RESEARCH ARTICLE

CHARACTERISTICS OF BURNS CONDUCTED UNDER MODIFIED PRESCRIPTIONS TO MITIGATE LIMITED FUELS IN A SEMI-ARID GRASSLAND

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ABSTRACT

In semi-arid grasslands of the North American Great Plains, fire has traditionally been viewed as having few management applications, and quantitative measurements of fire behavior in the low fuel loads characteristic of this region are lacking. More recently, land managers have recognized potential applications of prescribed fire to control undesirable plant species and to manage habitat for wildlife in this region. Working in the shortgrass steppe of northeastern Colorado over a 7-year period, we quantified peak temperatures, heating duration, and heat dosage produced near ground level during prescribed burns conducted under a wide range of fuel loads and weather conditions. We use an information theoretic approach to develop models that predict peak temperature and heat dosage as a function of weather parameters and fuel loads. Under the weather conditions that we examined, successful burns (>80% of target area burnt) occurred with fuel loads varying from 350 kg ha^{-1} to 1175 kg ha^{-1}, while burns with fuel loads <350 kg ha^{-1} generally failed to spread and burned less than 60% of

RESUMEN

En los pastizales semiáridos de las grandes planicies de Norteamérica, el fuego no ha sido contemplado tradicionalmente como una herramienta adecuada para la gestión del territorio, y no existen mediciones cuantitativas sobre su comportamiento. Recientemente, los gestores del territorio han reconocido las aplicaciones potenciales de las quemas prescritas para controlar especies indeseables y gestionar el hábitat para la fauna silvestre de la región. Trabajando en la estepa de pastos cortos del noreste de Colorado durante un periodo de 7 años, cuantificamos los picos de temperatura, duración del calentamiento y el calor recibido en las cercanías del suelo durante quemas prescritas conducidas bajo un amplio rango de cargas de combustibles y condiciones meteorológicas. Usamos para ello información desde una aproximación teórica para desarrollar modelos que predicen los picos de temperatura y la dosis de calor recibido en función de parámetros meteorológicos y de carga de combustibles. Bajo las condiciones meteorológicas examinadas, las quemas más exitosas (>80% del área objetivo quemada) ocurrieron cuando las cargas de combustibles variaron entre 350 y 1175 kg ha^{-1}, mientras que aquellas con cargas de combustible menores <350 kg ha^{-1} generalmente no se propagaban, quemando menos del 60% del área prescrita. Los picos de temperatura, la duración del calor, target areas. Peak temperatures, heat duration, and heat dosage during shortgrass burns: 1) were lower than reported for mixed grass prairies, 2) increased linearly with increasing fuel loads, and 3) were secondarily influenced by wind speed, ambient air temperature, and relative humidity. Compared to desert grassland, heat doses near the ground surface were similar, but peak temperatures were lower and heat duration longer in shortgrass steppe burns. Our findings provide quantitative predictions for heat production from fires in shortgrass steppe near the ground surface, where most plant meristems are located. Based on these relationships, we provide suggestions for burn prescriptions to achieve goals such as reducing abundance of undesirable plant species and providing habitat for native grassland birds.

y las dosis de calor recibido durante las quemas en esta estepa de pastos cortos fueron: 1) menores que aquellos reportados para las praderas de pastos mixtos, 2) se incrementaron linealmente con aumentos en la carga de combustibles, y 3) fueron influenciados de manera secundaria por la velocidad del viento, la temperatura ambiente, y la humedad relativa. Comparado con el pastizal de desierto, las temperaturas alcanzadas cerca de la superficie del suelo fueron similares, aunque los picos de temperatura fueron menores y la duración del calentamiento fue mayor en las quemas realizadas en la estepa de pastos cortos. En los incendios que ocurren en esta estepa, nuestros resultados permiten predecir cuantitativamente la producción de calor en las cercanías del suelo, donde están ubicados la mayoría de los meristemas de crecimiento. Basados en esas relaciones, brindamos sugerencias para quemas prescritas para lograr metas tales como reducir la abundancia de especies no deseables y proveer de habitat a los pájaros que habitan en esa estepa.

