therefore, the identification of tools to reduce purple threeawn abundance is desirable. We assessed the effects of summer and fall prescribed fire on purple threeawn plant basal area, tiller production, and plant mortality one growing season post fire in the northern Great Plains. Thermocouples and portable data loggers were used to measure the

RESUMEN

El comportamiento del fuego asociado a incendios silvestres y quemas prescritas es variable, pero juega un papel vital en la respuesta de las plantas al fuego. Entender la relación entre el comportamiento del fuego y la respuesta de las comunidades de pastizales ayudará a mejorar el uso de quemas prescritas para conseguir objetivos de manejo. El fuego es un importante proceso ecológico en muchos ecosistemas de pastizales y puede usarse como herramienta para mantener comunidades de pastizales y cambiar la composición de las comunidades. El pasto *Aristida purpurea* Nutt. es nativo a Norteamérica, tiene baja calidad de forraje y la capacidad de dominar comunidades al grado de convertirlas casi en monocultivos. Debido a esto, la identificación de herramientas para reducir su abundancia es deseable. Estudiamos los efectos de quemas prescritas de verano y otoño en el área basal de este pasto, su producción de hijuelos florales y mortalidad una temporada de crecimiento después de un incendio, al norte de las Grandes Planicies. Se utilizaron termopares y registradores portátiles de datos para medir la maximum temperature, heat duration, and heat dosage that individual purple threeawn plants experienced. Fire reduced basal area and tiller production 59% and 57%, respectively. Heat dosage (*C*-statistic = 0.69) and heat duration (*C*-statistic = 0.65) were good predictors of purple threeawn mortality. A restrospective analysis showed maximum temperatures were similar for fall and summer fires but heat duration and dosage were 44% and 21% greater for summer fires, respectively. Our results indicate that purple threeawn is a fire sensitive species. The ability to predict purple threeawn mortality could enhance the efficacy of prescribed fire as tool to restore purple threeawn and other *Aristida*-dominated plant communities.

temperatura máxima, duración del calor y dosis de calor experimentadas por plantas individuales de *A. purpurea.* El fuego redujo el área basal y producción de hijuelos en un 59% y 57%, respectivamente. La dosis de calor (estadístico *C* = 0.69) y duración del calor (estadístico *C* = 0.65) fueron buenos predictores de la mortalidad de la planta. Un análisis retrospectivo mostró que las temperaturas máximas fueron similares para los incendios de otoño y verano, pero la duración y dosis del calor fueron, respectivamente, 44% y 21% más altas en los incendios de verano. Nuestros resultados indican que este pasto es una especie sensible al fuego. La capacidad de predecir su mortalidad puede ayudar a mejorar la eficacia de las quemas prescritas para restaurar comunidades de plantas dominadas por *A. purpurea* y otras especies de este género.

Keywords: Aristida, fire behavior, heat dosage, maximum temperature, prescribed burn, range management, thermocouple

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INTRODUCTION

Fire is an important ecological process in grasslands and is characterized by high variability in its wild and prescribed forms. The variability associated with fires is largely determined by season of fire, fuel characteristics, and weather (Wright and Bailey 1982). The responses of grassland plant communities to fire during different seasons, under variable fuel characteristics and weather conditions are well-documented (Dix 1960, Cable 1967, Steuter and Wright 1983, Engle and Bultsma 1984). While season of fire, fuel characteristics, and weather are the primary drivers of fire variability, there are opportunities to augment that information by quantifying fire behavior (e.g., heat duration, heat dosage, rate of spread) using thermocouples or other devices. Measuring fire behavior could improve our understanding of the mechanisms driving individual plant and community response to fire (Vermeire and Rinella 2009, Fuhlendorf *et al.* 2011).

Prescribed fire is a tool that grassland managers can use to alter community structure, improve forage availability, and reduce the dominance of unwanted plants (Pyke *et al.* 2010). Grasses in the *Aristida* genus that occur on arid to semi-arid lands have demonstrated the ability to become the dominant member of a plant community, a phenomenon documented in North America, Africa, and Australia (Paton and Rickert 1989, Horn and Redente 1998, Kepe 2005). In North America, purple threeawn (*Aristida purpurea* Nutt.) is a native perennial grass with poor overall forage quality and the ability to form near monocultures and dominate for 60+ years (Costello 1944, Horn and Redente 1998). Nitrogen fertilization has been tested as a tool to reduce purple threeawn abundance with mixed results (Hyder and Bement 1972, Horn and Redente 1998, Strong *et al.* 2013). Fire appears to be a highly effective tool for reducing purple threeawn abundance, yet the mechanism driving purple threeawn's negative response to fire is unclear. In general, bunchgrasses, or tussock-forming grasses like purple threeawn, tend to be fire sensitive due to heavier fuel loads associated with individual plants and elevated growing points (Wright and Bailey 1982).