Keywords: *Bouteloua gracilis*, fire temperature, grassland, *Gutierrezia sarothrae*, heat dosage, heat duration, *Opuntia polyacantha*, semi-arid rangeland, western Great Plains

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INTRODUCTION

Fire is widely recognized as an important ecological disturbance process and management tool in grasslands of the North American Great Plains, but most research and management applications related to fire have focused on the more mesic and productive grasslands in the region (Wright and Bailey 1982, Anderson 2006, Fuhlendorf *et al.* 2009). In the western, semi-arid regions of the Great Plains, fire was historically viewed as having few management applications, and most early research was based on *post hoc* measurements from wildfires (reviewed by Wright and Bailey 1982 and Schientaub *et al.* 2009). Furthermore, semi-arid grasslands, particularly those with mean annual precipitation less than 400 mm, have been characterized as having fuel loads too low to allow for use of prescribed fire (Oesterheld *et al.* 1999). Over the past 25 years, however, rangeland managers have increasingly recognized the potential value of prescribed fire in the western Great Plains for management of particular plant species (McDaniel *et al.* 1997, 2000; Ansley and Castellano 2007; Vermiere and Roth 2011; Strong *et al.* 2013) and for wildlife habitat management (Augustine *et al*. 2007, Thompson *et al.* 2008, Augustine and Derner 2012).

Despite renewed interest in prescribed fire in the western Great Plains and increased use on public lands in the region, information on relationships between fuel loads, weather conditions, and the behavior of prescribed burns is relatively sparse. Previous studies have quantified heat production during prescribed burns in more mesic mixed grass and tallgrass prairies, where fuel loads are typically >1500 kg ha^{-1} (e.g., Stinson and Wright 1969, Ewing and Engle 1988, Strong *et al.* 2013), whereas quantitative relationships between fuel loads, weather, fire temperatures, and heat dosage have not been reported for the shortgrass steppe, where fuel loads are typically less than 1000 kg ha^{-1} (Milchunas *et al.* 1994). Early prescriptions for low-volatile fuels suggested burning with air temperatures of 21 °C to 27 °C, relative humidity of 20 % to 40 %, and winds of 3.6 m sec^{-1} to 6.5 m sec^{-1} (Wright and Bailey 1982), but were not specific to grasslands with low fuel loads. Based on work in desert grasslands of central New Mexico, USA, McDaniel *et al.* (1997, 2000) recommended modifying burn prescriptions in desert grasslands to occur with air temperatures of 22 °C to 28 °C, relative humidity of only 10 % to 20 %, winds of 3 m sec^{-1} to 8 m sec^{-1}, and fuel loads >500 kg ha^{-1}. Prescribed burns under these conditions achieved heat dosages (calculated as area under the time-temperature curve using a baseline of 0 °C) on the order of 10 000 °C·sec to 16 000 °C·sec, which in turn induced mortality of undesirable subshrubs (McDaniel *et al.* 1997). Studies are needed to examine burn characteristics under modified prescriptions that include lower relative humidity and higher temperatures than are typical of burns in mesic grasslands.

Here we report on prescribed burns conducted in the shortgrass steppe of northeastern Colorado, USA, over a 7-year period (2007 to 2013) that included burning under a wide range of weather conditions, fuel loads, and seasons. We used thermocouples to measure fire temperatures near the soil surface and calculated associated heat duration and dosage. We measured temperatures near the soil surface because plant meristems in the shortgrass steppe are primarily located near the ground surface. Direct effects of fire on grassland plants are most likely to be associated with heat production near the plant meristems, and understanding variability in relevant measures of heat production during prescribed fires is essential for understanding and predicting effects on plant populations and communities (Keeley 2009, Pyke *et al.* 2010, Vermiere and Roth 2011, Russell *et al.* 2013). Our objectives were to: (1) identify fuel and weather conditions that impede fire spread and effectively prevent implementation of prescribed burns, and (2) evaluate the relative influence of fuel loads, air temperature, wind speed, and relative humidity on peak temperatures, heat duration, and heat dosage near the ground surface.

METHODS

Study Area

Burns were conducted in native shortgrass steppe at the USDA-Agricultural Research Service's Central Plains Experimental Range (CPER), approximately 12 km northeast of Nunn, Colorado, USA (40° 50' N, 104° 43' W). Mean annual precipitation is 340 mm and topography is characterized by gently undulating plains. All study sites were located on fine sandy loam soils associated with the Loamy Plains ecological site (NRCS 2007). Two C_4 perennial grasses, blue grama (*Bouteloua gracilis* [Willd. ex Kunth] Lag ex Griffiths) and buffalograss (*B. dactyloides* [Nutt.] J.T. Columbus) dominate the vegetation (typically >70 % of annual net primary production). C_3 plants consisted primarily of the perennial gramminoids needleleaf sedge (*Carex duriuscula* C.A. May) and western wheatgrass (*Pascopyrum smithii* [Rydb.] A. Love), and the perennial forb scarlet globemallow (*Sphaeralcea coccinea* [Nutt] Rydb.).

Prescribed Burns

Burns occurred at two different locations, each of which had a different spatial scale. Hereafter, we refer to the first location as the small-scale burns, and the second location as the large-scale burns. Small-scale prescribed burns occurred in a set of 20 400 m^2 plots established in 2006 in upland shortgrass steppe that had not been grazed by livestock for the previous five years, and remained ungrazed throughout the study period. Four prescribed burn treatments with four replicate plots per treatment were implemented during 2006 to 2013, consisting of: (1) plots burned annually in late March or early April, (2) plots burned annually in October or November, (3) plots burned once every three years in late March or early April, and (4) plots burned once every three years in October or November. Hereafter we refer to these as annual spring, annual fall, triennial spring, and triennial fall burns, respectively. Spring burns occurred prior to any green-up in the dominant grass species, blue grama, and fall burns occurred after complete senescence of aboveground blue grama biomass. For each burn, we established a wetline on the two downwind boundaries, initiated backburns to create 1 m to 2 m wide blacklines on these boundaries, and then burned the remainder of the plot with a headfire lit with hand-held drip torches from the upwind boundaries. Plant responses to the burns conducted during 2006 to 2007 are reported by Schientaub *et al.* (2009). The four plots within a given treatment were always burned on the same afternoon, within a period of approximately two hours. In years in which both annual and triennial burns occurred, all eight plots were burned on the same afternoon. Although annual and triennial burns of the same season occurred under the same weather conditions, they differed in terms of fuel loads and hence were considered separately in analyses. Prior to each burn, fuel loads were measured by harvesting all standing plant biomass within two randomly located 0.25 m^2 quadrats in each plot. Litter, which we define as detached biomass lying on the ground surface, was not measured. During each burn, we measured temperatures of the headfire using six glass-insulated, Omega type-J wire thermocouples over-braided with stainless steel. Thermocouples were placed 1 cm above ground level and attached to dataloggers that recorded temperature at 1 sec intervals (Jacoby *et al.* 1992). During each burn, we also recorded mean wind speed, relative humidity, and air temperature. For analyses, we calculated mean weather parameters, fuel load, and temperature responses across all four replicate burns within a given treatment. No temperatures were recorded in 2006 or 2007, and no data from those burns are included here. During 2008 to 2013, we conducted a total of 60 prescribed burns on these plots under 15 different weather and fuel load conditions.

Large-scale prescribed burns were conducted in three replicate 65 ha pastures during the fall (October or November) each year during 2007 to 2010. We burned one quarter (16 ha) of each pasture each year in a rotation, with a different quarter burned each year. Pastures were grazed by cattle at a moderate stocking rate of 0.65 animal unit months (AUM) per hectare during May to October of each year, which is the stocking rate at which these pastures had been grazed in years prior to initiation of the burn study. (See Augustine and Derner [2014] for effects of this prescribed burn program on cattle foraging distribution and weight gain.) The three replicate burns were conducted on the same afternoon each year, using the same methods as the small-scale burns, except with wider blacklines. Prior to each burn, fuel loads were measured by harvesting all standing plant biomass within ten randomly located 0.25 m^2 quadrats in each burn site. During each burn, we again measured temperatures of the headfire with 6 Omega type-J thermocouples placed 1 cm above ground level and attached to dataloggers that recorded temperature at 1 sec intervals. During 2007 to 2010, we conducted a total of 12 prescribed burns in these pastures under four different weather and fuel load conditions.

Statistical Analysis

Based on the curves of temperature versus time for each thermocouple, we calculated heat duration as the number of seconds that temperature was above 60 °C (McDaniel *et al.* 1997, Strong *et al.* 2013). Heat dosage was calculated based on the temperatures measured during the interval when the temperature exceeded 60 °C. However, we recognized that authors of previous studies have used different baselines when calculating heat dosage. To compare our measurements to prior work in desert grassland (McDaniel *et al.* 1997, 2000), we calculated heat dosage as the sum of temperatures each second when temperatures were above 60 °C. In this calculation, if the temperature reached 61 °C for 1 second and was 60 °C or below for all other seconds, then the heat dose$_0$ was 61 °C·sec; we refer to this as "heat dose$_0$" to designate that the baseline was 0 °C. To compare our measurements to prior work in mixed grass prairie (Vermiere and Roth 2011, Strong *et al.* 2013), we also calculated heat dosage as the sum of difference between the temperature and 60 °C, for each second when temperature was above 60 °C. In this calculation, if the temperature reached 61 °C for 1 second and was 60 °C or below for all other seconds, then heat dose$_{60}$ is 1°C·sec; we refer to this as "heat dose$_{60}$" to designate that the baseline was 60 °C. All heat dosage calculations were based on a 1-second temporal resolution.