Fire injury to plant tissue is believed to occur when temperatures above 60 °C are sustained for an extended period of time (Stinson and Wright 1969, Wright and Bailey 1982) and is directly related to fuel load (Bebawi and Campbell 2002*a, b*). Thermocouples enable collection of fire temperature data to calculate heat duration (seconds of exposure to temperatures >60 °C) and total heat dosage (sum of exposure to temperatures >60 °C for each second) at the plant or community level. Although thermocouples have been criticized for their accuracy and ability to estimate heat flux in forested systems (Kennard *et al.* 2005, Bova and Dickinson 2009), they have proved to be an effective tool for studies of fire effects in several rangeland studies (Ewing and Engle 1988, McDaniel *et al*. 1997, Vermeire and Roth 2011). These measurements coupled with season of fire, fuel characteristics, and weather enable more complete descriptions of fire events, as well as the responses of plant communities. By taking detailed fire measurements, we increase the repeatability of a particular fire, enhancing our ability to use fire to achieve a desired outcome (e.g., purple threeawn reduction). The identification of a range in which maximum temperature, heat duration, and heat dosage have the greatest impact on purple threeawn could improve the efficacy of prescribed fire as a management tool for purple threeawn-dominated plant communities.

The objectives of our study were to (1) assess the effect of fire and nitrogen fertilization on purple threeawn tiller production and basal area, and (2) determine the relationship between purple threeawn mortality and maximum temperature, heat duration, and heat dosage.

METHODS

Study Area

We conducted this research in semi-arid mixed-grass prairie on Bureau of Land Management property near Terry, Montana, USA, from July 2011 to July 2012. Average annual precipitation for the area is 295 mm, with the majority occurring April through September. Mean annual temperature is 6.6 °C, with extremes of 44 °C during the summer and –43 °C during the winter. The frost-free growing season typically ranges from 105 days to 135 days (Western Regional Climate Center 2012).

Our study site was located within approximately 30 000 ha of cropland abandoned prior to 1910. The area was subsequently seeded to crested wheatgrass (*Agropyron cristatum* [L.] Gaertn) from 1936 to 1942 (McWilliams and Van Cleave 1960). The study site was characterized by flat, upland plains situated on a sandy ecological site over the Degrand soil series (a fine-loamy over sandy or sandy-skeletal, mixed, superactive, frigid Aridic Argiustolls) (USDA, NRCS 2010*a*). Our study site was located within a Bureau of Land Management grazing allotment that had been moderately to heavily grazed for at least 40 years. In 2009, a 3.2 ha exclosure was constructed to prevent cattle from grazing research plots.

Vegetation at our study site was dominated by the perennial C_4 (warm-season) bunchgrass purple threeawn and the perennial C_3 (cool-season) bunchgrass crested wheatgrass. Other C_4 perennial grasses present included sand dropseed (*Sporobolus cryptandrus* [Torr.] A. Gray), blue grama (*Bouteloua gracilis* [Willd. ex Kunth] Lag. ex Griffiths), buffalograss (*B. dactyloides* [Nutt.] Engelm.), and tumblegrass (*Schedonnardus paniculatus* [Nutt.] Trel.). Another C_3 perennial grass was needle and thread (*Hesperostipa comata* [Trin. & Rupr.]

Barkworth). Annual grasses were sixweeks fescue (*Vulpia octoflora* [Walt.] Rydb.), Japanese brome (*Bromus arvensis* L.), and cheatgrass (*B. tectorum* L.). The sub-shrub green sage (*Artemisia campestris* L.) was present, in addition to hairy goldenaster (*Chrysopsis villosa* [Pursh] Nutt.), and the biennial forb, yellow salsify (*Tragopogon dubius* Scop.). Annual forbs included field cottonrose (*Logfia arvensis* [L.] Holub) and woolly plantain (*Plantago patagonica* Jacq.). Plant nomenclature follows the USDA PLANTS database (USDA, NRCS 2010*b*).