We fit a suite of generalized linear models that predicted mean peak fire temperature, mean heat duration, and mean heat dose as a function of fuel loads and weather parameters. In addition, we examined the potential effect of scale of the burns in the suite of possible models in which scale was a categorical predictor (0 = small-scale burns; 1 = large-scale burns). We expected that wind speed could potentially have a non-linear effect on both response variables, in which temperature and heat dose could decline either when winds are too low or too high, so we considered first- and second-order parameters for wind speed in the suite of possible models. The second order parameter was (observed windspeed – mean windspeed)^2, in which mean windspeed averaged across all burn trials was 4.06 m sec^{-2}. With a total of six potential model parameters (fuel load, air temperature, wind speed, [wind speed – 4.06]^2, relative humidity, and scale of burn) we fit all of the 64 different possible models.

We used an information theoretic approach for model selection (Anderson 2008), in which we calculated Akaike's Information Criteria with a correction for small sample size (AICc) for each model. We then calculated the difference in AICc between each model and the model with the lowest AICc (ΔAICc), and calculated the associated Akaike weight for each model (Burnham and Anderson 2002). We used model averaging to estimate parameters for our final model, in which we calculated a weighted average for each parameter based on the subset of models that cumulatively comprised 95 % of the Akaike weights (Burnham and Anderson 2002). This approach allowed us to address the fact that several different models had strong and relatively similar empirical support. Rather than having to decide which was the "best model," model averaging allowed us to use the information in each of the top models to derive a final model that best predicts fire temperatures based on all available data (Anderson 2008).

RESULTS

Over the 7-year study period, we conducted burns with fuel loads varying from 97 kg ha^{-1} to 1175 kg ha^{-1} of standing herbaceous biomass, and recorded mean peak temperatures near ground level that varied from 60 °C to 187 °C (Figure 1). For the three sets of

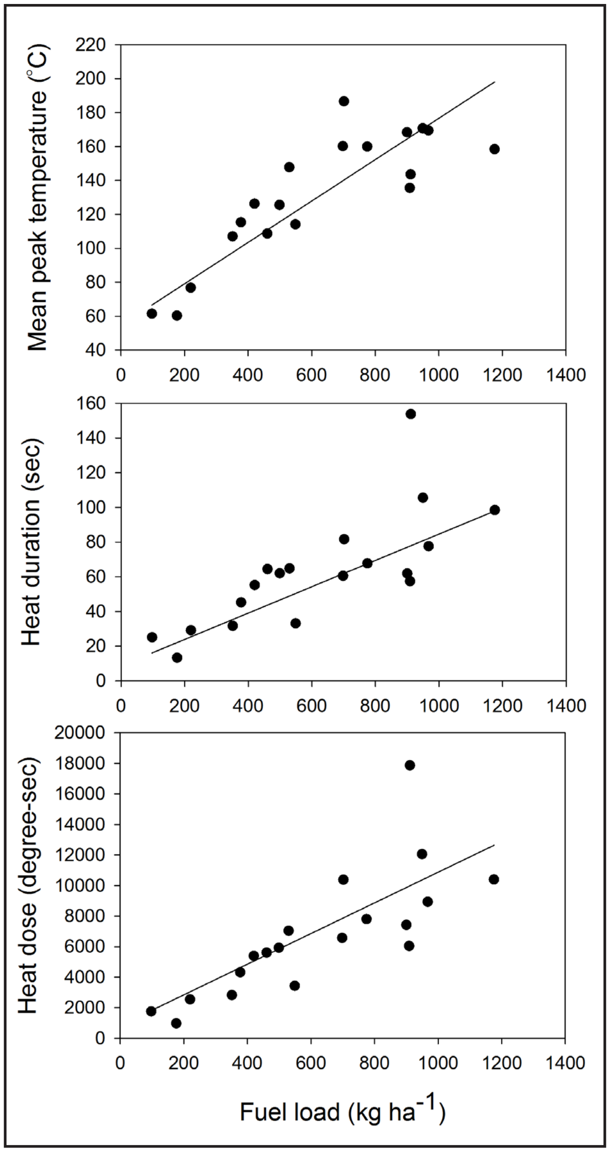

Figure 1. Mean peak temperature (°C), mean heat duration (seconds above 60 °C), and heat dose (°C·sec, calculated with a baseline of 0 degrees) measured 1 cm above ground level as a function of variation in fuel loads for prescribed burns in the shortgrass steppe of northeastern Colorado during 2007 to 2013. Lines show predictions based on the fuel load coefficient in fitted models reported in Table 2.

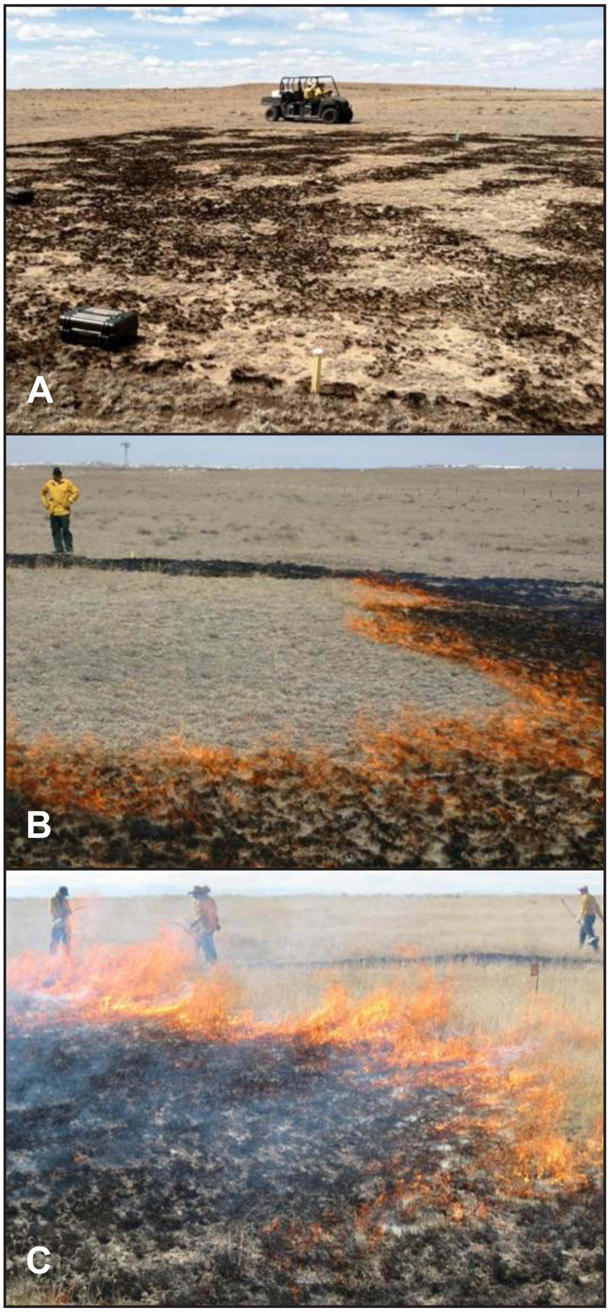

Figure 2. Examples of flame lengths and patchiness in burned areas associated with prescribed burns conducted with fuel loads of: (A) <350 kg ha^{-1}, (B) 350 kg ha^{-1} to 600 kg ha^{-1}, and (C) 700 kg ha^{-1} to 1000 kg ha^{-1} in the shortgrass steppe of northeastern Colorado.

burns conducted with fuel loads less than 350 kg ha^{-1}, the fires failed to carry across portions of the target area, resulting in only 42 % to 58 % of the thermocouples being burnt (Figure 2A). These percentages based on the thermocouples were similar to our visual estimates of the percent of the target area burnt. In the patches that did burn with extremely low fuel loads (i.e., <350 kg ha^{-1}), flame lengths were consistently less than 0.5 m and typically only 10 cm to 20 cm.

For burns conducted with fuel loads ≥350 kg ha^{-1}, burns were consistently successful in carrying across all or most of the target area. For 12 out of 16 of the sets of burns with fuels ≥350 kg ha^{-1}, the burns were homogeneous; 100 % of thermocouples burned and we visually estimated that close to 100 % of the target areas burned (Table 1). In the remaining four sets of burns, we visually estimated that ≥80 % of the target areas burned, and found that 83 % to 96 % of the thermocouples placed in the target areas burned. One set of burns was conducted with mean fuel loads of 350 kg ha^{-1} and relatively ideal weather conditions (see Table 1) that resulted in flames carrying successfully across the plots; we visually estimated that 85 % to 90 % of the plots were burned, and 83 % of thermocouples burned. However, these burns at fuel loads averaging 350 kg ha^{-1} produced very low heat duration and heat dosage (Table 1; Figure 1). This represents approximately the lowest fuel load in which burns can carry through blue grama-dominated grassland. The least homogeneous burn pattern in fuel loads ≥350 kg ha^{-1} occurred when we conducted three large-scale burns on 7 November 2008; we visually estimated that approximately 80 % of the target areas burned. These burns were conducted with high relative humidity (33 % to 38 %), high wind speeds (9 m sec^{-1} to 11 m sec^{-1}), and low ambient temperatures (9 °C to 11 °C). We returned to these sites two weeks later when relative humidity was lower (17 % to 24 %), winds were moderate (6 m sec^{-1} to 8 m sec^{-1}), and ambient temperatures greater (15 °C to 18 °C), and found that patches of grassland that had not burned previously were now able to carry the fire.