Experimental Design and Treatment Application

This study was nested within a larger study in which fire and nitrogen effects on purple threeawn abundance were tested by randomly assigning three levels of fire (no fire, summer fire, fall fire) and three levels of nitrogen (0 kg ha^{-1}, 46 kg ha^{-1}, 80 kg ha^{-1}) with three replications to 27 20 m × 20 m plots (Strong *et al.* 2013). We randomly selected 10 purple threeawn plants in each plot and measured them prior to treatment application and one growing season post fire. To discourage edge effects, plants selected were located at least 5 m from the edge of the plots.

We applied summer and fall fires on 7 September 2011 and 31 October 2011, respectively. All fires were set using the ring-fire method (Wright and Bailey 1982) and average fuel load for each plot was 2000 kg ha^{-1}. Summer fires (Figure 1) were applied when purple threeawn seeds began dropping and fall fires were applied following the first killing frost (−2.0 °C). Summer fires were applied with ambient temperatures of 29 °C to 31 °C, relative humidities of 15 % to 20 %, winds of 5 km h^{-1} to 13, and fine fuel moistures of 16 % to 27 %. Fall fires were applied with ambient temperatures of 16 °C to 20 °C, relative humidities of 28 % to 34 %, winds of 13 km h^{-1} to 30 km h^{-1}, and fine fuel moistures of 8 % to 11 %. Fuel moisture samples included live and dead plant material. Good fuel continuity allowed for 100 % fire coverage of all plots, across seasons of fire. Nitrogen fertilizer in the form of granular urea was applied 5 April 2012.

Figure 1. Summer fire plot burned in September 2011.

Thermocouple Measurements

We used HOBO® U12 J, K, S, T Thermocouple Data Loggers (Onset Computer Corporation, Bourne, Massachusetts, USA) with K-type Thermocouples (Omega Engineering, Inc., Stanford, Connecticut, USA) to create time-temperature profiles for individual plants. We placed thermocouples in each plot within the crown of a target plant (10 thermocouples $plot^{-1}$) and programmed the data loggers to record temperatures at one-second intervals (Figure 2). Maximum temperature was identified by finding the greatest value for each time-temperature profile. Heat duration was calculated as time (seconds) of heat greater than 60 °C and heat dosage was the sum of the products of time and degrees >60 °C·s (degree-seconds). We used these measurements to derive the mean maximum temperature, heat duration, and heat dosage that individual plants experienced (Table 1). Although we had 10 thermocouples in each plot, improper thermocouple installation (i.e., thermocouple tips were not fixed in the crown of the purple threeawn plant), prevented us from collecting data on all

Figure 2. Thermocouples and target plants in a plot burned in October 2011.

plants assigned a thermocouple. Those plants were not included in our plant-level analysis, resulting in differences in sample size for summer fires ($n = 55$) and fall fires ($n = 73$). Additionally, thermocouple data were used to create time-temperature profiles for each plot (i.e., the mean of plant time-temperature profiles).

Vegetation Measurements

We quantified plant response to treatments by measuring basal area and vegetative, reproductive, and total tiller production in July of each year. Basal area for individual plants was calculated by using a string and ruler to measure the circumference of each target plant. We conducted tiller counts on each plant to determine total tiller production, vegetative tiller production, and reproductive tiller production.

Statistical Analysis

We analyzed plot-level plant data using generalized least squares (MIXED procedure of SAS; Littell *et al.* 2006). The model included season of fire and nitrogen fertilizer as fixed effects. Response variables were plant basal area, vegetative tiller, reproductive tiller, total tillers, and percentage of total tillers in the reproductive state. All plants were used to determine treatment effects on basal area; however, only plants that survived were used to determine treatment effects on tiller production and percentage of total tillers in the reproductive state. Plot was the experimental unit and we set statistical significance at $P < 0.05$. In a second analysis, we tested maximum temperature, heat duration, and heat dosage as predictor variables for purple threeawn mortality with logistic regression (LOGISTIC procedure of SAS; Littell *et al.* 2006). Plant was the experimental unit and we set statistical significance at $P < 0.05$. Additionally, we used a re-

Table 1. Mean and range of thermocouple observations for individual plants[a] during summer and fall prescribed fires near Terry, Montana, USA.