Mean peak temperature, heat duration, and heat dose were all most strongly correlated with fuel loads (Figures 1 and 2; Table 2). Weather parameters also influenced fire temperature, heat duration, and heat dose, but over the range of the conditions in which our burns occurred, the influence of fuel load was 3.4 times (for peak temperature) to 5.6 times (for heat dosage) greater than the influence of any weather parameter (Table 2). For both peak temperature and heat duration, wind speed was the most important weather influence, followed by ambient air temperature (Table 2). For heat dosage, however, air temperature became the most important weather parameter, followed by wind speed (Table 2). After accounting for wind speed and air temperature, relative humidity had only a minor influence on any of the heat production measures (Table 2). We caution that this finding reflects the fact that most burns occurred with low relative humidity (8 % to 20 %), and the only time when we burned with relative humidity greater than 30 % was also under conditions of high wind speed and low ambient temperature (Table 1). For all measures of heat production, the scale of the burn had only a minor influence, with larger burns producing slightly higher peak temperature and slightly lower heat duration and dosage than small burns (Table 2).

Models included non-linear terms for wind speed, indicating that fire temperature and heat dosage declined at both low and high wind speeds (Table 2 and Figure 3). Maximum predicted peak fire temperatures occurred with wind speeds of 8 m sec^{-1} to 10 m sec^{-1}, whereas maximum predicted heat dose occurred with wind speeds of 2 m sec^{-1} to 4 m sec^{-1} (Figure 3).

DISCUSSION

Our results show that prescribed fires can be successfully conducted in shortgrass steppe with standing herbaceous biomass ≥350 kg ha^{-1} under appropriate weather conditions. For fuel loads of 350 kg ha^{-1} to 550 kg ha^{-1}, which are characteristic of years with average precipitation (340 mm at our study site) and moderate cattle stocking rates, temperatures near ground level ranged from approximately 110 °C to 150 °C, and heat durations varied from 40 sec to 77 sec. For fuel loads of 700 kg ha^{-1} to 1000 kg ha^{-1}, which occurred following growing seasons with above-average

Table 1. Summary of fuel load, weather conditions, and measurements of heat during prescribed burns conducted in native shortgrass steppe at the Central Plains Experimental Range in northeastern Colorado. Each row represents the mean of 3 or 4 burns conducted on the same day. TC = thermocouple, RH = relative humidity.

Year	Season	Fuel load (kg ha^{-1})	Air temp (°C)	Mean wind speed (m sec^{-1})	RH (%)	Scale	Mean peak temp. (°C)	Max. peak temp. (°C)	Mean sec >60 °C	Min. sec >60 °C	Max. sec >60 °C	Mean heat dose$_{60}$ (°C sec)[a]	Mean heat dose$_0$ (°C sec)[b]	Min. heat dose$_0$ (˚C sec)	Max. heat dose$_0$ (˚C sec)	TCs (*n*)	TCs burned (%)
2007	Fall	698	20.2	7.8	6.9	16 ha	160.2	202.8	61	32	84	2 943	6 573	2 651	9 488	18	100
2008	Spring	499	11.1	3.8	12.0	400 m^2	125.6	175.4	62	10	115	2 202	5 922	723	10 666	24	100
2008	Fall	549	11.0	10.8	33.6	16 ha	114.1	206.7	33	0	67	1 440	3427	0	8 844	18	83
2008	Fall	4 600	19.7	3.3	24.0	400 m^2	108.7	157.3	65	33	124	1 732	5 602	2 022	11 379	24	100
2009	Spring	420	18.9	5.2	8.8	400 m^2	126.3	168.4	55	29	105	2 083	5 396	2 005	9 591	24	100
2009	Spring	530	18.5	5.1	8.5	400 m^2	147.8	195.1	65	41	89	3 149	7 039	3 599	12 105	24	100
2009	Fall	1 175	10.8	2.7	13.7	16 ha	158.4	210.7	98	58	145	4 489	10 396	5 162	16 092	18	100
2009	Fall	967	18.6	2.7	12.5	400 m^2	169.5	207.7	78	29	101	4 273	8 934	2 047	11 607	24	100
2009	Fall	949	17.9	3.4	12.3	400 m^2	170.7	215.6	106	51	152	5 720	12 054	4 018	20 565	24	100
2010	Spring	909	16.9	2.5	10.0	400 m^2	135.6	193.9	57	0	80	2 594	6 037	0	10 804	24	96
2010	Fall	911	22.6	1.9	26.7	16 ha	143.6	261.1	154	103	209	8 640	17 865	12 064	25 049	18	100
2010	Fall	775	25.1	3.4	19.4	400 m^2	159.9	193.2	68	34	94	3 738	7 803	3 019	12 238	24	100
2011	Spring	900	19.3	1.4	20.2	400 m^2	168.4	208.9	62	29	92	3 713	7 425	3 348	11 253	24	100
2011	Fall	351	17.8	5.1	9.8	400 m^2	107.1	144.3	32	0	52	925	2 828	0	5 579	24	83
2012	Spring	378	18.3	4.4	14.8	400 m^2	115.4	136.0	45	0	58	1 603	4 316	0	5 885	24	96
2012	Spring	702	18.8	4.2	14.3	400 m^2	186.7	264.7	82	55	105	5 483	10 383	5 440	16 399	24	100
2012	Fall	176	16.3	3.0	26.8	400 m^2	60.3	89.5	13	0	64	173	970	0	5 315	24	42
2012	Fall	219	16.7	2.9	27.5	400 m^2	76.8	125.2	29	0	121	796	2 543	0	15 639	24	58
2013	Spring	97	19.2	3.7	11.5	400 m^2	61.5	85.8	25	0	105	254	1 759	0	7 013	24	54

[a] Calculation comparable to Vermiere and Roth (2011) and Strong *et al.* (2013).

[b] Calculation comparable to McDaniel *et al.* (1997, 2000).

Table 2. Parameter estimates and standard errors for generalized linear models predicting mean peak fire temperature (°C), heat duration (seconds above 60 °C), and heat dosage$_0$ (°C·sec; calculated with a baseline of 0 degrees) as a function of fuel load, wind speed, air temperature, relative humidity, and scale of the burn (0 = small scale, 1 = large scale) in shortgrass steppe of northeastern Colorado. The magnitude of effect for each parameter refers to the difference between the predictions for the maximum versus minimum value of that parameter.

Model parameter	Units	Range evaluated			Peak temperature (°C)			Heat duration (sec)			Heat dose$_0$ (°C·sec)		
		Min.	Mean	Max.	Parameter estimate	1SE	Effect size	Parameter estimate	1SE	Effect size	Parameter estimate	1SE	Effect size
Intercept					18.90			11.3			–1547.8		
Fuel load	kg ha^{-1}	97	614	1 175	0.12	0.01	131.4	0.08	0.02	81.9	10.0	2.0	10 819
Wind speed	m sec^{-1}	1.35	4.06	10.82	6.10	2.39	37.8	–0.41	1.30	24.9	–43.4	125.8	1 414
(Wind – 4.06)^2	m sec^{-1}				–0.56	0.42		–0.49	0.38		–24.3	33.6	
Air temperature	°C	10.8	17.8	25.1	0.78	0.68	11.0	0.58	0.73	8.3	136.1	108.1	1 932
Relative humidity	%	6.9	16.5	33.5	–0.17	0.28	4.5	0.09	0.27	2.3	8.8	30.5	233
Scale	(0,1)	0		1	7.52	4.43	7.5	–5.67	4.64	–5.7	–327.2	445.2	327

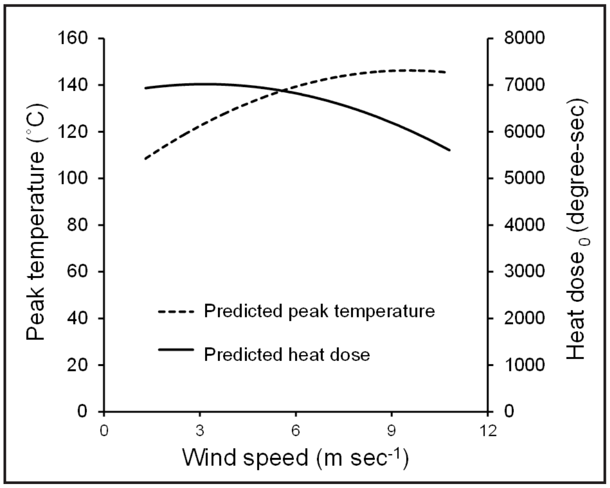

Figure 3. Predicted peak temperatures and heat doses for prescribed burns in shortgrass steppe of northeastern Colorado as a function of wind speed, based on models in Table 2.