	Summer fire		
Thermocouple measurements	**Mean**	**Maximum**	**Minimum**
Maximum temperature (°C)	222	433	86
Heat duration (s)	232	894	52
Heat dosage (°C·s)	10 352	25 624	1 094
	Fall fire		
Maximum temperature (°C)	241	487	85
Heat duration (s)	129	245	68
Heat dosage (°C·s)	8 205	18 706	1 771

[a] Used to build logistic regression model. $n = 55$ for summer fire; $n = 73$ for fall fire.

strospective analysis to examine the difference between seasons of fire. We used generalized least squares (MIXED procedure of SAS; Littell *et al.* 2006). The model included season of fire as a fixed effect; response variables were maximum temperature, heat duration, and heat dosage.

RESULTS

Weather

Growing season (April to August) precipitation in 2011 was approximately 414 mm, more than four times the average for the study area. The year following fire, 2012, growing season precipitation was 20% below average for the study area.

Plant Basal Area and Tiller Production

Nitrogen fertilizer had no effect on any response variable ($P = 0.100$). Summer fire and fall fire reduced purple threeawn plant basal area 64% and 54% ($P < 0.001$), respectively, and there was no difference in basal area between summer and fall fires. Summer fire and fall fire reduced vegetative tiller production 58% and 55% ($P < 0.001$), respectively, with no difference between seasons of fire. Reproductive tiller production was least for summer burned plants (5 ± 1 tiller plant^{-1}), intermediate for non-burned plants (10 ± 1 tiller plant^{-1}), and greatest for fall-burned plants (13 ± 1 tiller plant^{-1}, $P < 0.001$). Total tiller production was reduced 55% with summer fire and 39% with fall fire ($P < 0.001$; Figure 3A). The percentage of total tillers that were reproductive was similar between non-burned and summer burned plants but greater for fall burned plants ($P < 0.001$; Figure 3B).

Plant Mortality

Fire resulted in 10% mortality of purple threeawn plants that were surveyed (13 of 128 plants) and mortality was directly related to heat dosage and duration. Furthermore, summer fire accounted for 75% (10 of 13 plants) of purple threeawn mortality. Heat dosage was the best predictor of plant mortality, but heat duration was a reliable predictor as well (Table 2). Maximum temperature was not a good predictor of plant mortality.

When heat dosage rose above 10 000 °C · s, the probability of plant mortality exceeded 0.1 (Figure 4A). With heat duration, the probability of plant mortality reached 0.1 when temperatures were above 60 °C for 3 minutes (Figure 4B). The 95% confidence intervals illustrate that most of our data points were located on the lower end of heat dosage and duration, limiting our ability to make precise predictions about purple threeawn mortality at the upper range of heat dosage and duration.

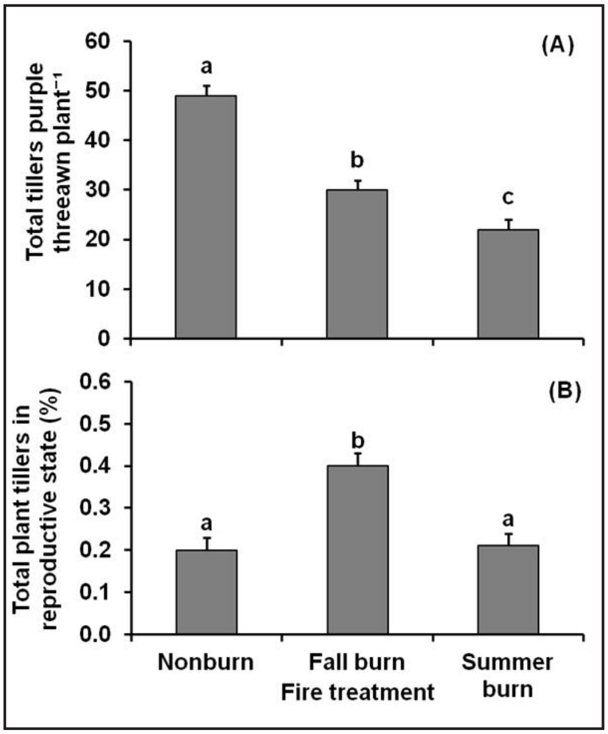

Figure 3. Fire effects on (A) total tiller production purple threeawn plant^{-1} (+ standard error of the comparison), and (B) percentage of total tillers in the reproductive state (+ standard error of the comparison) one growing season post fire near Terry, Montana, USA, in 2011. Means marked with the same letter are similar ($P < 0.05$).