precipitation, peak temperatures ranged from 136 °C to 187 °C and heat durations were notably greater, varying from 68 sec to 116 sec. As expected, peak temperatures in these shortgrass steppe burns were considerably lower than temperatures reported for northern and southern mixed grass prairies, where fuel loads are typically >1500 kg ha^{-1} (Stinson and Wright 1969; Strong *et al.* 2013). Heat dosages of our shortgrass steppe burns were similar to findings for desert grasslands of New Mexico (McDaniel *et al.* 1997), but the shortgrass steppe burns tended to have lower peak temperatures and longer heat duration. Although early fire prescriptions recommended burning when relative humidity is above 20 % (Wright and Bailey 1982), both our work and that of McDaniel *et al.* (1997) indicate that prescribed burns in arid and semi-arid grasslands with low fuel loads (<1000 kg ha^{-1}) can be more effectively conducted with lower relative humidity (10 % to 20 %) combined with air temperatures above 16 °C. Peak temperatures can be maximized by burning under higher wind speeds (8 m sec^{-1} to – 10 m sec^{-1}), whereas heat duration and heat dosage are maximized at lower wind speeds (2 m sec^{-1} to 4 m sec^{-1}; Figure 3).

Although we did not examine plant mortality in our burns, several previous studies have shown a close link between heat dosage and mortality of particular plant species that are commonly found in the shortgrass steppe. Based on prescribed burning studies in desert grassland of New Mexico, McDaniel *et al.* (1997) found that broom snakeweed (*Gutierrezia sarothrae* [Pursh] Britton and Rusby), which is an unpalatable subshrub that can be toxic to livestock, experiences substantial mortality when heat dose_0 of prescribed burns exceeds 10 000 °C·sec. In shortgrass steppe of Colorado, Augustine and Milchunas (2009) also found significant mortality of broom snakeweed in response to prescribed burns, but did not quantify burn conditions. To the extent that broom snakeweed mortality in shortgrass steppe is also optimized when heat dose_0 exceeds 10 000 °C·sec, this can be achieved by burning in fuel loads that exceed 700 kg ha^{-1} with wind speeds of 2 m sec^{-1} to 4 m sec^{-1}, ambient air temperatures above 16 °C, and relatively humidity below 30 %.

Prescribed fire can also be used to control prickly pear cactus (*Opuntia polyacantha* Haw.) in Great Plains rangelands (Bunting *et al*. 1980, Ansley and Castellano 2007, Augustine and Milchunas 2009, Vermiere and Roth 2011). Prickly pear cactus can be abundant in portions of the shortgrass steppe (Milchunas *et al.* 1989), which often is a concern for livestock producers. Although prickly pear does not suppress grass production, the spines prevent cattle from consuming grasses growing in close proximity, which can substantially reduce forage available to livestock (Bement 1968). Mortality rates of prickly pear cactus can be strongly influenced by weather conditions during burns (Ansley and Castellano 2007), which can be explained by variation in heat produced. Vermiere and Roth (2011) showed that prickly pear mortality rates increase as a function of the duration and heat dose generated during burns, with estimates of mortality quadrupling from ~0.2 to 0.8 as heat duration increases from 60 sec to 360 sec. Heat duration exceeding 60 sec during our shortgrass steppe burns occurred with fuel loads >530 kg ha^{-1}, and were optimized under the weather conditions described above for control of broom snakeweed. Furthermore, past studies have shown that prescribed burning under these conditions does not suppress productivity or induce mortality in dominant grass species (blue grama and western wheatgrass), provided that burns occur when grasses are dormant (Augustine and Milchunas 2009, Schientaub *et al.* 2009, Augustine *et al.* 2010).

Another motivation for using prescribed burns in the shortgrass steppe is to create nesting habitat for the mountain plover (*Charadrius montanus*) (Augustine and Derner 2012), which is a grassland bird of significant conservation concern in the western Great Plains (Knopf and Wunder 2006). Because the primary objective of burns to enhance habitat for this species is to simply reduce vegetation height and increase exposure of bare soil over a large area (Augustine and Derner 2012), our findings suggest that burning with fuel loads >350 kg ha^{-1} can achieve this goal. At the lower end of this range (350 kg ha^{-1} to 420 kg ha^{-1}), burns occurred under relatively ideal weather conditions with wind speeds of 4 m sec^{-1} to 5 m sec^{-1}, relative humidity of 8 % to 15 %, and air temperature >15 °C. At higher fuel loads (>450 kg ha^{-1}), homogeneous burns can be achieved under a wider range of weather conditions. Our model predictions cannot be extrapolated to semi-arid grasslands dominated by plant species that differ in canopy structure and fuel connectivity from the shortgrass steppe. However, we suggest that burn prescriptions in semi-arid grasslands can generally mitigate for low fuel loads through modified weather conditions that include lower relative humidity and higher air temperatures than has typically been recommended for prescribed burning in low-volatile fuels.

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