Table 2. Predictive ability of fire variables used in logistic regression model to test for purple threeawn mortality.

	Model information		
Predictor variable	***C*-statistic**[a]	**H-L test**[b]	**χ^2**
Heat dosage (°C·s)	0.69	0.47	0.04
Heat duration (s >60 °C)	0.65	0.92	0.02
Maximum temperature (°C)	0.55	≤0.01	0.54

[a] *C*-statistic is the predictive ability of the model.
[b] Hosmer-Lemeshow goodness of fit test (higher value = better fit).

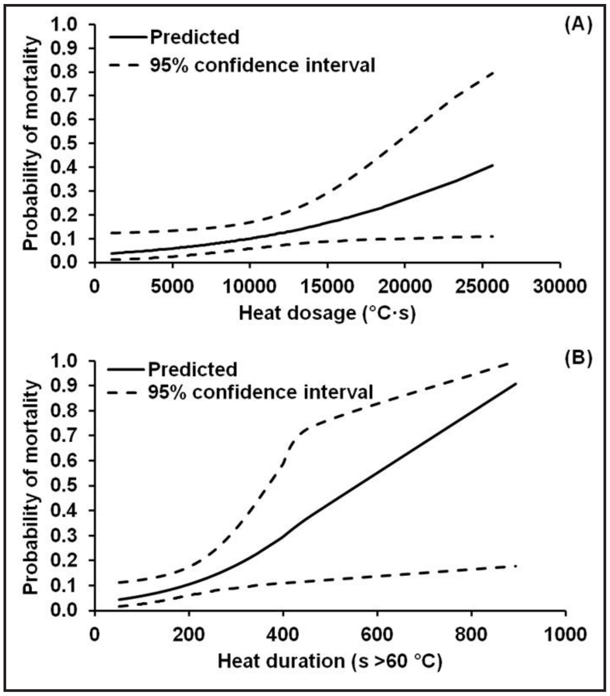

Figure 4. Predicted mortality and 95 % confidence interval for purple threeawn as a function of (A) heat dosage and (B) heat duration.

Season of Fire

Plot-level thermocouple data indicated that fire behavior was different between summer and fall fires ($P < 0.03$; Table 3). Average heat dosage and duration were greater during summer fires than fall fires. Fuel load and connectivity was similar between plots; however, fuel moisture was greater for summer fires than fall fires. Additionally, weather conditions varied between seasons with fall fires having stronger winds, drier fine fuel moistures, cooler ambient temperatures, and greater relative humidities than summer fires.

DISCUSSION

Nitrogen had no effect on purple threeawn basal area and tiller production in this study. The nitrogen fertilizer was applied in early April and precipitation did not occur at our study area until late April. The time between

Table 3. Maximum temperature (°C), heat duration (s), and heat dosage (°C·s) for plots burned during the summer and fall, respectively, near Terry, Montana, USA, in 2011. There were 9 summer fires and 9 fall fires. Means marked with the same letter are similar ($P > 0.05$).

	Thermocouple measurement		
Season of fire	**Max. temperature (°C)**	**Heat duration (s)**	**Heat dosage (°C·s)**
Summer fire	225[a]	221[a]	10 284[a]
Fall fire	223[a]	127[b]	7 505[b]
SEc[1]	13	10	761

[1] Standard error of the comparison.

when fertilizer was applied and when precipitation was received may have led to nitrogen volatilization. However, in a companion study, we found that nitrogen fertilizer had no effect on purple threeawn biomass or cover when precipitation was received the day of fertilizer application and subsequent growing season precipitation was above average (Strong *et al.* 2013).

Fire negatively impacted purple threeawn tiller production and basal area. Our observations are similar to experiments in New Mexico (Killgore *et al.* 2009), where fire reduced purple threeawn basal area and plants did not recover to pre-fire size for 4 yr to 5 yr post fire (Parmenter 2008). Reductions in basal area following fire are common in bunchgrasses due to the removal of litter accumulation near the center of the plant, and the high probability of plant tissue injury from the combustion of that litter (Ewing and Engle 1988). Our observed reductions in total tiller production correspond with other studies that reported reductions in current-year biomass and cover of purple threeawn following fire (Steuter and Wright 1983, Russell *et al.* 2013, Strong *et al.* 2013). Our results and the findings of others suggest that purple threeawn is susceptible to fire injury. Response of other *Aristida* species that occur on semi-arid lands is less clear. For example, the relative density of *A. ramosa* and *A. calycina* decreased with spring burning in Australia, but increased following a late-summer burn (Paton and Rickert 1989). *Aristida junciformis's* relative abundance was greater in nonburned plots than in plots burned during the winter or spring in Africa (Fynn *et al.* 2005). Further testing is needed to draw conclusions about the fire sensitivity of semi-arid *Aristida* species outside of North America.

Fall fire increased reproductive tiller production and summer fire decreased reproductive tiller production. Our fall fire observations support previous purple threeawn research in the southern mixed prairie on reproductive tiller production post fire (Trlica and Schuster 1969). Although vegetative reproduction is the most common form of propagation for native grasses in many grassland ecosystems (Benson *et al.* 2004), seed production appears to be important for purple threeawn propagation (Fowler 1986). Purple threeawn is a prolific seed producer (Evans and Tisdale 1972), with highly viable seeds well adapted to wind and animal dispersal. Therefore, our data indicate that summer fire is more detrimental to purple threeawn due to the observed reductions in total and reproductive tiller production.

Our data support the hypothesis that heat dosage and duration are important factors to consider in relation to purple threeawn production and mortality. The majority of the data points for heat dosage and duration were distributed at the lower end of their respective ranges, indicating that other factors (e.g., fuel load, rate of spread) were limiting the amount of heat dosage and duration each plant was experiencing. Therefore, mortality greater than 10% may not have been attainable under the conditions in which we burned. We showed that maximum temperature does not accurately predict plant mortality, which supports the findings of others (Bebawi and Campbell 2002*a*, Vermeire and Roth 2011, Russell *et al.* 2013). Furthermore, our retrospective analysis supports the tenet that maximum temperature provides limited information about plant response to a fire event and highlights the importance of taking detailed fire measurements focused on the duration of lethal temperatures.

One objective of this study was to highlight the importance of measuring fire behavior variables when relating plant mortality or production to fire. However, it must be acknowledged that other factors can affect plant mortality and production post fire (e.g., plant competition and post-fire growing conditions). The plant community in our study was comprised primarily of purple threeawn and crested wheatgrass. Purple threeawn is a C_4 perennial grass capable of producing a substantial root system that grows deep into the soil profile relatively quickly (Evans and Tisdale 1972). Crested wheatgrass is a C_3 perennial grass with a root system more similar to an annual crop (DeLuca and Keeney 1994) (i.e., a shallow root system). The differences in photosynthetic pathway and root physiology suggest that crested wheatgrass would have a minimal impact on purple threeawn production and mortality in our study. Additionally, these factors would affect plant response to the hot and dry post-fire conditions experienced during the 2012 growing season of our study. Purple threeawn has a high root:shoot ratio (Perkins and Owens 2003) and appears to be relatively resistant to drought (Fowler 1984), indicating that hot and dry weather would have a limited detrimental impact on purple threeawn. Additionally, a previous study conducted in the same area showed summer fire and fall fire reduced purple threeawn basal cover substantially, regardless of whether post-fire growing season precipitation was above or below average (Strong *et al.* 2013).

Prescribed fire is one of many vegetation management tools at the disposal of grassland managers. The propensity of fire to reduce tiller production of purple threeawn, as well as of other *Aristida* species, suggests that fire could be used to improve community diversity in *Aristida*-dominated plant communities on semi-arid land worldwide. In the northern Great Plains, purple threeawn is rarely utilized by cattle due to poor forage quality relative to other species in the area. Along with fire-related reductions of purple threeawn, fire should increase the overall palatability of purple threeawn by removing the awns and litter associated with purple threeawn. The apparent sensitivity of purple threeawn and resilience of prominent native species to summer fire (Vermeire et al. 2011, Strong *et al.* 2013) offers opportunities for using summer fire to improve community composition. Additionally, heat dosage and duration were better predictors of purple threeawn mortality than maximum temperature. With that information, managers can implement prescribed fire to purple threeawn-dominated plant communities under conditions that will maximize heat dosage and duration, thus increasing purple threeawn mortality. Our study is one example of how measuring certain fire variables can enhance our understanding of plant response to fire. As fire research progresses in rangeland ecosystems, detailed fire measurements coupled with environmental data can help us identify the factors influencing plant or community response and improve the efficacy of prescribed fire as a vegetation management tool.

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